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Workshop on Helicopter Health and Usage Monitoring Systems, Melbourne, Australia, February 1999

Graham F. Forsyth (Editor)

DSTO-GD-0197

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

Over the last 10 years, helicopter Health and Usage Monitoring Systems (HUMS) have moved from the research environment to being viable systems for fitment to civil and military helicopters. In the civil environment, the situation has reached the point where it has become a mandatory requirement for some classes of helicopters to have HUMS fitted. Military operators have lagged their civil counterparts in implementing HUMS, but that situation appears set to change with a rapid increase expected in their use in military helicopters.

A DSTO-sponsored Workshop was held in Melbourne, Australia, in February 1999 to discuss the current status of helicopter HUMS and any issues of direct relevance to military helicopter operations.
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Contents

1. Introduction

Helicopters have a higher rate of accidents due to technical causes than public transport, fixed-wing aircraft so it should come as no surprise that equipment capable of detailed monitoring of critical helicopter functions is now routinely fitted to medium-sized and larger helicopters used by civil operators. This equipment is usually referred to by the name "Health and Usage Monitoring Systems" (HUMS) although most of the HUMS in service concentrate mainly on assessing the health of the helicopter and have only rudimentary usage monitoring.

Military operators have been slower than civil operators to implement HUMS in their fleets. However, there are good reasons for this. Military helicopters, in general, are operated at a much lower rate of effort (ROE), expressed as flight hours per year, and are kept in service for a much longer period. Military operators also have less need to minimize training and test flying than civil operators since these types of flying may be regarded by the military as a legitimate function rather than as a deviation from the main purpose. These factors mean that, although current HUMS may show similar rates of return for both military and civil helicopters, when expressed as return per unit flying time, military operators have a lower rate of return than civil operators per unit of calender time.

This difference means that military operators are showing more interest in improving the usage monitoring component of these systems.

It is noticeable that the amount of time by which military operators lagged their civil counterparts in installing accident data recorders is much greater than that for the installation of HUMS.

The following papers were presented at a Workshop coordinated by the Airframes and Engines Division of DSTO Aeronautical and Maritime Research Laboratory in Melbourne, Australia, on February 16 and 17, 1999. Papers were presented by authors from HUMS manufacturers, research institutions, helicopter operators, and other parties. Most of the papers presented at the Workshop have been included in this document, in the format provided by their respective authors. Some papers, however, were not available for inclusion at the time of publication.

2. Acknowledgments

The Helicopter Health and Usage Monitoring System (HUMS) Workshop was arranged via a committee comprising:-

Graham Forsyth, as convenor,
Neil Kennedy, representing RAAF Williams,
Paul Marsden,
Graeme Messer,
Luther Krake, and
Bill Clark (who is on secondment from the US Navy)

3. Preliminary Timetable as at 22nd January, 1999.

The following preliminary timetable was prepared on behalf of the HUMS Workshop committee by Graeme Messer.

Time	Day 1 - Tuesday 16 February		
0830 - 0900	Registration		
0900 - 0915	Official Welcome		
0915 - 0955	**John Gill** **Rick Muldoon**	BFGoodrich US Navy	Integrated Mechanical Diagnostics (IMD) HUMS
0955 - 1020	**David Horsley**	RAF AMDS, UK	Introduction of HUMS into the RAF
1020 - 1035	**Keith Mowbray**	Helitune, UK	"Modular Distributed HUMS - an Overview"
1035 - 1100	Morning Tea Break		
1100 - 1140	**Charles Trammel,** Gerald Vossler	Smiths Industries	"UK Ministry Of Defence Health and Usage Monitoring System (HUMS)"
1140 - 1210	**Pierre Feraud**	Eurocopter, France	"Commitments of the Helicopter Manufacturer Regarding HUMS Activities"
1210 - 1235	**J. Bird,** M. Mulligan, D. Little	NRC/IAR/SMPL DND/ATESS Canada	"Developments in Non-intrusive Diagnostics for Engine Condition Monitoring"
1235 - 1335	***Lunch***		
1335 - 1440	***AMRL Technical Site Tours (AOSC, HTTF, SETH)***		
1440 - 1510	**Larry Dobrin**	Chadwick-Helmuth, USA	"Health Monitoring of Helicopters - Applications and Achievements"
1510 - 1540	**David Blunt,** Peter O'Neill, Brian Rebbechi	AMRL, RAN-NALMS, AMRL	"Vibration Monitoring Of Royal Australian Navy Helicopters"
1540 - 1605	***Afternoon Tea Break***		
1605 - 1635	**C.J. (Nelis) Botes**	AMS, South Africa	"Health and Usage Monitoring System for the British Aerospace Military Aircraft and Aerostructures New Generation Hawk Lead-In-Fighter"
1635 - 1705	**Charlie Crawford**	GTRI, USA	"HH-60G Mission Usage Spectrum Survey Methodology Overview"
1705 - 1730	**Graham Forsyth**	AMRL	"An Econometric Model for HUMS Cost Benefit Studies"

Time	Day 2 - Wednesday 17 February		
0815 - 0830	*Registration for Wednesday-only attendees*		
0830 - 0850	**Brian Rebbechi**	AMRL	Machine Dynamics
0850 - 0930	**Jarek Rosinski**	Design Unit - Gear Technology Centre, Newcastle, UK	Gear Noise and Vibration – Research at UK Gear Technology Centre
0930 - 1000	**Robert Cant**	Vibro-Meter, UK	"ROTABS: Re-Writing the Manual on Rotor Track and Balance"
1000 - 1030	**Yujin Gao, R. B. Randall**	Uni of NSW	"Detection of Bearing Faults in Helicopter Gearboxes"
1030 - 1100	Morning Tea Break		
1100 - 1140	**John F. Reintjes**	NRL, USA	"LASERNET Machinery Monitoring Technology"
1140 - 1210	**Paul Howard,** John F. Reintjes	Paul L. Howard Ent. NRL, USA	"A Straw Man for the Integration of Vibration and Oil Debris Technologies"
1210 - 1225	**Grier McVea**	AMRL	Sensitivity of Oil Debris Monitor in S-70A-9 Intermediate GB.
1225 - 1325	*Lunch*		
1325 - 1430	*Rooivalk Inspection (subject to arrival of helicopter at 1300)*		
1430 - 1500	**C.J. (Nelis) Botes**	AMS, South Africa	"Health and Usage Monitoring System for the Denel Aviation Rooivalk Attack Helicopter"
1500 - 1515	**Ben Parmington**	AMRL	Oil Debris Rig Design
1515 - 1530	**Domenico Lombardo**	AMRL	"Helicopter Structural Usage Monitoring Work at DSTO Airframes and Engines Division"
1530 - 1555	*Afternoon Tea Break*		
1555 - 1625	**Alan Draper**	MOD PE, UK	"Fatigue Usage Monitoring in UK Military Helicopters"
1625 - 1705	**David J. White**	AeroStructures, USA	"Structural Usage Monitoring Using the MaxLife System"
1705 - 1725	**Peter Frith**	AMRL	Engine Gas Path Condition Assessment
1725 - 1735	*Closing Session*		
1900 - 1930	*Pre-dinner drinks - Observation Deck, Rialto on Collins*		
1930 - 2230	*Conference Dinner - Oriel Room, Rialto on Collins*		

Table 1. Preliminary Timetable for Both Days

4. Papers Included in this Document

The following pages contain either the paper or a copy, as two slides per page, of the PowerPoint[1] Presentations of those authors who supplied these in time for inclusion in this document. The presentations have been included in the order determined by the preliminary timetable of the previous section except as noted below.

[1] PowerPoint is a registered trademark of Microsoft Inc for software generating presentation slides.

Alan Draper	MOD PE, UK	"Fatigue Usage Monitoring in UK Military Helicopters"	* 153
David J. White	AeroStructures, USA	"Structural Usage Monitoring Using the MaxLife System"	167
Andrew J. Hess, **Bill Hardman**	NAWC AD, USA	"SH-60 Helicopter Integrated Diagnostic Systems (HIDS) Program Experience and Results of Seeded Fault Testing."	+ 181
J.W. Bird, M.F. Mulligan, J.D. MacLeod, Capt D Little	IAR/NRC, Canada; Canada National Defence	"Developments in Non-Intrusive Diagnostics for Engine Condition Monitoring"	^ 203
M.C Havinga, **C.J. Botes**	AMS, South Africa	"Health and Usage Monitoring System for the Hawk Aircraft"	^ 217

Table 2. Papers (with Page Numbers) in order of Preliminary Timetable

A small number of the authors were able to supply their paper as a Microsoft Word document. These have been included in full on the following pages and marked with an asterix against the page number in the table.

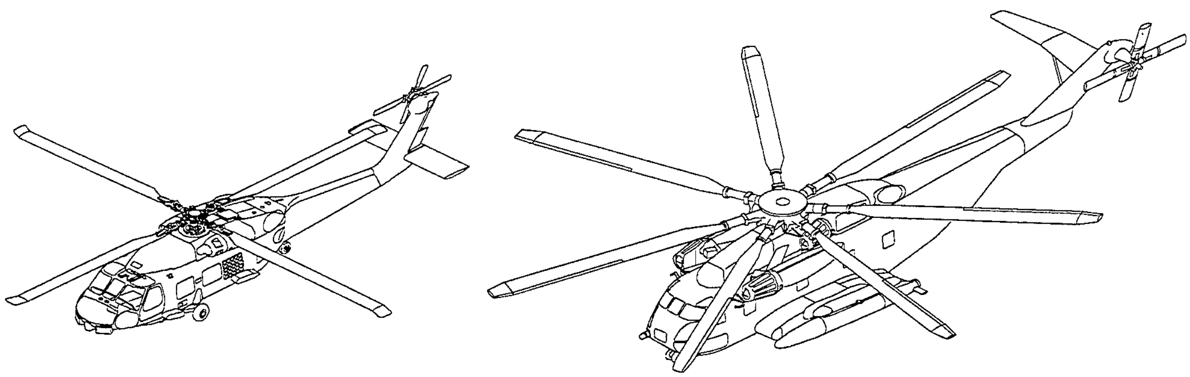
An additional paper has been accepted as a reserve (in case of cancellation or if the Rooivalk visit happens at a different time). This paper is marked + in the list above.

Two papers were received after the initial layout of this publication. They are included herein, but added to the end of the publication rather than in the correct order and marked with a ^ in the table. Other papers received after the cut-off may be copied separately but can not be included here.

BFGoodrich Aerospace
Aircraft Integrated Systems

Integrated Mechanical Diagnostics (IMD) Health Usage and Management System (HUMS)

John Gill, PhD, Site Manager
jgill@aisma.bfg.com, (781) 276-1412
Simulation and Algorithm Development Center
Bedford, Massachusetts



The United States Navy and United States Marines, in partnership with BFGoodrich Aerospace, have embarked upon an ambitious program to improve operational readiness and flight safety while slashing maintenance-related costs. That HUMS program is now on the cusp of an important milestone – installation of the first fully functional system on two aircraft types, the SH-60B support helicopter and the CH-53E cargo helicopter. The system has evolved under Joint Dual-Use Program Office's (JDUPO) Commercial Operations and Support Savings Initiative (COSSI) and is now referred to as IMD-HUMS. This paper presents the system's current state of evolution and outlines how the system will continue to evolve as we strive to achieve fleet-wide deployment. This paper will describe the components and processes that make up the fully functional and integrated system. It will also outline the near term implementation plan to prepare for eventual transition from initial installation to fleet-wide deployment.

The origins of this effort are documented in "SH-60 Helicopter Integrated Diagnostic System (HIDS) Program Experience and Results of Seeded Fault Testing" (Hess, Hardman and Neubert, 1998). The product of those, and related efforts, have produced the verified and validated processes, procedures and algorithms which comprise the IMD HUMS.

IMD HUMS

The IMD HUMS consists of an airborne system, a ground base system and open architecture software. The software enables efficient data and information exchange between the two systems and among other ground base stations. The airborne system acquires and processes data related to three specific areas; mechanical diagnostics, rotor track and balance, and service life utilization. The data is obtained primarily from specially mounted accelerometers and a tachometer, and the suite of original manufacture instrumentation. Information of immediate benefit to the flight crew is automatically (and can be selectively) displayed in the cockpit. However, the majority of the raw data and processed information is exported to the ground base station after landing. The ground base station is used to conduct preliminary analyses to aid local maintainers. The data and processed information is then forwarded to a networked computer for trending, prognostics and subsequent planning. The software is designed with flexible, configurable, published interfaces to allow other functionality to be readily integrated. The NT-based operating system uses an ODBC-compatible Oracle database. These features enable the effective transition of several Navy and Marines diagnostics and maintenance programs to the current highly integrated and flexible system.

Components

Airborne System. The airborne system consists of the original manufacture helicopter fitted with additional hardware and instrumentation. The hardware includes a Main Processing Unit, an optical tracker, Remote Data Concentrators (one for the SH-60 and two for the CH-53), a Cockpit Display Unit (CDU) and a Data Transfer Unit (DTU). Additionally, at least 30 and up to 70 sensors are mounted on the engine and drive train/rotor components to provide condition indicators. An independent tachometer and 1/rev indexer (at the tail rotor) are added to complete the sensor suite. The system can accept entirely analog or digital (1553 bus) signal input or both simultaneously.

The Main Processor Unit (MPU) is composed of a Primary Processor Unit (PPU) and a Vibration Processor Unit (VPU). See Figure 1. The PPU serves as the system controller by managing information both in and out. It receives information from the Remote Data Concentrator (RDC) and the VPU. The RDC provides information derived from the sensors and gauges that make up the original manufacturer's equipment suite (pressure gauges, tachometer(s), contact sensors, etc.). The VPU provides selected raw data signals as well as processed signals. During flight, the MPU acquires data at 1 hertz unless there is an exceedance or other noteworthy event. In the case of an exceedance, the MPU will acquire and record raw signals from the VPU for the exceedance duration plus and minus 15 seconds. The CDU provides an interface that allows the operator to view this data in real-time and provides password protected maintenance information. Based on the information requested, the MPU sends information to the CDU or both raw and processed flight data to the Ground Base System via the DTU. The DTU uses a PCMCIA flash memory card as a medium for temporary flight data storage. It is easily removable from the aircraft for data transfer to the ground station. The card serves a dual function as it is also used to upload the data needed to configure the on-board system as well as algorithms and other pertinent information.

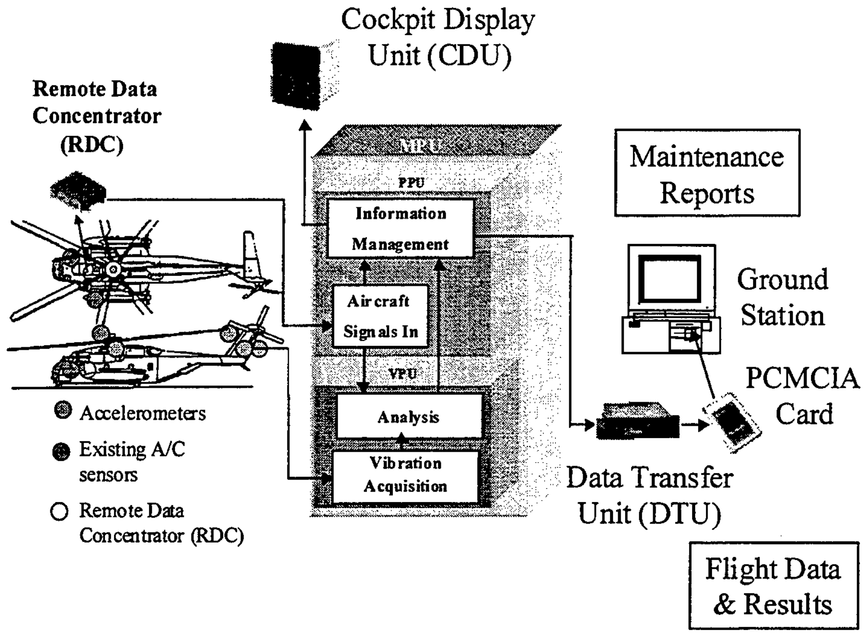


Figure 1. General Configuration of the Airborne System Primary Components

As mentioned above, the IMD HUMS airborne system functions include data acquisition and processing and aircrew advisories for selected events. It is also designed to automate several processes. It can be used to automate rotor track and balance Functional Check Flight (FCF) procedures. Likewise, it automates several engine checks. Maintainers can use the system to conduct flight line troubleshooting during diagnostic checks. FCF crews use the system to determine their maintenance effectiveness and also for basic information purposes. The algorithms and data used by the OBS to perform these and other functions are defined in a configuration utility resident on the ground station.

Ground Base System. The Ground Base System is made up of a series of networked ground base stations which configure flight-specific analysis to support either pilot or maintainer queries. The system provides access to a larger data set for trending, prognostics and planning. The ground stations are the primary user interface with the IMD system. The system is responsible for logging and maintaining all flight and maintenance data, performing aircraft configuration and parts tracking, supporting maintenance and engineering analysis of the flight data, generating engineering and management reports, and archiving data.

The IMD HUMS Ground Base System is integrated with the Naval Aviation Logistics Command Management Information System (NALCOMIS) to provide a complete equipment management solution. NALCOMIS is the Navy's squadron-level version of a standard aviation maintenance management information system. It is currently being upgraded to the newer version, known as Optimized NALCOMIS OMA, for use in the IMD project. It includes functions for maintenance management and record keeping, configuration and parts life tracking, flight record keeping and quality assurance. The IMD system is intended to reduce operation and support costs by providing timely and accurate information to aircraft fleet operators, maintainers, and flight personnel regarding the maintenance and serviceability of their aircraft. It automates maintenance activities scheduling and facilitates maintenance actions recording. Users can generate maintenance forecast and maintenance history reports for any collection of aircraft or assemblies, providing for timely and opportunistic scheduling of maintenance activities. The Portable Ground Station is a version that is to be used on deployment and at the flight line. It includes a sub-set of the Ground Station functions.

Functions

The IMD HUMS offers a comprehensive service suite, providing for Health Monitoring, Usage Monitoring and a Maintainer Interface. Health Monitoring includes Rotor Track and Balance with both continuous and prompted monitoring. It also includes Engine Performance Assessment with prompted checks and condition trending. In addition, it includes mechanical diagnostics of all drive train components, bearings and gears. Planned upgrades will include rotor assembly diagnostics. Certain Health Monitoring functions can be accessed via the Flight Data Recorder Interface. Usage Monitoring checks incoming data against preset thresholds and alerts the aircrew if exceedances are observed. This service includes Operational Usage (time tracking and cycle counting) and Structural Usage Monitoring (regime recognition, component usage and usage application). The three primary diagnostic functions (Mechanical Diagnostics, Rotor Track and Balance and Structural Usage) are presented below.

Mechanical Diagnostics. The diagnostics function provides both comprehensive integrated component by component mechanical diagnostics (IMD), as well as traditional NAVAIR 01-1A-24 procedures for the CH-53E, and A1-H60CA-VIB-000 procedures for the SH-60 models. The IMD diagnostics focus on individual gears, bearings and shafts. The function includes advanced diagnostics software that is both modular and upgradeable. The IMD COSSI system was designed to provide mechanical diagnostics capabilities far in excess of those offered by the Navy's NAVAIR 01-1A-24 Vibration and Analysis Test System (VATS) or equivalents, while still providing equivalent functionality in the aforementioned areas. Figure 2 shows the extent of the components covered by the IMD COSSI system for the SH-60 in comparison to those covered by the VATS. IMD COSSI data acquisition is fully automated and occurs without aircrew intervention, unless specifically requested. The system will autonomously provide Flight Safety Advisories in the event that signals associated with critical components exceed preset thresholds. In fact, the system is 178 Level B certified in accordance with the United States Federal Aviation Administration airworthiness certificate.

IMD COSSI's expert diagnostics depend highly upon advanced signal processing as well as the ability to determine component condition based on the signals and indicators obtained from a variety of diverse sources. Relying on a single sensor to indicate a component's wellness may give spurious indications due to sensitivity, the

H-60 Component Coverage Comparison

Bearings

	IMD	-24
Port Input Gear Roller 70952-08555	■	
Port Input Gear Double Timken SB-3354	■	
Port Input Pinion Roller Out 70952-08164	■	
Port Input Pinion Ball 70951-08362	■	
Port Input Pinion Inboard Roller SB-2165	■	
Port FWU Ball Input SB-1137-1	■	
Port FWU Ball Input SB-1137-2	■	
Port FWU Ball Output SB-1074	■	
Port Generator Drive Ball SB-1139-1	■	
Port Generator Drive Ball SB-1139-2	■	
Port Hydraulic Pump Drive Timken SB-3165-1	■	
Port Hydraulic Pump Drive Timken SB-3165-2	■	
Stbd Input Gear Roller 70952-08555	■	
Stbd Input Gear Double Timken SB-3354	■	
Stbd Input Pinion Roller Out 70952-08164	■	
Stbd Input Pinion Ball 70951-08362	■	
Stbd Input Pinion Inboard Roller SB-2165	■	
Stbd FWU Ball Input SB-1137-1	■	
Stbd FWU Ball Input SB-1137-2	■	
Stbd FWU Ball Output SB-1074	■	
Stbd Generator Drive Ball SB-1139-1	■	
Stbd Generator Drive Ball SB-1139-2	■	
Stbd Hydraulic Pump Drive Timken SB-3165-1	■	
Stbd Hydraulic Pump Drive Timken SB-3165-2	■	
Tail Takeoff Thrust SB-3220	■	
Tail Takeoff Preload SB-3217	■	
Output Shaft Roller SB-2560	■	
Output Shaft Timken SB-3612	■	
Fan Bearing 210SFFC	■	▒
MRC Hanger Bearing 1 SB-1138-1	■	
Fafnir Hanger Bearing 2 SB-1138-2	■	
Hanger Bearing 3 SB-1138-3	■	
Hanger Bearing 4 SB-1138-4	■	
Port Main Bevel Pinion Timken SB-3313	■	
Port Main Bevel Pinion Roller SB-2205	■	
Stbd Main Bevel Pinion Timken SB-3313	■	

	IMD	-24
Stbd Main Bevel Pinion Roller SB-2205	■	
Main Rotor Shaft Roller SB-2561	■	
Main Rotor Shaft Timken Preload SB-3504	■	
Main Rotor Shaft Timken Thrust SB-3409	■	
Main Rotor Swash Plate Bearing	■	
Hydraulic Pump 4 Thrust SB-3265	■	
Hydraulic Pump 4 Preload SB-3217	■	
Planet Carrier Spherical Roller SB-2307-1	■	
Planet Carrier Spherical Roller SB-2307-2	■	
Planet Carrier Spherical Roller SB-2307-3	■	
Planet Carrier Spherical Roller SB-2307-4	■	
Planet Carrier Spherical Roller SB-2307-5	■	
Pillow Block Bearing SB-1143	■	
Pylon Bearing SB-1144	■	
IGB Input Preload SB-3217	■	
IGB Input Thrust SB-3265	■	
IGB Output Thrust SB-3265	■	
IGB Output Preload SB-3217	■	
TGB Input Preload SB-3217	■	
TGB Input Thrust SB-3266	■	
TGB Output Thrust SB-3353	■	
TGB Output Preload SB-3314	■	
Tail Rotor Pitch Change Bearing	■	
Port Engine Bearing 1	■	
Port Engine Bearing 2	■	
Port Engine Bearing 3	■	
Port Engine Bearing 4	■	
Port Engine Bearing 5	■	
Port Engine Bearing 6	■	
Stbd Engine Bearing 1	■	
Stbd Engine Bearing 2	■	
Stbd Engine Bearing 3	■	
Stbd Engine Bearing 4	■	
Stbd Engine Bearing 5	■	
Stbd Engine Bearing 6	■	

Gears

	IMD	-24
Port Input Spiral Bevel Pinion	■	
Port Input Spiral Bevel Gear	■	
Port Free Wheel Spiral Bevel	■	
Port Acc Drive Bevel Pinion	■	
Port Gen Spur Gear	■	
Port Hyd Pump Spur Gear	■	
Port Main Spiral Bevel Pinion	■	
Stbd Input Spiral Bevel Pinion	■	
Stbd Input Spiral Bevel Gear	■	
Stbd Free Wheel Spiral Bevel	■	
Stbd Acc Drive Bevel Pinion	■	
Stbd Gen Spur Gear	■	
Stbd Hyd Pump Spur Gear	■	
Stbd Main Spiral Bevel Pinion	■	
Main Bevel Gear	■	
Sun Gear	■	
Planet Spur Gear	■	
Ring Gear/Carrier Assembly	■	
TTO Main Bevel Gear	■	
Oil Pump Drive Spur Gear	■	
Oil Pump Driven Spur Gear	■	
TTO Pinion Spiral Bevel Gear	■	
IGB Input Pinion Bevel Gear	■	
IGB Output Bevel Gear	■	
TGB Input Pinion Bevel Gear	■	
TGB Output Bevel Gear	■	
Oil Cooler Fan	■	■

Shafts

Port Free Wheel Unit Shaft	■	
Port Quill Shaft	■	
Port Gen Shaft	■	▒
Port Hyd Shaft	■	▒
Stbd Engine Input Shaft	■	■
Stbd Free Wheel Unit Shaft	■	
Stbd Quill Shaft	■	
Stbd Gen Shaft	■	▒
Stbd Hyd Shaft	■	▒
Outer Shaft	■	
Planet Carrier	■	
Main Rotor	■	
Lube Pump Shaft	■	
Tail Takeoff Shaft	■	▒
Pylon Shaft	■	■
Tail Rotor Shaft	■	■
Grounded	■	
Port Engine Power Shaft	■	■
Stbd Engine Power Shaft	■	■
Port Eng Comp Rotor Shaft	■	
Stbd Eng Comp Rotor Shaft	■	
Tail Shaft Section 1	■	▒
Tail Shaft Section 2	■	▒
Tail Shaft Section 3	■	▒
Tail Shaft Section 4	■	▒
Tail Shaft Section 5	■	▒
Disconnect Coupling	■	
IntGBInput Shaft	■	

H-60 Special Procedures

	IMD	-24
Axial Fan Health Monitoring	■	■
Cabin Vibration Signatures	■	■
Engine Input Module Monitoring	■	■
Engine Output Shaft Balancing	■	■
Engine Vibration Signature	■	■
Tail Pylon Vibration Signatures	■	■
Tail Rotor Balancing	■	■

■ Complete Diagnostic

▒ Partial Diagnostic

Note: In some situations the -24 procedures will indicate a fault with a group of individual components and will require further investigation to determine the actual fault.

Figure 2. Component Coverage Comparison Between H-60 and NAVAIR 01-1A-24

efficiency with which the sensor receives the intended signal, robustness of the analysis algorithm(s), etc. To preclude this, the results obtained by analyzing signals obtained from multiple sensors are artfully combined to provide a single indicator that is both distinct and robust.

In normal operation, the VPU acquires data from a selection of sensors and tachometers, as commanded by the PPU. The PPU has a master configurable data acquisition schedule commanding the VPU to acquire data when (and only when) data capture windows (flight conditions) are correct. Data is acquired from the designated suite of sensors, and all channels (regardless of type) are reviewed for data quality. The data quality assurance routines provide a means to reject data in the event of a malfunctioning sensor, broken wire or connector, or defective electronics circuit. When data quality has been confirmed, the tachometer channels are first processed to provide drive train speed information. Each data channel is calibrated and gained as required, and then a series of shaft, gear, and bearing diagnostics are applied to components associated with that particular sensor. The outputs of these calculations are diagnostics indicators, which the VPU then sends to the PPU for evaluation and combination. Diagnostics indicators from like components and different sensors are then combined using a variety of proprietary evaluation methodologies to arrive at a health condition for that particular component. Each component health condition is constantly evaluated during flight to assure vehicle safety.

All component diagnostic indicators, condition data, and selected raw data channels are transferred via the data transfer unit to the ground based station for additional analysis, reports, manipulation, and archiving. The ground-base station can support helicopter maintainers and technicians with diagnostic troubleshooting guidance and on-line repair procedures. Similarly, the system supports engineers and analysts, enabling data review and diagnostic algorithm evolution to address new or optimized diagnostics procedures. In this manner, the system provides useful information both immediately and practically, while enabling the analyst to review data and mature the system. Please contact Dr. Jim Gottwald (jgottwal@aisma.bfg.com) for technical details related to the mechanical diagnostics functions.

Rotor Track and Balance. The physics behind rotation-induced vibration for both main and tail rotors is well understood. All helicopters exhibit varying degrees of low-frequency vibration generated by the main and tail rotors at multiples of the rotor rotation frequency. These low frequency vibrations can be very unpleasant to the helicopter occupants (whose modal frequencies are the same) and are the driving forces behind rotor track and balance initiatives. One type of vibration is a function of the blade passage rates of the main and/or tail rotors. These vibrations can be minimized through thoughtful design. The other type of vibration is caused solely by small differences among the (nominally similar) blades themselves. Manufacturers allow for three types of rotor/blade adjustments to reduce the vibration; hub-weight pockets/brackets, adjustable pitch-control rods and one (or more) adjustable tabs mounted on the blade's trailing edges.

Two basic approaches are used to minimize unpleasant vibrations; minimizing blade track deviation and minimizing directly measured vibration. The blade track deviation approach seeks to minimize deviations at one point in the blade azimuth. The concept is that if the deviations are small, resulting vibration will also be low. A more direct approach is to measure and minimize the actual vibration. ROTABS™ is the IMD COSSI rotor balancing system that uses vibration data obtained from fuselage mounted sensors for both balancing and tracking. This technique obviates the need for hand-held or fuselage-mounted optical tracking devices. It is particularly well suited for full time operation and tactical military situations. Please contact Dr. Sam Ventres (sventres@aisma.bfg.com) for technical details associated with the ROTABSTM technique.

The IMD COSSI rotor track and balance software recommends adjustments to some or all of the three previously mentioned alternatives (weight, control rod, tabs) to effect an efficient solution. It includes a rotor-balancing algorithm that uses vibration and track data when available. However, the algorithm also functions properly with vibration data only, for example, when a tracker is either not installed or is unable to operate. The balancing system is being validated with a series of acceptance trials at Patuxent River Naval Air Station. Flight testing in the fall of 1998 and early this year demonstrated that the ROTABSTM algorithms are very robust and capable. The technique succeeded in bringing out-of-balance blades into balance on the first trial each time for ten trials on two different aircraft types. The two aircraft tested were the 4-bladed SH-60B support helicopter and the heavyweight, 7-bladed CH-53E Cargo Helicopter. The tests were conducted to confirm that the ROTABSTM algorithms could derive track and balance solutions equal to or better than those of the NAVAIR 01-1A-24 procedures. In each case, the algorithms recommended changes that brought the blades into acceptable vibration levels and often offered changes that would reduce the vibrations to an extremely low level. This type of performance is intended to offer more options to maintenance flight commanders. During tactical situations, the system can be configured to provide the minimum number of changes needed to bring vibrations to an acceptable level. During routine operations, a more comprehensive set of changes might be invoked to eliminate undue vibration. For example, fine-tuning the rotor's performance might reduce the need for adjustments in a subsequent tactical situation. Planned improvements include vibration- and tracking-based diagnostics for rotor head faults, such as faulty lead-lag dampers, worn pitch control rods or vibration dampers.

Usage Monitoring. One primary IMD COSSI program objective is to introduce and institutionalize a family of automated structural usage data acquisition and processing algorithms. Given this capability, parts life determination is individualized and now based upon the actual helicopter usage. The usage monitoring subsystem determines the percentage of flight time the helicopter has spent in each flight mode (regime) as well as the specific regime(s) sequence. The regime data is then used to calculate the rate that various structural components are being used up and when they need to be removed from service to maintain the required reliability rate.

A regime is the basic building block of an aircraft usage monitoring system. Some examples of regimes are takeoff, hovering, level flight, various turns and landing. Time histories of flight parameters are analyzed to determine the instantaneous phase of flight. Normal acceleration (Nz), power and yaw rates are parameters that define subsets of regimes that can exist within the confines of a basic regime. The time spent within each regime, during a given flight is measured and tabulated as part of a usage spectrum. It is almost impossible for an aircraft to be flown into every regime on a single flight. However, over a period of time, the aircraft can be expected to fly into every basic regime. The continuing summation of this multi-flight experience defines the usage spectrum for the aircraft and its components.

Regime recognition is performed to map recorded aircraft parameter data to a set of ground/flight regimes. The process output includes several summary reports as well as calculated adjustments to the useful life of specific components. The first report called the regime sequence report (i.e., flight profile) represents the time history of the aircraft operation, listing the sequence of regimes encountered. The flight spectrum report summarizes the distribution of time spent in each regime and how often the regime is repeated. Computed component usage is then aggregated to the sum of the usage already carried by the system for that specific component.

In addition to providing an accurate determination of parts usage, the algorithms introduce improved data collection accuracy via automation. Usage data are collected for each flight of each aircraft - a process that produces a massive amount of usage information. Automated analysis converts this data into manageable information that is then archived and automatically distributed to enhance the logistics decision-making process. This automated data collection enables individualized parts life determination, addressing the actual usage of each aircraft in the fleet. Additionally, all fleet aircraft in the model are now treated to the same effective margins of safety by the improved system of algorithms. This approach retains the high confidence levels (6-9's, or "one-in-a-million" probability of catastrophic failure) historically embodied in the original safety regulations. By the same token, it eliminates inappropriate and unwanted parts life penalties. Please contact Dr. Harrison Chin (hchin@aisma.bfg.com) for technical details related to the usage monitoring functions.

Note: The "equivalent safety" imperative mentioned above dictates a need for affordable human oversight using automated and semi-automated procedures. IMD HUMS provides this oversight capability. The oversight will diminish as confidence in the system improves, but it will always be present. The system objective is a process that allows engineering management the opportunity to randomly inspect the data as a quality assurance function or to inspect on exception.

Deployment Schedule and System Characterization

Two aircraft (one aircraft of each type) are now being fitted with the IMD HUMS system. Five additional aircraft of each type will be fitted by July 1999. These aircraft will be deployed in operational squadrons and serve as data sources for accelerated system characterization. Navy, Marine and BFGoodrich engineers will jointly analyze data obtained from operational service. It will be used to hone the system sensitivities and allow the customer to confidently set cautionary thresholds and exceedance levels. The data will subsequently be used to determine the effectiveness of developmental algorithms by comparing their performance to the results obtained by using current techniques. Together with Optimized NALCOMIS OMA, IMD HUMS enables the Navy and Marine Corps to start the transition to true condition-based aviation maintenance. This new capability to capture actual usage and condition, coupled with total visibility into the current component configuration for each aircraft, makes possible the process re-engineering that leads to extensive operations and support cost savings.

Conclusion

The IMD HUMS has become reality under an aggressive schedule due to the close cooperation between user and provider. The Integrated Product Team concept which united US Navy, US Marine and BFGoodrich team members throughout this effort has produced a system which will fulfill the promise of improved operational readiness and flight safety with reduced maintenance-related costs. That close relationship will continue as the system is installed and deployed on operational aircraft of both types. More importantly, this program will serve as the prototype leading to additional savings to be realized by installing like systems on a much wider variety of complex aircraft and ground vehicles.

References

1. Hardman, W., Hess, A., and Neubert, C. "SH-60 Helicopter Integrated Diagnostic System (HIDS) Program Experience and Results of Seeded Fault Testing", American Helicopter Society 54th Annual Forum, Washington, DC, May 20-22, 1998.

The author is indebted to the United States Navy and United States Marine customer representatives and his BFGoodrich teammates for providing expert guidance and review while writing this paper. Several years of joint effort, documented in working papers, programmatic and engineering briefings and corporate proprietary reports, was reviewed and consolidated for this paper.

MODULAR DISTRIBUTED HUMS

An Overview

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Helitune

INNOVATION THROUGH EXPERIENCE

Defining the System

- JAHUMS
- UK MOD
- DSTO
- RITA
- EUROCOPTER

Helitune

INNOVATION THROUGH EXPERIENCE

HUMS Requirements

- Modular
- Flexible
- Expandable
- Cost Efficent
- Affordable

Helitune

INNOVATION THROUGH EXPERIENCE

Ultra ELECTRONICS

The Common Modules

- RTB
- Engine Exceedences
- Engine Vibration
- Transmission Monitoring
- Usage

Helitune

INNOVATION THROUGH EXPERIENCE

Ultra ELECTRONICS

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Availability

- RTB (Yes)
- Engine Monitoring (Yes/Partner)
- Engine Vibration (Yes)
- Transmission (Yes/Partner)
- Usage (Yes/Partner)

Helitune INNOVATION THROUGH EXPERIENCE

On Board Laser Tracker

- Designed to Survive the Environment
- RITA Compliant Output
- No Reflective Tape
- Active only during Acquisition
- Accuracy within 1mm
- Expansion Capability

Helitune INNOVATION THROUGH EXPERIENCE

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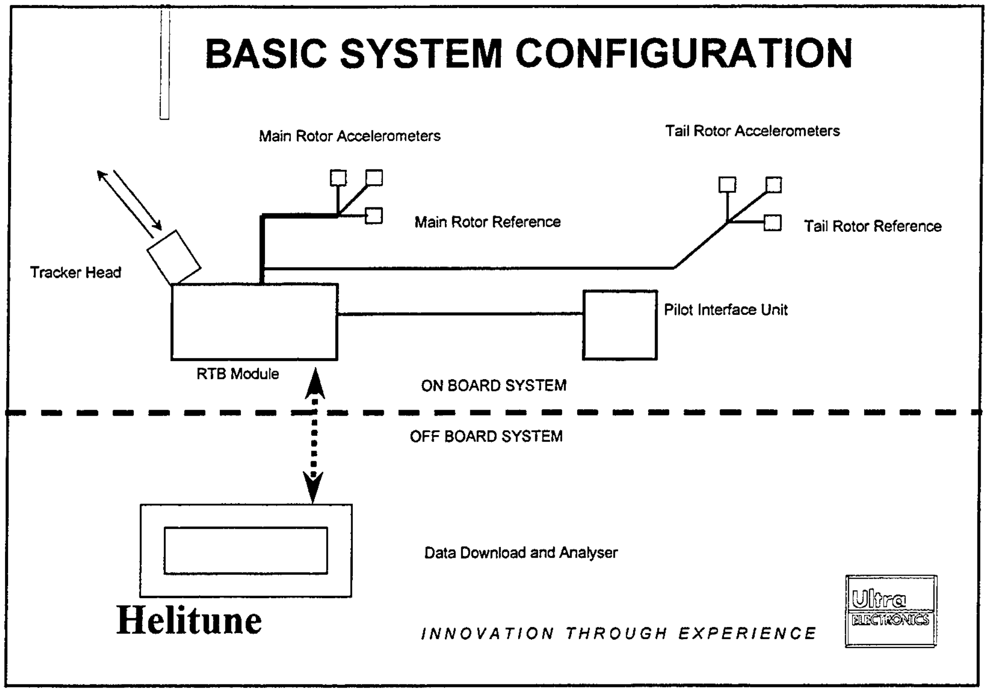

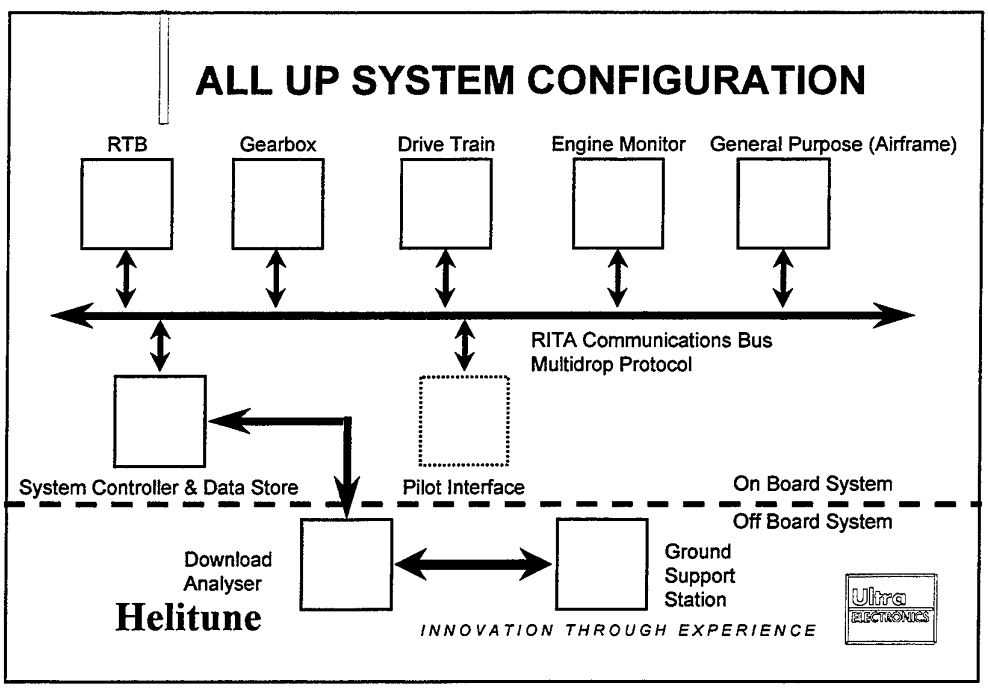

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Distributed Modular HUMS Conclusions

- Practical Solution
- Technology is Available today
- Pick and Mix the Technology
- Affordable
- Easy upgrade for New Technology
- Flexibility for the end user

Helitune INNOVATION THROUGH EXPERIENCE

Engine HUMS Functions

- EES monitoring
  - Smiths Industries EEMS
    - OUT-04: 3.2.9
- Engine IDM/QDM monitoring
  - As for general debris monitoring
    - Discrete inputs for chip detectors
    - Vickers Tedeco QDM
    - Smiths Industries IDM
    - OUT-04: 3.2.9

Helitune INNOVATION THROUGH EXPERIENCE

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Transmission HUMS Functions

- Transmission parameter exceedance monitoring
  - As for general exceedance monitoring
  - Gears, bearings, shafts
  - Diagnostic Indicators
  - Statistical Change Detection
  - Exceedance reporting on GSS
  - OUT-04: 3.2.5

Helitune

INNOVATION THROUGH EXPERIENCE

Ultra Electronics

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
(DSTO AUSTRALIA)
WORKSHOP ON HELICOPTER HEALTH AND USAGE MONITORING

FEBRUARY 16-17, 1999
VICTORIA, AUSTRALIA

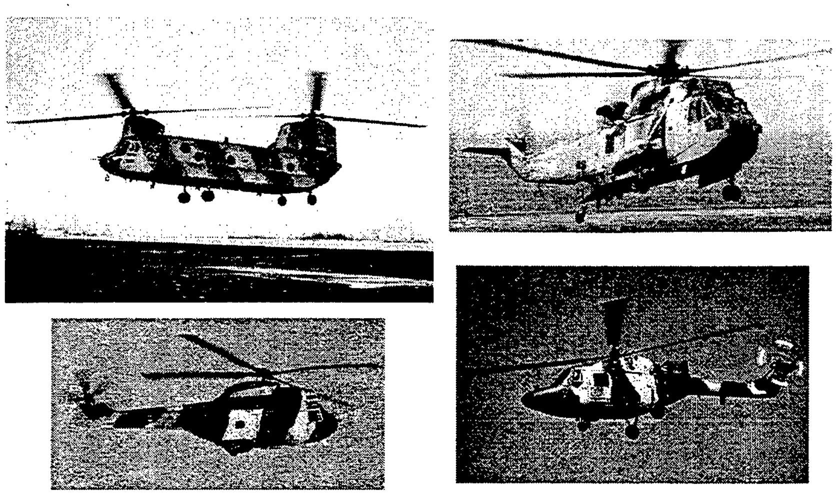
UK MINISTRY OF DEFENCE HEALTH AND USAGE MONITORING SYSTEM (HUMS)

CHARLES TRAMMEL
GERALD VOSSLER, PH.D.

SMITHS INDUSTRIES
Aerospace

Information Management Systems - Grand Rapids, 3290 Patterson Ave., S.E., Grand Rapids, MI 49512-1911

UK MOD HEALTH AND USAGE MONITORING SYSTEM



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UK MOD HUMS REQUIREMENTS

- **Key requirements**
  - Single system for (4) MoD helicopters - Chinook, Sea King, Puma, and Lynx
  - Same airborne system used for each helicopter (except Naval variants).
  - Same HUMS Ground Station (HGS) user interface for each helicopter
- **Airborne HUMS elements**
  - Crash survivable Cockpit Voice and Flight Data Recorder (CVFDR)
  - Automatic Rotor Track and Balance (RTB) data acquisition
  - Transmission, rotor, airframe and engine health monitoring
  - Aircraft and engine usage monitoring
  - Display of Built-In-Test (BIT), warnings, alerts and system status
  - Data storage and capability of transferring HUMS data to the HGS
- **HUMS Ground Station (HGS) elements**
  - Reporting problems detected by the airborne HUMS
  - Set-up of the airborne HUMS
  - HUMS database maintenance, data browsing and system support
  - Expert evaluation capability

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SI SOLUTION - HUMS BUILDING BLOCKS

CONDITION BASED MAINTENANCE

Usage	**Exceedance**	**Rotor Track and Balance**	**Vibration Analysis**
Sensor Data Acquisition			
Cockpit Voice and Flight Data Recording			

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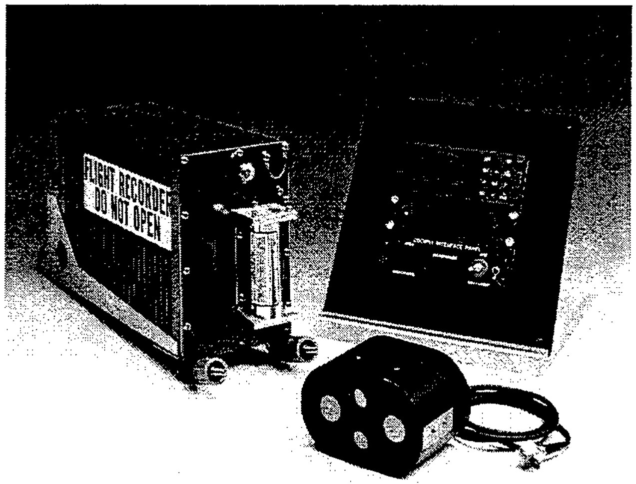
HUMS AIRBORNE SYSTEM ELEMENTS



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AIRBORNE SYSTEM SUMMARY

- **Data Acquisition and Processing Unit (DAPU)**
  - Provides all airborne HUMS data acquisition and processing functions
  - Contains an internal Crash Protected Memory (CPM) for CVFDR Data
  - Modular 1/2 ATR short chassis design, 17 lbs.
- **Cockpit Control Unit (CCU)**
  - Provides display and function-select capabilities for the HUMS
- **Data Transfer Device (DTD) Memory Card Receptacle (MCR)**
  - Supports Type II PCMCIA ATA Flash RAM memory card DTD
- **Cockpit Interface Panel (CIP)**
  - Contains the area microphone and audio amplifier interface for the CVFDR
  - Provides a NATO standard headphone receptacle for monitoring purposes
  - Contains a Ground Readout Equipment (GRE) receptacle
- **Active Optical Blade Tracker (AOBT)**
  - Small, compact, two lens design
  - Baseline Chinook HUMS utilizes two trackers
    - > Forward rotor - nose mounted
    - > Aft rotor - tunnel mounted, flush

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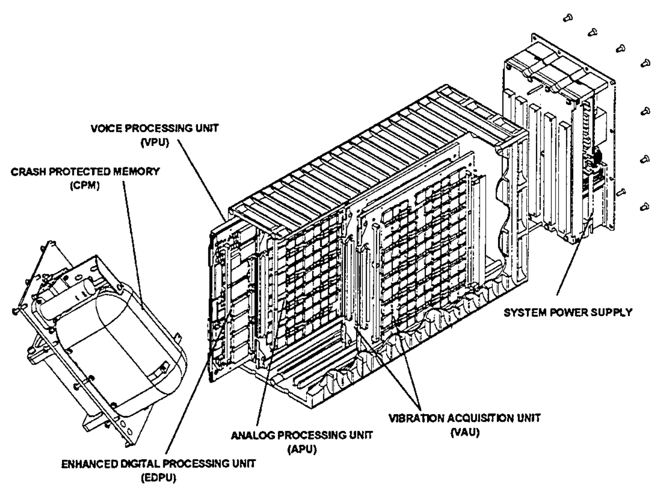
DATA ACQUISITION AND PROCESSING UNIT (DAPU)



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UK MOD GROUND SUPPORT SYSTEM (GSS) FEATURES

- **GSS elements**
  - Maintenance functionality for 1st, 2nd and 3rd line provided by a network of HUMS Ground Stations (HGS) which include
    - > Fixed Ground Stations (FGS)
    - > Ruggedised Portable Ground Stations (RPGS)
  - CVFDR Replay Stations (CRS)
  - Portable Maintenance Aids (PMA)
  - Data Recovery and Playback Evaluation System (DRAPES)
- **HGS functions**
  - Reporting problems detected by the airborne HUMS and directing maintenance actions
  - RTB using Composite Measurement Record (CMR) approach
  - Data browsing
  - Expert evaluation capability
  - Set-up of the airborne HUMS
  - HUMS database maintenance
  - System support and administration

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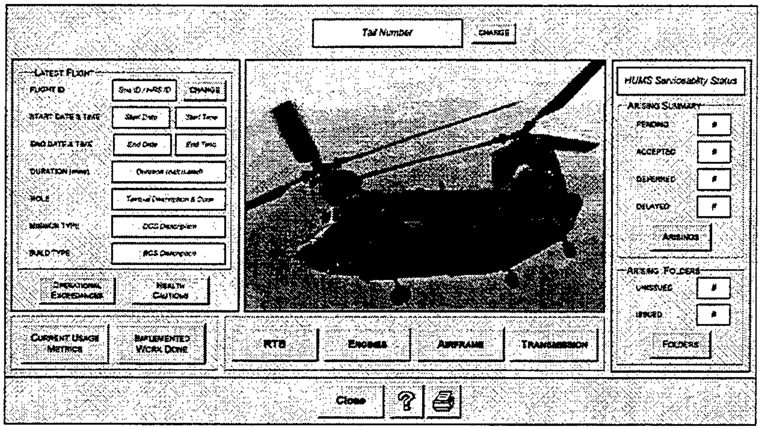
HGS MAINTAINER REVIEW



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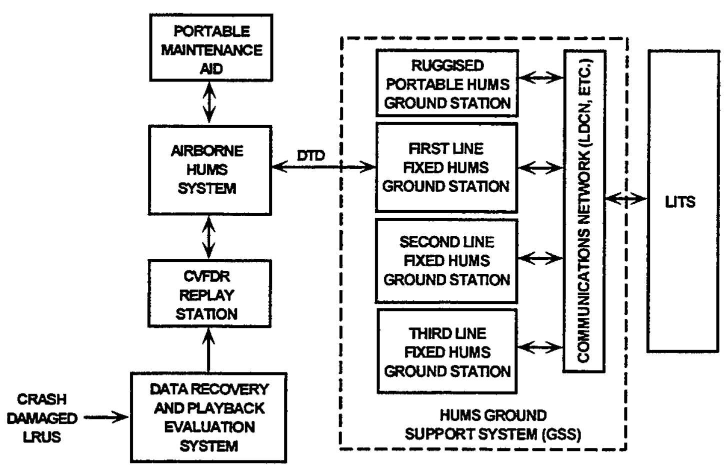
GROUND SUPPORT SYSTEM ELEMENTS



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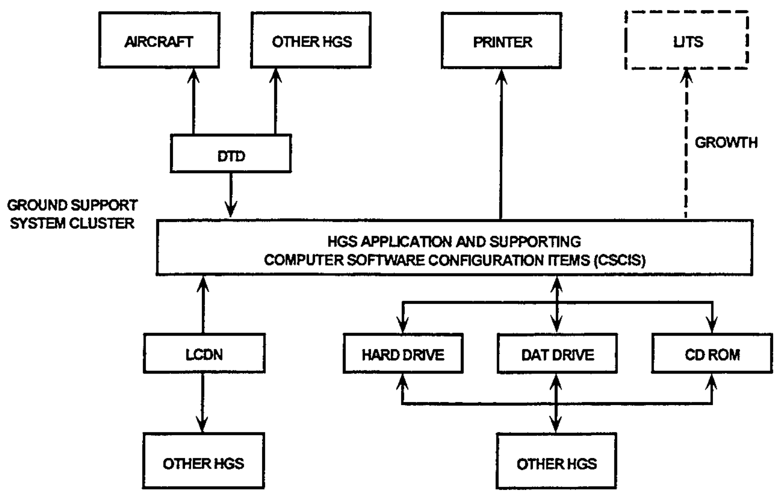
HGS ARCHITECTURE



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AIRBORNE HUMS CONFIGURATION BY THE HGS

- **CVFDR**
  - FDR parameter inhibit
  - CVR inhibit
- **Exceedances and alerts**
  - thresholds
  - message text and when enunciated
- **Flight regimes**
  - parameters
  - minimum / maximum limits
  - median filter
- **Vibration measurement definitions**
- **Vibration measurement scheduling**
  - for each flight regime
  - for each manual request
- **Diagnostic Condition Indicator (CI) calculations**
- **DTD file configuration for wrapping and enunciation of 80% full**

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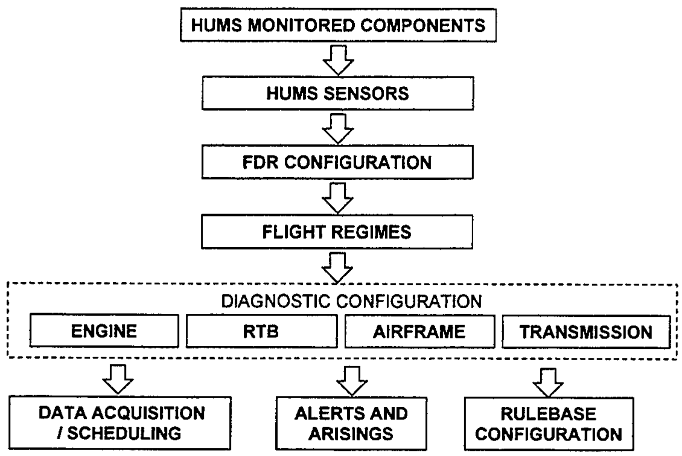
HUMS CONFIGURATION OVERVIEW



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CVFDR

- **Requirement**
  - Comply with regulatory requirement for crash-survivable Cockpit Voice (CV) and Flight Data (FD) recording
- **Function**
  - Captures CV (intercoms and area microphone) and FD onto crash-survivable memory
- **Benefit**
  - Enables incident or mishap analysis
  - Improves accuracy of flight time recording
  - Correlates CV and FD to events (arisings)

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CVFDR - OPERATION

- **Cockpit Voice Recorder (CVR) operation**
  - Audio data is recorded from power on to power off
  - Audio sources
    - > Pilot's headset
    - > Copilot's headset
    - > Area microphone contained in Cockpit Interface Panel (CIP)
  - Crash Protected Memory provides 1 hour of recording before overwriting
  - Audio monitor output jack provided in CIP
- **Flight Data Recorder (FDR) operation**
  - EUROCAE ED-55 MOPS specifies the required FDR parameters
    - > Continuous and discrete signals
    - > Over 200 wires connected to existing CH-47 wiring harnesses
  - Flight data recording starts once engine start has been detected and stops 10 minutes after engines stop or upon removal of power
  - Crash Protected Memory provides 8 hours of recording before overwriting
  - Pilot Event Marker button provided on CCU

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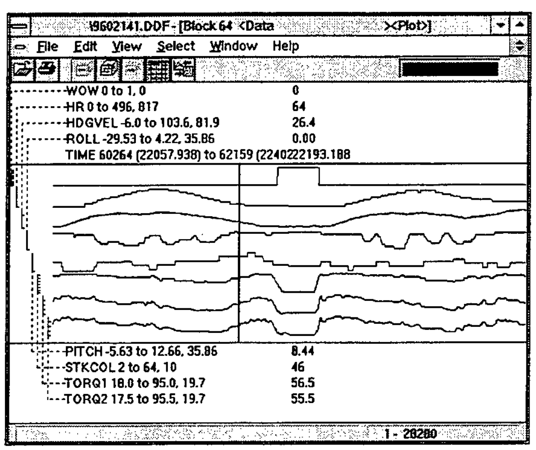
CVFDR - REPLAY GRAPHICAL DISPLAY



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USAGE

- **Requirement**
  - Provide automated usage data collection, computation, and recording
- **Functions**
  - Airborne calculation of usage for airframe, engine/transmission and Auxiliary Power Unit (APU)
  - Cumulative usage compilation on ground station
- **Benefits**
  - Improves accuracy and visibility of usage parameters
  - Enables failure prediction
  - Potentially reduces usage due to "command presence" onboard
  - Allows transition from time-based to condition-based maintenance schedules

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USAGE AIRBORNE OPERATION

- **Types of usage data**
  - Engine usage data
  - Aircraft usage data
  - APU usage data
- **Usage data**
  - is collected and recorded per HUMS recording session
  - is stored in both the DTD and internally in the DAPU
  - is displayable on the CCU for the previous HUMS recording session
- **Specific criteria established for usage parameters**
- **Usage computed in the airborne element per HUMS recording session**
- **Usage data stored on the DTD for download to the HGS**
- **CCU menus allow for displaying of usage data from the previous flight**
- **Cumulative usage data compiled on the HGS**

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EXCEEDANCE MONITORING

- **Requirement**
  - Provide automated exceedance monitoring and recording
- **Functions**
  - Monitor parameters against configurable limits
  - Records exceedance magnitude and duration
  - Options for display of exceedances to aircrew, maintainers
  - Continuously checks validity of parameters
- **Benefits**
  - Enables corrective measures to prevent material failures and avoid mishaps

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EXCEEDANCE OPERATION

- **Specific criteria with configurable limits established for exceedance parameters**
- **Exceedance limits and display text configured on the HGS**
- **Display option for exceedances configured on the HGS**
  - Display on the CCU when they occur
  - Display on the CCU after the aircraft returns to the ground
  - Display on the post-flight report
  - Display on the report to the line maintenance engineer
  - Display on the report to the 3rd line engineer
- **Exceedance limits and display options uploaded to airborne HUMS via the DTD**
- **All continuous exceedance parameters checked for validity**
  - Parameter reasonableness tests utilized
  - Invalid parameters not allowed to generate an exceedance
- **Exceedance data stored on DTD**
- **Exceedance data downloaded to HGS via the DTD**

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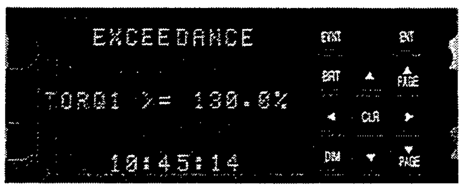
CCU EXCEEDANCE DISPLAY

- **Engine 1 torque exceedance detection and display example**
- **Exceedance display includes time of day when the exceedance was detected**
- **Exceedance must be acknowledged to clear from CCU**
- **CCU returns to the previously displayed screen after the exceedance is acknowledged**



ROTOR, TRACK AND BALANCE (RTB)

- **Requirement**
  - Provide adjustment recommendations to return RTB within limits after one flight under normal operation
  - Return system within limits after major maintenance within three flights
- **Functions**
  - Automatic and manual data capture during defined flight regimes
  - Data reasonableness checks
  - RTB alert checks
  - Ground-based diagnostics and adjustment calculations
- **Benefits**
  - Eliminates Functional Check Flights (FCF) for fine adjustments to RTB
  - Reduces FCF for RTB following rotor system maintenance
  - Reduces RTB-induced vibrations that cause structural fatigue, crew fatigue, and reduced avionics reliability
  - Detects non-adjustable faults (growth)

AIRFRAME VIBRATION MONITORING (AVM)

- **Requirement**
  - Provide airframe structure health monitoring
- **Functions**
  - Monitors airframe vibrations
  - Performs continuous scan and threshold checks across flight regimes
  - Provides configurable alerts to crew, maintainers
- **Benefits**
  - Supports life extension initiatives
  - Reduces probability of failure and mishap

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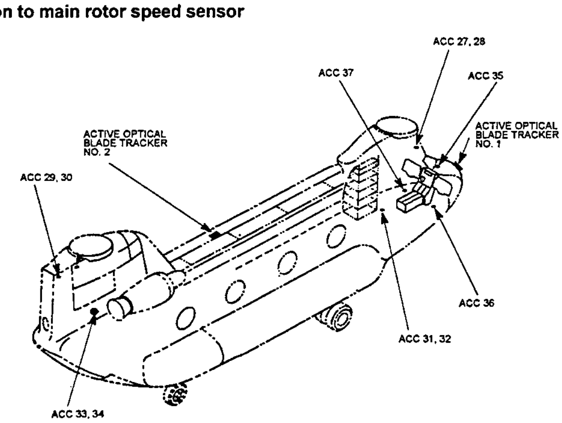
RTB/AVM - SENSOR LOCATIONS

- **(2) Active Optical Blade Trackers**
- **(11) Accelerometers for main rotor, aft rotor and Self Tuning Vibration Absorbers (STVA)**
- **Connection to main rotor speed sensor**



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RTB/AVM - AIRBORNE OPERATION

- **Day/night tracker operation**
  - System defaults to day mode
  - Night mode selectable from CCU main menu
- **Automatic RTB/AVM operation**
  - System default
  - Data acquired only while in defined flight regimes
    - Flight regimes based on acquired and computed flight data parameters
    - Flight regime recognition criteria are configurable via the ground station
- **Manual RTB operation**
  - Manual operation selectable from CCU main menu
  - Operator provided ability to initiate RTB
  - List of RTB flight profiles displayed
  - Acquire data display identifies selected profile
  - Acquisition complete identified on display

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RTB/AVM - ACQUISITION/PROCESSING

- **Acquisition modes**
  - Synchronous time average (RTB)
  - Synchronous or asynchronous power average (airframe)
  - Synchronous real time (rev-by-rev data)
- **Condition Indicators**
  - Evaluation of main rotor order amplitudes (configurable)
  - Typically 1R, 2R, 3R, 6R, 9R, 12R, 15R, 18R, 21R, and 24R
  - 1R phase
  - Average track and lag values for each rotor blade
  - Track split values for each rotor system
- **Processing**
  - Comparison of Condition Indicator (CI) amplitudes to limits
  - Alert annunciation in air/on ground (configurable)
  - Computation of RTB corrections as required (on HGS or PMA)

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RTB/AVM - AIRBORNE CAUTIONS

- **Cautions are alerts related to health**
- **RTB cautions categories**
  - RTB accelerometer values
  - RTB track & lag data
- **Cautions verification**
  - Data integrity & reasonableness checks
  - Repeat acquisitions
  - Uses convergence algorithm
- **Display of cautions**
  - Immediate display to the pilot via the CCU
  - Display to the pilot via the CCU when Weight-On-Wheels (WOW) is achieved
  - Display on post flight report
  - Display to maintenance engineer
  - Display to third level personnel

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RTB/AVM - GROUND SYSTEM OPERATION

- **RTB warnings which are enabled for pilot debrief will be viewed like exceedances**
- **RTB diagnostics run automatically after the pilot debrief is complete and produce maintenance arisings**
  - Arisings are produced if the RTB measurements acquired during the flight are out of tolerance
    - > Suggested adjustments are provided
    - > Capability to review acquired measurement data is provided
    - > Capability to review/modify adjustments is provide for "what if" capability
  - Arisings are produced if action is required to "tune" the adjustments
  - Maintenance adjustments must be entered into HGS for consistency and validation

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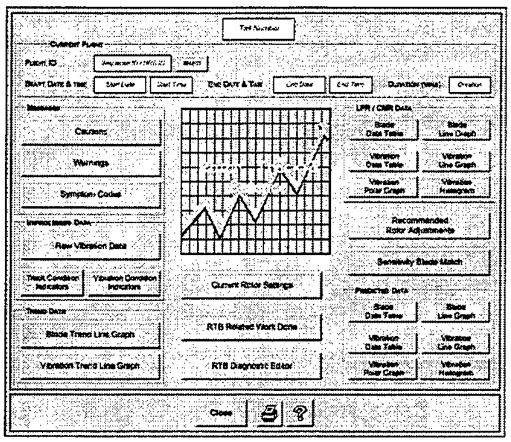
RTB GROUND SYSTEM INTERFACE



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TRANSMISSION VIBRATION MONITORING (TVM)

- **Requirement**
  - Provide transmission components health monitoring and diagnostics
- **Functions**
  - Detects faults in gear, bearing, and shaft by monitoring vibration signatures
  - Performs continuous scan and threshold checks across flight regimes
  - Provides configurable alerts to crew, maintainers
- **Benefits**
  - Enables prediction of transmission failures and initiation of maintenance
  - Provides diagnostics and isolation of defective components
  - Reduces probability of failure and mishap

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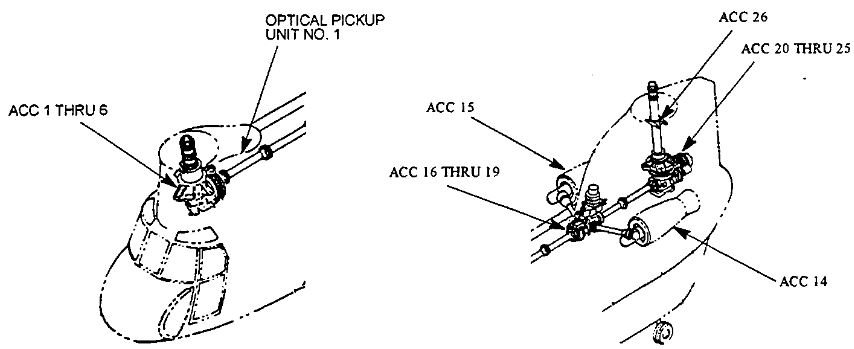
TVM - INSTALLATION LOCATIONS

- (26) Accelerometers for monitoring main drive and accessories
- Shaft speed sensors
  - Existing multi-pulse inputs from the engine free power turbines
  - Optical pickups at front end of the forward gearbox sync shaft and input to the aft gearbox



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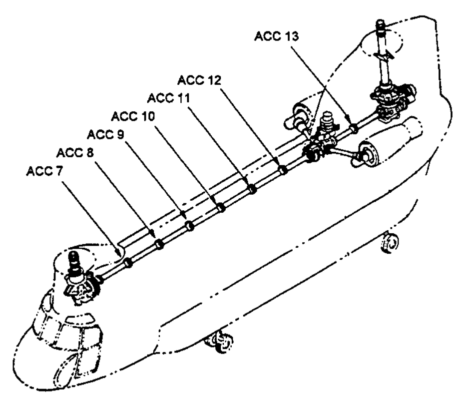
TVM - INSTALLATION LOCATIONS



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TVM - ACQUISITION/PROCESSING

- **Acquisition modes**
  - Synchronous signal averaging - gears and shafts
  - Envelope spectrum analysis - bearings
  - Data acquired only while in defined flight regimes
    - Flight regimes based on acquired and computed flight data parameters
    - Flight regime recognition criteria are configurable via the ground station
- **Processing**
  - Test Condition Indicator values against thresholds and produce Defect Indicators
  - Combine Defect Indicators to identify defect category/type (e.g. instrumentation defect, shaft imbalance, misalignment, localized gear defect, bearing defect, etc.)
  - Alert annunciation in air/on ground (configurable)
- **Ground System Operation**
  - TVM warnings which are enabled for pilot debrief will be viewed like exceedances
  - TVM diagnostics run automatically after the pilot debrief is complete and produce maintenance arisings
  - Maintenance adjustments must be entered into HGS for consistency and validation

SMITHS INDUSTRIES DSTO HELICOPTER HUMS WORKSHOP FEBRUARY 16 - 17, 1999 32

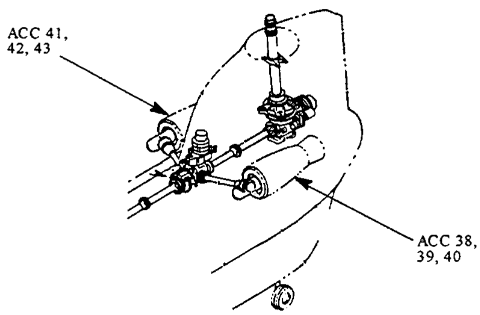
ENGINE VIBRATION MONITORING (EVM)

- **Requirement**
  - Provide engine health monitoring and diagnostics
- **Functions**
  - Detects faults in engine shaft and accessories by monitoring vibration signatures
  - Performs continuous scan and threshold checks across flight regimes
  - Provides configurable alerts to crew, maintainers
- **Benefits**
  - Enables prediction of engine failures and reduces false removals
  - Provides diagnostics and isolation of defective components
  - Reduces probability of failure and mishap

SMITHS INDUSTRIES DSTO HELICOPTER HUMS WORKSHOP FEBRUARY 16 - 17, 1999 33

EVM - SENSOR LOCATIONS

- (3) Accelerometers on each engine located on the engine lifting point, inlet housing and diffuser housing front face
- Shaft speed multi-pulse inputs from the engine gas generators and free power turbines



SMITHS INDUSTRIES   DSTO HELICOPTER HUMS WORKSHOP FEBRUARY 16 - 17, 1999   34

EVM - ACQUISITION/PROCESSING

- Acquisition modes
  - Asynchronous power spectra
  - Data acquired only while in defined flight regimes
    - > Flight regimes based on acquired and computed flight data parameters
    - > Flight regime recognition criteria are configurable via the ground station
- Condition Indicators
  - Shaft order amplitudes (configurable)
    - > Typically 1st & 2nd gas generator and free power turbine shaft orders
  - Broadband amplitudes
- Processing
  - Comparison of shaft order and broadband amplitudes to limits
  - Alert annunciation in air/on ground (configurable)
- Ground System Operation
  - EVM warnings which are enabled for pilot debrief will be viewed like exceedances

SMITHS INDUSTRIES   DSTO HELICOPTER HUMS WORKSHOP FEBRUARY 16 - 17, 1999   35

Charles Trammel - 18

UK MOD HUMS SUMMARY

- **System design with building block approach to allow easy configuration for**
  - Cockpit Voice and Flight Data Recorder (CVFDR) operation
  - Usage and exceedance monitoring
  - Rotor Track and Balance (RTB)
  - Airframe Vibration Monitoring (AVM)
  - Transmission Vibration Monitoring (TVM)
  - Engine Vibration Monitoring (EVM)
- **UK HUMS Chinook Program will**
  - Tailor and qualify airborne and ground systems
  - Provide an Aircraft Design Authority (ADA) approved installation design

SMITHS INDUSTRIES DSTO HELICOPTER HUMS WORKSHOP FEBRUARY 16 - 17, 1999 36

Charles Trammel - 19

HEALTH MONITORING OF HELICOPTERS
Applications and Achievements

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ABSTRACT

History has taught us that the growth of helicopter health monitoring has been more evolutionary that revolutionary. Only the most sophisticated of helicopter operators whether it be military or commercial invests in the manpower and training to incorporate some of the software tools made available by "HUMS" suppliers. Developmental offerings of prospective products and claims of dramatic benefits are in most instances unrealized.

As events unfold, we are seeing that permanent on-board monitoring of basic helicopter functions are nevertheless yielding significant benefits, largely from availability of continuous recorded data for both immediate flight line usage and also for post flight analysis. The most fundamental of monitoring functions; that of rotor track and balance is yielding important information regarding not only the rotor system but that of associated components.

The extension of rotor track and balance basics yields important clues as to how carefully applied diagnostics to other rotating components can similarly benefit from the more intensive examination of newly available data.

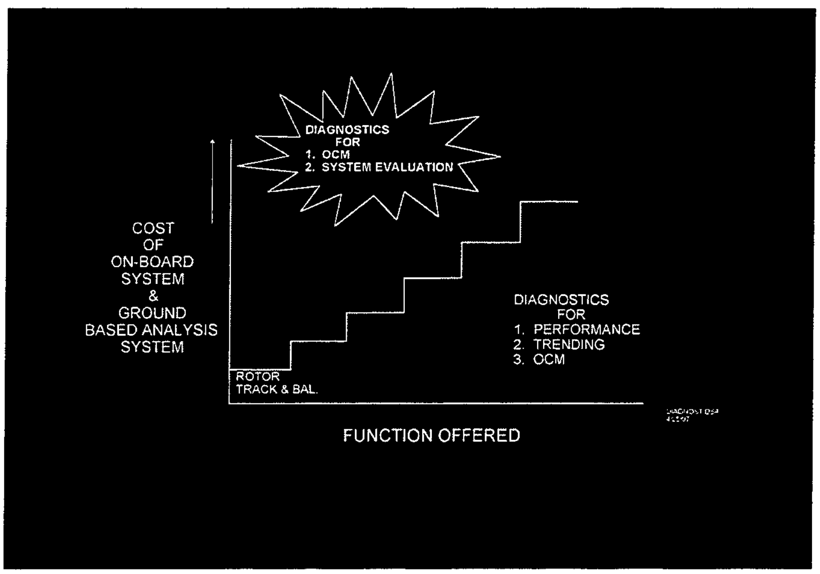
This paper will present some of the findings that are now possible and the conclusions as to how expansion of basics can lead to a more powerful operational utility of health monitoring tools.

The continuous monitoring of data aboard a helicopter has been defined by the CAA Health Monitoring Advisory Group (HMAG) as a Health and Usage Monitoring System (HUMS). The HMAG Reports Document refers to HUMS as "Monitoring systems that offer a variety of techniques capable of enhancing currently accepted maintenance techniques". HMAG goes on to define "Usage" monitoring as "a process which assesses the life consumption (usage) of critical components, systems, and structures by monitoring actual damage exposure"[1]. In most current applications there is little information that will enable the health monitoring user to assess the life consumption against any manufacturer or constructor supplied data. The absence of usage applications does in no way diminish the value of helicopter health monitoring. In this paper we will concern ourselves only with the results of helicopter health monitoring derived over seven years of Health Monitoring Systems (HMS) application experience based upon forty years of portable balancer development and application.

Health Monitoring Systems (HMS) are a reality, are generally accepted by both the military and commercial helicopter community and have proven themselves as contributing to lowering the cost of ownership, and improving safety. The pioneering accomplished in North Sea applications for oil companies has been producing results for over then years. Seven years of experience on the entire fleet of USAF helicopters under far more stringent budgets have vouchsafed the process although under far more modest functional terms. Both examples are applications directed to the operational use of large helicopters under extreme mission requirements. In the first example, mission profiles include climate extremes and governmental regulation to ensure safety of flight under the circumstances. In the second example mission profiles includes climatic considerations and as an additive, the continual demand for improving mission availability.

But there is a major distinguishing characteristic between the above two examples that exemplifies the dichotomy that exists in the practical implementation of HMS. In the first instance as exemplified by the North Sea installations, we see developed systems that represent comprehensive monitoring, while the latter case represents maintenance matched monitoring.

Comprehensive monitoring is not acknowledged as a universal need by helicopter operators. In a cost competitive commercial world, unless driven by regulation, the driver for acceptance of the feature/function is benefit vs cost. Often, a major consideration in the formula for acceptance is maintenance matching. Maintenance matching is simply a conscious recognition as to whether the maintenance procedures for the offered feature/function are reasonably consistent with the established procedures or planned improvements of the operator. Operators are well advised to add the cost of a significant or massive overhaul of the means and methods for maintenance into their benefit vs cost calculations.



FEATURES/FUNCTIONS VS. COST

From the above we take the position that:

1. Health monitoring of helicopters is generally accepted.
2. Comprehensive monitoring of the helicopter is not universally accepted.
3. Features and functions beyond the basics need to be individually justified to include the necessity to modify, improve and invest into maintenance procedures.

Justification problems that arise when adding to the maintenance task are identified as:

1. Civil and military operators are not prepared to undertake the added maintenance burden represented by a comprehensive Health Monitoring System without investment.
2. Investment in additional maintenance by adding personnel or requiring procedural changes is a financial burden that needs to be added into the benefits vs cost formula.
3. Maintenance cost addition is a competitive burden for the civil operator.
4. Maintenance cost addition is a budget justification problem for the financially stressed military.

There is a powerful argument for permanent Health Monitoring. There is an equally powerful argument for operational application of a given feature/function only as it can prove itself from the viewpoint of operational merit.

Helicopter manufacturers from our subsystem supplier viewpoint have recognized the intrinsic value represented by health monitoring and have cooperated with the HMS/HUMS community in providing products accordingly. Cases in point are the Super Puma EuroHUMS™ offering[2] and more recently the health monitoring systems installed at the factory on the MD900 and the EC-135. In the latter cases the highlighted feature is automatized monitoring of main rotors and the tail (NOTAR and Fenestron respectively), plus engines. Even though limited in announced functions to the most basic, operators are gaining the following benefits:

- Continuous vibration monitoring enables an operator to adjust imbalances while they are of a "micro" rather than "macro" in effect.

- Use of such systems ordinarily requires a simple delta in maintenance procedures already in use with significant additional investment.

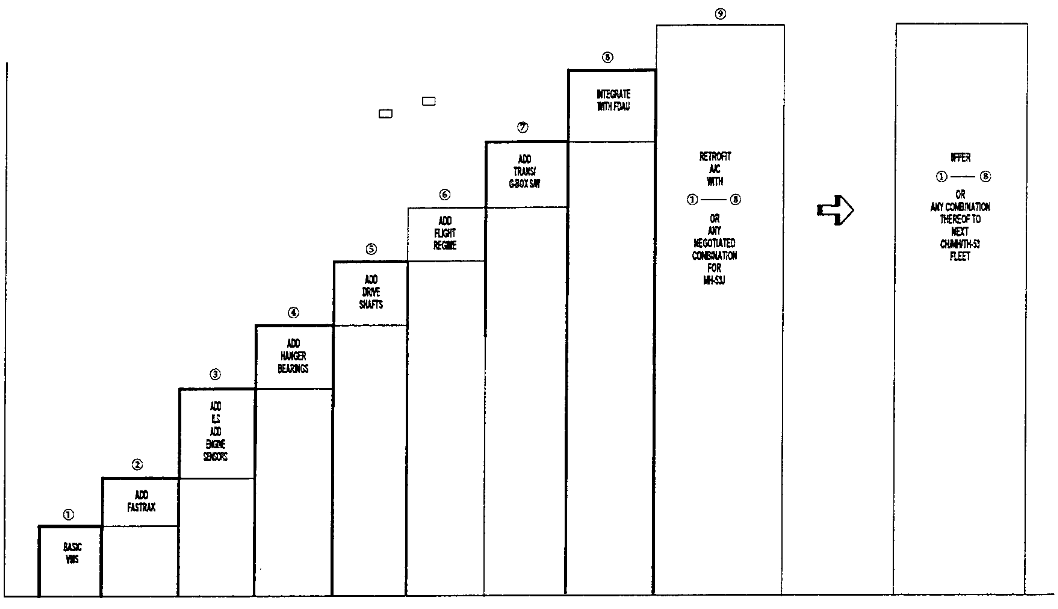
- Near real time feedback (providing in-flight or immediate post flight solutions) enables adjustments and corrections between flights, eliminating the need for costly test flights.

- Gather in and recording vibration data from inception on a new helicopter enables later analysis for purposes such as:
  - Introducing additional diagnostics as demand and affordability levels are reached
  - Detecting trends in helicopter behavior
  - Comparative vibration performance changes after parts changes
  - Ongoing fleet data correlation
  - Providing data for establishment of cautionary exceedance levels, typically in conjunction with manufacturer of engines, airframe, rotor blades.

With acceptance and adoption of basic systems satisfying basic needs, the industry is charged with the responsibility of applying what has been learned to extend and improve. Such extensions and improvements take two forms:

- Adding to the scope of justified monitoring features without appreciable addition to the maintenance task, and
- Learning more and gaining additional utility from basic functions already in place

To illustrate the former, we present the pattern for program development used in the application of vibration monitoring for the USAF MH53J helicopter. Once a series of basic features is mastered and there is a pay-off, an expansion step is taken as illustrated below:



GROWTH OF A HEALTH MONITORING SYSTEM

In each instance, maintenance and logistic planning parallels or precedes implementation. Using this approach the operator absorbs the full utility of his basic tools – and as we are learning is even able to extend their utility. Upon mastery, it is then possible to add expansion features.

Adding functions becomes largely a software issue and perhaps the addition of sensors rather than one of total hardware change.

For the USAF, after several years of operational use of the basic system, an expansion system was authorized.

The expansion objectives;

- Core system objectives:
    - Integration of Optical Tracker into Main Rotor Software.
    - Sensor additions and software upgrades to incorporate tail rotor and engine
    - driveshaft monitoring.
    - Software memory and storage increases.
- Optional system upgrades:
    - Installation of Cockpit control Unit
    - Enhanced PCMCIA download
    - Flight time log/Total flight time record

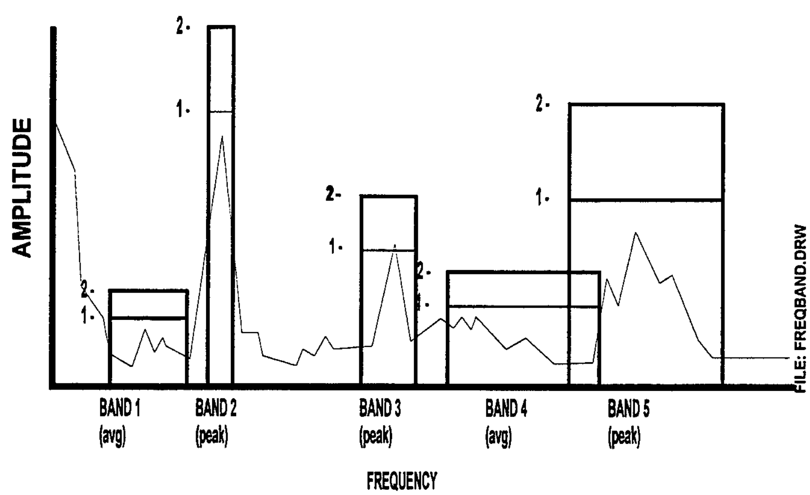
Meanwhile, the process of extending the value of basic functions continued. In this the second category of adding value, software was incorporated to;

- Correlate and integrate optical track data

  Until continuous vibration monitoring was implemented and became routine, the phenomena of track impact on overall track and balance was not fully understood. With sufficient gathered data, it was then surmised that correlation of the two sets of data would give new insight into rotor smoothing. In a classic case history, it was learned that by tracking the blades of the six bladed helicopter while gathering balance data, one could gather harmonics representing all six blades. The "six per rev" feedback combined with the balance data allowed a rotor smoothing solution of an aggravated and intolerable vibration level introduced when composite material rotor blades were chosen.

- Enable a Monitor Log

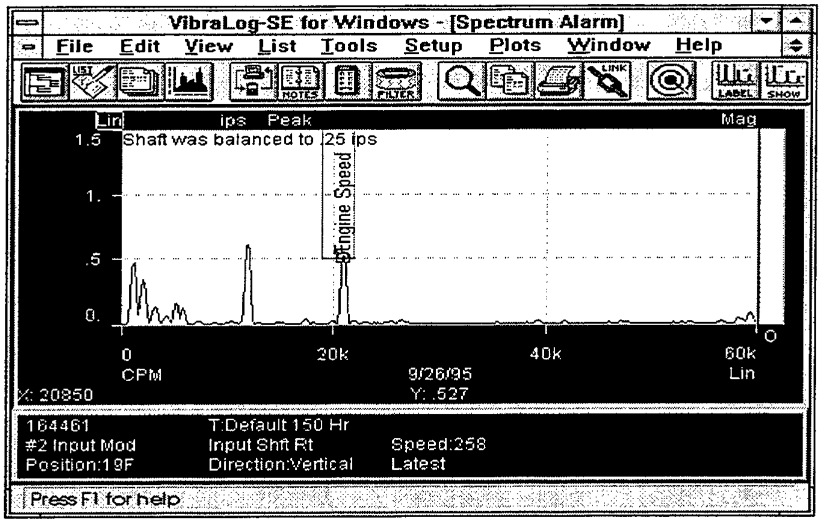
  Spectral based feedback was enabled to allow "at will" sampling into specific conditions of interest. Each spectrum routinely taken consists of 400 frequency bins and each "snapshot" requires only several tenths of a second to take. Enabling the monitor log simply meant limiting the stored data to defined frequencies representing major rotational components. This log as conceived then permitted tailoring the responses collected to those of primary interest. For example, storage of monitored frequencies could be limited to the focus of temporary interest as shown below, measuring 1)Peak frequency-highest amplitude,2)RPM of the peak frequency and 3)Total vibration energy in the band – the RMS measurement of the amplitude of each bin in the band.



FREQUENCY BANDS IN A SPECTRUM

- Spectrum Plot Print

An example of spectral plot prints showing uploadable alarms/advisories based upon exceedance selections is depicted below:



This renewed focus on expanding basic techniques is one of important byproducts of continuous monitoring of the helicopter. As more sophisticated monitoring is introduced such as formalized gearbox and bearing monitoring, the process of data extraction from the more basic functions is expected to broaden the utility of such monitoring in the continued quest for comprehensive diagnostics.

At this writing, health monitoring has been applied to over two hundred helicopters. Each HUM and HMS application can recite its' own case histories to add to the record.

CONCLUSIONS

In actual practice and experience using helicopter health monitoring systems the advantages gained by continuous monitoring has directed operators to find new value in the basics of monitoring. Practical tools that are extensions of techniques in practice are emerging giving added insight into the maintenance task. The fruitful expansion of current procedures are adding value to the monitoring task and yielding practical results.

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[1] Usage Monitoring Working Group (UMWIG) Briefing to CAA Health Monitoring Advisory Group (HHMAG) 17 November 1993.

[2] EuroHUMS is a trademark of the Allegheny Teledyne Corporation

VIBRATION MONITORING OF ROYAL AUSTRALIAN NAVY HELICOPTERS

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Peter O'Neill, RAN - NALMS
Brian Rebbechi, DSTO - AMRL

Abstract

This paper provides a brief background of helicopter vibration monitoring in the RAN, and describes the integrated vibration monitoring system currently being introduced into their fleet of S-70B-2 Seahawk and SK-50 Sea King helicopters. This system incorporates standard commercial airframe rotor track and balance equipment, and an AMRL-developed transmission vibration monitoring system. Both incorporate permanently mounted sensors wired to cabin receptacles, and carry-on/carry-off vibration analysers.

Introduction

Historically, vibration analysis in helicopters has been carried out to maintain acceptable levels of Rotor Track and Balance (RT&B) and airframe vibration. Maintenance procedures that include weighing rotor blades and static pitch lever adjustments generally provide acceptable initial operation of the rotating system from an airworthiness viewpoint. RT&B measurements are used to refine these initial static adjustments, and also during regular maintenance to compensate for minor component degradation. The main purposes of rotor track and balance are to ensure acceptable levels of vibration at crew stations, and to reduce airframe loads.

A more recent application of helicopter vibration analysis is to assess the health of the drivetrain, and in particular the integrity of the main and tail rotor gearboxes. The civil application of health monitoring has received considerable impetus from the Civil Aviation Authority (CAA) in the United Kingdom. Since 1984, they have strongly promoted a program to introduce Health and Usage Monitoring Systems (HUMS) into all medium and large helicopters used for commercial charter operations [1]. This program has had considerable success, as there are now in the order of 160 helicopters equipped with HUMS operating in the UK [2]. Despite this civilian adoption of HUMS, the application to military helicopters has been, by comparison, much slower, although there are a number of demonstration programs – for example, the United States Navy [3]. One of the reasons for this more gradual introduction into the military sphere is related to the military requirement for operations away from a stable base, and the limited access to logistics systems under these conditions, as described in [4].

While RT&B measurements have always played a mandatory role in RAN helicopter operations, it is less well known that the RAN has also been involved in helicopter drivetrain monitoring since 1977. The following sections provide a brief background of the RAN helicopter vibration monitoring program, and describe the integrated vibration monitoring system currently being introduced into their S-70B-2 Seahawk and SK-50 Sea King helicopters. The introduction of this system marks the first permanent installations of RT&B, and drivetrain vibration monitoring equipment into Australian military helicopters.

RAN Helicopter Vibration Analysis Program

The RAN have carried out regular airframe/RT&B measurements on all their helicopters since their introduction to the fleet. Generally, these measurements are carried out at scheduled maintenance intervals, or when rotating components are replaced, or to investigate reports of high vibration. The measurements are carried out using portable vibration balancer/analysers, and low-frequency vibration transducers (optimised for rotor and blade-pass frequencies) temporarily mounted at various airframe locations. The time required to instrument the aircraft for these measurements, however, is quite considerable. For example, for the S-70B-2, the installation/removal time for a routine vibration check (150 hr interval) will take 4 hours, and for a post major service (600 hrs) will take 8 hours.

In 1977, an additional vibration analysis program for health monitoring of the main rotor gearboxes of the Wessex and Sea King helicopters was introduced. This was termed the Recorded Tape Vibration Analysis Program (RTVAP). Some support to the program was provided by Westland Helicopters (manufacturer under licence of the Wessex and Sea King), and AMRL was tasked to provide expert advice as required. The equipment used in this program comprised a single high-frequency bandwidth accelerometer (optimised for gear mesh frequencies) on the main rotor gearbox, with the output processed via an amplifier and recorded on a 4-channel analogue FM tape recorder. A synchronous timing signal from the gearbox was also recorded. This was derived from the aircraft 115 VAC electrical supply – the generators being geared into the main transmission. Analysis was carried out with ground-based equipment, comprising an FFT (Fast Fourier Transform) analyser, and printer. This program was later revised to take advantage of time-domain synchronous averaging techniques [5, 6 and 7], with equipment developed at AMRL installed at NAS Nowra for this purpose [8]. During the period 1977 to 1991, there were 30 investigations [9] of unusual Wessex and Sea King main rotor gearbox vibration, with the analyses either confirming, or providing the initial warning of, a defect.

Because of the success of the vibration analysis program, but also in view of the need to reduce maintenance hours, the RAN considered that the permanent installation of transducers and wiring would be a cost-effective exercise. A decision was taken in 1996 by the (then) Naval Aircraft Logistics Office (NALO) to hard-wire all RAN Seahawk and Sea King helicopters with permanently installed transducers, cabling and junction boxes. The data collection/analysis equipment would be carried on board for the particular flight. The advantages to the RAN in this approach are that:

a) the existing portable rotor track and balance equipment is used as before, thus requiring no significant change to existing maintenance procedures;
b) there is a large saving in maintenance effort/time;
c) the RAN continue to make cost-effective use of existing equipment; and
d) should suitable on-board equipment become available in the future, then most of the hard-wired equipment could still be utilised.

System Description

The integrated vibration monitoring system currently being implemented in the S-70B-2 and SK-50 helicopters is basically a combination of the Chadwick-Helmuth 8500C balancer/analyser, and an AMRL-developed transmission vibration monitoring system, with some cross-coupling between sensors [10, 11]. The installations in the S-70B-2 and SK-50 helicopters differ only in the number and placement of transducers. Chadwick-Helmuth Company was awarded the contract to develop and provide the installation kits in 1997.

A block diagram of the system components actually hard-wired into the aircraft is shown in Figure 1. The input selector unit provides the cross-coupling of sensors between the analysers, as well as some multiplexing of the photocell signals. It has two multi-position rotary switches, one of which selects between: (a) rotor track and balance, (b) engine drive shaft balance[1], and (c) transmission vibration analysis. The second switch is for use in the transmission vibration analysis mode only, and selects which one of the photocell signals is to be used: tail, or left/right engine drive shaft.[2]

A break down of the number of sensors in each aircraft is shown in Table 1. The sensor locations for the S-70B-2 are shown in Figure 2, and for the SK-50 in Figure 3.[3]

Table 1. Sensors

	S-70B-2	SK-50
Gearbox Accelerometers	7	5
Engine Accelerometers	2	4
Airframe Velocimeters	16	8
Magnetic Pick-up	1	1
Photocells	3	1
Blade Tracker	1	1
Total	**30**	**20**

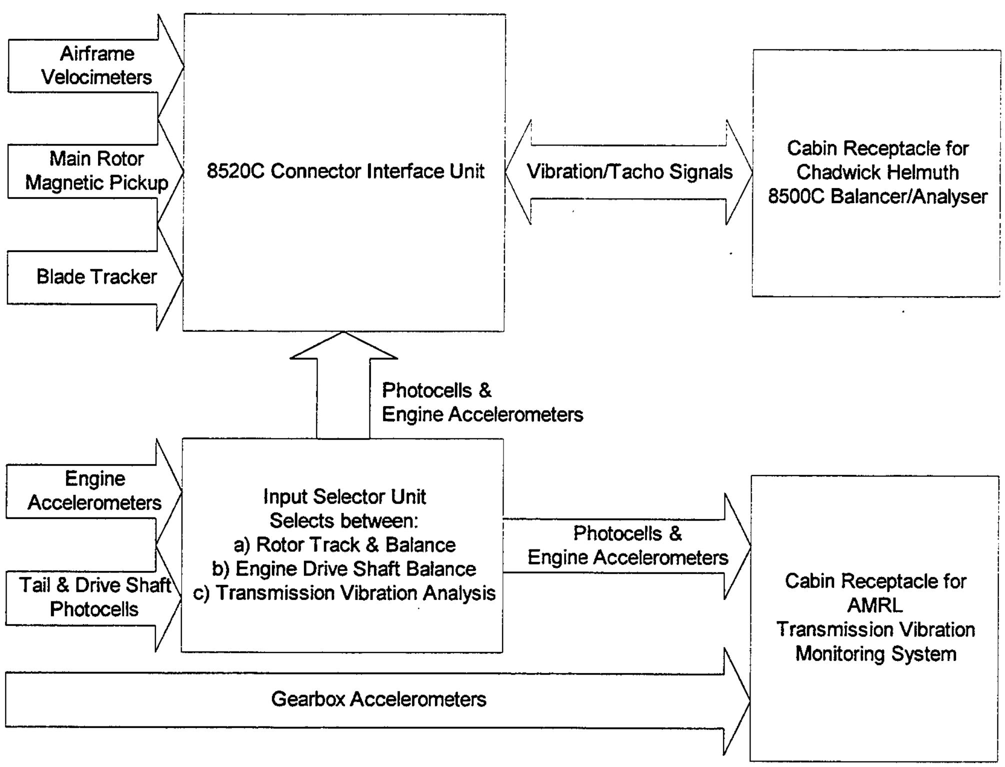

Figure 1. Block Diagram of Hard-wired Components

[1] Applicable to the Seahawk only - not implemented in the Sea King.
[2] See footnote 1.
[3] Illustrations curtesy of Chadwick-Helmuth Company.

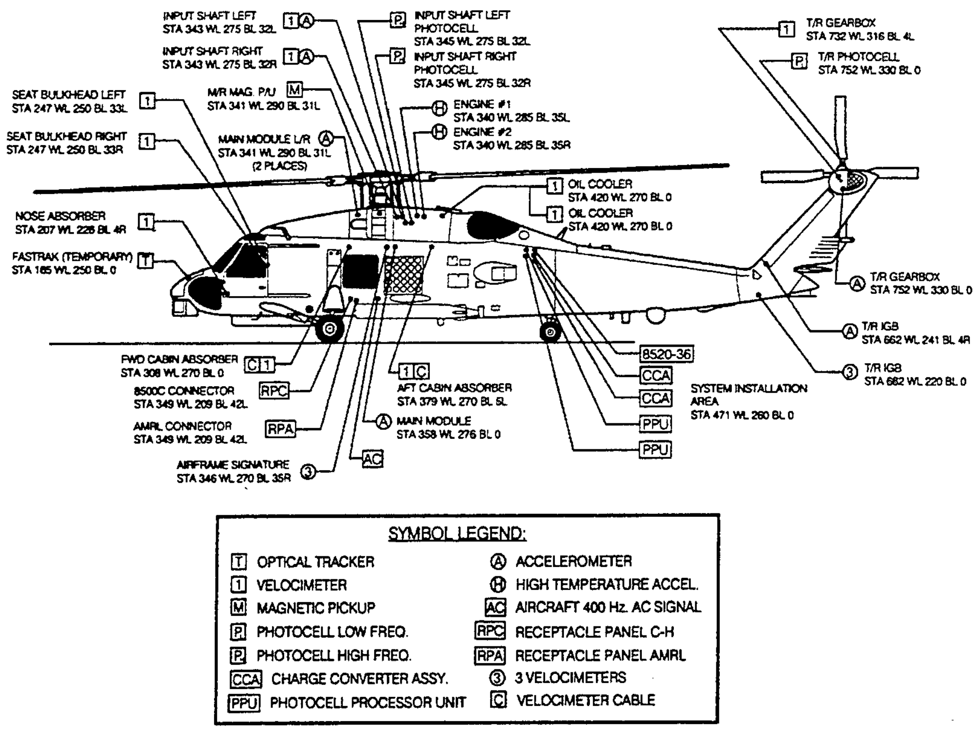

Figure 2. S-70B-2 Seahawk Installation

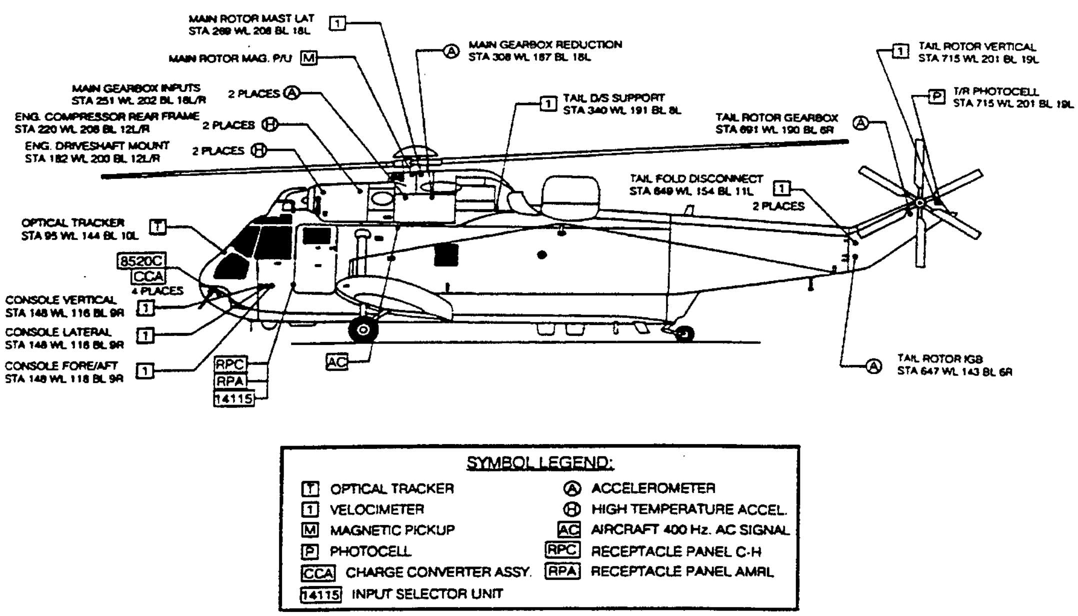

Figure 3. SK-50 Sea King Installation

Chadwick-Helmuth 8500C

The Chadwick-Helmuth 8500C (Figure 4) is a balancer/analyser with broad usage on many fixed and rotary wing aircraft throughout the Australian Defence Force. It performs a number of standard FFT analyser functions together with "Smart Chart" balancing and blade tracking routines. Data collected with the 8500C can also be up-loaded into the Chadwick-Helmuth PC software package Vibralog for trending and comparing with various warning/alarm limits.

As shown in Figure 1, the 8500C takes inputs from a number of sensors mounted throughout the aircraft. Chadwick-Helmuth EMI velocimeters are used for all airframe locations, but Endevco model 6233C-50 (high temperature - 900°F) accelerometers with Chadwick-Helmuth integrating charge amplifiers (C-H P/N 8225-6H2) are used for the engines. A Banner photocell (C-H P/N 12900) is mounted on top of the tail pylon to provide a tacho signal from the tail rotor. Additionally, in the S-70B-2 only, two Chadwick-Helmuth photocells (C-H P/N 10200) are utilised for high speed engine drive shaft balancing.

All transducer cabling is routed back to a Chadwick-Helmuth 8520C connector interface unit permanently mounted in a central location. In the S-70B-2, this is in the transition bay behind the main fuel tank, while in the SK-50, it is in the nose avionics bay. A multi-conductor cable connects the 8520C to a receptacle in the aircraft cabin. In the S-70B-2 the cabin receptacle is below the sensor operator's window, in the SK-50 it is near the floor behind the centre console between the pilot seats (the rear of the nose avionics bay). Connection between the 8500C and the cabin receptacle is achieved with the standard cable supplied in the 8500C rotor track and balance kits.

Operation of the 8500C is achieved by loading a data collection route for the aircraft via a 3½" disk. The 8500C steps through this route, prompting the user with the flight regimes required for the each data collection. This data is then analysed within the unit, with the results shown on the display panel, and saved to disk. The results can also be printed out on an in-built thermal printer. Data saved on the disk can be up-loaded into Vibralog for trending purposes.

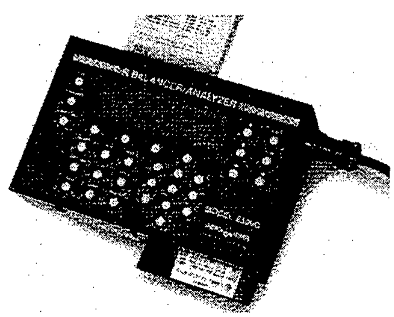

Figure 4. Chadwick-Helmuth 8500C

AMRL Transmission Vibration Monitoring System

The AMRL transmission vibration monitoring system (Figure 5) consists of a ruggedised laptop computer with three internally mounted ISA data acquisition cards: a signal conditioning card, an anti-alias filtering card, and an analogue-to-digital converter card. All but the signal conditioning card and the connector interface, which were custom designed at AMRL, are commercial off-the-shelf equipment. This system has been developed out of previous experience gained with the RTVAP system, and being completely computerised, eliminates many of the problems associated with the use of the tape recorder in that system. The AMRL system was flight trialed in an Australian Army S-70A-9 Black Hawk helicopter in 1995 [12].

The system has seven input channels for constant-current low-impedance type accelerometers, and two tacho channels. The accelerometer channels have a wide range of software programmable gains (1, 1.5, 2, 3, 4, 6, 8, 12 and 16) to accommodate both strong and weak signals, and make the best use of the analogue-to-digital converter's (12 bit) dynamic range. These channels also have access to over-range, and short-circuit/open-circuit detection to ensure the integrity of the vibration signals. The tacho channels use unity gain isolation amplifiers to prevent potentially high voltages from damaging the data acquisition cards. Resistive voltage dividers are used to bring the amplitude of the tacho signals within ±5 V.

The computer is powered from the aircraft 28 VDC supply. As shown in Figure 1, it takes inputs from a number of accelerometers and photocells. Most gearboxes, or gearbox modules, have one accelerometer, although in both aircraft the main rotor gearbox has three, with one mounted near each input, and one mounted on the ring gear. A synchronous timing signal signal for the main transmission is also derived from a separate connection to the aircraft 115 VAC supply – the AC generators being directly geared to the main transmission.

The cabling for all the gearbox accelerometers is routed directly to the AMRL cabin receptacle, which is located next to the 8500C cabin receptacle. These accelerometers are powered by the AMRL system, and are not interconnected with the 8500C. The photocells and engine accelerometers, however, are routed through the input selector unit, as these are used by both the 8500C and the AMRL system.

In flight, the system is operated by turning the computer on, and running a data acquisition program. This systematically steps through all the data acquisitions required for that aircraft, prompting the user with the required flight regime for each acquisition, and saving the data to disk. Generally, there is only one acquisition for each gearbox, although the main rotor gearbox requires more due to the large variation in shaft speeds within that gearbox. For the S-70B-2, acquisition times vary from 5 seconds for the input modules, to 60 seconds for the epicyclic gears of the main module. Acquisitions are started with a single key press, and all data are automatically checked for integrity. If there are errors, the user is prompted to re-acquire the data. Real-time vibration signals can also be visually inspected on the computer display using an oscilloscope function. Once all data is acquired, the system can be shut down for the rest of the flight.

Post flight, the raw vibration data are processed and analysed. This consists of systematically computing the synchronous average (ie vibration signature) of every gearbox shaft, and comparing various condition indices derived from these averages with warning and danger limits. Any limit exceedances will be listed in an automatically generated analysis report, and subject to further investigation by AMRL and NALMS. The results of all analyses will also be archived and trended at a central location using a commercially available software package. Data transfer will either be via modem, flash-memory card, or zip disk.

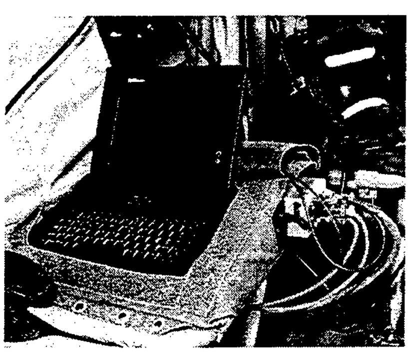

Figure 5. AMRL Transmission Vibration Monitoring System

System Installations and Flight Trials

Initial installations of the RAN system to confirm installation kit requirements and procedures were undertaken at NAS Nowra in late January to early February 1998, by RAN, DSTO, Chadwick-Helmuth Company, and VMS Industries personnel.

The S-70B-2 installation, on aircraft tail number N24-008, took about 7 working days, while the installation on the SK-50, tail number N16-100, took about 5 working days. The difference in installation times reflects the larger number of transducers in the S-70B-2. Apart from a few minor problems with brackets and connectors, both installations went according to plan, and flight trials in both aircraft confirmed the correct operation of the system.

The rest of the aircraft kits (15 for the S-70B-2, and 6 for the SK-50) will be received in July 1998. Installation in the remaining aircraft will proceed on an opportunity basis. Generally, this will happen during scheduled routine maintenance.

Concluding Remarks

a) The RAN has a long history of using vibration analysis in helicopters for both RT&B and drivetrain health monitoring.
b) The benefits of vibration monitoring, together with this past experience, and a desire to reduce aircraft maintenance time/effort, has led the RAN into a hard-wiring program for all their S-70B-2 and SK-50 aircraft.
c) The integrated vibration monitoring system being installed in these helicopters is a combination of the existing RT&B equipment and an AMRL transmission vibration monitoring system.
d) The initial installations, and flight trials of the systems, in these aircraft have been successfully completed.
e) These trials have confirmed there will be significant savings in maintenance hours for vibration analysis activities.
f) Hard-wiring kits for the remaining aircraft will be delivered in July 1998, and the installations of these kits will begin later this year.

Acknowledgments

Considerable time and effort has gone into this project from numerous people at the following organisations:

- Royal Australian Navy
- Defence Science and Technology Organisation
- Chadwick-Helmuth Company
- VMS Industries

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11. *Installation/Checkout Guide SK-50 Sea King Model 8500C Hardwire*, Chadwick-Helmuth Company, Document No. 14355.

12. Blunt D M & Dutton S A, *A Lightweight Vibration Monitoring System for the S-70A-9 Black Hawk Transmission*, DSTO-TR-0036, AR-009-697, November 1996.

HH-60G MISSION USAGE SPECTRUM SURVEY
METHODOLOGY OVERVIEW

for WORKSHOP on HELICOPTER HEALTH and USAGE MONITORING
at AMRL, 16 FEB 99, MELBOURNE AUSTRALIA

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TECHNICAL APPROACH

- THIRTY SIX (36) IN-FLT PARAMETERS; only 4 NEW SENSORS
  - 12 Mux Bux, 10 A/C Sys, 8 Calculated, 2 Key Board
- FORTY EIGHT (48) BASIC FLT REGIMES (GTRREC)
  - Focus on Most Critical Maneuvers
  - Track Transient Maneuver Severity
  - Maximize Potential Benefits to USAF CRT's
    - Distinguish Damaging from Non-Damaging Flt Time
    - Provide Flexible Database for Post Analysis
- NINE (9) DISCRETE PARAMETER CHANGES
- SIX (6) SPECIAL INSPECTION EXCEEDANCES
- BANDED PARAMETERS (16 max); 10 H_z SAMPLE RATES

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HH-60G IN-FLT PARAMETERS

	Sensor		Sensor
1. Pilot's Ind Airspeed	Mux Bus	19. Pitch Rate	Mux Bus
2. Co-Pilot's Ind Airspeed	A/C Sys	20. Roll Rate	Mux Bus
3. Outside Air Temp	New	21. Yaw Rate	Mux Bus
4. Barometric Press Alt	Mux Bus	22. Left Main LG WoW	Mux Bus
5. Barometric Rate of Descent	A/C Sys	23. Right Main LG WoW	A/C Sys
6. Radar Altitude	Mus Bus	24. Engine Start GW	Key Board
7. Normal Load Factor at A/C CG	New	25. Engine Start CG	Key Board
8. Main Rotor Speed	A/C Sys	26. Refueling Probe Ext	A/C Sys
9. No 1 Engine Torque	A/C Sys	27. INS Heading	Mux Bus
10. No 2 Engine Torque	A/C Sys	28. INS Roll Attitude	Mux Bus
11. Avg Engine Torque	Calculated	29. INS Yaw Attitude	Mux Bus
12. Longitudinal Cyclic Pos	A/C Sys	30. Trim Ball Signal	A/C Sys
13. Lateral Cyclic Pos	New	31. Δ Fuel Quantity	Calculated
14. Collective Pos	A/C Sys	32. Gross Weight	Calculated
15. Directional Pedal Pos	New	33. Percent Vh	Calculated
16. Roll Attitude	Mux Bus	34. Equiv Rotor Tip Spd	Calculated
17. Pitch Attitude	Mux Bus	35. Roll Rate	Calculated
18. Elapsed Time	Calculated	36. Yaw Rate	Calculated

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EQUIV RETREATING BLADE INDICATED TIP SPEED (ERITS)

$$\mathrm{ERITS} = \left(V_R \sqrt{\frac{\rho}{\rho_o}} - V_I \right) \sqrt{\frac{W_o}{W} \frac{A_o}{A}}$$

Where

- V_R **Blade Rotational Tip Speed (kts)**
- V_I **Indicated Airspeed (kts)**
- W_o **Normalizing GW = 16,500 lbs**
- W **Actual GW**
- A_o **Normalizing Load Factor = 1g**
- A **Actual Load Factor**

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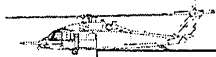

GTRREC BASELINE REGIMES

1. Rotor Stopped
2. Ground Operations / Taxi
3. Taxi Turn
4. Lift to Hover
5. Normal Takeoff from Ground
6. Rolling Takeoff
7. Jump Takeoff
8. Hover/Low Speed Flight
9. Climbing Hover/Low Speed Flight
10. Descending Hover/Low Speed Flight
11. Normal Takeoff from Hover
12. Not Used
13. Left Hovering Turn
14. Right Hovering Turn
15. Hover/Low Speed Maneuvering
16. Evasive Maneuvering
17. Climb
18. Acceleration
19. Level Flight
20. Dive
21. Left Sideslip
22. Right Sideslip
23. Turn
24. Climbing Turn
25. Descending Turn
26. Symmetric Pullout
27. Pushover
28. Partial Power Descent Entry
29. Partial Power Descent
30. Partial Power Descent Recovery
31. Autorotation Entry
32. Steady Autorotation
33. Autorotation Turn
34. Autorotation Pullout
35. Autorotation Pushover
36. Autorotation Recovery
37. Aerial Refueling
38. Rolling Pullout
39. Normal Deceleration
40. Normal Approach
41. Quick Stop
42. Side Flare
43. Normal Landing
44. Roll-on Landing
45. Autorotation Landing

46-49. Control Reversals

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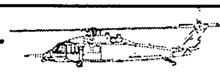

GTRREC IDENTIFIED EVENTS

DISCRETE PARAMETER CHANGES

101.	DEK Record, Troop Changes
102.	Right Main WOW On
103.	Right Main WOW Off
104.	Refueling Probe Extended
105.	Refueling Probe Retracted
106.	Fuel Quantity Increasing On
107.	Fuel Quantity Increasing Off
108.	Rotor Start
109.	Rotor Stop

SPECIAL INSPECTIONS REQUIRED

201.	Overspeed, 127% - 136% Nr
202.	Overspeed, 137% - 141% Nr
203.	Overspeed, above 141% Nr
204.	Overtorque, 107% - 127% for > 10 secs
205.	Overtorque, 127% - 144% for > 10 secs
206.	Overtorque, above 144%

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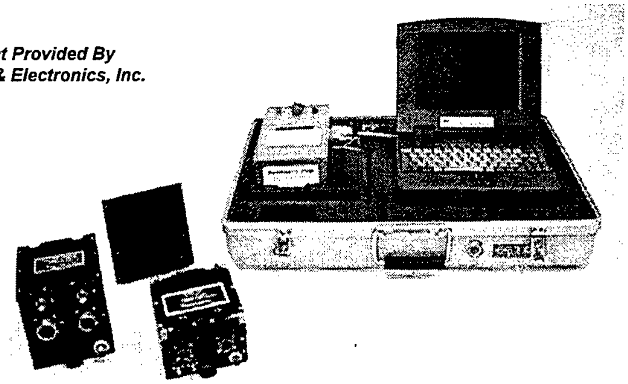
USAGE MONITORING EQUIPMENT

Equipment Provided By
Systems & Electronics, Inc.



HH-60G Mission Usage Spectrum Survey Equipment
From left to right: Signal Data Converter, Data Entry Keyboard, Recorder-Converter (with Memory Unit), and the Ground-Based Maintenance Data Processing Station

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ALGORITHM DEVELOPMENT

GEORGIA TECH REGIME RECOGNITION (GTRREC)

- ***FOCUS ON MOST CRITICAL MANEUVERS***
- ***ID REGIMES CONSISTENT with EXISTING FLT LOAD SURVEY DATABASE***
- ***TRACK TRANSIENT MANEUVER SEVERITY***
- ***MAXIMIZE POTENTIAL BENEFITS to USAF CRT'S***
  - ***DISTINGUISH DAMAGING from NON-DAMAGING FLT TIME***
  - ***PROVIDE FLEXIBLE DATABASE for POST ANALYSIS***

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REGIME CLASSIFICATION (DATABASE STORAGE)

- **3 LEVELS OF REGIME CLASSIFICATION**
  - CONDITION ID (Altitude, GW, Refuel Probe Status)
  - REGIME ID (1-45 Baseline Regimes + Control Reversals)
  - TRANSIENT / SEVERITY ID (A/S, Peak Nz, Max Roll Attitude, Max Roll Rate, Max Yaw Rate, ERITS Levels)
- **ADDITIONAL CLASSIFICATIONS**
  - A/C TAIL NUMBER / LOCATION
  - FLIGHT NUMBER / DATE
  - MISSION TYPE, A/C CONFIGURATION

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DATABASE STORAGE METHODOLOGY

Example: Turn to the Lt with 45° AOB @ 0.8 Vh for 25.7 sec

COND ID	REG ID	TRANS / SEVERITY ID	
0 - 1 - 0	23	6 - 4 - 13 - 9 - 7 - 94 - 6 - 0	➔ 25.7

COND ID: ALTITUDE BAND - GW BAND - IR PROBE

TRANS / SEVERITY ID: ENTRY AIRSPEED - PEAK NZ - MAX ROLL ATTITUDE - MAX ROLL RATE - MAX YAW RATE - %TIME/ERITS LVL

12 DATA FIELDS ASSOCIATED WITH EACH TIME IN REGIME

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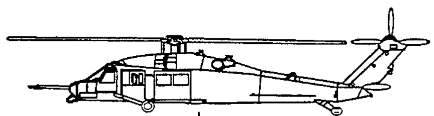
OPERATIONAL OVERVIEW



DATA RECORDING		
DATA DOWNLOADING	*MAINTENANCE DATA PROCESSING STATION*	*U. S. AirForce*
	↓ -- *Binary Download File*	↓
DATA PROCESSING	*GTRREC*	*Georgia Tech Research Institute*
	↓ -- *Recognized Flight Regimes*	
DATA STORAGE	*ORACLE*	

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OPERATIONAL SITES

S / N	Location	Mission	Flt Hrs
88-26109 &	Nellis AFB, NV	Weapons Sch	286.5
91-26353		Ops Test	371.1
82-23718 &	Kirtland AFB, NM	Training	252.1
82-23689		Training	136.0
92-26462 &	Moody AFB, GA	SAR	143.6
92-26465*		SAR	192.7
		TOTAL	1382.0

*Deployed to Turkey as of 7/23/97

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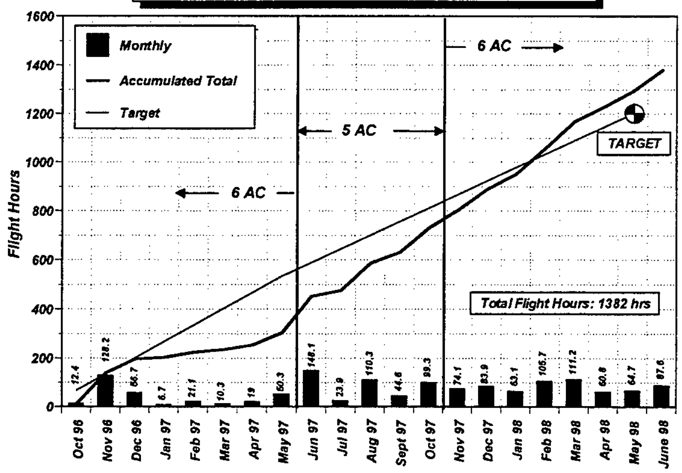
OPERATIONAL USAGE PHASE ACCUMULATED FLT HRS



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RESULTS by AIRCRAFT

- ***SURVEY DATA PRESENTED by AIRCRAFT with***
  - *80 Charts in Final Report; 30 Comparisons with Army Spectrums*
- ***COMPOSITE RESULT SHOWN for EACH CONDITION***
- ***STEADY STATE REGIMES by AIRSPEED***
- ***TRANSIENT MANEUVERS by Nz, ERITS, BANK ANGLE***
- ***SIGNIFICANT RESULTS:***
  - *Weapons School A/C Performs More Turns & Partial Power Descents*
  - *Training A/C Perform More Autorotations*
  - *SAR A/C (including OCONUS data) Least Damaging*

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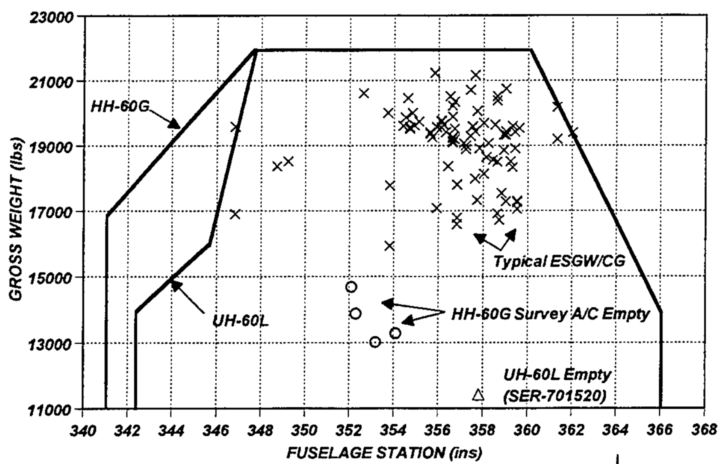
ACTUAL GW/CG ENVELOPE



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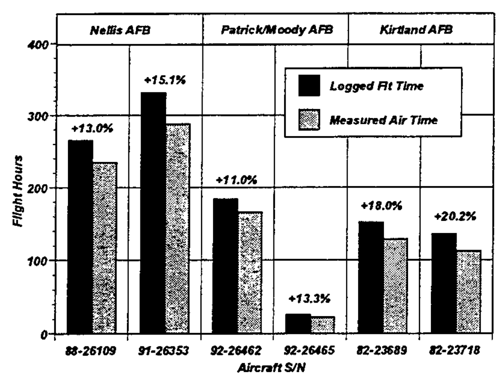
LOGGED vs MEASURED FLT TIME

Note: Based on Available Operational Logs



MISSION (S/N)	% OVER
SAR (462,465)	11.3%
Weapons Sch (109)	13.0%
Ops Testing (353)	15.1%
Training (689,718)	19.0%
Composite	14.8%

Total Flt Hrs: 1382

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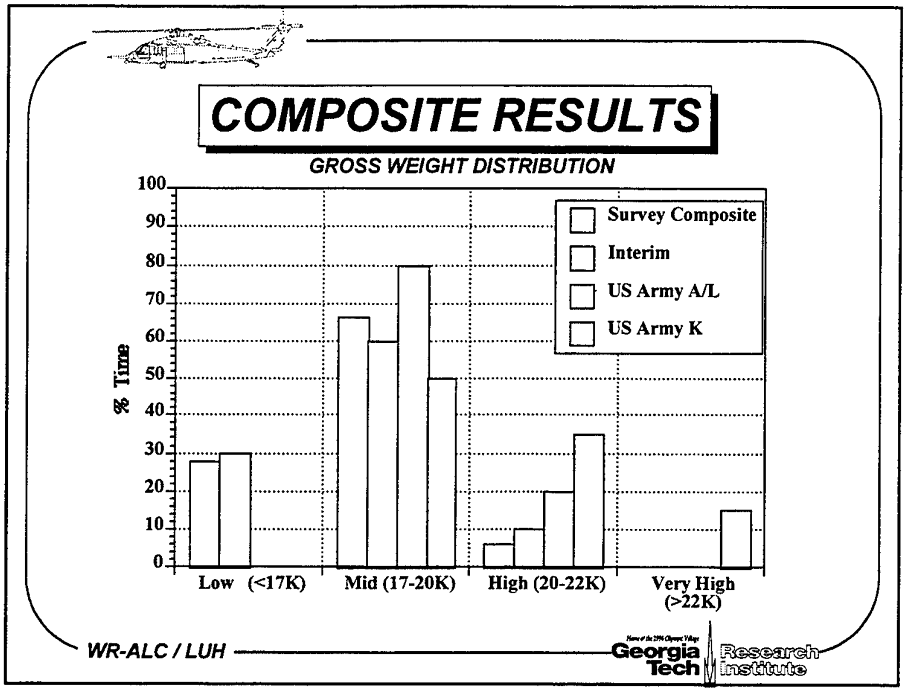

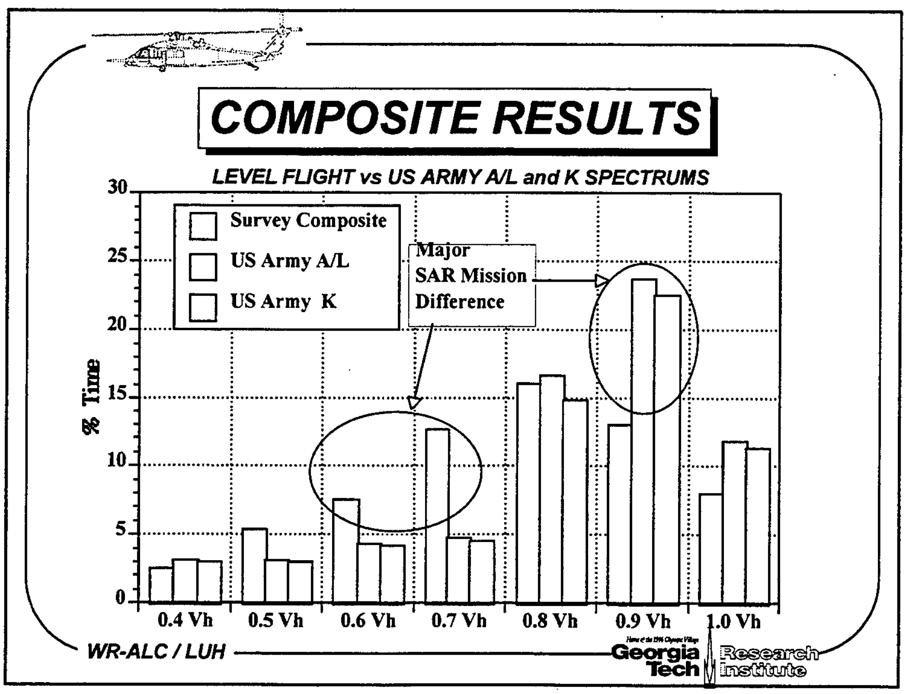

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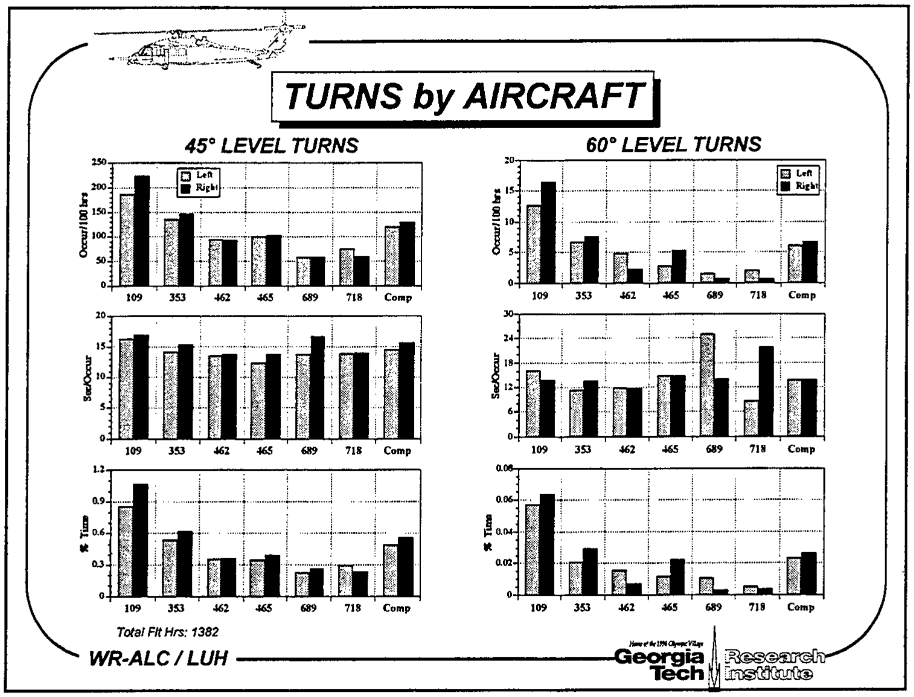

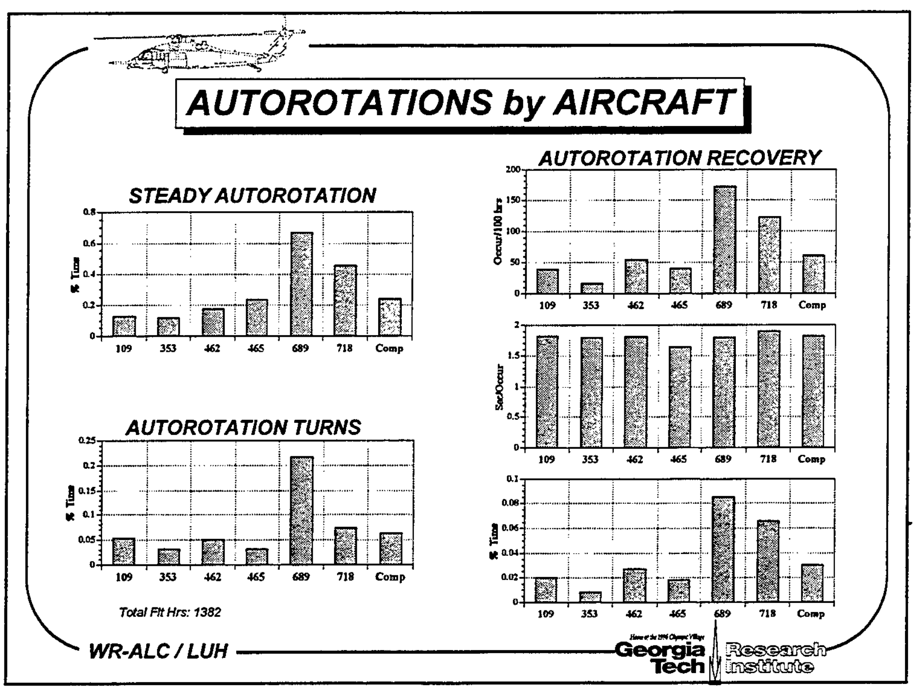

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APPROACH to SPECTRUM DEVEL

- ***ARMY UH-60A/L SPECTRUM as STARTING POINT***
- ***REPLACE ESTIMATES with MEASURED DATA***
  - *Prorates: GW, Alt, Dive Speed & Sideslip Direction*
  - *Percent Time in Regime*
  - *GAGs/Flt & Min-Max Cycles*
- ***EVENTS NOT MEASURED ARE CARRIED FWD***
  - *Droop Stop Pounding*
  - *Control Checks*
- ***HOVER/LOW SPEED FLT TIME SPREAD over HOVER, SIDEWARD & REARWARD FLT REGIMES***
- ***HOVER MANEUVER TIME SPREAD over LOW SPEED ENTRY/RECOVERY REGIMES***

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WORST CASE METHODOLOGY

- ***APPLIED to MOST DAMAGING REGIMES***
  - *Partial Power Descents and Dives*
  - *Left and Right Turns (30°, 45°, 60°)*
  - *Moderate and Severe Pullouts*
  - *Autorotation Entry/Recovery*
  - *Run-on Landings*
- ***WORST AIRCRAFT %TIME USED***
  - *Exceptions:*
    - *45° and 60° Turns: Worst Base Used*
    - *Auto Ent/Rec: Mean + 3.5σ (Excluding Training A/C)*

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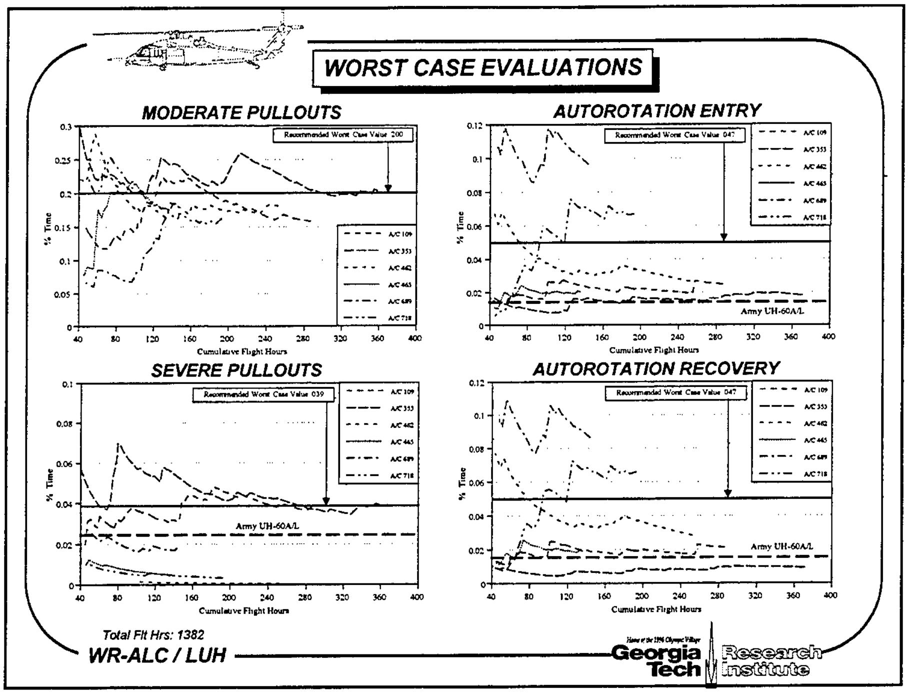

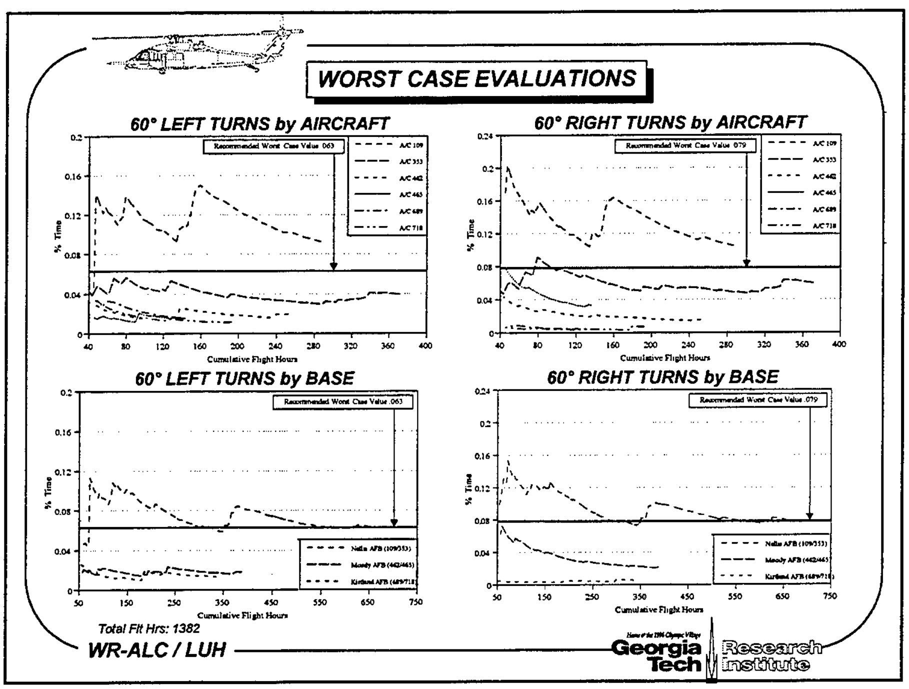

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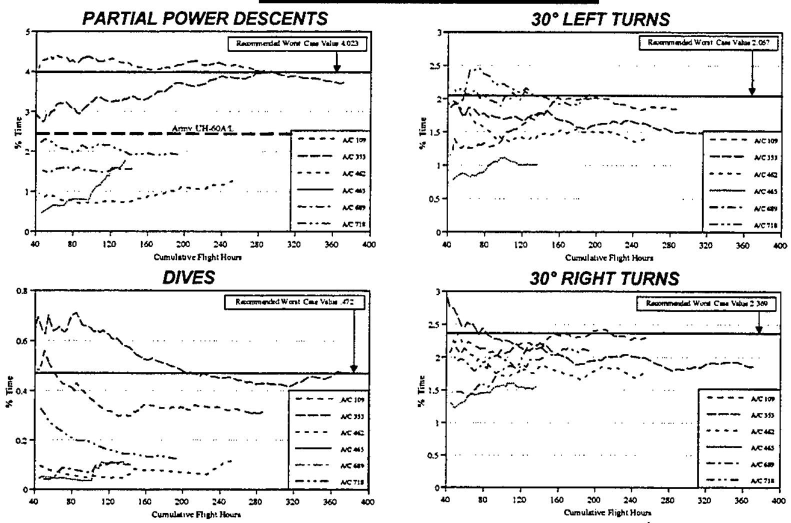
WORST CASE EVALUATIONS



Total Flt Hrs: 1382

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SPECTRUM NORMALIZATION

- ***TIME ADDED for WORST CASE RAISED MISSION DURATION above 103%***
- ***NON-DAMAGING REGIME TIMES SCALED DOWN***
- ***MODERATE DAMAGING REGIMES UNCHANGED***
  - *Climb*
  - *Level Flight at 1.0 Vh*
  - *Sideslips*
  - *Control Reversals (hover and forward flight)*
  - *Take-offs and Normal Landings*
- ***TAKE-OFF / LANDING OCCURRENCES MATCHED***

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WORST SURVEY AIRCRAFT in DAMAGING MANEUVERS

	WEAP SCH	OP TEST	SAR		TRAINING		WORST
MANEUVER	109	353	462	465	689	718	A/C
Partial Power Descent	4.025	3.732	1.265	1.765	1.575	1.920	109
Dive	.314	.472	.116	.110	.101	.124	353
30° Left Turn	1.850	1.451	1.397	1.014	2.026	2.067	718
30° Right Turn	2.370	1.862	1.759	1.551	2.001	2.107	109
45° Left Turn	1.169	.772	.477	.438	.358	.386	109
45° Right Turn	1.408	.871	.496	.516	.425	.302	109
60° Left Turn	.093	.039	.019	.016	.015	.012	109
60° Rt Turn	.105	.059	.015	.033	.004	.007	109
Moderate Pullout	.158	.200	.181	.174	.185	.163	353
Severe Pullout	.038	.039	.001	.005	.018	.003	353
Auto Entry	.025	.018	.026	.020	.097	.067	689
Auto Recovery	.021	.009	.028	.019	.087	.066	689
Run-on Landing	.040	.005	.029	.009	.022	.007	109
Total	11.616	9.529	5.809	5.670	6.914	7.231	109

Note: Data Shown as % Time

Total Flt Hrs: 1382

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HH-60G RECOMMENDED SPECTRUM

	UH-60 A/L Without ESSS			Recommended Spectrum		
Gross Weight Prorate	80% Low-Mid GW		20% High GW	94% Low-Mid GW		6% High GW
REGIME	SEC / OCC	OCC/100 hrs	% TIME	SEC / OCC	OCC/100 hrs	% TIME
Hover			1.763			3.497
Sideward Flt Left			0.250			0.496
Sideward Flt Right			0.250			0.496
Rearward Flight			0.250			0.496
Climb			4.198			6.597
Level Flt 0.1VH			2.367			4.695
Level Flt 0.2VH			1.579			3.132
Level Flt 0.4VH			3.157			2.383
Level Flt 0.5VH			3.157			5.200
Level Flt 0.6VH			4.341			7.261
Level Flt 0.7VH			4.736			12.152
Level Flt 0.8VH			16.675			15.414
Level Flt 0.9VH			23.679			12.526
Level Flt 1.0VH			11.839			8.045
Sideslip			1.000			1.829
Autorotation			1.335			0.235
Partial Power Descent			2.500			4.025
Dive			2.324			0.472
Take Off	6.0	400	0.665	5.3	231	0.343
Hover Turn Left	12.0	165	0.550	7.6	138	0.292
Hover Turn Right	12.0	165	0.550	7.3	107	0.216
30 Deg Left Turn	20.0	750	4.166	11.8	631	2.067
30 Deg Right Turn	20.0	750	4.166	12.6	677	2.370
45 Deg Left Turn	15.0	160	0.665	14.0	244	0.948
45 Deg Right Turn	15.0	160	0.665	14.8	270	1.109
60 Deg Left Turn	7.0	63	0.124	12.2	19	0.063
60 Deg Right Turn	7.0	63	0.124	12.2	24	0.080
Left Autorotation Turn	15 (10)	55	0.209	9.1	12	0.031
Right Autorotation Turn	15 (10)	55	0.209	8.9	13	0.031

Most Damaging Regime

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HH-60G RECOMMENDED SPECTRUM Cont.

	UH-60 A/L Without ESSS			Recommended Spectrum		
Gross Weight Prorate	80% Low-Mid GW	20% High GW		94% Low-Mid GW	6% High GW	
REGIME	SEC / OCC	OCC/100 hrs	% TIME	SEC / OCC	OCC/100 hrs	% TIME
Hover Approach	4.0	500	0.557	21.2	304	1.791
Normal Landing	3.0	350	0.264	3.4	210	0.200
Run-on Landing	7.0	50	0.098	6.8	21	0.040
Pedal Rev in Hover	1.5	110	0.046	1.8	46	0.023
Pedal Rev in Fwd Flt	1.5	294	0.122	1.3	17	0.006
Long Rev in Hover	1.5	110	0.046	2.1	274	0.160
Long Rev in Fwd Flt	1.5	294	0.122	2.0	333	0.185
Lateral Rev in Hover	1.5	110	0.046	2.1	74	0.043
Lateral Rev in Fwd Flt	1.5	294	0.122	2.0	131	0.073
Collective Rev in Hover	N/A	N/A	N/A	1.5	55	0.023
Collective Rev in Fwd Flt	N/A	N/A	N/A	2.0	72	0.040
Moderate Pullout	10.0	100	0.278	4.6	157	0.200
Severe Pullout	5.0	18	0.025	4.0	35	0.039
Autorotation Entry	2.0	25	0.014	2.0	85	0.047
Autorotation Recovery	2.0	25	0.014	2.0	85	0.047
Entry Sideward Flt Left	2.5	180	0.125	2.5	140	0.097
Recov Sideward Flt Left	2.5	180	0.125	2.5	140	0.097
Entry Sideward Flt Right	2.5	180	0.125	2.5	140	0.097
Recov Sideward Flt Right	2.5	180	0.125	2.5	140	0.097
Entry Rearward Flt	2.5	180	0.125	2.5	140	0.097
Recov Rearward Flt	2.5	180	0.125	2.5	140	0.097
Droop Stop	1.0	500		1.0	500	
Extra Maneuvers	5.0	0.1		0.0	0	0.000
PO 3G SD	5.0	2	0.003	0.0	0	0.000
GAGs / Flt		300			181	
Min - Max		100			50	
Total			100.000			100.000
Most Damaging Regime						

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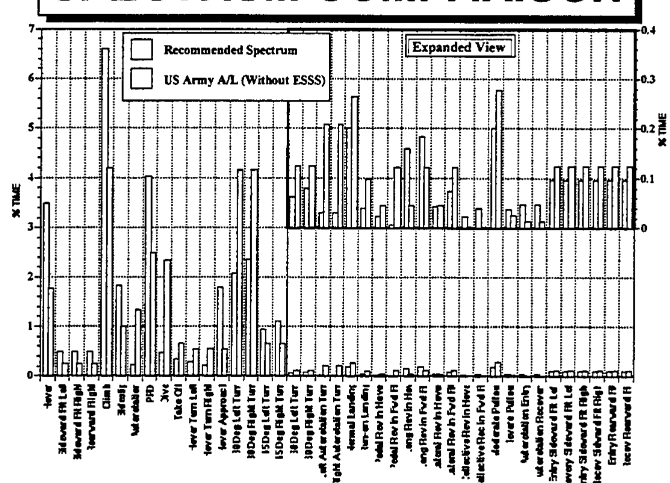
SPECTRUM COMPARISON



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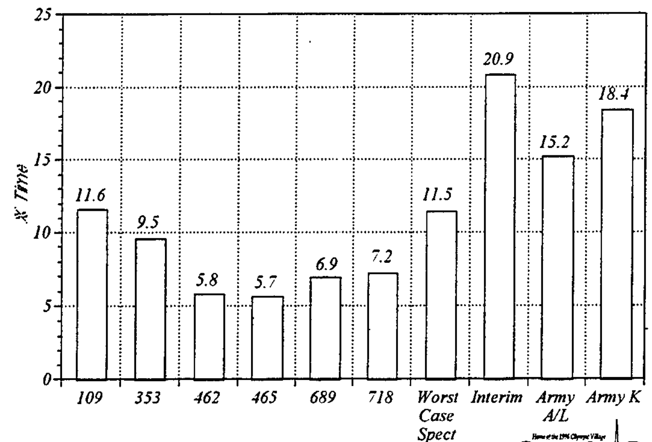
DAMAGING FLT TIME by AIRCRAFT

FINAL RESULTS



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CRT ADJUSTMENT METHODOLOGY

- **FLIGHT REGIMES**

  USAF DAMAGE = ARMY DAMAGE * (USAF %TIME)

- **GAG/FLT CYCLES & DROOP STOP POUNDING**

  USAF DAMAGE = ARMY DAMAGE * (USAF OCCUR/100 hrs)

- **CRT CALCULATION from DAMAGE**

  CRT (hrs) = 100

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ESTIMATED CRT's from RESPECTIVE SPECTRUMS

COMPONENT	PART NUMBER	Component Retirement Times (hrs) US Army*	USAF**	Difference
Main Support Bridge	70400-08116-048	910	1200	+290
Right Tie Rod	70400-08114-051	1000	1700	+700
Lateral Bellcrank	70400-08150-045	2300	3250	+950
Main Rotor Cuff	70150-09109-041	2400	3400	+1000
Aft Support Bridge	70400-08117-049	2700	2900	+200
Lateral/Aft Servo Beam Rail	70219-02134-050	2700	7700	+5000
Forward/Aft Servo Beam Rail	70219-02134-052	2800	3600	+800
Primary Servo Beam Rail	70209-22103-052	3200	3500	+300
Fwd Servo Beam Railing	70219-02134-048	3300	4250	+950
MR Spindle with Tierod	70102-08216-041	3500	3750	+250
Right Tie Rod Attachment Bolt	SS5025-4H10	3700	3700	0
MR Primary Servo Beam Rail	70209-22103-054	3800	4350	+550
MR Blade Expandable Pin	70103-08107-101	4700	6400	+1700
Tail Rotor Output Shaft	70358-06620-101	5000	6100	+1100
Main Rotor Hub	**70103-08112-041**	**5100**	**5000**	**-100**

* Current US Army UH-60L Spectrum (Without External Stores
** Recommended USAF HH-60G Spectrum

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CONCLUSIONS

- ✓ USAF WORST CASE SPECTRUM DEFINED which APPEARS LESS DAMAGING than ARMY ESTIMATED UH-60A/L SPECTRUM
  - ✓ SURVEY YIELDS LESS TIME at GW > 20K than any SERVICE SPECTRUM
  - ✓ USAF SPENDS MORE TIME in HOVER/LOW SPEED FLT
  - ✓ AUTO ENTRIES/RECOVERIES 235% MORE FLT TIME with TRAINING A/C
  - ✓ WEAPONS SCHOOL AIRCRAFT INCUR MOST DAMAGING FLT TIME (PRIMARILY PPD's and LEVEL TURNS)
  - ✓ MEASURED GAG CYCLES are ABOUT HALF SPECTRUM ESTIMATES
- ✓ LOGGED FLT TIME AVGS 15% > RECORDED FLT TIME, EFFECTIVELY REDUCING CRTs & INCREASING FLT TIME BASED MAINTENANCE
- ✓ ERITS EFFECTIVE TOOL for QUANTIFYING MANEUVER SEVERITY
- ✓ POTENTIAL IMPACT on CRTs POSSITIVE for 9 of 10 COMPONENTS
- ✓ POTENTIAL NEED to REDUCE MR HUB CRT from 5100 to 5000 flt hrs
- ✓ USAF's CONTINUED use of UH-60A/L CRT's is CONSERVATIVE

WR-ALC / LUH

Georgia Tech Research Institute

Charlie Crawford - 17

DSTO

An Econometric Model for HUMS Cost Benefit Studies

Graham Forsyth
Helicopter Life Assessment
Airframes and Engines Div
AMRL

DSTO

Background Information

Models <u>changes</u> in costs and benefits with respect to a 'baseline' condition for a specific HUMS

- Concept arose from DSTO support to ADO Working Party on CDR and HUMS
- Original version internal use
- Considerable work spent on making it robust enough to distribute more widely

The 'baseline' condition is usually non-HUMS but may be a lower specification HUMS installation

DSTO

Benefits modelled in HUMSSAVE (1)

Health Monitoring Benefits

- 1. Safety
  - Reduced total-loss accidents
  - Reduced repairable-damage accidents
- 2. Rotor Smoothing
  - Reduced maintenance flying
  - Savings on RT&B test equipment
  - Reduced avionics replacements
  - Reduced structural damage
- 3. Other Maintenance Benefits

DSTO

Benefits modelled in HUMSSAVE (2)

Usage Monitoring Benefits

- No need for conventional life substantiation program
- Exceedance monitoring benefit
- Accurate logging of flying time
- Reduced consumption of life-limited parts

Fleet Management Benefits

- Improved logistics control

12 equations / 29 variables

DSTO

Costs modelled in HUMSSAVE - Capital Costs

The model divides the capital costs of HUMS into two categories:

- fleet engineering costs which are specific to the aircraft type and independent of the number of aircraft to be fitted with HUMS, and
- per aircraft capital costs for equipment, sensors, cabling, installation, certification and spares.

3 equations / 12 variables

DSTO

Costs modelled in HUMSSAVE - Running Costs

The model includes running costs resulting from:

- staff training,
- HUMS equipment maintenance,
- consulting advice,
- software upgrades,
- ground station upgrades,
- data management, and
- mission payload penalty.

1 equation / 9 variables

DSTO

Financial Items Modelled in HUMSSAVE

Require to compare a fixed capital cost to a benefit distributed over the life of the aircraft

Conventional Discounted Cash Flow approach relates future cash flows to a Net Present Value (NPV).

- NPV = future cash flows X Discount Factor
- Discount Factor = Discount Rate integrated over the period of time HUMS is to be fitted
- Discount Rate = rate of real interest

Method defined by Australian Department of Finance

DSTO

Equations

All defined in publication:-

Australian Defence Organisation Working Party On Strategic Planning For Helicopter Accident Data Recording and HUMS - *Guidance Paper No 3: HUMS Cost-Benefit Analysis Methodology*

Included in all distributions of HUMSSAVE software.

DSTO

Equations - sample $B_{hs} = p_h \times r_{ta} \times M \times h \times y$

B_{hs} savings due to additional health monitoring detecting faults that would have led to total loss of aircraft

p_h proportion of total-loss accidents which would be prevented by fitment of additional health monitoring equipment above the specified baseline

r_{ta} total-loss accident rate for aircraft fitted with baseline health monitoring equipment

M average cost of a total-loss accident

h hours flown/year (ROE) per aircraft

y expected remaining service life (years)

DSTO

Framework

Visual Basic program

Originally written in VB3

Now VB4 but still 16-bit code

- **Windows 3.1x, 95, 98 and NT**

Next version will be VB6 and 32-bit

- **Windows 95/98 and NT/2000 only**

DSTO

DATASETS

ADO HUMS Working Party defined three datasets:-

- Generic (included in all distributions of HUMSSAVE)
- Chinook CH-47D (restricted to ADO and related military)
- AIR 87 (restricted to ADO and related military)

Other datasets supplied (or to be supplied) by users

DSTO

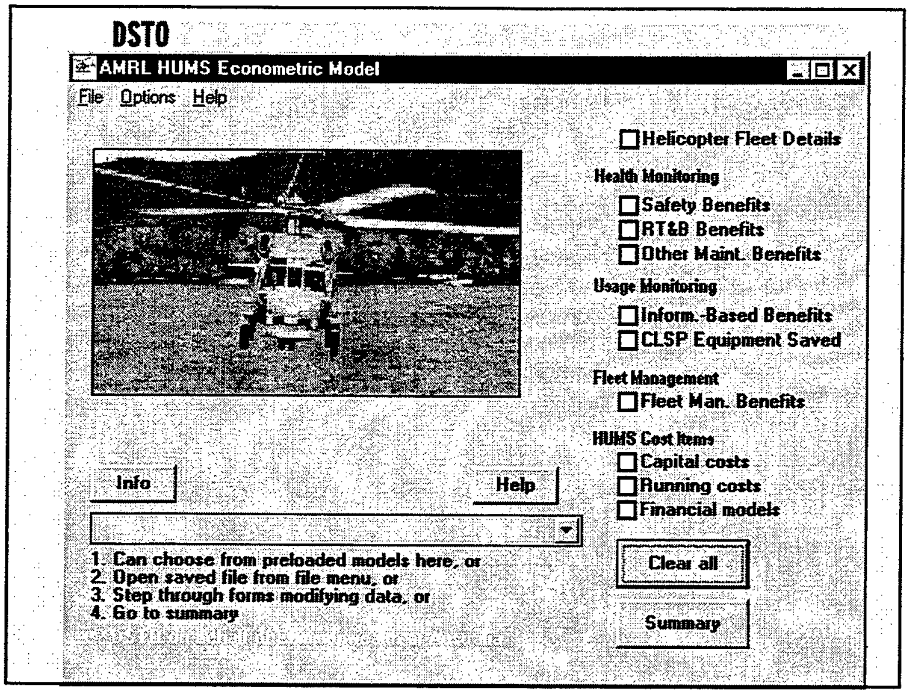
Entry

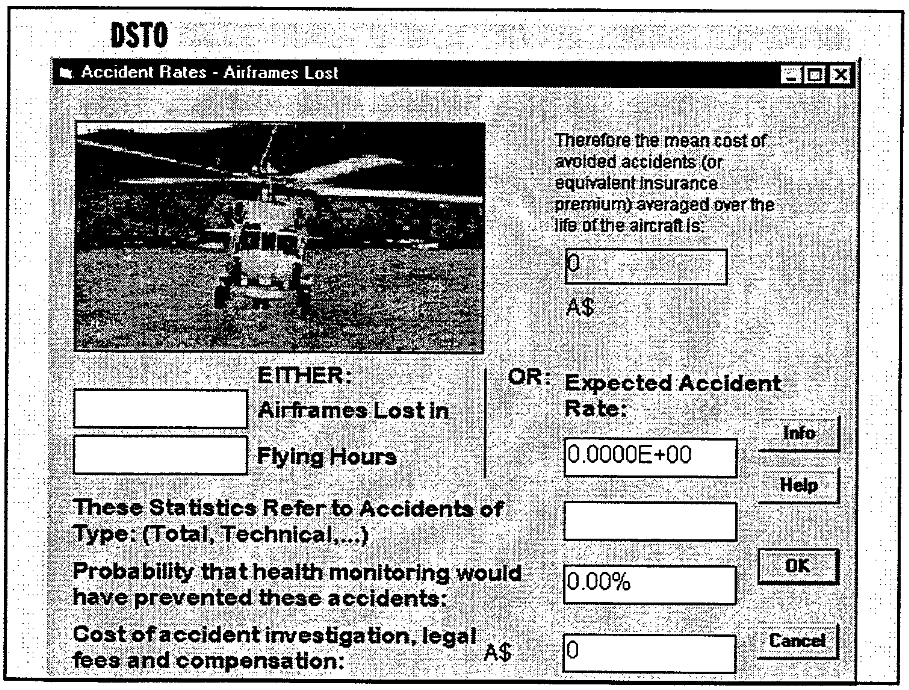
All of the variables used by the program are entered from:-

- File containing a pre-built model, or
- User file, or
- Data entry form

A sample data entry form ----

- Blank opening screen
- A data entry form
- A completed entry (generic example)
- Summary form





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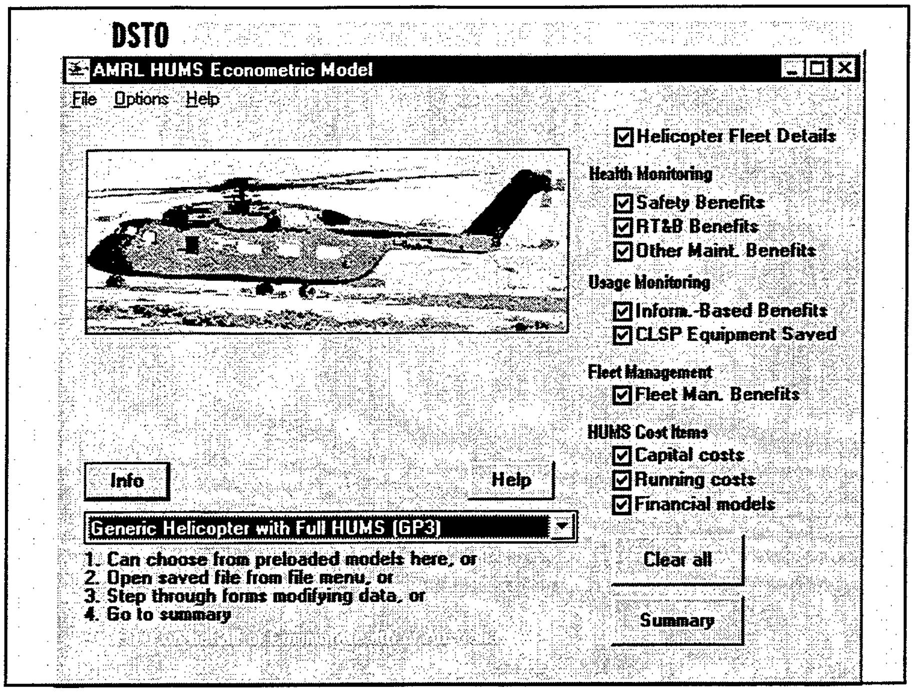

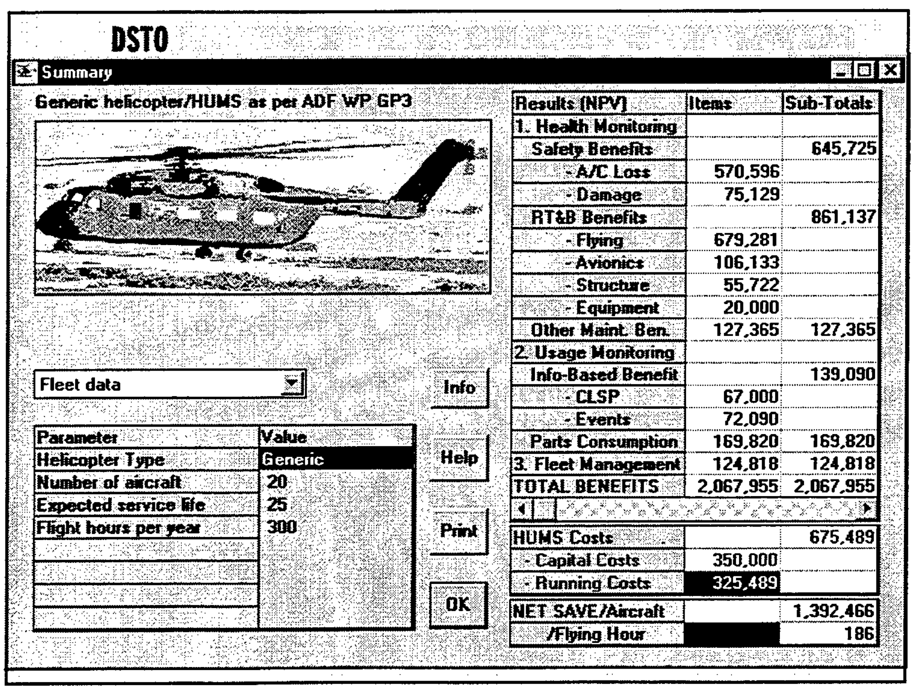

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DSTO

Distribution - 2 versions (Source code restricted to AMRL)

OPEN

- Includes program, PDF version of Guidance Paper 3, help files and generic example
- Distributed by email as a single file or a set of four messages; or a pair of floppy disks

MILITARY

- Includes program, PDF versions of Guidance Papers 3, 4 (Chinook) and 5 (AIR 87), help files and Generic, Chinook and AIR 87 examples
- Distributed by CD-ROM

DSTO

Year 2000 Issues

Limited testing to date

- No problems found
- Microsoft don't claim VB4 fully compliant
- No date fields used in datasets, only in file creation area

Further testing likely

DSTO

Possible Upgrade Paths for HUMSSAVE Program

Dataset-Creation Wizard

Confidence Levels

Sensitivities

No decision as yet that any of these will actually be programmed

DSTO

Possible Upgrade 1: Dataset-Creation Wizard

Process:

- Start with generic data
- Modify with guidance
  - Answer questions
- Create model and start HUMSSAVE

Advantage:

Don't need to know values for all 40 variables

Disadvantage:

Need to define default values for each variable

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DSTO

Possible Upgrade 2: Confidence Levels

Process:

- Enter a confidence level for every input defined
- Calculate confidence level for each output

Advantages:

- Highlight the level of confidence that can be placed on the model's outputs
- Clearly shows areas where more information beneficial

Disadvantages:

- Additional information required to current datasets
- Some confidence levels are not easy to quantify

DSTO

Summary

Generic helicopter/HUMS as per ADF WP GP3

Airframe losses

Info

Help

Print

OK

Parameter	Value
Total airframes lost	4
Total flying hours	100,000
Airframe loss rate	4.00E-05
% avoided via HUMS	20.00%
Stats type: all/tech/etc	Technical
Accident investigation etc	1,000,000

Results (NPV)	Items	Sub-Totals
1. Health Monitoring		
Safety Benefits		645,725
- A/C Loss	570,596	
- Damage	75,129	
RT&B Benefits		861,137
- Flying	679,281	
- Avionics	106,133	
- Structure	55,722	
- Equipment	20,000	
Other Maint. Ben.	127,365	127,365
2. Usage Monitoring		
Info-Based Benefit		139,090
- CLSP	67,000	
- Events	72,090	
Parts Consumption	169,820	169,820
3. Fleet Management	124,818	124,818
TOTAL BENEFITS	2,067,955	2,067,955

HUMS Costs		675,489
- Capital Costs	350,000	
- Running Costs	325,489	

NET SAVE/Aircraft		1,392,466
/Flying Hour		186

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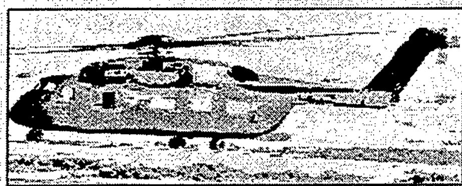
DSTO

Summary

Generic helicopter/HUMS as per ADF WP GP3



New Columns

Airframe losses

Input

Calculated Info

Parameter	Value	%
Total airframes lost	4	25
Total flying hours	100,000	
Airframe loss rate	4.00E-05	
% avoided via HUMS	30.00%	50
Stats type: all/tech/etc	Technical	
Accident investigation etc	1,000,000	100

Help

Print

OK

Results (NPV)	Items	Sub-Totals	%
1. Health Monitoring			
Safety Benefits		968,587	
- A/C Loss	855,894		xy
- Damage	112,693		xy
RT&B Benefits		861,137	
- Flying	679,281		xy
- Avionics	106,133		xy
- Structure	55,722		xy
- Equipment	20,000		xy
Other Maint. Ben.	127,365	127,365	xy
2. Usage Monitoring			
Info-Based Benefit		139,090	
- CLSP	67,000		xy
- Events	72,090		xy
Parts Consumption	169,820	169,820	xy
3. Fleet Management	124,818	124,818	xy
TOTAL BENEFITS	2,390,817	2,390,817	
HUMS Costs		675,489	
- Capital Costs	350,000		xy
- Running Costs	325,489		xy
NET SAVE/Aircraft		1,715,328	
/Flying Hour		229	xy

DSTO

Possible Upgrade 3: Sensitivity

Process:

- Calculate effect of changes to INPUT values on Net Saving
- Show on Input Area of Summary as either:
  - Input Sensitivity Factor (as % change in Net Saving / % change in variable)
  - Graph showing slope of Net Saving for Changes in Input

Advantages:

Highlight important input parameters

Current datasets OK - No Additional Info. required

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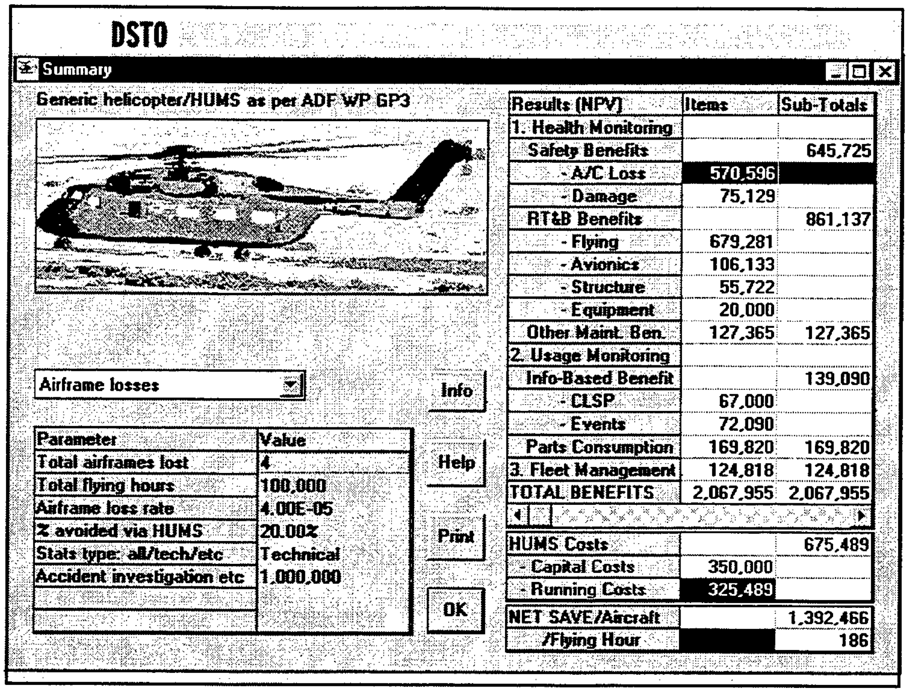

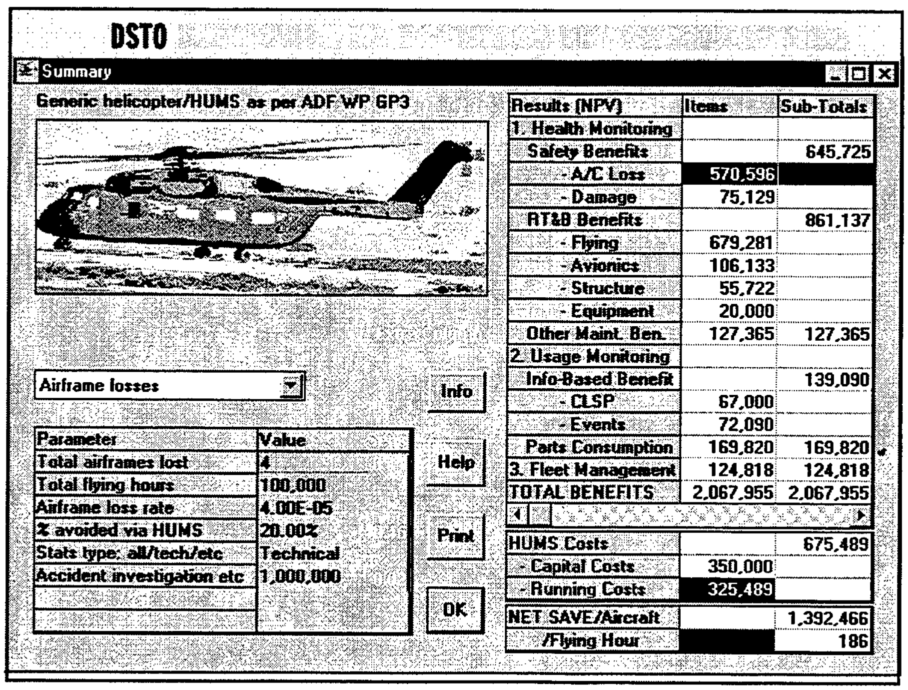

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DSTO

Acknowledgments

The Equations

- Ken Fraser
- Dom Lombardo

The Framework

- Richard Adams

Distribution

- Keith Mowbray
- About 60 users

Graham Forsyth - 14

ROTABS™

RE-WRITING THE MANUAL ON ROTOR TRACK AND BALANCE

Robert Cant

vibro-meter

CORPORATE PEDIGREE

- Member of the MEGGITT Group
- Close fit with Endevco
- Turnover £ 35 M
- Personnel 550 world-wide
- Prime Customers: Boeing, Aerospatiale, Eurocopter, RR,GE,PW

vibro-meter

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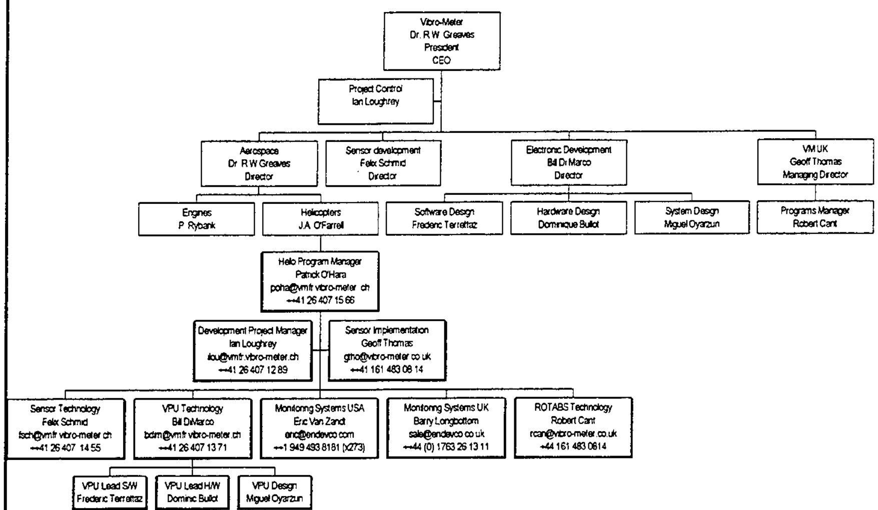
HELICOPTER PROGRAM MANAGEMENT CHART



vibro-meter

ROTABS™

ROtor **T**rim

And

Balance **S**ystem

vibro-meter

Robert Cant - 2

PRINCIPLE

ROTABS™

"A unique, patented system that makes a MULTI PLANE ANALYSIS based on the philosophy that the rotor set-up that produces the LEAST VIBRATION will be the best possible combination for performance, comfort and reduced structural fatigue."

vibro-meter

REQUIREMENTS

- **Sensors (Accelerometers: Tri,Bi x2,Uni, Speed Probe x2)**
- **Cable Assemblies**
- **Acquisition and Processing Unit**
- **Control and Storage Unit**
- **ROTABS™ SW for Acquisition**
- **ROTRIM™ SW for Maintenance Recommendation**

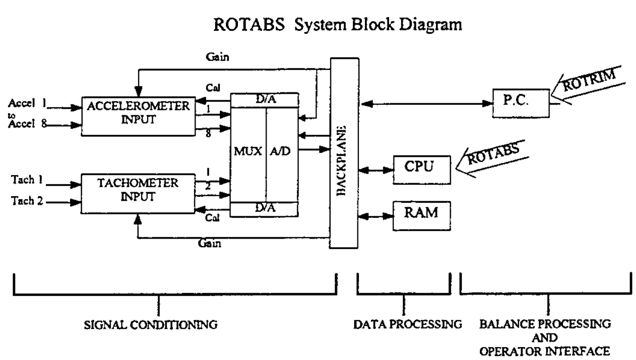
vibro-meter

SYSTEM DESIGN

- Total System Capability: Vibro-meter produce
  - Sensors (Vibration& Speed)
  - Avionics Hardware
  - ROTABS™ firmware
  - ROTRIM™ software
- Portable or On Board System
- Certified

vibro-meter

SYSTEM



ROTABS and ROTRIM are trademarks of Vibro-Meter

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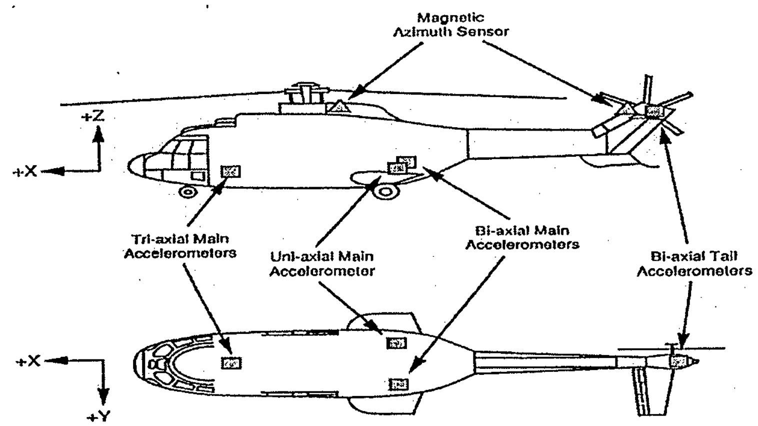
SENSOR LOCATIONS



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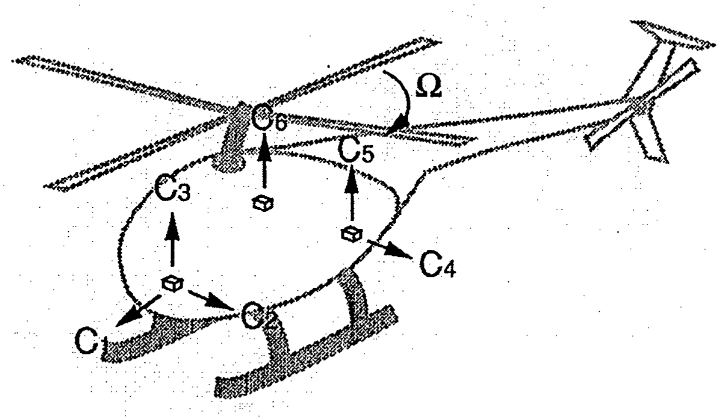
SENSOR ORIENTATION



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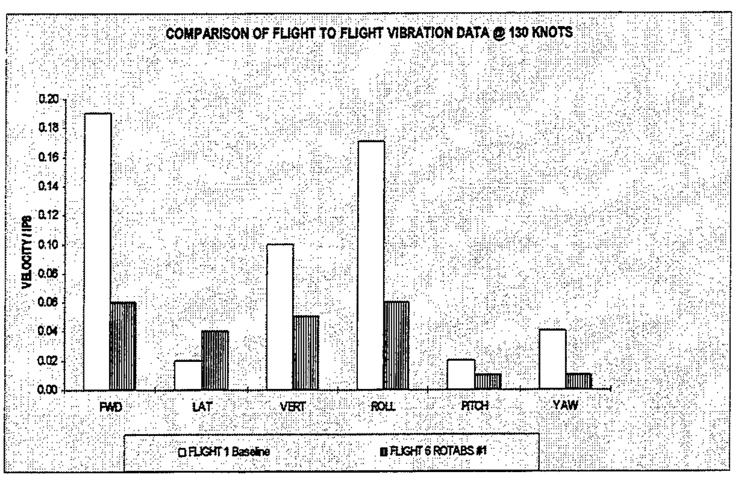
FEATURES

- Balance in 6 degrees of freedom
- Capability to balance multiple harmonics
- Ability to optimise the balance position
- Facility to prioritise the balance optimisation by flight condition
- Trackerless operation

vibro-meter

ROTABS DEMONSTRATION - SAAF ORYX



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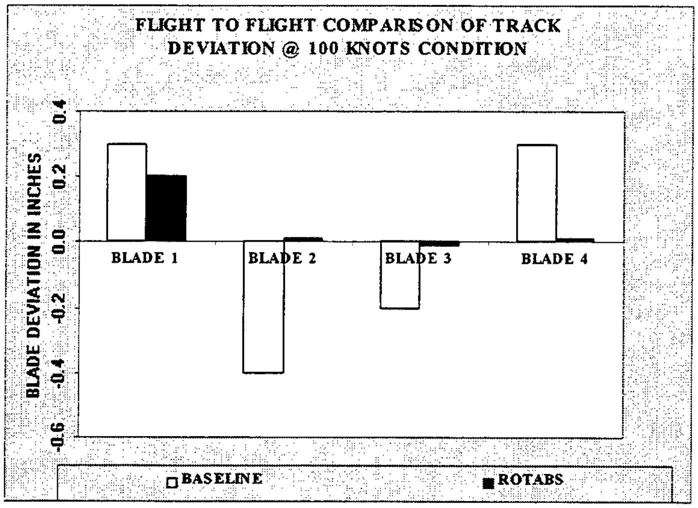
ROTABS DEMONSTRATION - SAAF ORYX



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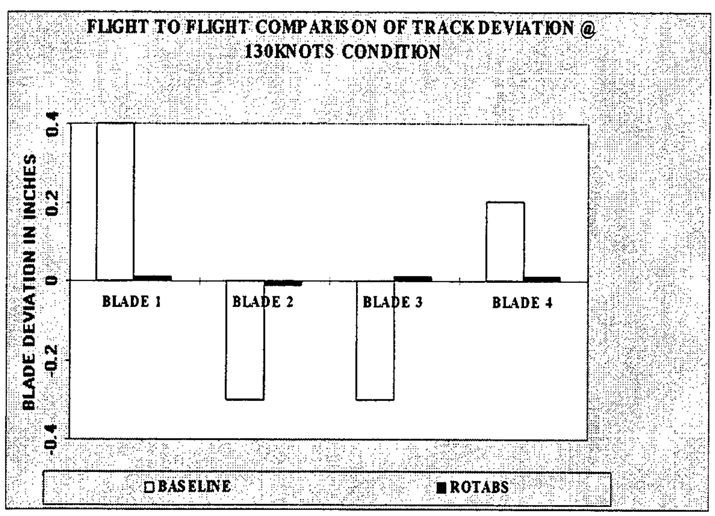
ROTABS DEMONSTRATION - SAAF ORYX



vibro-meter

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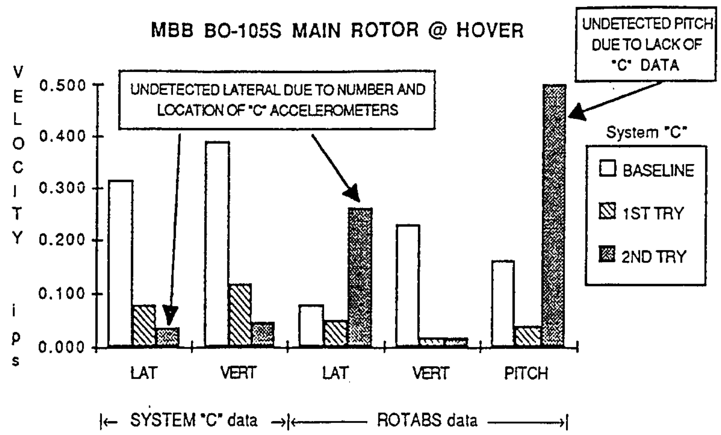
ROTABS DEMONSTRATION - BO-105S



vibro-meter

EXPERIMENTAL PROOF

- Lowest ever vibration levels
- Blade track within limits
- Indirectly tracks over complete rotor revolution
- No rotor stress increase with ROTABS™ implementation
- Seeded rotor fault trials are in progress

vibro-meter

Robert Cant - 8

TRIED & TESTED

- Single , Axial Rotors - From Enstrom Shark To Mil Mi-8, SPMK II
- Co-axial Rotor - Kamov Ka-32
- Twin Rotors - Chinook
- Small, Medium & Heavy Helos

vibro-meter

STATUS

- ROTABS™ is an integral part of the Eurocopter *A*ircraft Recording and Monitoring System *EUROARMS*
- Preferred technology for the Eurocopter new 'light' HUMS system
- Part of the BFG/VM HUMS system for the US NAVY COSSI programme.
- Exclusive use within REGA Swiss Air Ambulance operation since 1991 for Alouette III, BO 105, A109-2 helicopters.

vibro-meter

Robert Cant - 9

BENEFITS

- Complete Characterisation Of Helicopter
- Lower vibration levels
- Consistent One (1) Flight To Trim
- All Weather Operation, Day / Night, Dust / Smoke
- Balance tailored to Mission Requirements
- Increased aircraft availability
- No optical tracker required

vibro-meter

CONCLUSIONS

- More comprehensive system
- Superior balance result
- Simplified / safer operation
- High reliability system
- Stand-alone or integrated system

vibro-meter

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The University of New South Wales
DSTO CEVA

DETECTION OF BEARING FAULTS IN HELICOPTER GEARBOXES

Y. Gao, R. B. Randall
DSTO *Centre* of *Expertise* in *Vibration Analysis*
School of Mechanical and Manufacturing Engineering
The University of New South Wales
Sydney 2052, Australia

HUMS 99, Melbourne

The University of New South Wales
DSTO CEVA

HUMS 99, Melbourne

Introduction

Bearing Fault Detection by Vibration Analysis

- •FT spectral analysis;
- •Cepstral analysis;
- •Statistical parameters;
- •Envelope analysis [with or without SANC (Self Adaptive Noise Canceling)];
- •CPB (Constant Percentage Bandwidth)spectral analysis;

Automatic Diagnosis of Bearing Faults

Vibration Analysis Techniques as Data **Preprocessors**

Neural Networks as Bearing Condition **Classifiers**

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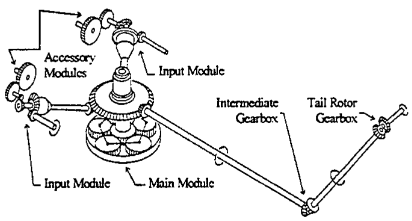
DSTO CEVA

Bearing Fault Detection by Vibration Analysis

Difficulties :
- Bearings deep inside the gearbox
- Impossible to mount sensors on Bearing Housings
- Shaft speeds: 4 ~ 350 Hz

Data :
- Provided by the US Navy
- From four gearboxes of the same specification
- Two Faulty bearings on the STBD side and one planetary bearing with a roller fault



Helicopter Transmission

HUMS 99 Melbourne

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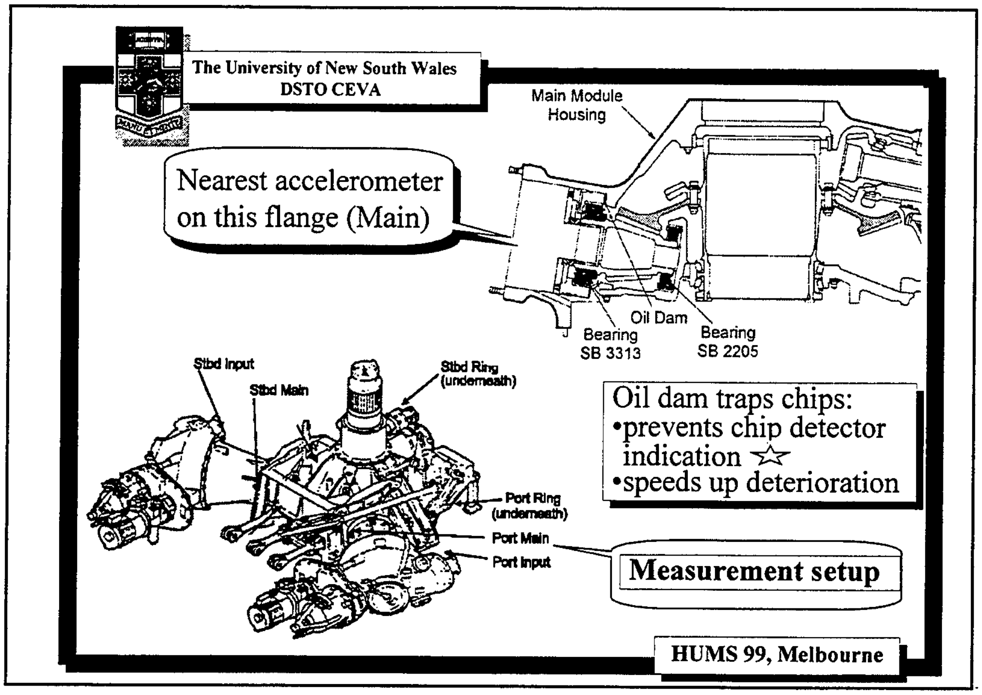
Vibration Signature of the Pinion Bearing Faults

Pinion Inner Race Fault:
- Spalled inner race with gradual transit
- Changes the relative meshing position between the main and pinion gears, leading to overall modulation through the gear train at the pinion shaft speed

Pinion and Planet Roller Faults:
- spalled rollers
- generating impulse forces at twice roller spin frequency
- Modulated at the cage speed

HUMS 99, Melbourne

Yujin Gao - 2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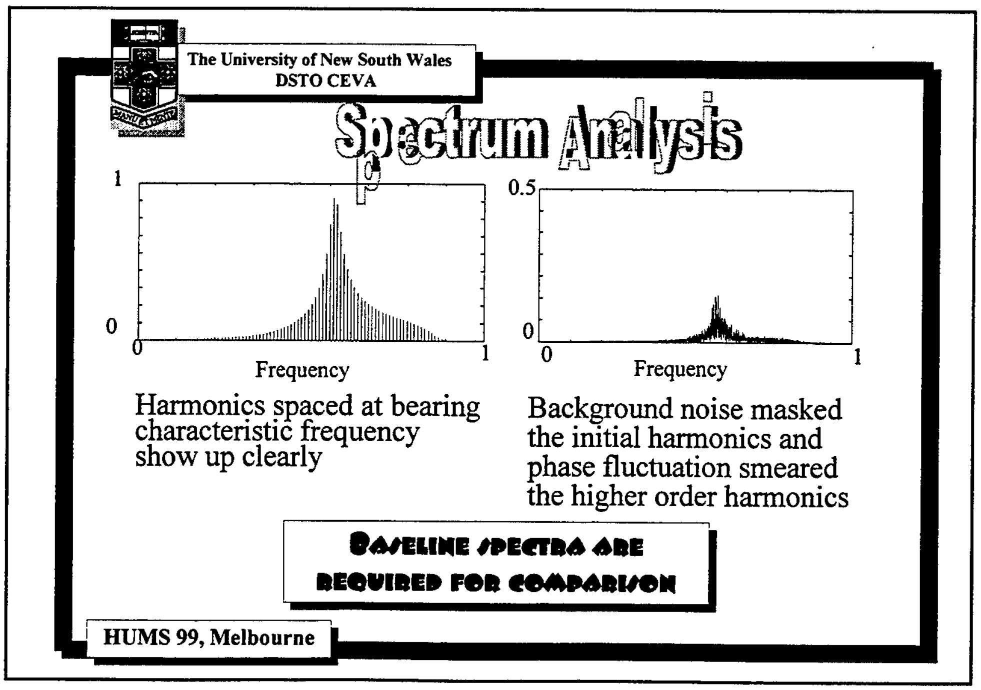
DSTO CEVA
Nearest accelerometer on this flange (Main)
Main Module Housing
Oil Dam
Bearing SB 3313
Bearing SB 2205
Stbd Input
Stbd Main
Stbd Ring (underneath)
Port Ring (underneath)
Port Main
Port Input
Oil dam traps chips:
•prevents chip detector indication ☆
•speeds up deterioration
Measurement setup
HUMS 99, Melbourne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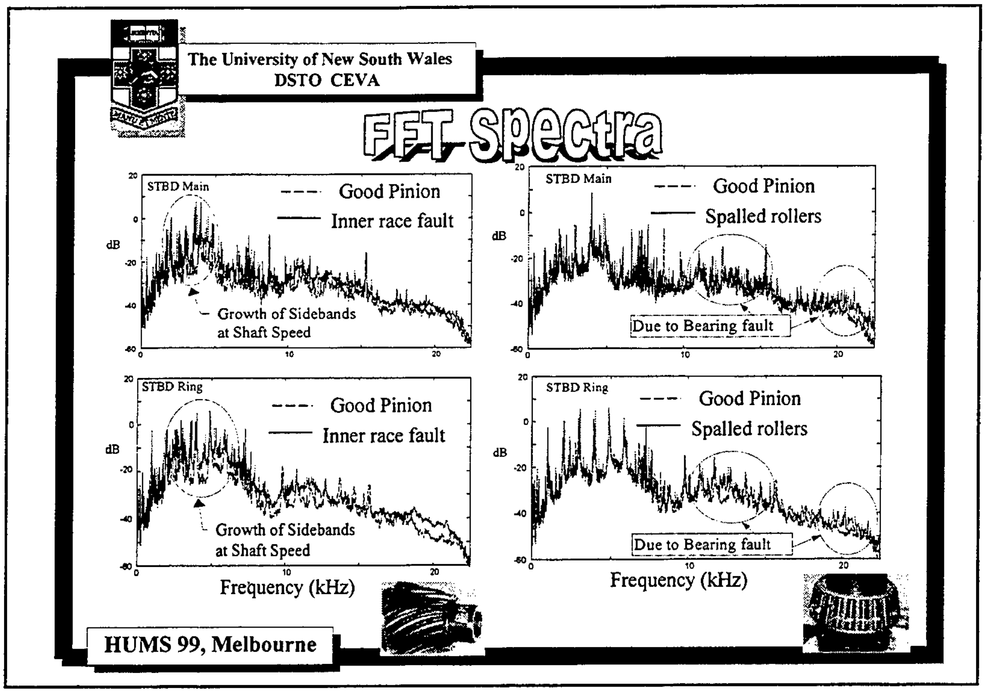
DSTO CEVA
Spectrum Analysis
1
0
0
1
Frequency
0.5
0
0
1
Frequency
Harmonics spaced at bearing characteristic frequency show up clearly
Background noise masked the initial harmonics and phase fluctuation smeared the higher order harmonics
Baseline spectra are required for comparison
HUMS 99, Melbourne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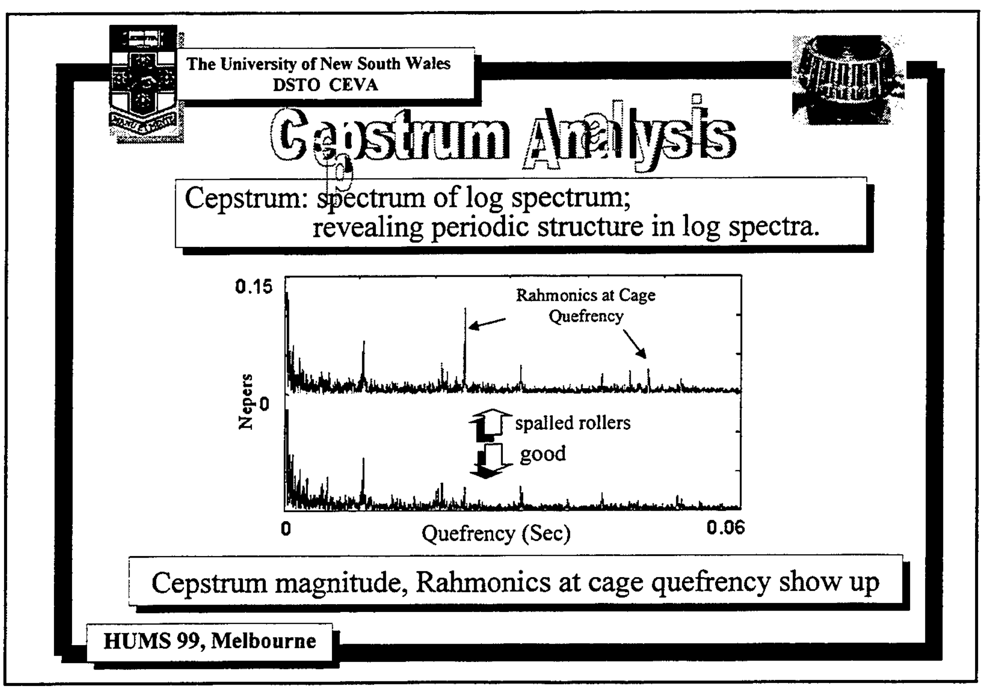
DSTO CEVA
FFT Spectra
STBD Main
Good Pinion
Inner race fault
dB
Growth of Sidebands
at Shaft Speed
STBD Main
Good Pinion
Spalled rollers
dB
Due to Bearing fault
STBD Ring
Good Pinion
Inner race fault
dB
Growth of Sidebands
at Shaft Speed
Frequency (kHz)
STBD Ring
Good Pinion
Spalled rollers
dB
Due to Bearing fault
Frequency (kHz)
HUMS 99, Melbourne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DSTO CEVA
Cepstrum Analysis
Cepstrum: spectrum of log spectrum;
revealing periodic structure in log spectra.
0.15
Rahmonics at Cage
Quefrency
Nepers
0
spalled rollers
good
0
Quefrency (Sec)
0.06
Cepstrum magnitude, Rahmonics at cage quefrency show up
HUMS 99, Melbourne

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Statistical Parameters

- **Kurtosis**
- **Skewness**
- **Crest Factor**
- **Applied to envelope signals**

	Kurtosis		Skewness		Crest Factor	
	Good	Faulty	Good	Faulty	Good	Faulty
STBD Main	3.00	4.56	0.70	1.21	2.84	3.37
STBD Ring	3.53	4.34	0.90	1.14	2.90	3.13
STBD Input	3.51	3.72	0.90	0.95	2.96	3.27
Port Main	3.38	5.25	0.83	1.26	3.27	3.71
Port Ring	3.21	4.85	0.76	1.27	3.15	3.35
Port Input	3.70	3.85	0.96	0.99	3.28	3.01

	Kurtosis		Skewness		Crest Factor	
	Good	Faulty	Good	Faulty	Good	Faulty
STBD Main	4.55	3.83	1.13	0.99	4.07	3.06
STBD Ring	4.09	4.27	1.04	1.08	3.93	3.94

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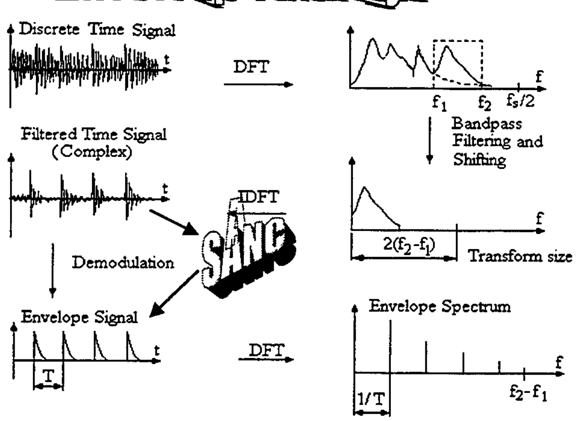
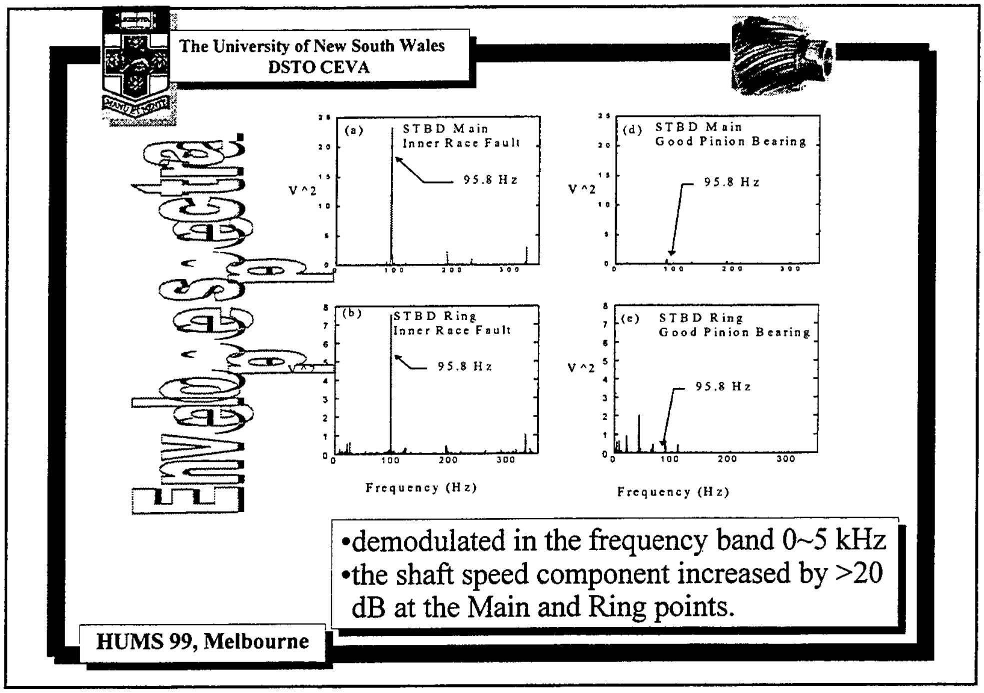
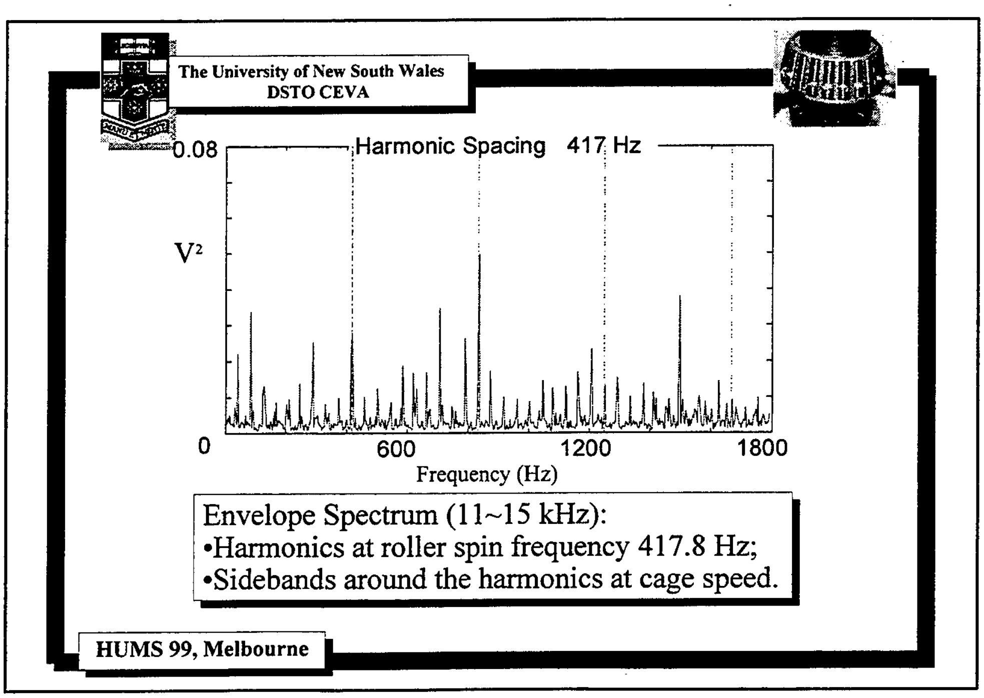
Envelope Analysis

ADVANTAGES:
- Flexibility in Choosing Passbands
- Ideal Filtration for Separating Adjacent Frequency Events
- Combination with SANC (Self Adaptive Noise Cancelling)

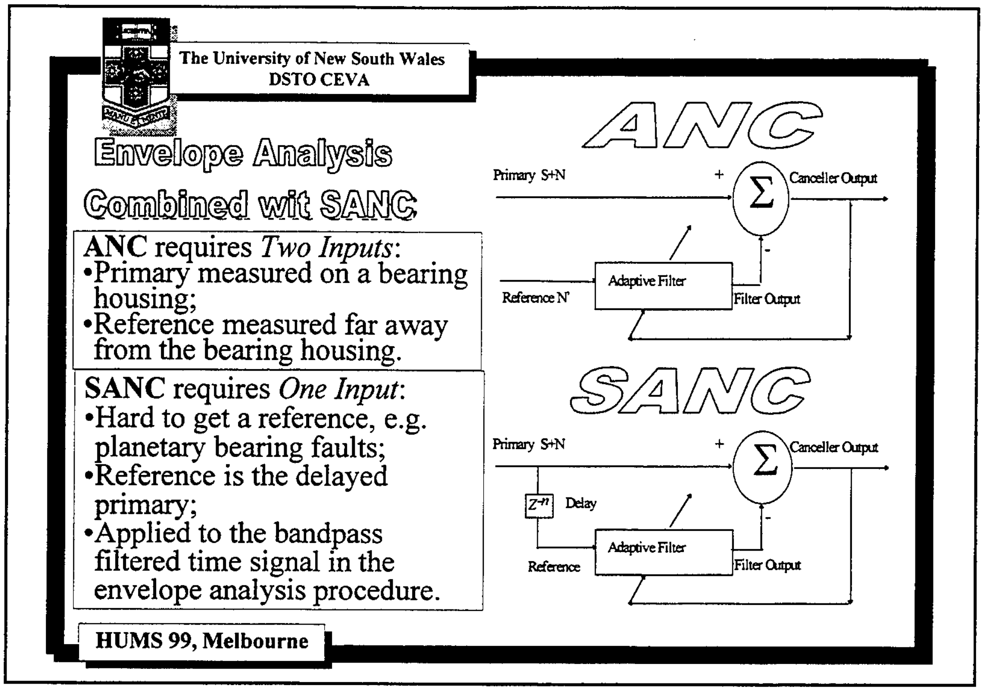


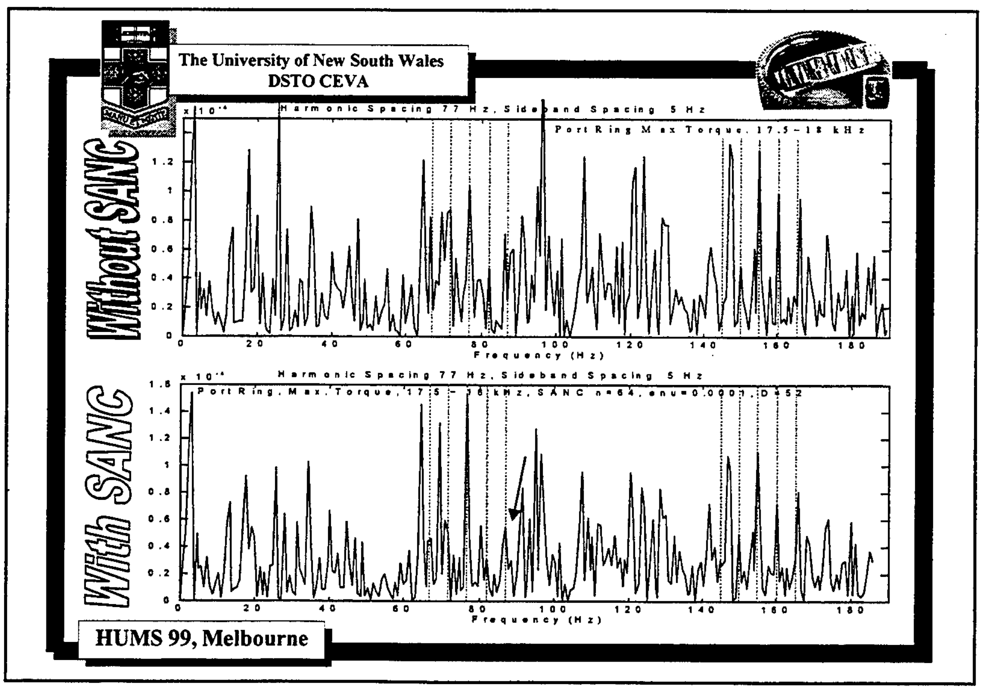
HUMS 99, Melbourne

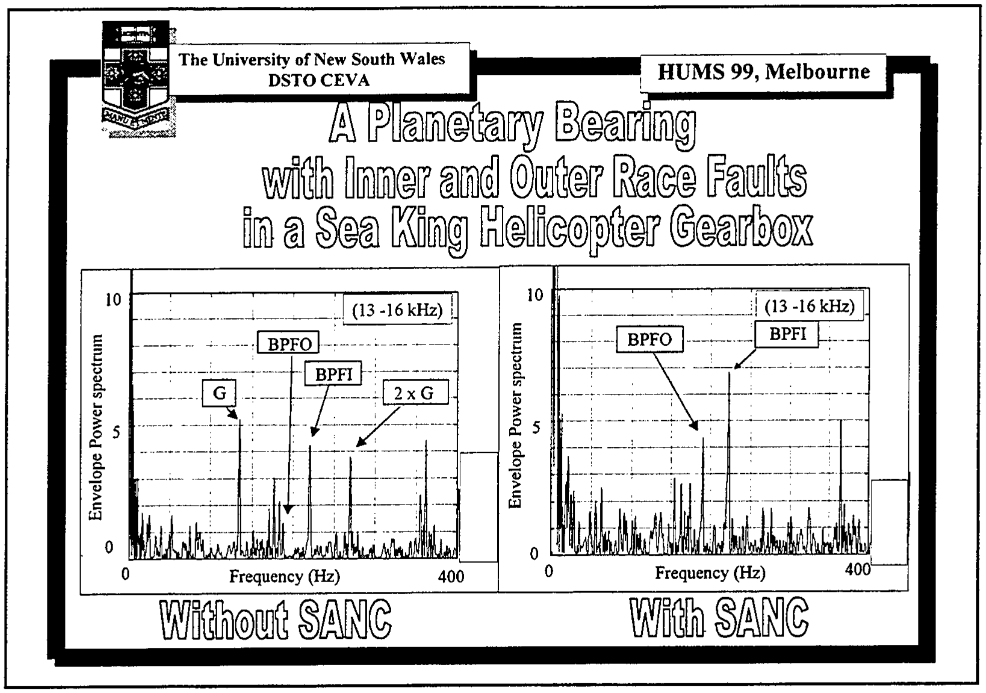

The University of New South Wales
DSTO CEVA
Envelope Spectra
(a) STBD Main Inner Race Fault
95.8 Hz
(d) STBD Main Good Pinion Bearing
95.8 Hz
(b) STBD Ring Inner Race Fault
95.8 Hz
(e) STBD Ring Good Pinion Bearing
95.8 Hz
V^2
Frequency (Hz)
•demodulated in the frequency band 0~5 kHz
•the shaft speed component increased by >20 dB at the Main and Ring points.
HUMS 99, Melbourne

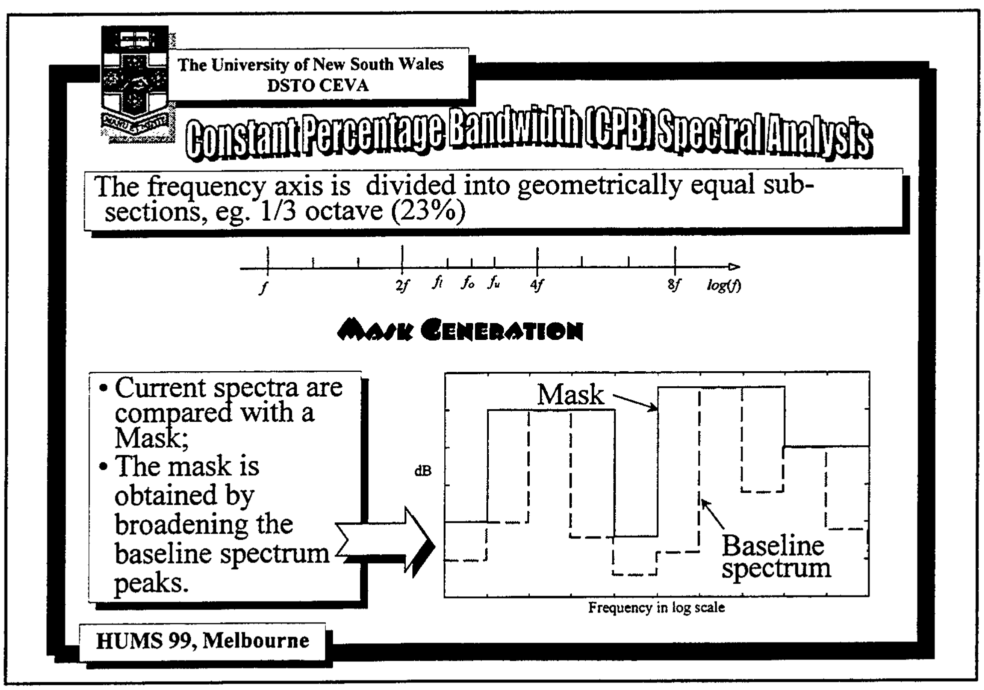

The University of New South Wales
DSTO CEVA
0.08
Harmonic Spacing 417 Hz
V2
0
600
1200
1800
Frequency (Hz)
Envelope Spectrum (11~15 kHz):
•Harmonics at roller spin frequency 417.8 Hz;
•Sidebands around the harmonics at cage speed.
HUMS 99, Melbourne

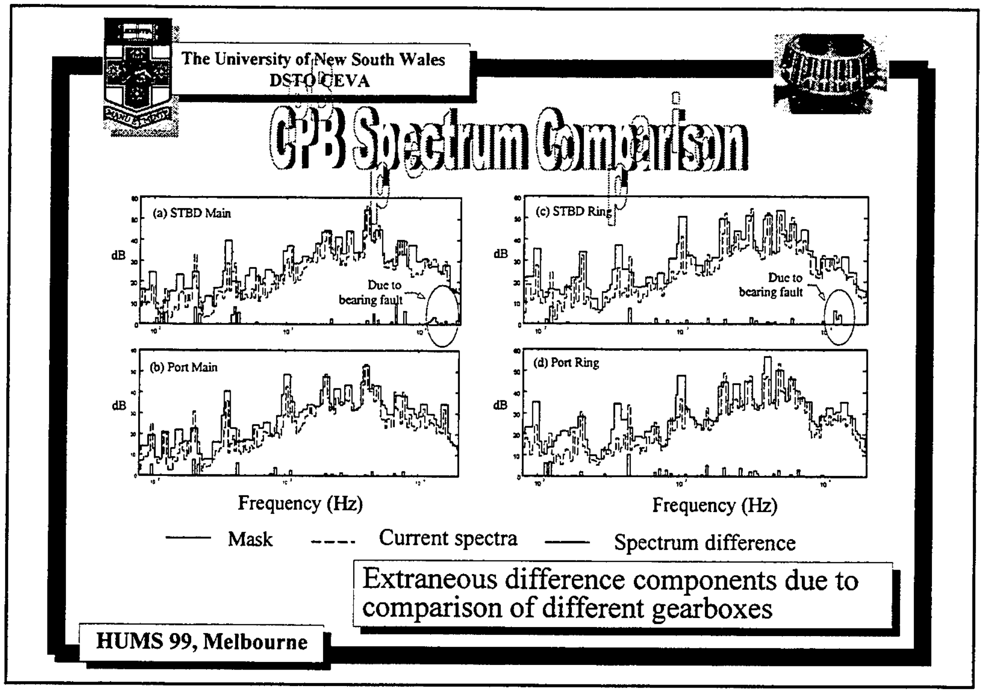
Yujin Gao - 6

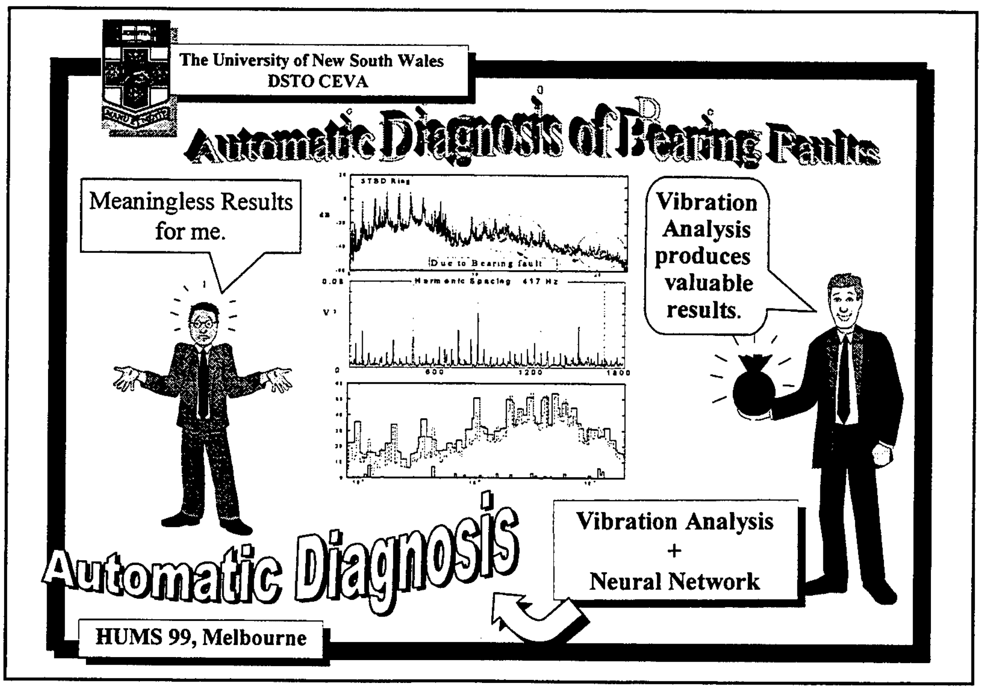

The University of New South Wales
DSTO CEVA
Envelope Analysis
Combined wit SANC
ANC requires Two Inputs:
•Primary measured on a bearing housing;
•Reference measured far away from the bearing housing.
SANC requires One Input:
•Hard to get a reference, e.g. planetary bearing faults;
•Reference is the delayed primary;
•Applied to the bandpass filtered time signal in the envelope analysis procedure.
ANC
Primary S+N
+
Σ
Canceller Output
Adaptive Filter
Reference N'
Filter Output
SANC
Primary S+N
+
Σ
Canceller Output
Delay
Adaptive Filter
Reference
Filter Output
HUMS 99, Melbourne


The University of New South Wales
DSTO CEVA
Without SANC
Harmonic Spacing 77 Hz, Sideband Spacing 5 Hz
Port Ring Max Torque, 17.5 - 18 kHz
Frequency (Hz)
With SANC
Harmonic Spacing 77 Hz, Sideband Spacing 5 Hz
Frequency (Hz)
HUMS 99, Melbourne


The University of New South Wales
DSTO CEVA
HUMS 99, Melbourne
A Planetary Bearing
with Inner and Outer Race Faults
in a Sea King Helicopter Gearbox
10
5
0
Envelope Power spectrum
(13 -16 kHz)
BPFO
BPFI
G
2 x G
0
Frequency (Hz)
400
10
5
0
Envelope Power spectrum
(13 -16 kHz)
BPFO
BPFI
0
Frequency (Hz)
400
Without SANC
With SANC


The University of New South Wales
DSTO CEVA
Constant Percentage Bandwidth (CPB) Spectral Analysis
The frequency axis is divided into geometrically equal sub-sections, eg. 1/3 octave (23%)
f
2f
fl
fo
fu
4f
8f
log(f)
Mask Generation
• Current spectra are compared with a Mask;
• The mask is obtained by broadening the baseline spectrum peaks.
Mask
dB
Baseline spectrum
Frequency in log scale
HUMS 99, Melbourne

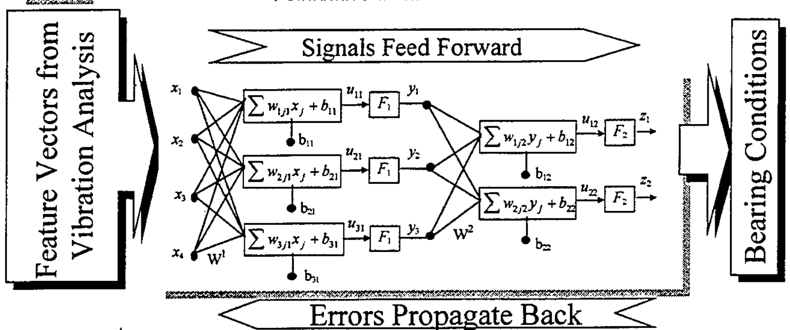

The University of New South Wales
DSTO CEVA
CPB Spectrum Comparison
(a) STBD Main
(c) STBD Ring
(b) Port Main
(d) Port Ring
dB
Due to bearing fault
Frequency (Hz)
Frequency (Hz)
Mask
Current spectra
Spectrum difference
Extraneous difference components due to comparison of different gearboxes
HUMS 99, Melbourne


The University of New South Wales
DSTO CEVA
Automatic Diagnosis of Bearing Faults
Meaningless Results for me.
Vibration Analysis produces valuable results.
Due to Bearing fault
Harmonic Spacing 417 Hz
Automatic Diagnosis
Vibration Analysis + Neural Network
HUMS 99, Melbourne

The University of New South Wales
DSTO CEVA

HUMS 99, Melbourne

Neural Network



Gradient Descent Algorithm

$$\Delta_p w_{ik2}(t) = \eta (z^d_{pi} - z_{pi}) \frac{\partial F_2(u^p_{i2})}{\partial u^p_{i2}} y_{pk}$$

$$\Delta_p w_{kj1}(t) = \eta F_1'(u^p_{k1}) x_{pj} \sum_{i=1}^{M} (z^d_{pi} - z_{pi}) F_2'(u^p_{i2}) w_{ik2}$$

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DSTO CEVA

Data Preprocessors Used by Others

Users	Preprocessor	Feature Vector	Comments
Staszewski Worden Tomlinson	Wigner-Ville distribution (WVD)	The frequency slice at the second gear mesh harmonic	Impulse features of the gear fault
Paya Easat Badi	Wavelet Transform (WT)	10 most dominant amplitudes and their wavelet numbers	Not necessarily reflecting the change by bearing faults
Zhang Ganesan Xistris	Statistical Parameters	Peak-to peak value, mean value and Crest Factors (CF)	Maybe suitable for bearing service life, not for diagnosis
Li Ma Hwang	Bicoherence Analysis	Bicoherence values at two pairs of selected frequencies	Suppressing white noise rather than discrete noise

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Yujin Gao - 10

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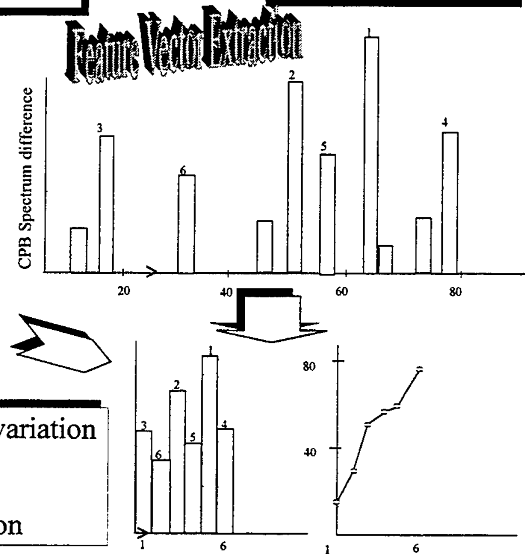
Feature Vector Extraction

CPB Spectrum Analysis as
Preprocessor

1. Calculating Current CPB Spectra;
2. CPB Spectrum Difference (from the Mask);
3. Feature vectors: *Dominant spectrum difference components and their frequency indices.*



- •Compensate for speed variation
- •Vibration criteria in dB
- •Wide Frequency range
- •Greater data compression

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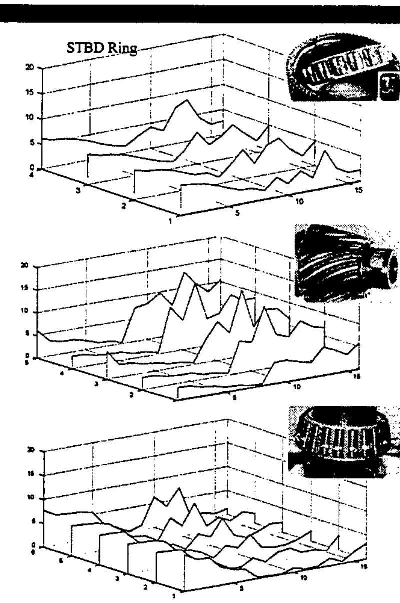
Feature Vectors from the 8 dominant Components



Engine Torque for the Measurements

Bearing Faults	Engine Torques (ftlb)
Planet Roller	100, 200, 300, 356
Pinion Inner Race	100, 200, 250, 300, 375
Pinion Roller	100, 150, 200, 250, 300, 365

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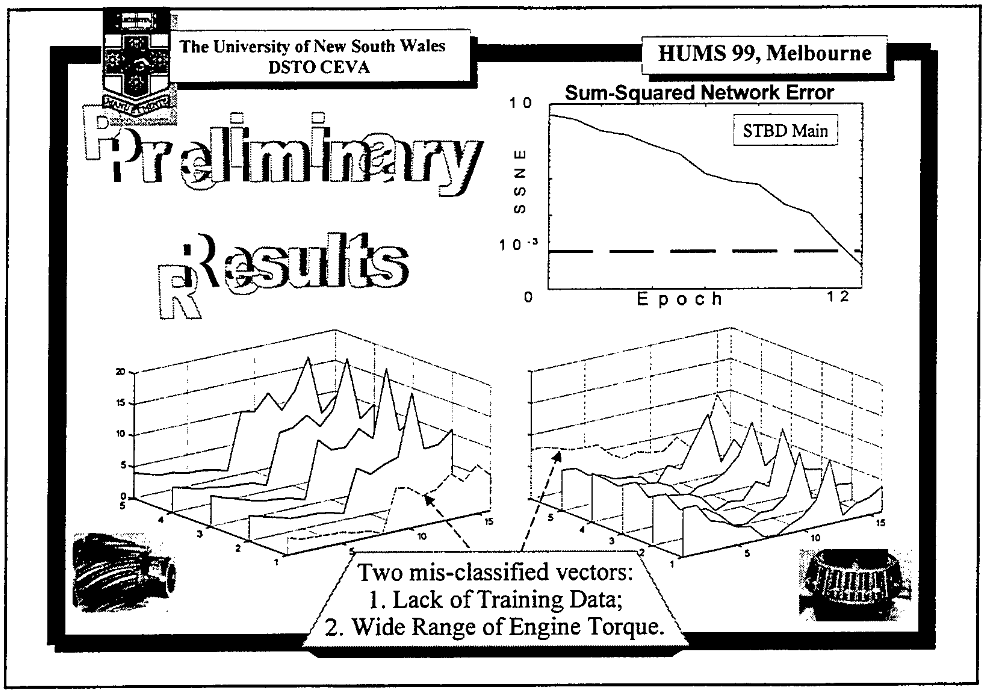

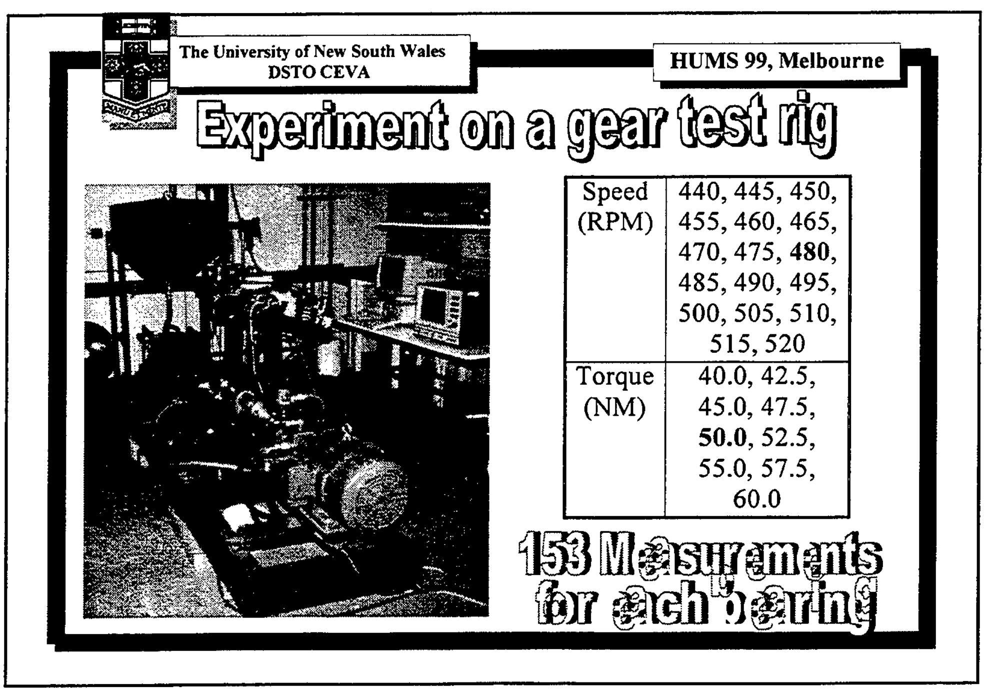

Speed (RPM)	440, 445, 450, 455, 460, 465, 470, 475, **480**, 485, 490, 495, 500, 505, 510, 515, 520
Torque (NM)	40.0, 42.5, 45.0, 47.5, **50.0**, 52.5, 55.0, 57.5, 60.0

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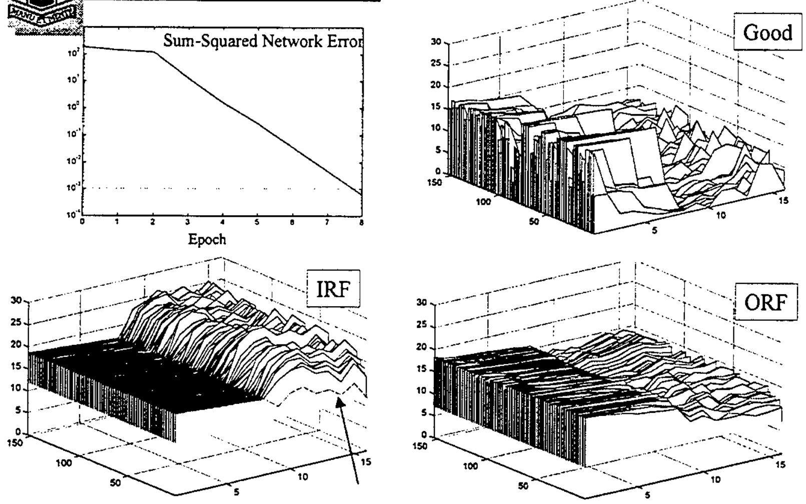

One vector in the IRF group at the lowest shaft speed and torque is mis-classified into the ORF group.

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Conclusions

Spectral Analysis:
- Requirement of baseline spectra;
- Sideband growth & spectrum level increase.

Cepstral Analysis:
- Periodic structures in log spectra;
- Better than Kurtosis

Statistical Parameters:
- Applied to bandpass filtered envelope signals;
- May produce confusing indication.

Envelope Analysis:
- Digital implementation;
- Flexibility in choosing passbands;
- Harmonic family & Sidebands ;
- Combination with SANC.

CPB Spectral Analysis:
- Wide frequency range with limited samples;
- Comparison with mask;
- Stable detection information.

Neural Network
- CPB spectrum analysis is a valid data preprocessor;
- Good success rate with helicopter gearbox bearing faults (based on limited data) and the bearing faults in the gearbox test rig;
- Too expensive to experience all the faults we would like to diagnose;
- Solution - Mathematical models and digital simulation.

LASERNET MACHINERY MONITORING TECHNOLOGY
LASERNET MACHINERY MONITORING TECHNOLOGY

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TECHNOLOGY BRIEFING

DSTO WORKSHOP
MELBOURNE, AU

2/16/99

LASERNET MACHINERY MONITORING TECHNOLOGY

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C. HOLLOWAY	**Lockheed Martin Tactical Defense Division** **Akron, OH**

John Reintjes - 1

LASERNET MACHINERY MONITORING TECHNOLOGY

MOTIVATION

- DEVELOP OIL ANALYSIS TECHNOLOGY FOR ADVANCED CBM WITHIN MULTI-COMPONENT ONR PROGRAM
- NEW TECHNOLOGY SHOULD
  - PROVIDE INFORMATION AS TO
    - IS THERE A FAULT IN THE EQUIPMENT?
    - IF SO, WHAT TYPE OF FAULT IS IT AND HOW BAD IS IT?
  - PROVIDE COMPLEMENTARY INFORMATION FOR DATA FUSION WITH OTHER SENSORS
    - SAME TYPE OF FAULT IDENTIFICATION INFORMATION
    - INDEPENDENT CORROBORATION
  - HAVE ABILITY TO PROVIDE INPUT FOR PROGNOSTIC MODELS

LASERNET MACHINERY MONITORING TECHNOLOGY

MOTIVATION

- SAFETY
- AFFORDABILITY
- RELIABILITY
- IMPROVED CAPABILITY WHILE DOWNSIZING

John Reintjes - 2

LASERNET MACHINERY MONITORING TECHNOLOGY

Machinery Monitoring

- STATE VARIABLES
  - TEMPERATURE
  - PRESSURE
- FAULT DIAGNOSTICS
  - VIBRATION
  - OIL ANALYSIS
- TWO COMPONENTS OF OIL ANALYSIS
  - OIL DEBRIS ANALYSIS - LASERNET&LASERNET FINES
    - CONDITION OF OIL WETTED MACHINERY
    - PARTICULATE CONTAMINATION OF HYDRAULIC/FUEL SYSTEMS
  - OIL CONDITION ANALYSIS - INFRARED SPECTRAL ANALYSIS
    - FUEL/WATER/COOLANT CONTAMINATION
    - BREAKDOWN OF BASE STOCK/ADDITIVE PACK

LASERNET MACHINERY MONITORING TECHNOLOGY

SHORTFALLS IN CURRENT OIL ANALYSIS

- AIR
  - INADEQUACY OF EXISTING CHIP DETECTORS
  - INADEQUACY OF EXISTING LAB BASED MONITORING
  - INABILITY OF ALTERNATIVE TECHNOLOGY TO IMPROVE ON BOARD TECHNOLOGY
- SEA
  - INADEQUACY OF EXISTING LAB BASED MONITORING
    - LONG TURN AROUND TIME
    - INADEQUATE FAULT IDENTIFICATION

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LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET TECHNOLOGY

- DETERMINES TYPE, SEVERITY AND RATE OF PROGRESSION OF MECHANICAL FAULTS BY MEASUREMENT OF SIZE DISTRIBUTION, SHAPE AND RATE OF PRODUCTION OF PARTICLES
  - DIRECTLY IDENTIFIES FAULT TYPE
  - IDENTIFIES AND TRACKS MULTIPLE INDEPENDENT FAULTS
  - DIRECTLY TRANSITIONS TO ON LINE OPERATION
  - CAN BE COMBINED WITH OTHER MACHINERY SENSORS - VIBRATION, TEMPERATURE, PRESSURE - FOR IMPROVED EARLY FAULT IDENTIFICAITON AND REDUCED FALSE ALARM
  - CAN BE COMBINED WITH ON LINE OIL CONDITION SNSOR FOR COMPREHENSIVE OIL ANALYSIS SYSTEM

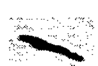
LASERNET MACHINERY MONITORING TECHNOLOGY

Fault Source and Shape Features

Fault Source


Fatigue Spall


Cutting


Severe Sliding


Sand (Contaminant)

Shape Features

- Maximum Diameter
- Area
- External Compactness
- Perimeter
- Circularity
- Aspect Ratio (Area / Maximum Diameter^2)
- Curvature

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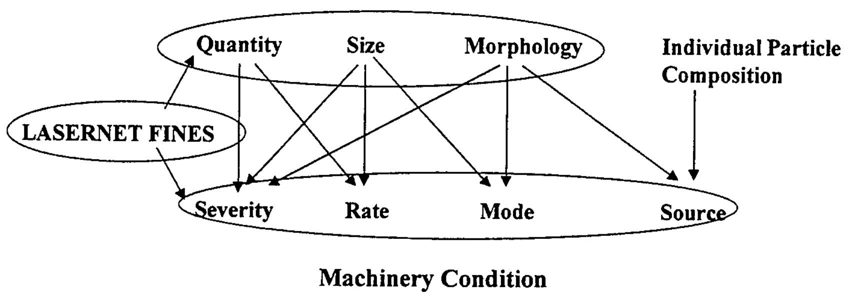
LASERNET MACHINERY MONITORING TECHNOLOGY

PARTICLE CHARACTERISTIC/MACHINERY MAPPING



Brian Roylance
University College of Swansea
Wales, UK

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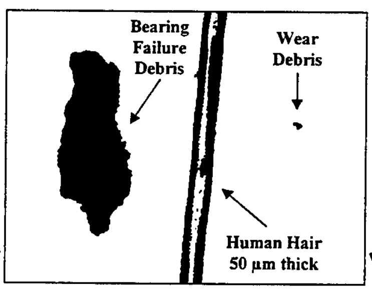
LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET

Measurements
Failure Related Debris

Implementation
Real Time In-line

Benefits
Save Platforms/Crew
Mission Execution

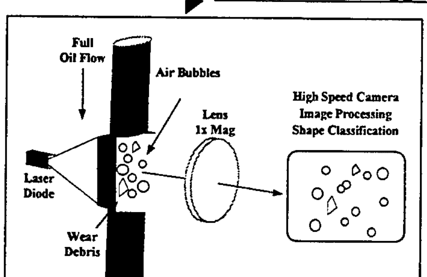


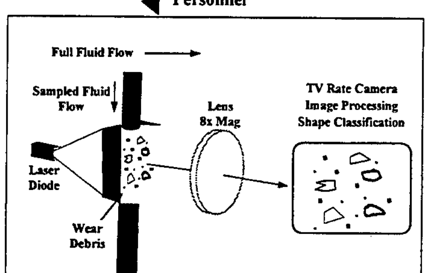
LASERNET FINES

Measurements
Wear Debris
Fuel, Hydraulic Contamination

Implementation
Batch Processors
Continuous On-line Monitor

Benefits
Life Extension
Mission Readiness
Reduced Maintenance Cost, Personnel





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LASERNET MACHINERY MONITORING TECHNOLOGY

CHARACTERISTICS

- LASERNET
  - EARLY FAILURE DETECTOR - AVOIDS CATASTROPHIC LOSSES
  - DETECTS FAILURE RELATED PARTICLES > 100MICRONS
  - IDENTIFIES FAULT TYPE FROM PARTICLE SHAPE, SIZE AND RATE OF PRODUCTION
- LASERNET FINES
  - DETECTS PROGRESSION OF FAULTS FROM ONSET
  - DETECTS PARTICLES GREATER THAN 5 MICRONS,
  - CLASSIFIES PARTICLES GREATER THAN 20 MICRONS ACCORDING TO WEAR CLASS,SIZE DISTRIBUTIONS
  - FAULT TYPE IDENTIFICATION AND TRENDING

LASERNET MACHINERY MONITORING TECHNOLOGY

REAL TIME ON LINE OPTICAL OIL DEBRIS MONITORS

TECHNOLOGY APPLICATIONS

- **LASERNET - FULL TIME ON LINE MONITOR**
  - **HIGH VALUE HIGH RISK ITEMS WHERE IMMEDIATE KNOWLEDGE OF FAULT DEVELOPMENT IS CRUCIAL AND/OR RAPID FAILURE DEVELOPMENT IS LIKELY**
- **TURBINE ENGINES AND GEARBOXES IN**
  - **Military helicopters**
  - **Commercial helicopters**
  - **Commercial and Military fixed wing aircraft**
  - **Heavy land vehicles**
    - **military - tanks, assault vehicles**
    - **commercial - rail, construction, off road vehicles, mining**

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LASERNET MACHINERY MONITORING TECHNOLOGY

REAL TIME ON LINE OPTICAL OIL DEBRIS MONITORS

TECHNOLOGY APPLICATIONS

- LASERNET FINES - OFF LINE BATCH PROCESSOR
  - FOR CASES WHERE WEAR IS AN ISSUE, FAILURES DEVELOP MORE SLOWLY OR WEAR IS BENIGN IN NATURE.
  - INGESTED CONTAMINANT DETECTION
- TURBINE/RECIPROCATING ENGINES (DIESEL, GASOLINE), HYDRAULIC SYSTEMS, COMPRESSORS

  military - ship, planeside (fleet operation, e. g carrier aircraft), splash lubricated gearboxes, land vehicles (fleet operation)

LASERNET MACHINERY MONITORING TECHNOLOGY

REAL TIME ON LINE OPTICAL OIL DEBRIS MONITORS

TECHNOLOGY APPLICATIONS

- LASERNET FINES - FULL TIME ON LINE SAMPLING
  - RAPID FAILURE DUE TO CONTAMINANT OR WEAR MODE, REMOTE DEPLOYMENT, RAPID TURN AROUND
    - HYDRAULIC PUMPS
    - HIGH SPEED TURBINES (AUXILIARY POWER UNITS)
  - REDUCED MANNING PLATFORMS

  military strike aircraft
  assault vehicles - hydraulics,engines
  mining, off-road - hydraulic systems
  commercial air - hydraulic systems

- LASERNET FINES/LASERNET - COMBINED ON LINE

  high risk turbines in strike fighters

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LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET

LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET AVDS PROGRAM

- SYSTEM TESTED ON T700 ENGINE AT NAWC TRENTON
- FALSE ALARM RATE ESTABLISHED IN REALTIME MEASUREMENTS
- DEBRIS IDENTIFICATION USING DEBRIS FROM BEARING FAILURE TESTS AND WEAR ATLAS

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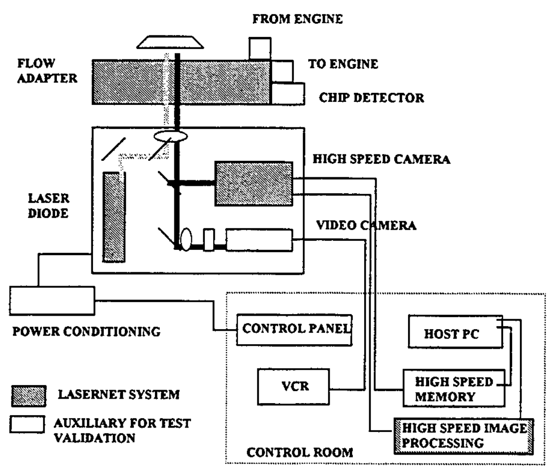
LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET AVDS TEST PROGRAM GOALS

- DEMONSTRATE ACCEPTABLY LOW FALSE ALARM RATE
  - FUNCTIONAL:NO MORE THAN 1 FALSE PULL IN 2000 OPERATING HOURS
  - OPERATIONAL: LESS THAN 1 MISCLASSIFICATION OF BUBBLE PATTERN AS 250 µm DEBRIS PARTICLE EVERY HOUR
- ACCEPTABLE DEBRIS DETECTION RATE
- FAULT IDENTIFICATION

LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET AVDS TEST CONFIGURATION



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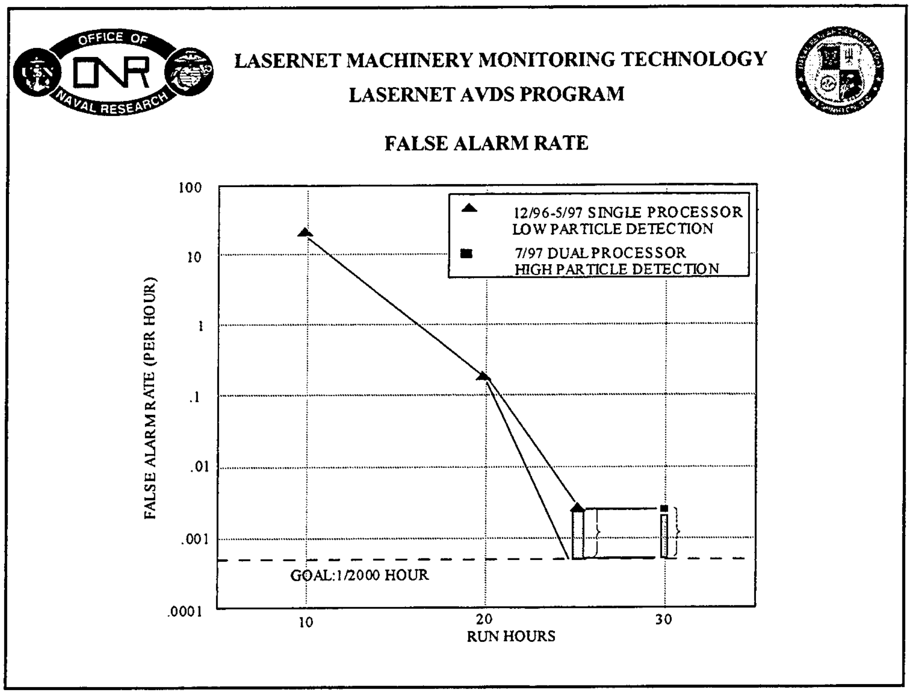

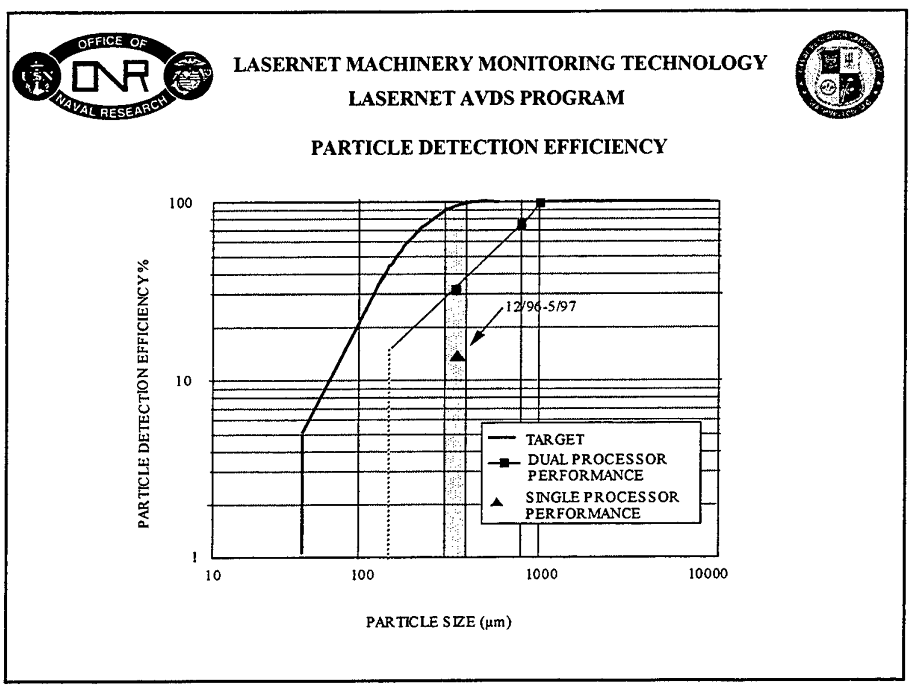

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LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET AVDS ACCOMPLISHMENTS

- **Developed hardware and algorithms for real time high speed classification of air bubbles and debris**
- **Demonstration of system on lab bench and turbo thrust engine**
- **Successful real time operation of high speed image acquisition/processing system on T700 engine**
- **Successful neural net FAULT IDENTIFICATION USING debris from known data base**
- **Successful classification of air bubble patterns and debris with high speed processor**
  - BUBBLE MIS CLASSIFICATION RATE COMPATIBLE WITH TARGET FALSE ALARM RATE WITH DUAL PROCESSOR ARCHITECTURE
- **Design and layout for flight package for T700/H60**

LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET FINES

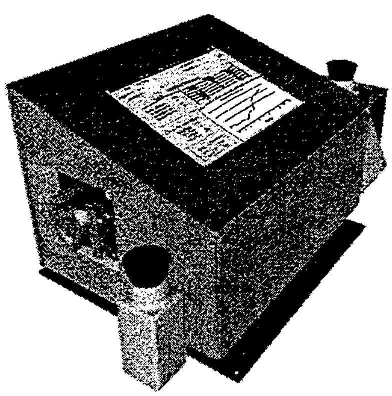
LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET FINES
INTEGRATED PRODUCT DEVELOPMENT TEAM

ACCELERATED TRANSITION FROM LABORATORY TO INSTRUMENTATION

LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET FINES Optical Oil Debris Monitor



FEATURES

- Measures size distribution of particles larger than 5 microns
- Wear classification for particles larger than 20 microns
- Compatible with hydraulic fluids and synthetic and mineral based lubricants
- Automatically adjusts for fluid darkness
- Neural network inference engine for wear type classification
- Internal data storage for trending analysis
- Local area network interface to Integrated Condition Assessment System (ICAS)
- Touch panel and LCD graphical-user-interface display
- Built-in-test (BIT) capability

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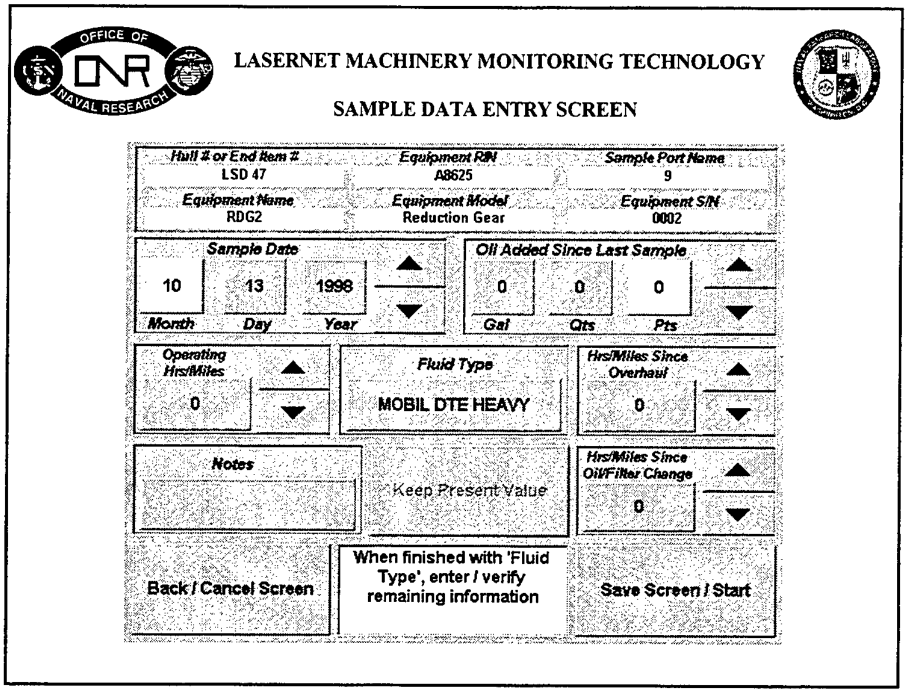

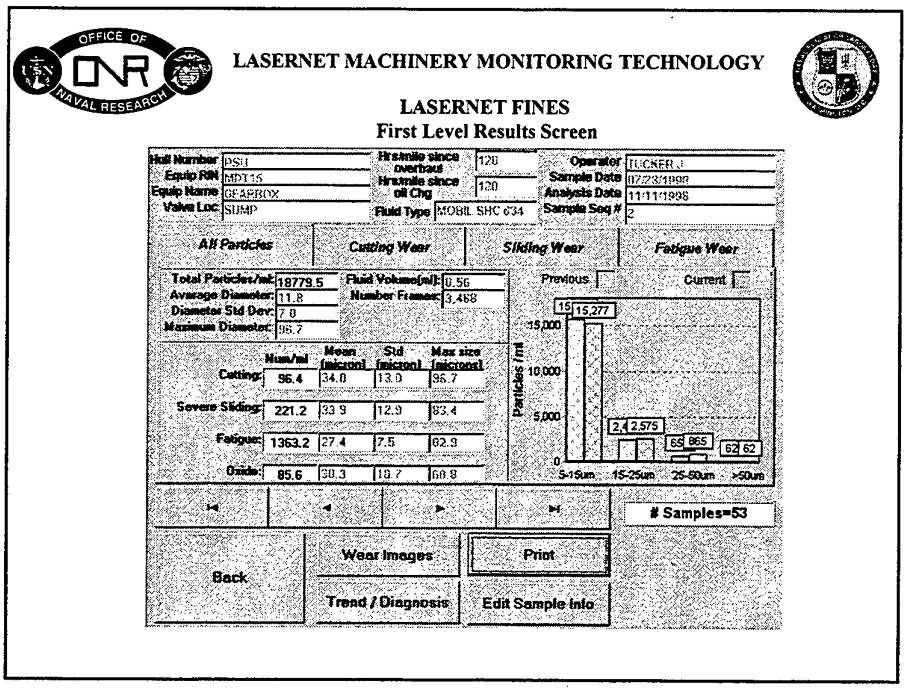

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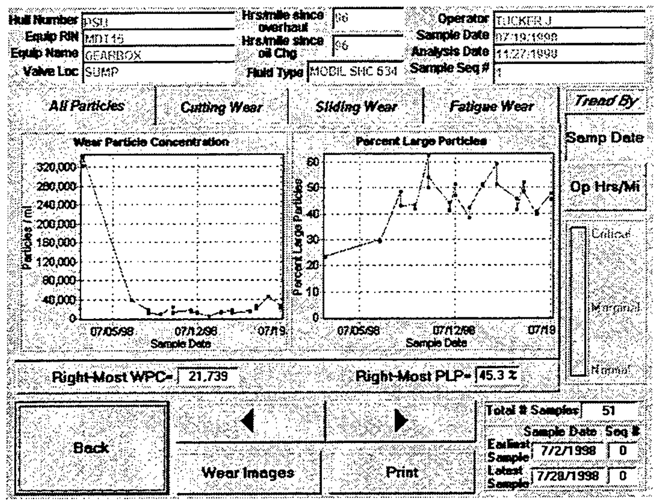
LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET FINES
Trended Results Screen



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LASERNET MACHINERY MONITORING TECHNOLOGY

LASERNET FINES
CURRENT DEPLOYMENT

● **USS RUSHMORE**	**PROPULSION DIESELS** **HYDRAULICS** **GEARBOXES** **BEARINGS** **CENTRAL COMPUTER INTERFACE** **SHIP ENVIRONMENT OPERATION**
● **R/V THOMPSON**	**PROPULSION DRIVE TRAIN**
● **NEWPORT NEWS SHIPBUILDING**	**DIESEL GENERATORS** **HYDRAULICS**
● **PSU (ONR PROGRAM)**	**ACCELERATED GEARBOX FAILURES** **UNDER CONTROLLED CONDITIONS**

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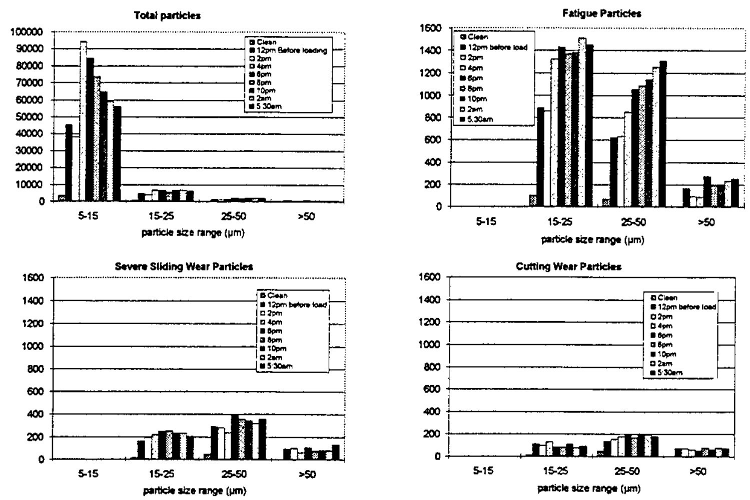
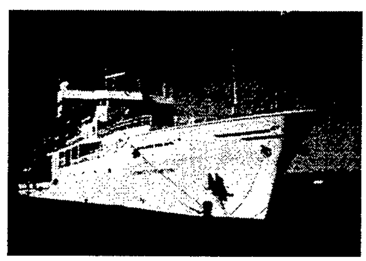
Splash Lubricated Gear Box Accelerated Failure Test

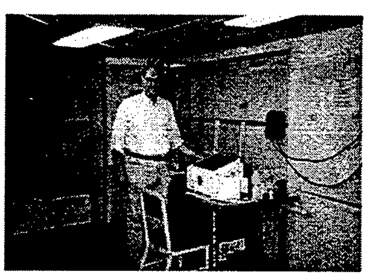


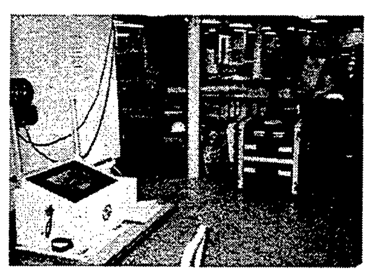
Root cause of failure - Overtorque- is seen in fatigue particle distribution (25-50 microns), not in total, small particles or other wear classes

LASERNET MACHINERY MONITORING TECHNOLOGY R/V THOMPSON INSTALLATION

- **ONR OCEANOGRAPHY FLEET**
- **MONITOR RECURRING FAILURE IN STEERABLE DRIVE GEAR BOX**
- **VALIDATE AGAINST TEARDOWN**
- **BASELINE LUBRICATION AND HYDRAULIC SYSTEMS**







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LASERNET MACHINERY MONITORING TECHNOLOGY

CURRENT STATUS

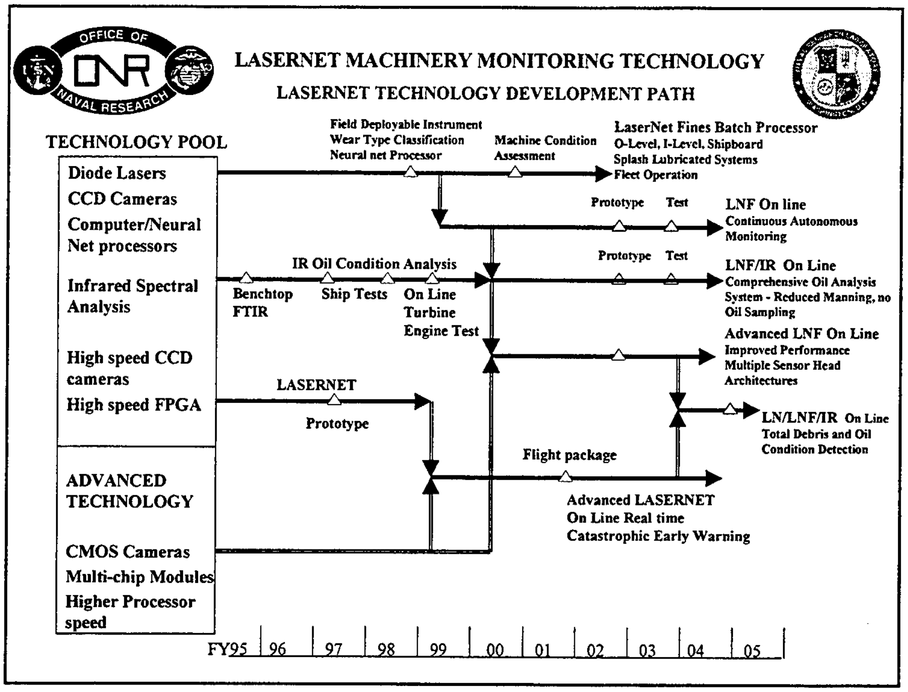
- LASERNET
  - PROTOTYPE DEVELOPED FOR TURBINE ENGINE TEST
  - ALL ASPECTS OF LASERNET DEMONSTRATED
  - IMPROVED FALSE ALARM LEVEL ACHIEVED
  - FLIGHT PACKAGE DESIGNED
- LASERNET FINES
  - DEPLOYABLE COMMERCIAL PRODUCT DEVELOPED -
    - O-LEVEL, I-LEVEL, SHIPBOARD ANALYSIS
  - SHIP AND SHORE TESTING IN PROGRESS
  - COMMERCIALIZATION AGREEMENTS IN PLACE

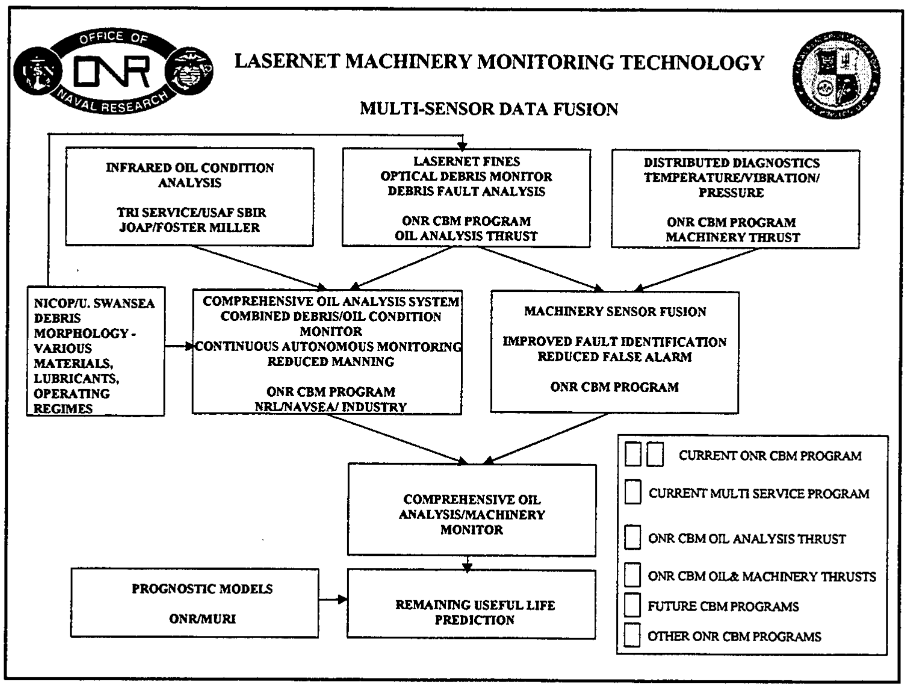
LASERNET MACHINERY MONITORING TECHNOLOGY

NEXT STEPS

- LASERNET
  - MINIATURIZED COMPONENTS, FLIGHT PACKAGE
    - SMALL COMPACT HIGH SPEED CAMERA
    - MODIFIED PROCESSOR BOARDS
    - IMPLEMENTATION OF TWO PROCESSOR ARCHITECTURE
  - TEST ON ENGINE, GEARBOX FOR FAULT IDENTIFICATION
- LASERNET FINES
  - ON LINE OPERATION
  - MACHINE CONDITION ASSESSMENT CRITERIA
- COMBINED LASERNET/LASERNET FINES
  - ARCHITECTURE DESIGN FOR COMBINED CAPABILITIES

John Reintjes - 16





John Reintjes - 17

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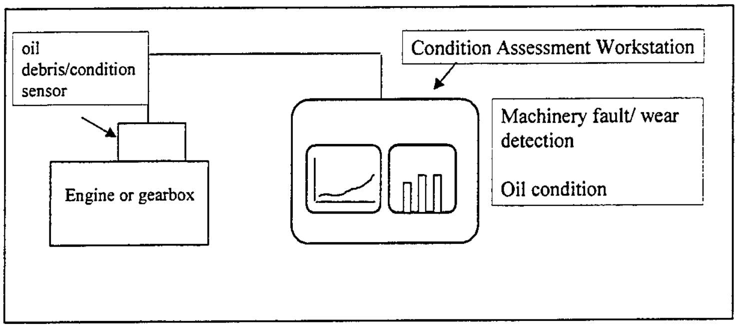
LASERNET MACHINERY MONITORING TECHNOLOGY

Future Comprehensive On-board Oil Analysis System Example



- **On line automated oil condition/debris monitor -reduce watch-stander workload/Eliminate manning in engineering spaces**
-
- **On-board condition assessment - no remote lab analysis**
- **Automated fault detection, trending, severity and prognosis**

John Reintjes - 18

A Straw Man for the Integration of Vibration and Oil Debris Technologies

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Abstract:

Diagnosis of faults in mechanical systems has traditionally involved analysis of vibration data and analysis of oil borne debris captured by magnets placed in the lubricating oil stream and has relied heavily upon trained expert analysis of data. Because the technologies are expert intensive and quite different in practice, they have remained basically separate analytical technologies. Each technology requires specific expert interpretation of data. Generally, neither answers the question "what's failing and how bad is it?". Data in "g's rms." and "parts per million of iron" will normally be compared to limit values. This usually occasions review by a trained technician to determine the course of action to be followed and may or may not signal the existence of a problem. Optical analysis of oil borne debris by experienced technicians can provide additional information on machine condition well in advance of failure, but the accuracy of the analysis is still highly dependent on the capability of the human expert.

Attempts to automate these analysis processes have mostly been rewarded by a high incidence of false alarms. Operators of early HUMS systems overcame these limitations by employing human expert analysis of data. Sometimes multiple indications were required before a problem was recognized.

Currently HUMS systems must rely almost exclusively upon vibration analysis for detection of most faults, partly because automation of oil debris analysis has fallen behind basic HUMS technology development. While some of the critical HUMS detectable faults do not produce significant levels of oil borne debris, there are many that do. Reliance on prior technology, such as chip detectors and particle sensors / counters, has not allowed development of a truly robust, low false alarm rate, mechanical diagnostic system. New oil debris technology, such as LaserNet, which directly identifies the surface fatigue fault mode(s) from particle shape, can assess severity, and trend growth of significant faults could provide a way forward for integration of vibration and oil debris technologies to produce a superior diagnostic approach. This paper identifies some current technology roadblocks and offers a straw man framework for such an integration process.

Vibration Diagnostic Technology Background :

The characteristics of structure borne vibration signals have been analytically and empirically related to faults in machinery. Analysis packages for vibration frequency spectrum, order domain, broad and narrow band, cepstrum, and others have grown as vibration analysis hardware has become more available and affordable. For most industrial machinery applications the tools are at hand to allow trained vibration technicians to analyze and trend developing faults and plan corrective action before a major machine outage occurs. Again, the capability of the expert largely determines the success of the operation.

These tools and techniques tend to falter in the applications where higher background levels of vibration are present. Such applications as aircraft (especially helicopter) transmissions, where vibration levels reach several hundred "g's" and failures can progress rapidly, have traditionally required entirely new analysis tool sets. Feature vectors and neural nets operating on raw accelerometer signals or signals processed in the frequency domain, or digital signal averages are all part of these tool sets. These tools are often complex and computationally intensive. The time required for these analyses permit only periodic sampling of critical transmissions and often require ground-based computation to define the most important signal features. While this technology has made great progress over the last decade, there remains considerable room for improvement before it can answer the basic question -- "what's failing and how bad is it?" with high reliability and without false alarms.

Oil Debris Monitoring Technology Background:

Vibration analysis is an inferential technology. That is, one can infer the condition of machinery from analysis of data. Oil debris, on the other hand, is generally evidential. Debris on a magnetic plug presents clear evidence of a surface fatigue failure in progress. For applications such as aircraft gear boxes, where failure progression times are short, periodic manual sampling and visual analysis of debris can result in delays and reduced sortie rates. Electric chip detectors are widely applied in critical gearbox applications and can give warning of near term impending failure in many cases. The accompanying penalty is often false alarms caused by non-failure related debris bridging the detector gap. Automated oil debris analysis systems that are designed to monitor debris generation in real time, detect debris size and provide debris count trending data have been developed over the past two decades as replacements for electric chip detectors. Most attempts to deploy these systems have yielded unacceptable false alarm rates caused by the EMI and vibration environment on aircraft (predominantly helicopters). Even if these false alarm issues are resolved through redesign, the current electromagnetic sensing technology systems provide only particle size and count data, but do not differentiate between fault and non- fault sourced debris and do not determine what type of fault exists. In short they still do not address the basic question --"what's failing and how bad is it?".

The Straw Man Goal:

Most Defense Forces and industrial operations are now committed to the implementation of Condition Based Maintenance to reduce total ownership costs. The success of this effort hinges on the development and improvement of existing enabling technologies in the area of machinery condition monitoring, oil debris analysis, and machinery health prognostics. The goal proposed for an integrated mechanical diagnostic system is to provide machinery fault data directly rather than as a feature of a vibration signal or as numbers of particles. This goal will allow the user to functionally move the determination of machinery fault type and severity to on board and eliminate the need for and delay attendant to remote laboratory analysis and expert data interpretation.

There are several "next steps" in the process. One step is to develop the technology to interpret the characteristics of oil borne debris in terms of mechanical fault type identification and severity and translate this to machinery condition and remaining life assessment terms. A second step is to improve the detection, identification and classification ability of vibration analysis technology to permit clear identification of fault type and severity rather than just vibration signal feature and to translate this to machinery condition and remaining life assessment terms. A third step is to combine the condition assessment information from these two technologies on a weighted basis and add corroborating information from other sensors such as temperature, pressure and flow. This can serve to confirm the condition of machinery, provide better fault coverage, earlier fault detection and elimination of the high false alarm rates attendant to current automated machinery condition assessment systems.

One technology that currently has demonstrated the ability to determine wear and fault classification as well as size distribution of debris particles is the optical oil debris monitor, LaserNet, and LaserNet Fines. LaserNet Fines has been developed into an instrument usable at O-level, I-level and on board ship for determining particle sizes down to 5 microns and fault type (surface fatigue failure, sliding wear, and or cutting wear). On line versions of LaserNet and LaserNet Fines are currently being developed for airborne and shipboard applications. Technical operation details are available from the co-author at the U. S. Naval Research Laboratory.

Achieving this fault identifying capability not only with oil debris technology, but also with vibration analysis technology is a key step in providing comprehensive machinery condition monitors for on line operation that will allow continuous autonomous monitoring, supporting reduced manning and reduced maintenance operations and costs.

An Example Approach:

The LaserNet technology identifies debris particles and determines particle type in three major classes in much the same way that a trained debris analysis technician does. The edge roughness, appearance and particle shape aspects of the several classes are reliably (but not perfectly), rapidly and automatically separated. Since, in the early stages of failure, there may be competing failure modes, it is important to determine not only particle count but also particle type and thus type of failure. As an example, surface fatigue spalling may ultimately cause machine failure, but detection of particulate contamination shapes can allow corrective action that will delay the onset of failure.

The reporting of particle characteristics and incipient fault type and severity can also provide a measure of fault severity and, when machine type history is added, provide an indication (not perfect and very dependent upon machine use environment) of probable time to machine failure.

Machine fault type and degree of progression can now be reliably determined by LaserNet technology. Machinery condition determination and prognosis from oil debris particle shape and amount can be substantially improved by considering the relative trends of the major wear fault types as determined by LaserNet. The trends of each particle shape category can identify the fault type and trends in severity. As an example, consider the case where a combined LaserNet / LaserNet Fines on-line unit is monitoring lubricating oil flow in an operating machine. Dr. John Reintjes of NRL has postulated that the fault type progression may be determined from plots of the relative particle shape / fault type particle counts or particle generation rates over time. Further, these characteristics may be represented by a series of numerical feature vectors which might then be matched to patterns of previous machine behavior and provide an automation of the condition assessment process. Figure 1 is a series of notional plots of particle shape indicators of fault types that might be present in this machine. The vertical axis might be either count or rate data, while the horizontal axis is operating time. While these are just notional they do serve to illustrate the point. Work is in process to automate features vectors for these plots that can be used to develop quantitative representations of machine condition.

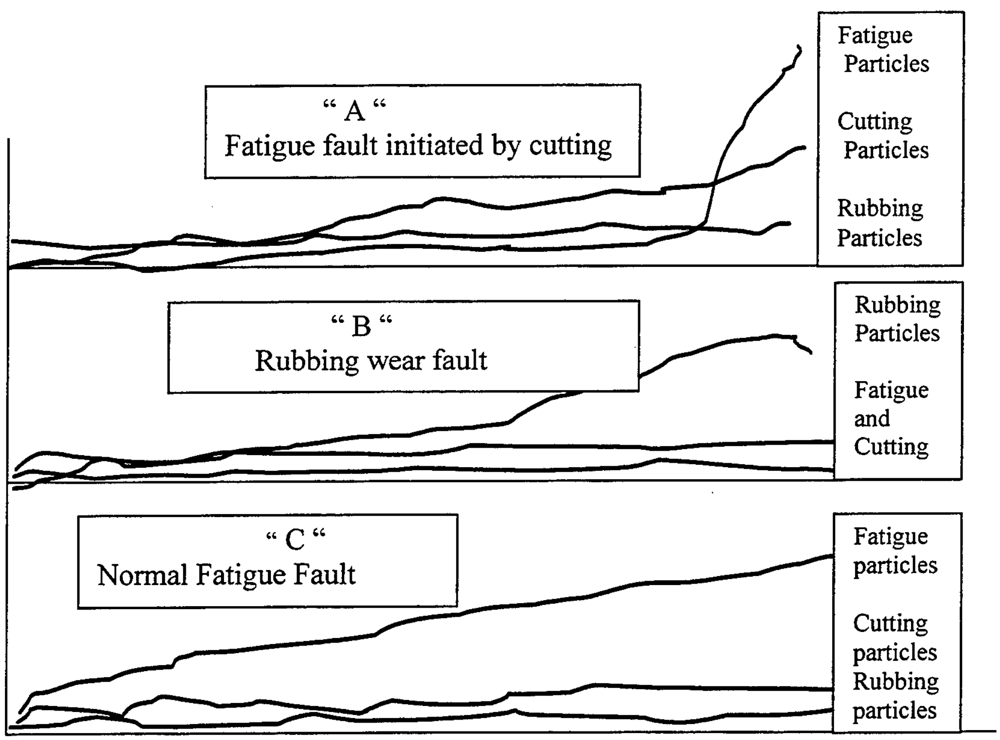

Figure 1.
LaserNet Fault Type Notional Plots

The translation of this approach or a similar one to the vibration technology regime is needed to accomplish the integration of technologies. The translation is by no means an easy task, but the reward is commensurate with the effort. While the present vibration systems can provide some measure of fault detection, the end result lacks the value of an integrated low false alarm machinery diagnostic system

The Issues and Tasks:

The main issues in the oil debris diagnostic area are automation of the curve analyses shown in numerical terms and setting pattern recognition masks to automate the alarm function.

The tasks in the vibration area involve improving the feature vector clarity and linking features (or feature pairs) to specific faults, such as fatigue crack, surface fatigue, etc. It may be that the newer Neural Net technology developing within the diagnostic community may provide a shorter route to the goal even though the financial investment to date in the feature vector approach will provide high inertia against change. Figure 2. illustrates a notional flow chart to update the current vibration feature vector sets, advance the LaserNet technology and integrate the resultant technologies into an integrated machinery diagnostic system that meets the needs of current and future applications.

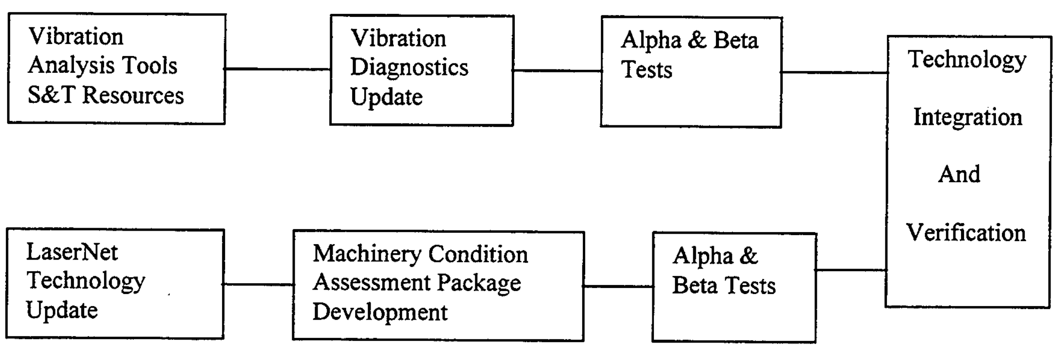

Figure 2.
Straw Man Technology Development and Integration Road Map

A key ingredient to the success of the program is development and application of both alpha and beta test beds. The goal will almost certainly not be achieved by mathematical analysis alone. These test beds need to be highly representative of actual conditions that will be encountered in the application set that the system is designed for. Many of the past failures to meet diagnostic performance can be directly traced to the failure to adequately test in realistic operational environments while the technology was being developed.

With reductions in real terms of 15 to 30% per year in defense department operation and maintenance budgets, and maintenance becoming the only remaining source of cost savings to maintain a competitive posture in industry, the urgency of this effort is self-evident.

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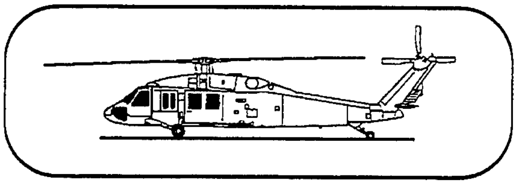
Helicopter Structural Usage Monitoring Work at DSTO Airframes and Engines Division



By
D. C. Lombardo

Presented to
Helicopter Health and Usage Monitoring Workshop
held at
Aeronautical and Maritime Research Laboratory
Melbourne, Australia, 16 - 17 February 1999

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Outline

- Pilot Questionnaire Usage Survey for Black Hawk
- Quantitative Usage Monitoring Program for Black Hawk
- Usage Monitoring Research
  - Economic Effectiveness of Usage Monitoring
  - Gross Weight Prediction
  - Application of Artificial Intelligence Techniques

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Pilot Questionnaire Usage Survey for Black Hawk

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Black Hawk
Australian-Unique Usage Spectrum

- **A usage spectrum attempts to describe worst aspects of anticipated missions**
- **S-70A-9 accepted into service with Component Retirement Times (CRTs) based on U.S. Army UH-60A usage spectrum**
- **Army, RAAF not sure if UH-60A spectrum appropriate**
- **Sikorsky contracted to create a new spectrum**
- **DSTO-AED involved as adviser to Army and RAAF**

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Black Hawk
Australian-Unique Usage Spectrum

- **Data for new spectrum obtained by:**
  - Mission Monitoring Forms (filled out daily)
  - Long-Form Questionnaire
  - Aircrew interviews
  - Sikorsky "witnessing" of ARA flights
- **New spectrum created as part of Phase 1 of contract (produced mid-1994)**
- **Impact of new spectrum assessed by looking at five components**

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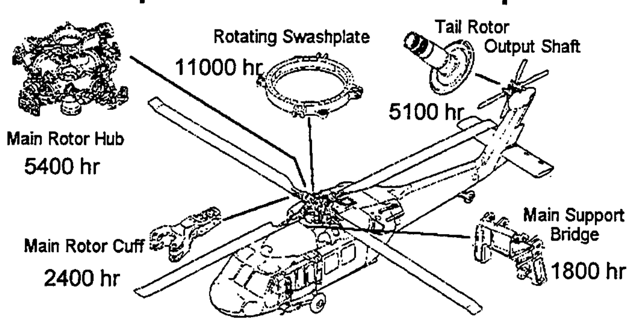
New Spectrum - Phase 1 Components



- **Components chosen to represent wide range in CRTs**
- **Impact study showed worrying results**
- **Typical reduction in life: 50%**

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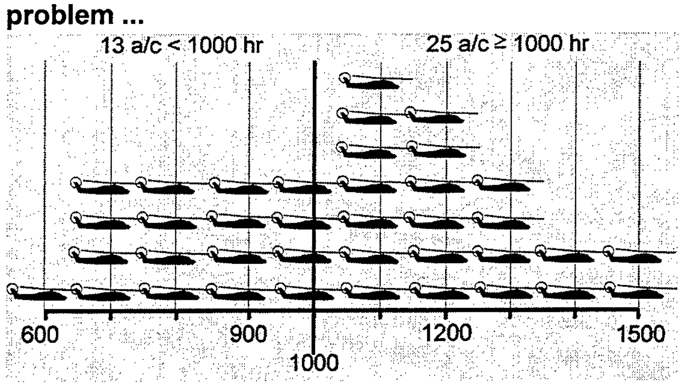
Problems of Phase 1 CRTs

- MR Cuffs and Main Support Bridge decreased from 2400, and 1800 hours to about 1000 hours. Therefore, problem ...



Aircraft airframe hours (to nearest 1000 hour) at Nov. 94

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Post-Phase 1

- Hence, Phase 2 was initiated to produce new CRTs based on new spectrum
- However, Phase 2 results not expected till late 1995 (actually delivered January 1996)
- Phase 1 results were not "binding" on the Army - (Impact study only)
- What to do between receipt of Phase 1 and Phase 2 results?

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Interim CRTs

- Quote from RAAF:
  "If the reduced [Phase 1] *lives ... are implemented, 27 aircraft will be grounded ... and in 12 months the entire fleet will be grounded"*
- Not enough spares of Main Support Bridge
  12-month lead time for new spares
- RAAF asked AED for advice on flying the components beyond 1000 hours
- Interim CRTs used by Army based on DSTO-AED risk analysis.
  - Only 1 aircraft grounded immediately and 3 grounded after 12 months

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Phase 2

- Phase 2 looked at 12 components to produce "definitive" CRTs
- Phase 2 of the program involved
  - Eliminating unrepresentative loads (e.g. loads due to firing Hellfire missiles from the ESSS)
  - Updating material SN curves
  - Taking account of more detail in Aust. spectrum
- Phase 2 results delivered January 96
- Results were variable - some CRTs increased, some decreased

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Quantitative Usage Monitoring Program for Black Hawk

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Quantitative Measurement Program

- New spectrum developed from subjective data
- Only limited cross-checking possible of data
- Army/RAAF want to obtain quantitative data
- Only option is an in-flight measurement program

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Program Features

- Usage will be recorded in an operational environment
- Loads monitoring is unlikely to be part of the program
- On-board recording equipment required to measure appropriate parameters
  - Pilot stick positions
  - Airspeed
  - Altitude, etc
- Software required to convert recorded data to flight conditions and hence usage

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Program Features (cont)

- Ideally, all aircraft would be fitted with the equipment
- Practically, two or three aircraft will be fitted at any one time
- Two year recording program (individual aircraft may have equipment for about 6 months at a time)
- Need at least one aircraft at Townsville (Operational Squadron) and one at Oakey (School of Army Aviation)

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Program Players

- RAAF - Technical Airworthiness Authority
- Army - Operational Airworthiness Authority
- Sikorsky - Black Hawk Manufacturer
- DSTO - Scientific Adviser to Army and RAAF
- Equipment supplier
- Software supplier

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DSTO Role in Program

- Advise on the equipment and software
  - What is to be measured and recorded
  - What equipment is practical
  - Cost/capability/benefit trade-offs
- Assist in validating the equipment and software
- Ensure that the operational data are valid

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Program Result

- A quantitatively-measured usage spectrum for Australian Black Hawk operations
- A definitive set of CRTs for Black Hawk
- A defined base from which to manage the structural integrity of the Black Hawk
- An "education" element for both DSTO and Army/RAAF
- Maybe on-going recording beyond the two-year initial period
- Will not necessarily lead to CRTs > Phase 2 CRTs

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Usage Monitoring Research

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Economic Effectiveness of Usage Monitoring

- For usage monitoring to be economically effective for a given operator's fleet then:
  - At least some helicopters must be being used less severely than assumed at design

    AND
  - Most components must be achieving their rated CRT
- International collaborative program (DSTO, US Army, Canadian DND) to determine:
  - Proportion of components which reach their CRTs
  - If proportion is low, then determine reasons why components don't reach their CRTs

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Gross Weight Estimation

- Gross weight is an important input parameter for fatigue calculations
- Fatigue calculations only require approximate weight value (within a few hundred pounds)
- Many possible measurement techniques - direct and indirect
- Work conducted via an indirect method, using pilot control positions, to estimate weight.
- Results
  - At speeds > 30 kt, good correlation (± 5% error)
  - At speeds < 30 kt, poor correlation

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Application of Artificial Intelligence Techniques

- Aim: To see if it is possible to identify what flight condition a helicopter is in by using data from a single source
- Machine learning methods used
  - Artificial Neural Network (ANN)
  - Nearest Neighbour Algorithm
  - Decision Tree Algorithm
- Current work concentrated on identifying steady-state, level flight conditions

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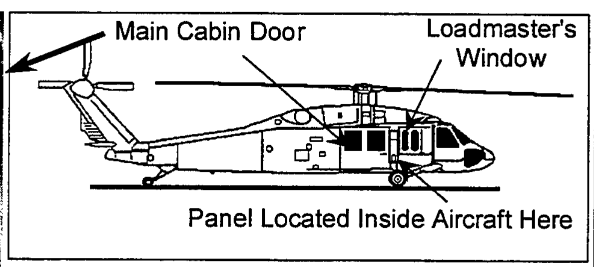
Flight Test Data (1)



Flight data available from previous Black Hawk investigation

Used strains measured at a point on a right-hand internal panel as shown

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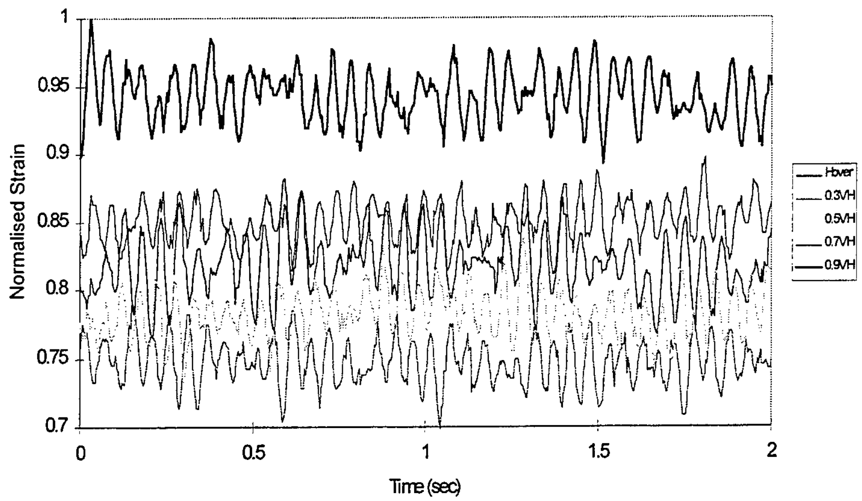
Example of Time History Data



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Data Processing

- Converted data from time domain to frequency domain and used values at

1.1 Hz	1/4 × MR
2.15 Hz	1/2 × MR
4.3 Hz	Main Rotor Frequency
8.6 Hz	2 × MR
12.9 Hz	3 × MR
17.3 Hz	4 × MR (Blade passing freq.)
19.8 Hz	Tail Rotor Frequency
34.6 Hz	8 × MR

- Also, used mean strain value
- All values within a frequency normalised to the range 0 - 1

Domenico Lombardo - 12

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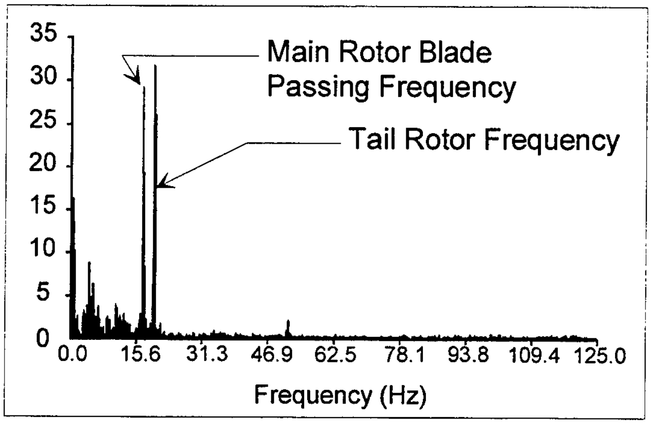
Example - Frequency Domain Data



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Results

- **Ten sets of training/test data used**
- **ANN**
  - **ANN training data - Acceptably low error rate and trained quickly**
  - **ANN test data - Error rates greater than for training data, but not at unacceptable levels (except for two cases)**
- **Nearest Neighbour**
  - **Error rates in assigning correct class: 0 to 14%**
- **Decision Tree**
  - **Error rates in assigning correct class: 0 to 14%**

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Important Parameters

- Performed sensitivity analysis using Nearest Neighbour (simpler, quicker than ANN)
- Important parameters in identifying flight condition:
  - Mean strain
  - 2 × MR frequency
  - 4 × MR frequency

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Conclusions

- Indirect measurements can be used to identify steady-state flight conditions
- Results are promising, even though data were not ideal
- Important parameters were identified
- However ...
  - Data from a single strain gauge are not enough to identify flight conditions with high reliability
  - Transient flight conditions will be more difficult to identify

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Summary

- **Pilot questionnaire data used to create new usage spectrum for Australian Black Hawks**
  - Led to maintenance penalty due to increased severity
- **Quantitative program proposed for measuring Black Hawk usage**
- **Usage monitoring research looking at:**
  - Economic effectiveness of usage monitoring - how many components actually reach their rated CRT?
  - Estimation of gross weight from indirect measurements
  - Application of AI techniques to examine problems of identifying flight conditions with minimal information

D/DHP/16/2/43 15 JAN 99

FATIGUE USAGE MONITORING IN UK MILITARY HELICOPTERS

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Abstract

This paper describes the evolution of fatigue monitoring in UK military helicopters. The development of indirect mathematical relationships, to calculate fatigue damage from helicopter Health and Usage Monitoring System (HUMS) sensor data, is also discussed. The paper concludes with the concept of the Fatigue Usage Monitoring System (FUMS) management tool developed under contract from the MoD by MJA Dynamics, Hamble, UK.

Introduction

1. The present method of ensuring the structural safety of UK military helicopters is to ensure that all critical components are withdrawn from use before any predictable failures occurs. Whilst this method has been successful in minimising the number of fatigue failures in service, it is costly and there remains doubt as to its true effectiveness, due to the flexible and unpredictable nature of military helicopter operations. As a result the UK Ministry of Defence (MoD) has the ambition to provide a capability to monitor fatigue consumption of individual aircraft and their critical components. This paper evaluates the progress made to date and the work currently under contract to realise this ambition.

Military Fixed Wing Aircraft Fatigue Monitoring

2. Traditionally, the majority of UK military aircraft types have been designed to safe life principles, in that the target fatigue life of the aircraft is defined and the aircraft should reach this point without the need for significant repairs or inspections.

3. Fatigue life consumption on fixed wing aircraft has been based on fatigue meters and Design Authorities' fatigue formulae. After each sortie, the readings on the face of the fatigue meter are recorded along with other pertinent information such as number of take offs and landings, fuel, and the type of mission the aircraft undertook. This information is then inserted into the Design Authorities' fatigue formula for that aircraft type, and the fatigue consumption for that flight calculated. By accumulating the fatigue consumption after each flight, it is possible to index the fatigue usage against the safe life of the aircraft; zero Fatigue Index (FI) signifies a brand new aircraft off the production line, and 100 FI signifies an aircraft at the end of its original design life.

4. The above procedure sounds very simple and, in essence, effective. However, the procedure is fundamentally dependent on the fatigue meter, which is not really a meter for counting fatigue cycles; it is a counting accelerometer mounted at the aircraft Centre of Gravity (CoG). The Design Authority (DA) has to convert the measured accelerations at the CoG and thereby estimate the stresses in the main structural elements of the airframe. In doing so, many 'engineering judgements' have to be made on the aerodynamic loadings based on how the aircraft is to be flown. To overcome errors in engineering judgement, safety factors are included in the fatigue calculation.

5. The situation described remained the MoD's position until the occurrence of several fatigue related incidents. These may have been avoided if there had been a greater understanding of how fatigue life was being consumed in service. Such an understanding would allow the fatigue formulae to become more accurate and enable the DA to conduct full scale fatigue tests representative of in service airframe loads.

6. To improve on the existing situation, the following three mechanisms were introduced: Operational Loads Measurement (OLM), Statement of Operating Intent and Usage (SOIU) and Fatigue Budgeting.

Operational Loads Measurement

7. Operational Load Measurement requires an aircraft to be fitted with strain gauges so that the structural loads experienced in flight can be measured directly. An OLM is normally undertaken on one or two aircraft per aircraft fleet every three years. The aircraft would be selected as representative of the modification and structural state of the rest of the fleet. The strain gauges are usually attached at locations similar to those of the original full-scale fatigue test. The data from the aircraft is recorded normally over 12 months and it is analysed to assess whether the assumptions made in the fatigue calculations remain valid; i.e., the stresses experienced map the stresses predicted. It also allows the fatigue formulae to be updated. It is important that the OLM aircraft is used in the same manner as the rest of the fleet; otherwise, the analysis will not be representative.

Statement of Operating Intent and Usage

8. The Statement of Operating Intent and Usage (SOIU) is a mechanism through which the MoD can inform the DA on how the MoD is using its aircraft. Aircrew record the fatigue meter readings as well as sortie profile codes, which represent the nature of their last flight; i.e., low-level attack, air combat, high level transit, etc. The codes are used in the fatigue formulae, however, the sortie profile can be logged and analysed separately to establish fleet operating patterns. These are reviewed annually and the SOIU updated. The revised SOIU is then passed to the DA who is tasked with assessing the impact of any changes of usage pattern on the fatigue consumption of the aircraft. Variations in usage pattern usually require the fatigue formulae to be amended.

Fatigue Budgeting

9. For some UK fleets, fatigue budgets/restrictions have been imposed to ensure that airframes can reach their planned out of service date or major overhaul period. The form of restrictions can vary: i.e. maximum number of fatigue units that can be consumed each 1000 flying hours, or tauter restrictions on maximum g rating. Budgeting fatigue is always unpopular with the operator, however, it does provide a means of control and can prevent accidents
through fatigue failure.

10. By adopting these additions, the fixed wing community was able to get a stronger grasp on how fatigue was being consumed by increasing the resolution of the information being obtained from the fatigue meters.

Military Helicopter Fatigue Monitoring - Past and Present

11. UK military helicopters currently have no form of fatigue consumption monitoring device fitted. Like fixed wing aircraft, helicopters have their fatigue lives calculated on assumed usage spectra though usage is based on total flying hours not manoeuvres. Fitting the fatigue meter straight into helicopters would be ineffective as rotary wing fatigue damage is not purely related to symmetric manoeuvres, gust loads and ground air ground cycles. Other factors such as main and tail rotor torque loads, vibratory and controls loads, CoG and pilot handling techniques need to be taken into account. The structural integrity of helicopters is also dependent on fatigue sensitive components in the transmission and rotor system as well as the airframe. The absence of fatigue monitoring devices for helicopters has traditionally been overcome by applying further conservative factors adding financial penalties to the cost of ownership.

12. Until the developments of recent years, there was no cost effective way of measuring loads on individual helicopters. It was considered, therefore, that a better way to control fatigue was to have a greater understanding of helicopter usage. The usage can be balanced against original design assumptions, and a crude estimate of fleet fatigue consumption can be obtained.

13. As for the fixed wing community, a number of procedures were adopted to monitor usage more effectively, namely: Statement of Operating Intent (SOI), Manual Data Recording Exercise (MDRE) and Operational Data Recording Trials (ODRT).

Statement of Operating Intent

14. The rotary wing Statement of Operating Intent (SOI) has effectively the same purpose as the fixed wing SOIU in that it informs on how the MoD uses its aircraft. It indicates the proportion of time spent at various speeds, altitudes and mass along with the normal duration of sorties, the number of landings carried out and the proportion of time spent with under-slung loads. The SOI forms the basis of the calculation of fatigue life in terms of flying hours. In service, should the operator identify that the missions flown are outside the parameters expressed in the SOI, they are reported to the DA for analysis of the effect on fatigue life.

15. Whereas reviewing the fixed wing SOIU can be based on an analysis of actual sortie profile codes, helicopter SOIs are based solely on a review by engineering and air staff in liaison with the operators. Formal reviews are conducted every three years.

Manual Data Recording Exercise

16. If exceptions to the SOI are reported, there will normally be insufficient information for the DA to assess its impact. To obtain more information, a manual data recording exercise (MDRE) is conducted. This requires a member of the aircrew to monitor and record selected flight parameters over a sample range of missions. The effectiveness of MDRE is limited to the accuracy and detail in which the parameters are recorded. Aside from this limitation, the MDREs are a simple and cost effective solution for providing basic information.

Operational Data Recording Trials

17. Operation Data Recording Trials (ODRTs) are the rotary equivalent of the OLMs and at present are the only method the MoD has to determine helicopter flight loads. Normally, one aircraft of the fleet is fitted with strain gauges on selected components, and then the aircraft is flown through typical missions. To ensure that the greatest breadth of operational information is obtained, the aircraft is detached to different units and locations. The results of the ODRTs are analysed by the DA to assess the impact on fatigue life. ODRTs are, however, very expensive to undertake and the strain gauges can be very unreliable when attached to dynamic components. ODRTs have been therefore limited to new types of helicopter or those types where concern on flight loads has been raised.

Helicopter Health and Usage Monitoring Systems (HUMS)

18. The combination of the above techniques provides an assurance on how the MoD helicopter fleets deviate from the original design usage spectrum allowing the fatigue lives to be reassessed. There are, though, significant deficiencies with this approach:

- The techniques review fleet usage and not individual aircraft usage; due to the unique flexibility of helicopter operations there is the possibility that fatigue life safety margins may be exceeded in certain aircraft and not even achieved in others.

- It is difficult to link ODRT data to the manoeuvres being flown, so there is a certain error factor in the analysis of the information that can have adverse effects when forecasting the changes in operational usage.

19. Even if the actual usage remained within the original design spectrum, the generous factors included in the prediction of fatigue life could lead to components being retired prematurely. This increases the cost of ownership and reduces operational availability of aircraft. The components are also designed with significant strength margins to achieve the desired overhaul life under the worst-case flight profile assumptions. This over-strength results in heavier components, which may affect aircraft performance.

20. The next evolutionary process to attain individual helicopter monitoring devices has been the introduction of helicopter Health and Usage Monitoring Systems (HUMS).

21. Helicopter HUMS were initially developed in the early 1980s with a substantial involvement by the Royal Navy in vibration monitoring techniques. Subsequently, the Civil Aviation Authority (CAA) Helicopter Airworthiness Review Panel Report in 1984 recommended the implementation of HUMS to improve the airworthiness of civilian passenger carrying helicopters. Further impetus came from a number of accidents in the North Sea including the crash of a commercial Chinook in 1986. Although the CAA did not mandate the use of HUMS, they have required the fitting of a Cockpit Voice and Flight Data Recorder (CVFDR) to all civilian helicopters of over 2730 kg All Up Mass (AUM).

22. Following a feasibility study, in 1994, the MoD adopted the policy that HUMS would be fitted to all major helicopter types operated by the 3 services. Both flight safety and cost of ownership issues drove this decision. Chinook is currently being embodied with the MoD's Generic Helicopter Health and Usage Monitoring System (GHHUMS), provided by Smiths Industries. This will be followed, in due course, by HUMS for Sea King, Puma and Lynx. Merlin and the WAH-64 will have their own HUMS fitted.

23. HUMS utilises incipient fault symptoms from sensor measurements to initiate maintenance actions. Certain parameters are monitored and any exceedances over an acceptable threshold are reported. This in itself will assist in maintaining aircraft structural integrity through:

- Reducing vibration levels through constant monitoring of rotor systems and allowing preventative maintenance to be taken before vibration levels become damaging. HUMS also eliminates the need for dedicated check flights to track and balance the rotors.

- By monitoring the vibration characteristics of rotating components, i.e., drive shaft, gearbox, etc., it would be possible to detect incipient failures; research has already shown that advanced techniques can detect small cracks in gear teeth before they become critical.

- Damaging events such as over-torque, over-speed and over-stress can be detected automatically and reported to the engineers so that the appropriate corrective action can be taken.

24. HUMS methodology utilises incipient fault symptoms to trigger maintenance actions including component replacement. HUMS is therefore a diagnostic system that infers presence of faults from symptoms. It is applicable to faults that produce measurable symptoms and have low growth rates that provide adequate warning before severe failure. There is a need, therefore, for a prognostic system that provides advanced probabilistic indications of failures, even for faults growing with undetectable symptoms; the system should know how each aircraft is being flown and how much fatigue is being consumed with each flight. HUMS incorporates, however, a sensor fit on MoD helicopters and records flight parameters that can be utilised in a fatigue monitoring system and development work was initiated to exploit this to give MoD helicopters a fatigue monitoring capability.

Helicopter Fatigue Monitoring - Future Considerations

25. Fatigue monitoring systems generally fall within two categories: Flight Condition Recognition (FCR) and Flight Load Monitoring (FLM).

<u>Flight Condition Recognition</u>

26. Flight Condition Recognition (FCR) involves the continual monitoring of flight parameters so that the duration in each flight condition can be placed in a matrix similar to a design usage spectrum. Fatigue damage on components is calculated using safe life techniques, but in this case the actual flight spectrum is used rather than the assumed spectrum. With earlier FCR systems, the matrix was predefined, therefore the systems were initially constrained to recognising predetermined flight conditions. This can be a limitation for military applications when new manoeuvres are performed. Flight outside the matrix envelope cannot always be identified and some intelligence is required by the system to ensure that manoeuvres are placed in the correct area of the matrix. There have also been difficulties in recording All Up Mass (AUM) and Centre of Gravity (CoG) accurately. MoD research using Chinook ODRT data identified that calculating fatigue life on a flight profile basis generally led to a reduced life in comparison with flight load monitoring techniques.

Flight Load Monitoring

27. Flight Load Monitoring (FLM) uses load measurements taken from the aircraft in flight to calculate component fatigue damage. There are two methods in which the loads can be measured: direct and indirect methods.

Direct Method

28. This technique requires data from a large number of strain gauges and load sensors fitted on all critical locations of the aircraft. Maintaining a large number of strain gauges across a fleet of helicopters can be very expensive. The gauges must be accurately bonded and calibrated. Gauge performance needs to be monitored to detect undesirable degradation. The gauges must also be able to provide information on mean and alternating stresses in all weather conditions without loss of accuracy. There is also difficulty in installing gauges to the wide variety of dynamic components that require monitoring as these may need slip rings to transmit signals back to the data-logging unit. Slip rings are sensitive to contamination of oil and grease. In general, the reliability and fatigue life of strain gauges has improved significantly, but typically, a 5% inaccuracy in strain gauge measurement can cause around a 20% error in fatigue damage. Further development is required before strain gauges alone can give a high resolution picture of helicopter fatigue consumption.

29. Another potential device for direct measurement of loads and their subsequent effect on fatigue consumption would be Fatigue Exposure Indicators. FEIs could work as go / no go gauges. A coupon of material would be attached to the component being monitored and would be designed to degrade at a rate that is related to the usage experienced by that component. The coupon would need to show signs of 'distress', probably in the form of a crack, before the safe life of the component was consumed. The coupon, however, would face the same mounting difficulties as strain gauges and must remain secured to the parent structure throughout its life; if it is detached, all information would be lost and the worst case would have to be assumed.

Indirect Method

30. This technique calculates the fatigue consumption of components from normal flight parameters. The calculation software is generally based on a model-based framework, and usually utilises regression analyses, holometrics or neural networks. The main purpose of indirect monitoring systems is to organise and develop useful relationships between the chosen parameters and fatigue, and to identify damaging flight characteristics. In other words, the indirect systems 'weigh' and associate the parameters in such a way that damage to any component can be calculated unambiguously.

31. Indirect techniques can overcome the technical difficulties presented with direct measurement systems. Once development is complete, they could provide a cheaper solution for fatigue monitoring in helicopters. However indirect systems utilise technologies that are widely considered as immature. Mindful of the potential savings that could be achieved against a direct system, the MoD has sponsored research to develop the model-based indirect approach further. The approach has stemmed from mathematical models developed over the last 17 years by MJA Dynamics (MJAD). Reference [1] describes the approach and traces its history. In 1993, the model-based approach was used to evaluate the fatigue damage of structural and rotating helicopter components [2 and 3]. In 1994, the model-based approach evolved into a mathematical network framework as described in [4 and 5]. The mathematical networks establish relationships between loads/fatigue and the data taken from HUMS sensors such as: vibration levels and frequencies; helicopter speed, accelerations, and orientation angles; and main rotor, tail rotor and engine control inputs.

Establishing the indirect relationships

32. The core of each developed indirect relationship is a mathematical network, which provides a framework that allows interactions between Artificial Intelligence (AI) techniques and mathematical formulae [5]. Figure 1 shows a simplified schematic that illustrates the generic function of the network. Each network consists of a number of sub networks that can work in parallel to each other. The networks can check the integrity of parameters and can

correct suspect values through interpolation. Lost or corrupt signals can be also reconstructed from redundant measurements. Noisy signals can be filtered and smoothed.

33. A set of merging functions can be used to combine the input parameters. The functions should be derived from mathematical models or engineering relationships. The time trace of each merging function is divided into a number of time blocks. Each block contains a number of points. For each block, features such as average, standard deviation, etc., can be extracted from the values of the merging function. A set of compressors can be used to compress a large number of features to a smaller number. The compressors can compress the features such that the contribution of the features that relate significantly to the desired output is rewarded and the signal noise attenuated. A set of features can be classified by a module called the state decider. The state decider can also be driven by mathematical or engineering relationships. Alternatively, the state decider can be a network that learns the relevant states from a set of examples.

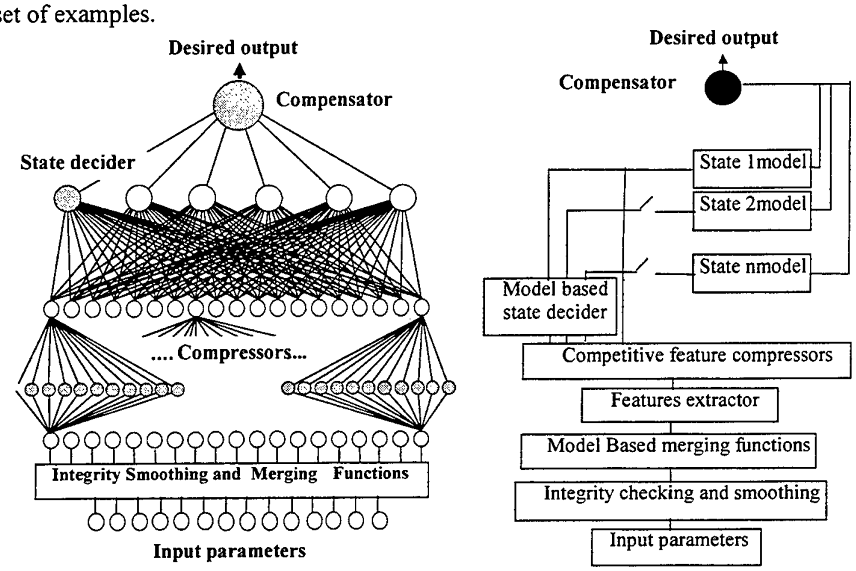


Figure 1

34. Generally, the state decider can learn how to identify states from a set of features through supervised and/or unsupervised learning. The output of the state decider can be used to select an appropriate state model. Each state model can be embedded into a network that receives a set of compressed (and non-compressed) features and delivers an output. The differences between the output values of a state model and the desired values can be mitigated through a module called the compensator. The compensator can be based, for example, on expert rules, statistical processes or engineering relationships. It can be also a separate network. The process of calculating/ assigning the 'weights' of the individual modules (i.e. their significance) of the mathematical network is called training.

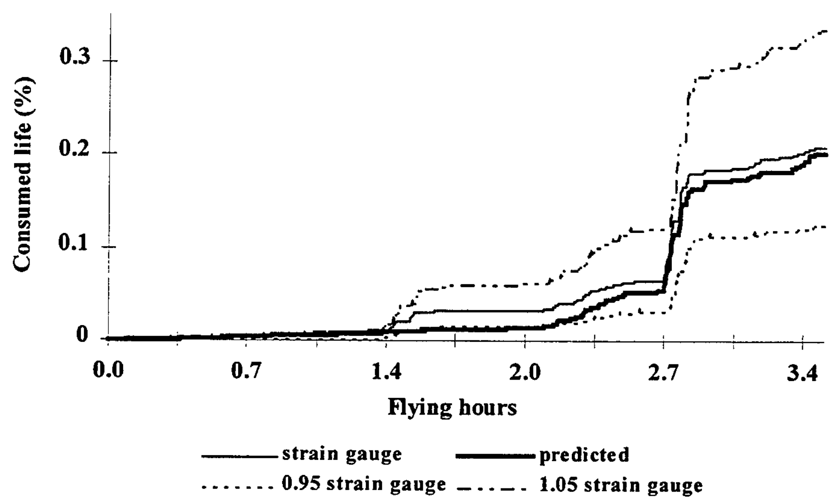
35. To enable the various relationships in the network to be established, it is necessary to have a large quantity of flight data. The cost of supplying actual flight data can be prohibitive so use was made of MJAD's mathematical helicopter simulator, to develop the indirect measurement devices [1]. The mathematical models were configured to simulate a Lynx helicopter (though Sea King and Chinook simulation can be run) and combine: a non-uniform induced velocity induced wake model, detailed non-linear aerodynamic data, flap-lag-torsion aero-elastic models, a fuselage multi-degrees of freedom model, a general helicopter trim algorithm and a suite of fault simulations. The fault simulations include: mass imbalance, pitch link faults, trim tab faults, blade delamination, blade/airframe fractures, moisture absorption, hydraulic damper faults, hinge faults and blade irregularities. The simulated helicopter can perform manoeuvres such as; accelerations, decelerations, bank turns, sideways flights, push-over, pull-up, descent and climb. The model can also be configured to perform complex manoeuvres. The model has been validated regularly against actual flight measurements and its outputs are considered sufficiently accurate to generate synthetic data.

36. The indirect relationships developed to date have involved fatigue of helicopter components, the synthesis of tail and main rotor torque, vibration and fatigue of dynamic helicopter components, All Up Mass and Centre of Gravity.

Fatigue of Helicopter Components

37. Three mathematical networks were taught to predict the fatigue damage of the main rotor blade lug, the pitch link and the main lift frame barrel nut of a Lynx using approximately 10.5 flying hours of data [4]. By considering the HUMS sensor data from another 5.8 flying hours, the networks were blind tested. The network synthesised the fatigue of the three components from the following HUMS sensors: outside air temperature, indicated airspeed, collective lever position, cyclic stick position, lateral stick position, tail rotor pitch angle, normal acceleration, lateral acceleration, roll rate, pitch rate, yaw rate, main rotor rpm, pitch attitude, roll attitude and torque of engines. The successful results of the blind tests demonstrated the potential of the technique and it was concluded that the networks could provide reasonable prediction even if the helicopter role was changed or calibration errors in the data were present: The flight data used to blind test the networks included manoeuvres which had not been seen during the training of the mathematical networks, and the calibration factors of the control stick positions were not available; the control stick positions had been adjusted three times during data gathering. Even under these conditions, the networks' accuracy was found to be better than the accuracy of a strain gauge system with 5% measurement error. A representative results file is shown in Figure 2.

Figure 2 - Blind synthesis of blade lug fatigue from FDR parameters



AUM & CoG

38. Flight envelopes of helicopters depend on parameters such as AUM and CoG. Flying a helicopter outside the permissible ranges of AUM and CoG can cause severe vibration, increase maintenance costs and degrade safety. Since the values of these two parameters vary and cannot be measured during flight, synthesising them by fusing readily available HUMS sensor parameters would be advantageous. A study was conducted to investigate the prediction of AUM and CoG over a wide range of flight conditions for both Sea King and Chinook. Taking the Chinook as an example, the MJAD mathematical model was configured and used to generate a synthetic HUMS database. Variability induced by operational effects was simulated by running the mathematical model at different heights and temperatures. Variability such as equipment inaccuracies, were simulated by randomly contaminating the database with a percentage error to reflect the variability seen in an actual HUMS database. The introduction of random variability contaminated the relationship to an extent where large errors would arise from predictions made by any system.

39. Mathematical networks were developed to output AUM and CofG in hover through to 100kts [6]. The networks implemented processing techniques such as normalisation of velocity and density, and filtering over a number of acquisitions to reduce the level of contamination in the database. A collective prediction technique, which evaluated the mean/median over a number of network predictions, was also implemented. The networks were 'blind tested' using parts of the database not involved in network training.

40. The Chinook operating data manual states that in order to account for torque measurement system inaccuracies, the all up mass for out of ground effect hover should be reduced by approximately 360kg (AUW of

3530N). In hover, the mathematical network predicted AUM to within 355 kg in 83% of cases, with no error in the synthetic AUM greater than 1019kg (AUW of 10000N) in over 200000 data samples. The CofG was predicted to within 25mm in 74% of cases, with an error greater than 100mm in less than 0.5% of cases. At 100kts, the mathematical network predicted AUM to within 355 kg in 94% of cases, with no error in the synthetic AUM greater than 764 kg. The CofG was predicted within 25mm accuracy in 86% of cases, with no error in the synthetic CofG greater than 85mm in over 200000 data samples. A representative results plot is shown in Figure 3.

41. Further work was performed to investigate the effects of reducing the size of the training set. The results of blind testing showed that the size of the database could be significantly reduced with only little reduction in the accuracy of the AUM and CofG prediction. This would significantly reduce the amount of flights required to gather the training data.

42. The general prediction capabilities of the network were very good. The availability of an accurate indication of AUM/CG using standard HUMS sensors would provide invaluable data with which to review and refine MoD helicopter usage assumptions.

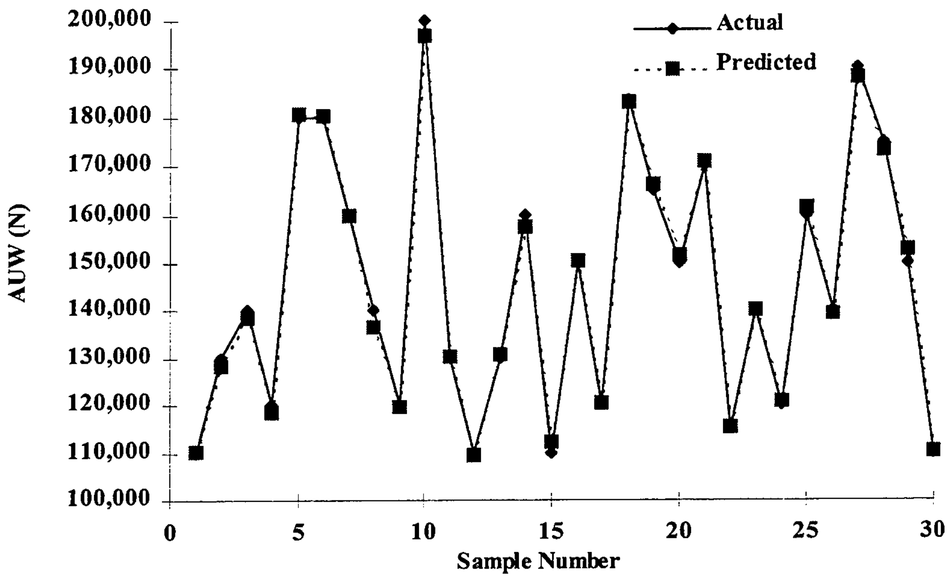


Figure 3 - Blind synthesis of the Chinook AUW

<u>Synthesising Main And Tail Rotor Torque</u>

43. The tail rotor and associated drive shafts are vulnerable components of helicopters. Whilst many tail rotor related incidences have occurred over the years, most helicopters do not have equipment that can provide pilots with a means of observing the tail rotor torque and/or triggering exceedance alarms. On most helicopters, only engine torque meters are fitted. These do not provide correct measures of main rotor and tail rotor torque.

44. Accurate knowledge of main rotor torque can lead to accurate tracking of transmission component fatigues lives and could reduce the maintenance penalties associated with exceedances. Collective pitch angle gauges do not provide adequate information about torque, not only because the accuracy and resolution of these devices, but also because the dependency of the torque on other parameters such as wind speed and cyclic controls.

45. Work was performed to demonstrate that main and tail rotor torque could be synthesised, by mathematical networks, and to assess whether the fatigue damage of transmission systems, and related components, can be evaluated from synthetic torque [7].

46. Over 15 flying hours of data covering a variety of manoeuvres were used to train and blind test the mathematical networks. The data had been acquired from a Lynx Mk 9 helicopter flown by GKN Westland Helicopters Limited (GWHL) over two and a half years. This involved four pilots and different helicopter configurations. Representative results files are shown in Figures 4 and 5.

47. The mathematical networks were constructed and relationships developed that could synthesise main and tail rotor torque adequately at rates of 0.82 and 6.5 samples/second within average errors of less than 2.5% and 5% respectively. At these rates, the quasi-steady (low cycle) torque can be reasonably portrayed. The networks synthesised successfully main and tail rotor torque for manoeuvres that were not seen by the network during training. This investigation suggested that an FDR-based measuring device could have been more durable than a strain-gauge device. For four flights, the mathematical networks indicated zero tail rotor torque at zero rpm, and the strain-gauge device indicated about 1800 lb ins. The mathematical networks could operate on a subset of FDR parameters, and could cope with calibration problems. The AUM and fuel consumption would not be required for torque prediction. This would eliminate any additional requirements for a means of announcing crew, stores and/or weapons upload and download.

48. Mathematical networks were designed, and validated, for helicopters lacking engine torque devices. Excluding the engine torque did not influence the synthetic tail rotor torque significantly, and the average error in synthetic main rotor torque was about 4 to 8%. Information such as maximum torque between torque samples and intensity of 1/rev and 4/rev cycles would be required for general structural integrity purposes. The compensator and state decider of the mathematical networks could infer such information from HUMS sensors and quasi-steady torque values. The low cycle fatigue calculated from synthetic main rotor torque was in excellent agreement with the low cycle fatigue calculated from measured torque. The error in fatigue usage of flights covering a period of two and a half years was 2.54%.

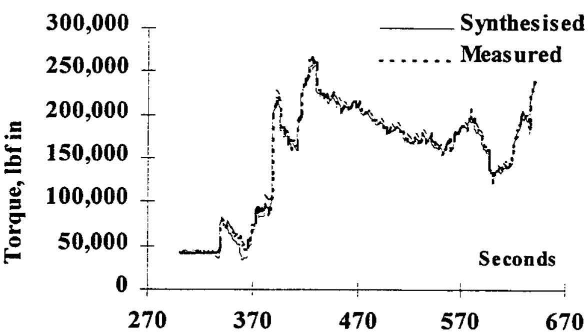


Figure 4 - Blind synthesis of main rotor torque

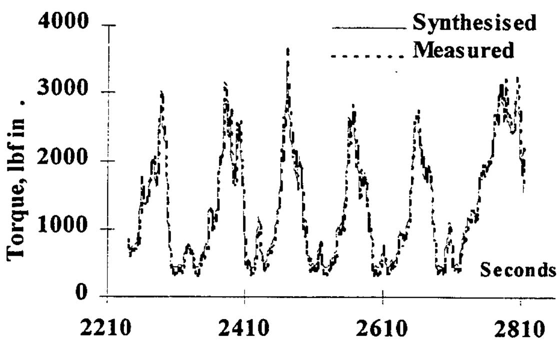


Figure 5 - Blind synthesis of tail rotor torque 1.5 years after training

<u>Establishing Relationships Between Vibration And Fatigue Damage</u>

49. The aim of this work was to establish the relationships between vibrations, loads and High Cycle Fatigue/Low Cycle Fatigue (HCF/LCF) damage [8].

50. To enable the loads generated from the MJAD mathematical helicopter simulator to be transformed into stresses, a Finite Element (FE) model was generated by the company. As the aim of the investigation was to establish the relationships between faults, vibration, loads and fatigue it was not necessary for the FE model to replicate the helicopter entirely provided that the outputs qualitatively represent the actual relationships. The FE model withstood static testing to 4g vertical loading and re-produced the natural frequencies of a full scale Lynx (fundamental/first bending and torsion modes.) For example, the FE model reproduced the frequencies of the fundamental bending modes and the first torsion mode within 0.85Hz of the actual values [9].

51. A suite of synthetic flights was generated for a range of steady flights and manoeuvres. The same suite of flights was then flown with induced faults such as mass imbalances and tab errors [10]. The FE model was used to transfer the hub loads from each of the synthetic flights into load traces. Two transfer methods were considered: a direct method and a frequency response method.

52. In the direct method, the mathematical model was used to produce six load traces at the rotor hub: three forces and three moments. Using these hub loads as inputs to the FEM, and performing transient analysis, the stress traces at a required location were evaluated. Whilst this direct method is relatively straightforward, the

computational costs are very high. Nevertheless, the direct method is a powerful recommended method for generating stress traces during complex manoeuvres.

53. In the frequency response method, the MJAD Lynx mathematical simulation produced the hub loads produced during a series of steady and manoeuvring flights. Both healthy and faulty Lynx helicopters were considered. The hub loads were transferred to stress time traces by the FEM using frequency response analysis. The stress traces were scaled up/down to known values close to measured values, assuming a linear relationship between stress (load) and strain. Strain time traces were produced to evaluate the relationships. It was found that 4R and 8R (where R = main rotor frequency) strain occurred in all cases. The amplitude of the 4R and 8R strain appear to remain approximately constant irrespective of pitch-link error. 1R strain is produced, which increases approximately linearly with increasing error. The mean strain remains approximately constant irrespective of error, but is influenced significantly by the aircraft manoeuvre.

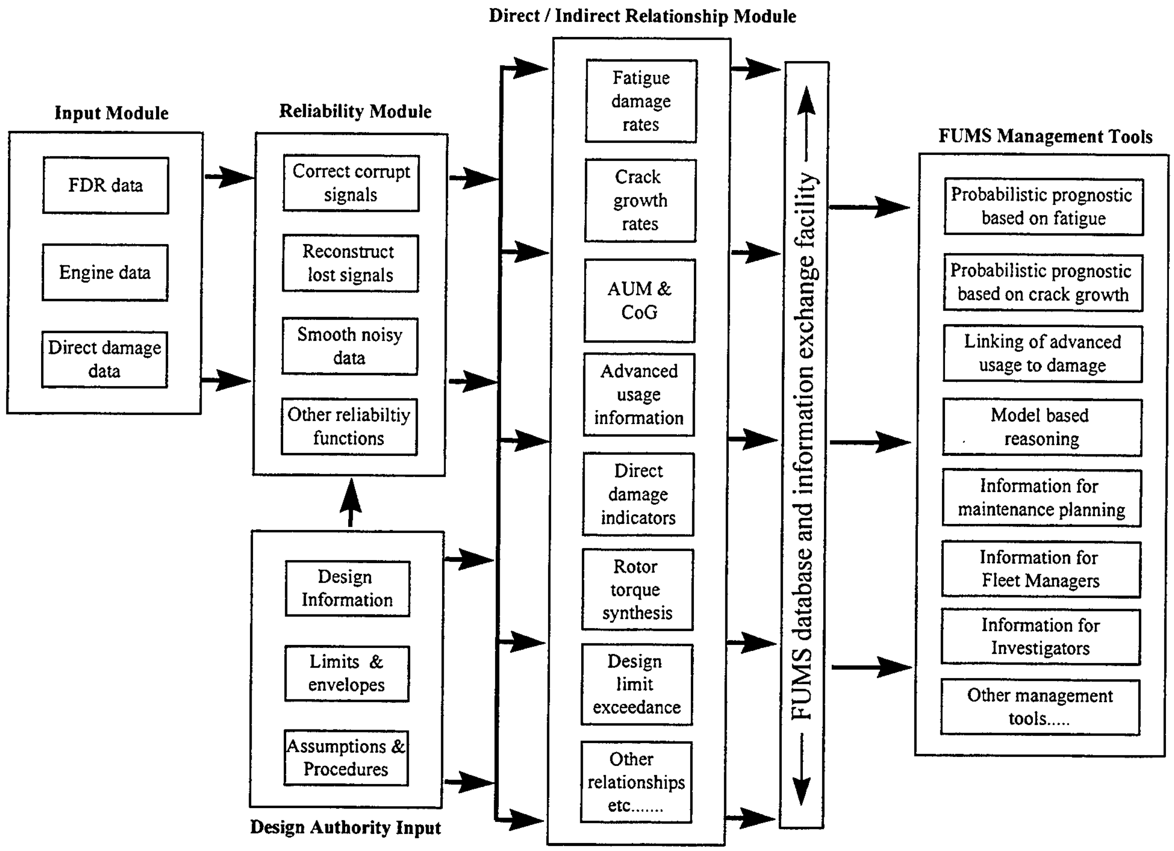
54. This work is due to be completed very soon though early indications suggests a reasonable accuracy within the majority of the flight envelope.

55. Deriving the individual relationships has provided a significant advancement in the maturity of indirect techniques. Each on its own could be made into a device that could make vast improvements to helicopter airworthiness. It was recognised early in their development however that to reap the maximum benefit of each they would need to be combined into an all encompassing monitoring system.

The Fatigue Usage and Monitoring System

56. The Fatigue and Usage Monitoring System (FUMS), as developed for the MoD by MJAD, is defined as "an advanced data management system that uses design limits and information specified by the DA and processes large volume of data in real time to extract structural integrity information including fatigue damage, loads, and usage." This information is then presented to the operators, maintainers, and engineering staff for fleet management purposes. The definition of FUMS includes the word management to signify this important requirement. The major components that make up the MJAD system are shown in Figure 6.

Figure 6 - The MJA Dynamics FUMS Model-Based Management Approach



57. FUMS can be thought of as a system that integrates a set of mathematical networks, which extract information from HUMS sensors, with traditional FDR parameters and produce understandable information on fatigue. FUMS evaluates damage, loads and usage, and perform probabilistic prognostics to address the questions of what, when and why. In order to provide robust prognostic information to maintenance planners and fleet managers, the reliability module of FUMS checks the system sensor measurements before processing them. FUMS, if required, corrects corrupt data and/or reconstructs lost signals.

58. In order to demonstrate the capability of the FUMS management system, further work has been contracted with MJAD. This work is based on three objectives:

- Demonstration of the feasibility of advanced usage monitoring software to link the usage to loads and damage and produce usage information for operation and maintenance planning.
- Demonstration of the compliance of FUMS with design limits and procedures specified by the DA by achieving high reliability of computed fatigue and usage.
- Demonstration of the feasibility of a FUMS management strategy to reduce airworthiness risk, increase availability, improve supportability and reduce costs of ownership of helicopter fleets by computing fatigue and usage information that can be linked to damage.

59. To achieve the first objective the mathematical models would be developed into an advanced usage software package incorporating the techniques required for improved accuracy and the artificial intelligence techniques to link the usage information to fatigue and damage. The software will generate uncalibrated fatigue damage indices solely from HUMS sensors and mathematical models. In-service data will be used to demonstrate the ability of the software to produce advanced usage information. The advanced usage software will be evaluated

through demonstrations to the MoD and the DA; and by using the feedback from them the final configuration of the software package will be refined.

60. The second objective will be achieved by assessing and evaluating the components of FUMS for accuracy and reliability and refining them if necessary. The critical evaluation of the FUMS models will require collection and analysis of DA fatigue substantiation information. A sensitivity analysis will be performed of the FUMS based models to inaccuracies of FDR parameters. The assessment will require the indirect computation of fatigue usage using inaccurate FDR parameters. Following the analyses, FUMS will be optimised to prevent system failures that impair airworthiness compliance.

61. To supplement the MJAD critical evaluation, an independent evaluation will be undertaken by the UK's Naval Aircraft Materials Laboratory of Gosport, Hampshire. NAML will be equipped with a PC platform including the software and mathematical models at the start of the project; and the FUMS evaluation software will be supplied to NAML during the life cycle of the project.

62. The third objective will be achieved by analysing a large volume of flight data and computing the fatigue and advanced usage information that can be linked to damage. Liaison processes will be established between the company and the Design and Support Authorities. In this way the current procedures for scheduling helicopter maintenance and critical component retirement will be scrutinised by MJAD, and current MoD Information Technology (IT) systems will be audited. The objectives of the audit would be: to identify the lessons learnt, to find the causes of any end-user difficulties, and to develop management strategy compatible with these IT systems. The FUMS software will concentrate on the demonstration of how the FUMS management strategy can reduce airworthiness risks, increase availability, improve supportability and reduce costs of ownership of military helicopter fleets.

63. Effectively, by the end of the current contract (Autumn 2000) the MoD plans to have a set of tools by which the FUMS technology can be demonstrated in service and fatigue consumption of individual aircraft can be monitored alongside current procedures.

64. The FUMS management system described is not limited to monitoring fatigue consumption in helicopters, the philosophy is also being considered for future fixed wing aircraft to replace the fatigue meter and fleet engine condition monitoring. The relationships in sub-networks may be different for other applications but the overall approach will be the same.

Conclusions

65. The work undertaken to date has helped to mature indirect monitoring system technology within the MoD. From the results so far presented, the MoD has been reassured that indirect measurement systems can provide accurate information for fatigue monitoring, which could be underwritten by the DA.

66. FUMS will never be completely based on indirect model relationships as there will always need to be verification between direct and indirect measurement devices either between fleets or individual aircraft. FUMS will not do away with the requirement for Operational Data Recording Trials (ODRTs) rather the information obtained from them will complement the information generated by FUMS and allow a degree of validation.

67. The MJAD FUMS technology is applicable not only to flight data from the FDR devices utilised in the MoD's Generic Helicopter HUMS (GHHUMS), but also to flight data from any appropriate FDR device. The MJAD system will be designed for the MoD with an open architecture approach: for example, further capabilities can be added and the outputs of modules developed by other companies could be brought into the FUMS management system. The MoD has progressed down the path of indirect measurement devices to overcome technical difficulties with installing strain gauges on dynamics components on helicopters. Commercial FCR devices have not been the focus of recent MoD attention due to limitations in the recognising military manoeuvres and flight conditions within the usage matrices. This is not to say that the MoD has discounted FCR devices, these have also improved significantly in the last 5 years. As the MoD prepares its staff requirements and undertakes its feasibility study for a helicopter fatigue monitoring system, the technical advantages of FCR based devices will be assessed objectively against FUMS and against direct measurement systems. The MoD is always committed to ensure that the most effective equipment is procured to satisfactorily fulfil its requirements.

68. The MoD is currently installing HUMS to its helicopters and the current programme gives a little breathing space for the development tasks for FUMS to be completed and then promoted. As HUMS data becomes available, the FUMS models will be able to run with more data sets to provide even greater confidence.

69. HUMS will never be able to undertake the full fatigue monitoring as HUMS utilises incipient fault symptoms to initiate maintenance action and is therefore a diagnostic system that infers presence of faults from symptoms. It is applicable to faults that produce measurable symptoms and have low growth rates that provide adequate warning before severe failure. FUMS is a prognostic system that provide advanced probabilistic indications of failures. Unlike HUMS, FUMS can cope with faults growing under a low usage rates with undetectable symptoms. HUMS and FUMS will always complement each other.

70. It is intended that FUMS will use the sensors provided with the MoD HUMS fit, however, the fatigue monitoring system finally procured may not be proprietary to any HUMS manufacturer. As with all MoD procurements, competition will be encouraged. Work on the MJAD FUMS to date has developed a technology new to the MoD helicopter community and has introduced more intelligent capabilities. The success of the HUMS programme will trigger the important funding required for the fleet implementation of FUMS. After over 50 years of UK military helicopter service, the capability to establish the fatigue consumption in individual MoD helicopters will be close to realisation.

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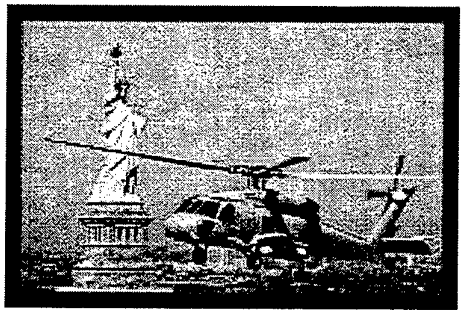
Aerostructures, Inc.



Helicopter Usage Monitoring Using the MaxLife System

DSTO Helicopter HUMS Workshop -- February 1999

Agenda

- Overview of Aerostructures
- Specialized Usage Monitoring Expertise
- AH-1W Usage Monitoring Results
- MaxLife System and Programs

AeroStructures, Inc.

David White - 1

Company History

- Founded in 1982 in Arlington, VA
- Analyze & assess USN aircraft structures
  - Fixed wing
  - Rotary wing

AeroStructures, Inc.

Capabilities

- All aircraft structural disciplines
- Alternative to aircraft primes
  - Independent
  - Competent
- Rapid response to customer needs

AeroStructures, Inc.

David White - 2

Aerostructures Organization

- Aerostructures, Inc. - Arlington, VA
  - NAVAIR - Patuxent River, MD
  - NADEPs - North Island, CA & Jacksonville FL
  - MCASs - Camp Pendleton, CA & New River, NC
  - AMCOM - Huntsville, AL
- Aerostructures Australia - South Melbourne
- Aerostructures Technologies - Port Melbourne

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USN Aircraft Structural Life Monitoring

- ~ 45 aircraft models
- ~ 5000 fixed and rotary wing A/C
- Combinations of methods
  - Flight hours
  - Counting accelerometers
  - Landings (carrier opns)
  - Number of flights
  - Multi-channel recorders
  - Strain Gages
- Helicopter flight regime recognition

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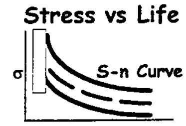
Component Design Fatigue Life Determination

- Design life objective: Protect safety.

Design flight spectrum
- Flight regimes
- % Time in regimes

Cyclic load & stress for each flight regime

Stress vs Life



- Assumes severe usage
- Very conservative

- Determined by flight test
- Conservative (?)

- Mean minus 3σ
- Very conservative

- Results: Premature retirement of safe parts.

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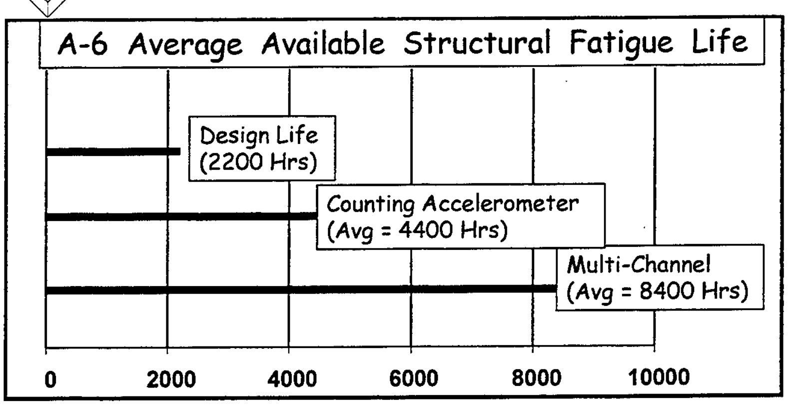
Improved Tracking Increases Usage
(Fixed Wing Example)



Fatigue Life - Flight Hours

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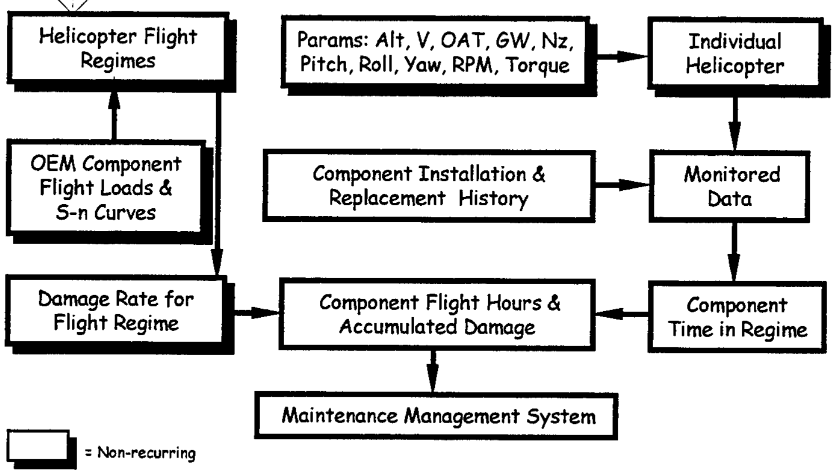
Helicopter Component Fatigue Life Monitoring



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AH-1W Flight Regimes

Over 1000 Flight Regimes

Start	3	Gunnery Run Dive	24
Takeoff	9	Ascent	51
Hover	9	Descent	63
Forward Flight	24	Acceleration	9
Sideward Flight	6	Deceleration	9
Rearward Flight	3	Autorotation	21
Sideslip	6	Recovery/Transition	24
Slow Speed Maneuver	12	Control Reversal	18
Climb	6	Quick Stop	9
Climbing Turn	72	Pitch Back Attack	3
Turn	408	Yo-Yo	6
Pullup	216	Landing	9
Pushover	9	Normal Shutdown	3

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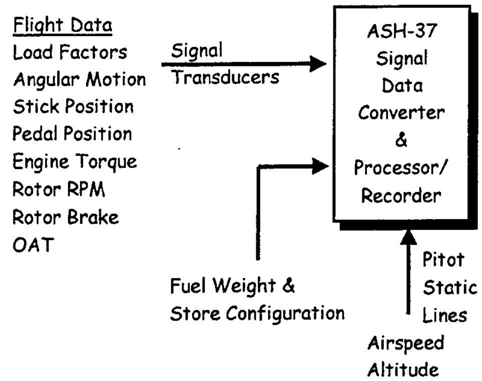
AH-1W Monitored Parameters



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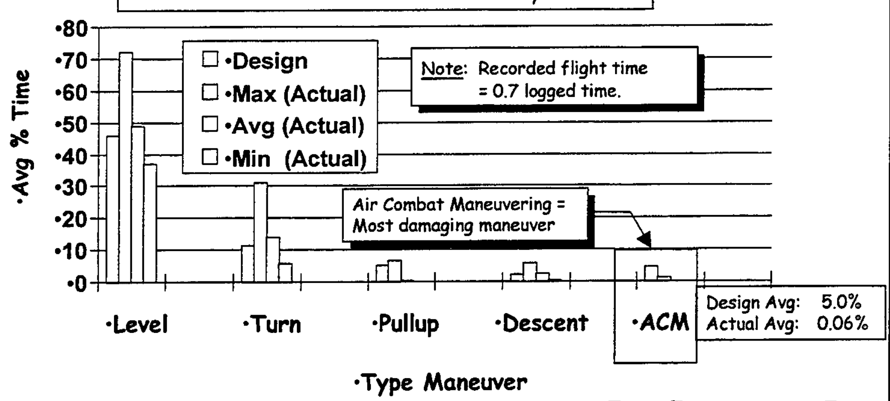
Variability in AH-1W Maneuvers

Based Upon Monitored Data

- 31 AH-1W aircraft in 6 squadrons
- >3300 hours data over 2 - 3 years



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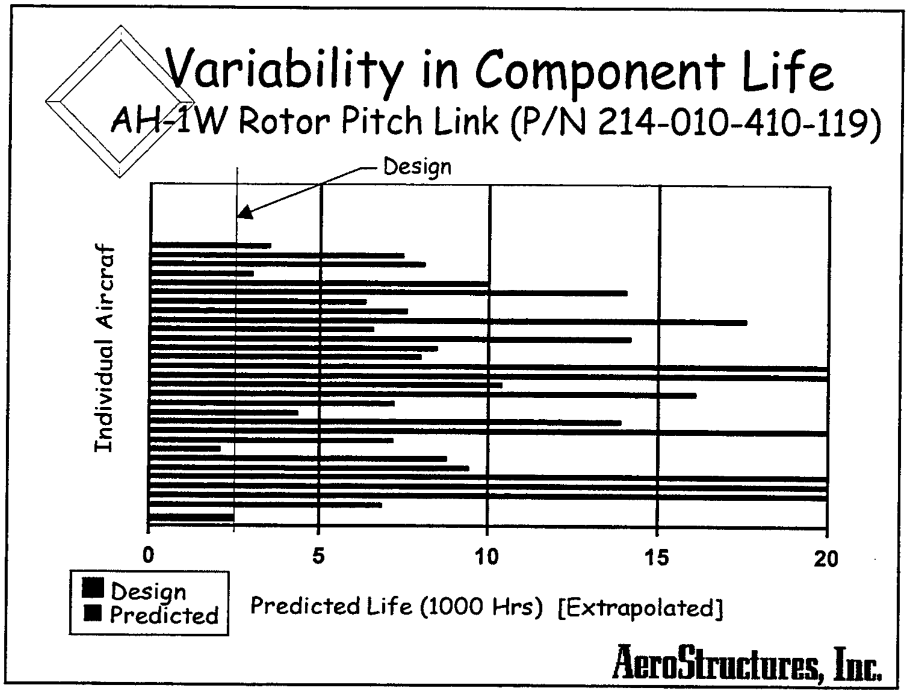

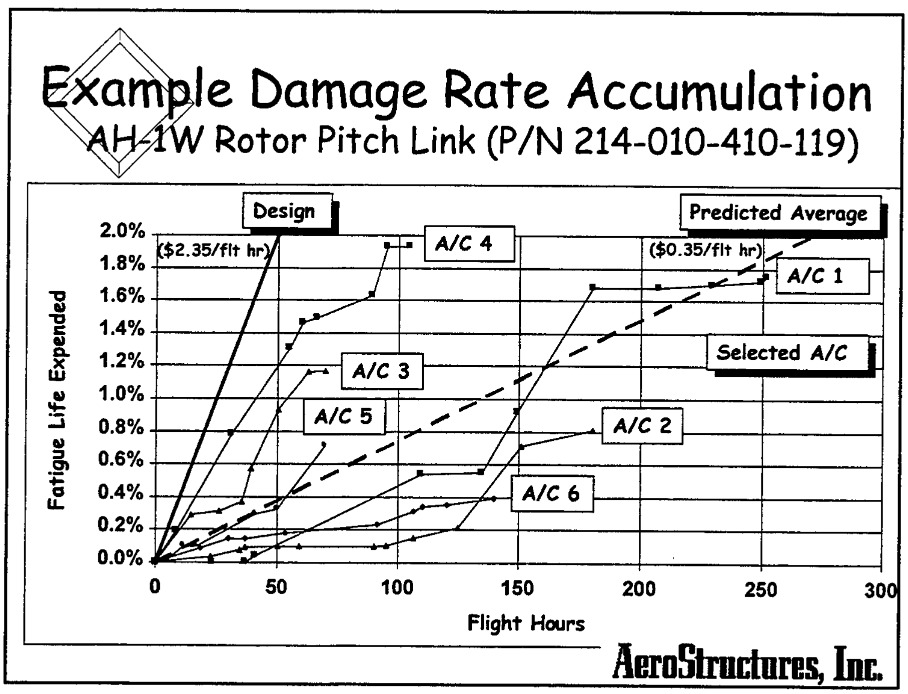

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Component Life Limits & Unit Cost

Average aircraft damage extrapolated to predict fatigue life

Removal & installation costs not included

Examples

REF	PARTS (Per S/S)	COST	Flight Hours DESIGN	Flight Hours PREDICT	PRED/DSN	Δ $/FLT HR
01	Yoke Assembly	$31280	2500	8350	3.3	$10.47
03	Spindle (2)	33400	4400	20000	4.5	5.92
05	Grip Assembly (2)	22960	4400	20000	4.5	4.07
06	Retention Strap (2)	7280	1250	1210	0.97	[0.19]
13	Main Rotor Blade (2)	161860	4400	9200	2.1	19.31
30	M/R Pitch Link Assembly (2)	5880	2500	16700	6.7	2.00
56	90° Gearbox Housing	10750	1400	6640	4.7	6.06
67	Wing, Left	31250	1500	6230	4.1	15.82
68	Wing, Right	31250	1500	20000	13.3	19.27
78	M/R Drag Brace	13690	1210	20000	16.5	10.63

Total (73 Part No's): $175.37

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Benefits Summary

- Monitoring component usage --
  - Reduces Operating & Support Cost
  - Enhances Safety
- Technical approach has been validated
  - USMC AH-1W
  - Benefit studies: H-60, H-46, H-2, H-53, H-64, H-65
- Opportunity to optimize monitoring approach
  - Simplify data acquisition
  - Streamline program implementation

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Monitoring Approach: Lessons Learned I

- Monitor only necessary parameters
- Ensure conservatism; not accuracy/precision
  - Calculate or finesse hard-to-acquire parameters
  - Require no action by aircraft crew
- Facilitate Implementation
  - Interface with automated maintenance systems
    - USCG Aviation Computerized Maintenance System (ACMS)
    - ADF Computer Aided Maintenance Management (CAMM)

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Required Helicopter Parameters

- Airspeed
- Altitude
- Rate of climb
- Outside air temp.
- Engine torque
- Main rotor speed
- Gross weight
- Vertical acceleration
- Yaw velocity
- Pitch angle
- Roll angle
- Weight on/off wheels

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Aerostructures Usage Monitoring Development Programs

- US Army Digital Source Collector (DSC) Program
  - UH-60 structural usage monitoring demonstration
- JAHUMS ACTD Module (SH-60 & CH-47)
  - Structural usage monitoring via flight regime recognition

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Helicopter Structural Usage Monitoring Data Sources

- Structural usage data sources --
  - Existing onboard systems -- [Army DSC]
    - Voice and Data Recorder Systems (VADR)
    - Night Vision HUD
    - Data bus
  - Health and Usage Monitoring Systems [JAHUMS]
  - Flight Data Recorders (FDR) [ARA]
  - Dedicated structural data monitoring systems
    - ASH-37 Structural Data Recorder Set (SDRS) [AH-1W]
    - New, reliable, low-cost system (MaxLife) [USN/USCG]

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MaxLife System Objectives

- Dedicated onboard usage monitoring system should be --
  - Affordable
  - Reliable
  - Transparent to crew
  - Light weight
  - Non-intrusive
  - No increase in workload

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Aerostructures MaxLife

- Non-developmental item (NDI) data acquisition system
  - Developed by Altair Avionics for Aerostructures
  - Derivative of FAA certified data acquisition system
  - Commercial-off-the-shelf (COTS)
  - Low-cost, light-weight, reliable system
  - Non-intrusive installation (installed in 8-hr shift)
  - Transparent to flight and maintenance crews
  - Complete logistics and maintenance support

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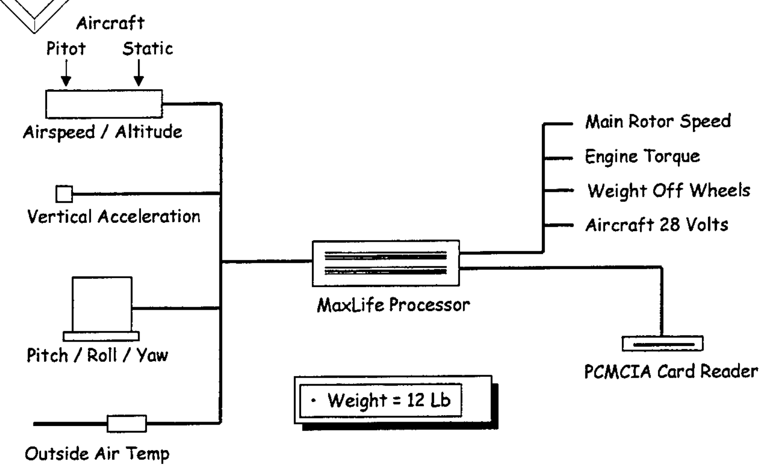
Aerostructures MaxLife System



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MaxLife Monitoring Programs

- ARA S-70A Flight Test Validation at ARDU
- NAVAIR H-60 Design Usage Spectrum Update
  - Monitor 6 HH-60Hs & 4 SH-60Fs for 6 months to update design usage spectrum
- NAVICP Helicopter Extended Life Program
  - Monitor 2 SH-60Bs for 4 months to demonstrate benefits
- USCG HH-60J Usage Monitoring Demonstration
  - Monitor 4 HH-60Js for 4 months to demonstrate benefits

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Implementation Challenges: Lessons Learned II

- Ceramic gyros can be sensitive to temperature drift
- Aircraft power interrupt can corrupt memory data cards
- Installation schedules can be influenced by the operator

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Summary

- MaxLife monitors helicopter usage -
  - Currently in HH-60H, SH-60F, SH-60B and HH-60J
  - Is meeting all design objectives
  - Is available to monitor helicopter usage
  - Will produce immediate cost and safety benefits

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SH-60 Helicopter Integrated Diagnostic System (HIDS) Program Experience and Results of Seeded Fault Testing

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Propulsion and Power Dept.
Patuxent River, Md.

The evolution of automated diagnostic systems for helicopter mechanical systems has been aided by a Navy program of systematic testing of drive train components having known anomalies (seeded faults) while simultaneously executing a suite of diagnostic techniques to identify and classify the mechanical anomalies. This program, called the Helicopter Integrated Diagnostic System (HIDS) has been carried out using an iron bird test stand (SH-60) at NAWC - Trenton, and SH-60B/F flight vehicles at NAWC - Patuxent River. The SH-60 HIDS program has been the Navy's cornerstone effort to develop, demonstrate, and justify integrated mechanical diagnostic system capabilities for its helicopter fleets. The objectives of the program were to:

1. Acquire raw data for multiple cases of "good" and seeded fault mechanical components on a fully instrumented drive train to support the evaluation of diagnostic algorithms and fault isolation matrices. Data is being acquired from 32 vibration channels simultaneously at 100 kHz per channel while a continuous usage monitoring system records parametric steady state data from the power plant and airframe.
2. Analyze vibration and other diagnostic indicators to evaluate sensitivity and performance of all available diagnostic methods when analyzing well-documented parts. Evaluate relative effectiveness of these various diagnostic methods, indicators, and their associated algorithms to identify and optimize sensor location com binations.
3. Demonstrate the ability to integrate and automate the data acquisition, diagnostic, fault evaluation and communication processes in a flightworthy system.
4. Integrate and evaluate comprehensive engine monitoring, gearbox and drivetrain vibration diagnostics, advanced oil debris monitoring, inflight rotor track and balance, parts life usage tracking, automated flight regime recognition, power assurance checks and trending, and automated maintenance forecasting in a well-coordinated on-board and ground-based system.
5. Provide an extensive library of high quality vibration data on baseline and seeded fault components. This data can be made available to anyone wanting to prove their diagnostic techniques or develop new capability.
6. Provide a "showcase", state-of-the-art, fully functional Integrated Mechanical Diagnostic system to act as a catalyst demonstration which might lead to interest in a fleet wide production application.

This paper will describe the overall program, the goals and objectives, the facilities used, the system evalu ated, the accomplishments and the results and conclusions obtained to date. The results of extensive gearbo and powertrain "seeded fault" testing will be presented. Lessons learned which can be applied to future Heli copter Usage Monitoring Systems (HUMS) and/or Integrated Mechanical Diagnostic (IMD) systems will also be discussed.

Introduction

Background

The U. S. Navy and U. S. Marine Corps have long had a requirement to improve several aspects of their rotary wing operations in order to improve readiness through more effective maintenance, eliminate losses of aircraft and personnel, and dramatically reduce maintenance related costs. The requirements to extend the service life of aircraft and the limitations on manpower have increased the urgency of affecting these types of improvements. A majority of the Class A mishaps (loss of aircraft and/or personnel) in Navy helicopters are caused by engine and drive train failures (Ref. 1). The need to accurately identify and diagnose developing faults in mechanical systems is central to the ability to reduce mechanically induced failures and excessive maintenance. The Navy has successfully developed and deployed fixed wing engine monitoring systems, notably on the A-7E and subsequent fighter/attack aircraft. These fixed wing Engine Monitoring Systems (EMS) have impacted flight safety, aircraft availability, and maintenance effectiveness. The Navy also successfully demonstrated a promising automatic mechanical fault diagnostic capability on its gearbox overhaul test stands in Pensacola, Florida.

The U.S. Navy would clearly benefit from a reliable state-of-the-art diagnostic capability on-board rotary wing aircraft. Based upon the Mission Need Statement (Ref. 1), such a system is expected to enhance operational safety and significantly reduce life cycle cost through it's ability to predict impending failure of both structural and dynamic drive system components and consequently direct on-condition maintenance actions and/or alert the pilot to conditions affecting flight safety.

There is currently considerable activity underway to develop integrated health and usage monitoring systems particularly for helicopter subsystems (transmissions, rotor head, engines, tail drive systems, etc.). A major challenge is acquiring and managing large quantities of data to assess the health and usage of the aircraft system.

A significant disadvantage of first generation commercial systems in 1992 was the lack of raw data acquired to validate and optimize the full, Integrated Mechanical Diagnostic (IMD) functionality. Such is a necessary component of any development effort in order to lend confidence to the users, that the system will reliably indicate mechanical and rotor system faults, avoid false alarms, and develop structural and mechanical system usage routines. These are the keys to preparing an IMD system for deployment.

Present Work

The Naval Air Warfare Center Aircraft Division is currently leading a comprehensive program as authorized (Ref. 2) to evaluate diagnostic technologies. The SH-60 was selected as the test vehicle because it offered the best availability of test assets and the highest potential for support because of the large fleet of aircraft among the Navy, Army and Coast Guard. The program designated Helicopter Integrated Diagnostic System (HIDS) uses state-of-the-art data acquisition, raw data storage, and algorithmic analysis provided under contract by Technology Integration Inc. [TII - now part of BFGoodrich Aerospace (BFG)] to evaluate the propulsion and power, rotor, and structural systems. Cockpit instruments and control positions are recorded during the entire flight for usage monitoring and flight analysis. Rotor track and balance is performed via the trackerless ROTABS system. Analyzing vibration signals acquired from a comprehensive suite of accelerometers assesses dynamic component health.

The program reported herein is structured to evaluate two functionally equivalent TII/BFG systems at the following test sites:

1. Flight Testing at NAVAIRWARCENACDIVPAX (Naval Air Warfare Center, Patuxent River, Maryland): Demonstrate the integration of a comprehensive integrated diagnostic system which performs rotor track and balance, mechanical and rotor system diagnostics, and dynamic and structural component usage monitoring. Evaluate the operability of the demonstration system and provide a foundation for the user interface requirements functional specification for fleet procurement. In addition, evaluate a real time engine performance estimation algorithm provided by General Electric Aircraft Engines in cooperation with Dr. Peter Frith of the Australian Mechanical Research Laboratory (AMRL) via implementation onboard the HIDS flight test aircraft.

2. Ground Testing at NAVAIRWARCENACDIV-TRENTON (Naval Air Warfare Center, Trenton, NJ): Conduct fault detection validation testing in a unique universal full scale Helicopter Transmission Test Facility (HTTF) which currently consists of the entire SH-60 power drive system (engines, transmission and tail drive system). Evaluate and validate the TII/BFG system and associated algorithms to detect seeded faults while building a base of raw data for evaluating other fault detection methods. In addition, the program is evaluating other advanced technologies in parallel with the TII system. The information generated from this testing will form a body of knowledge from which specifications can be written to procure effective production versions of the integrated diagnostic system.

The purpose of this paper is to describe the overall program, the diagnostic system, the NAVAIR-WARCENACDIVTRENTON test cell, the seeded fault testing, flight testing and major accomplishments to date.

Description

This section will describe the systems and facilities that are being used in support of HIDS. The test articles are the diagnostic technologies. The SH-60 test facilities are being utilized to exercise these diagnostic technologies.

HIDS Diagnostic System

In 1993, the NAVAIRWARCENACDIV awarded a competitive contract on the Broad Agency Announcement to TII for two functionally equivalent integrated diagnostic systems. (TII elected to make a substantial investment in the program through providing Commercial Off the Shelf (COTS) hardware and software.) One system was configured for rack mounting in the Trenton, NJ test cell and the other is flyable ruggedized commercial grade hardware. The TII system uses an industry-standard open architecture to facilitate modularity and insertion of new hardware and software. TII has divided the system into two main avionics units, the commercial off-the-shelf KT-1 aircraft parameter-usage monitor and the KT-3 vibration acquisition, analysis and rotor track and balance system. System architecture and data flow is shown in Figure 1. Though not a production type unit, the KT-3 is essential to acquire the raw data necessary to substantiate the diagnostics technology and obtain enough knowledge to write the minimum acceptable production specification.

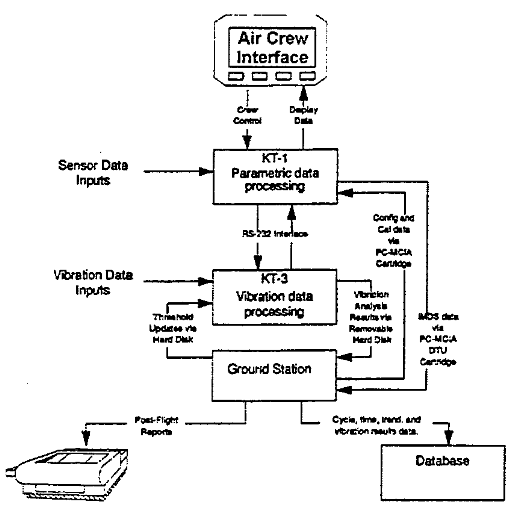

Fig. 1. Diagnostic System Architecture.

Structural Usage Monitor (KT-1): The TII/BFG system performs aircraft usage monitoring, engine condition monitoring, drive shaft condition monitoring, gearbox condition monitoring, chip detector monitoring and rotor track and balance. The first generation system (Aircraft 326) acquired aircraft and engine parameters during flight at a rate of three hertz, and the second generation system (Aircraft 804) at 10 hz. Averaged data is stored to a PCMCIA card at one hertz. If parameters (temperatures, pressures, speeds, pilot stick reversals, load rates, etc.) go into exceedance, all data acquired at the high data rate with a 15 second preview and 15 second post-view of the event is stored. This data provides the usage spectrum of the aircraft, engine performance information, and the flight regimes for trending gearbox vibration information and an actual record of the mission, and is available for post-processing for re-calculation of regime recognition and structural usage routines. The past 150 exceedance events are stored in non-volatile ram in the case of data card damage or loss. The list of parameters recorded includes those sanctioned by Navy structures competency for use to execute structural usage monitoring.

Engine Performance: The HIDS Cockpit Display Unit (CDU) depicted in Figure 2 interfaces with the pilot to execute and display results of automated NATOPS T700 engine health checks and Engine Power Performance Index (PPI) which are accomplished by the KT-1. A fourth order quadratic, the PPI is a best fit curve representing an engine degraded 7.5% from the specification line. The PPI output is a value in degrees C calculated from the 7.5% degraded line. This provides significant improvement by automating the acquisition and collecting hundreds of points per flight versus one or two. It can provide a warning to the pilot when an engine has degraded due to salt ingestion, sand erosion or other foreign object damage (FOD).

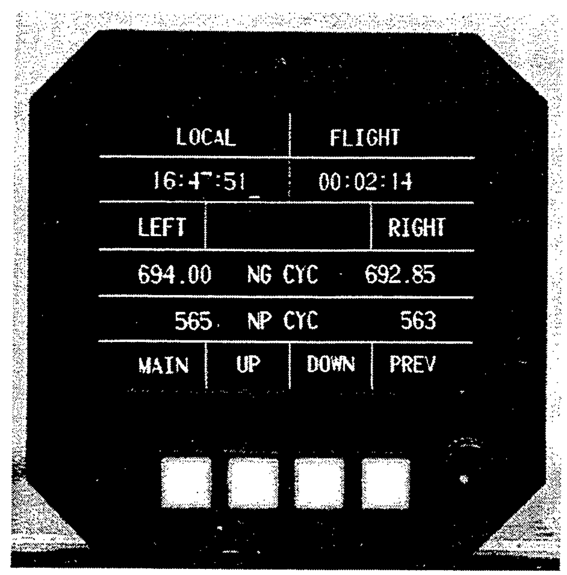

Fig. 2. Central Display Unit.

Vibration Based Mechanical Diagnostics: The focal point of this program was to explore a wide variety of diagnostic methods based upon vibration inputs, in a manner that would lead to a rational selection of reliable "production" techniques with a high confidence in accurate detections with low false alarm rates. Vibration data recorded at both Trenton, NJ and Patuxent River, MD uses the same acquisition system, sensors, mounting and accelerometer locations. The data sets are digital time series records, recorded simultaneously for up to 32 channels (accelerometers and tachometers), at 100,000 samples per second, 0-50Khz bandwidth, for 30 seconds. This proof-of-concept system records five sets of raw data per flight for post flight data analysis in the ground station. Drive system accelerometer locations are shown in Figure 3 for the input and main modules and Figure 4 for the tail section. The mechanical diagnostic system algorithms provided by TII/BFG under investigation are "classical," model based diagnostics. That is, the model is composed of the Sikorsky proprietary gear and bearing tables for the SH-60B drive system. No fault or anomaly detection training is required. The system provides three significant contributions to the development and verification of diagnostics for helicopters:

1. First, the system acquires data from all channels simultaneously. This makes it possible to use multiple channels to analyze a single component; an essential element of false alarm reduction. Today, the HIDS system is the only flying data acquisition system that has demonstrated the ability to record the raw and processed data set for an entire aircraft propulsion and power drive system. The HIDS system saves raw time series data, for all channels including tachometers for post flight evaluation and future algorithm development. This minimizes the possibility that a malfunction in the preprocessing could contaminate the data base.

2. Second, the system has the capability to automatically adjust to provide good signal to noise ratios for all channels. The system starts each acquisition with a one second acquisition, and internally sets the gains based upon the measured signal amplitude to maximize dynamic range. The gain for each channel is recorded with the raw data for future analysis.

3. Third, is the capability for on-board processing. All gears, bearings and shafts are analyzed and the diagnostic result will be written to the KT-1 trend data according to flight regime. The raw data files can be held in RAM until the analysis is complete, then discarded if no anomalies are identified by the limit check. If a parameter is deemed to be in "maintenance" or "alarm" status by the KT-1 limit checks, the component of concern would have all of the accelerometers that are used for its analysis plus the aircraft tachometer saved as raw digital time series data for post flight investigation. When data is taken by a pilot-activated switch, raw data is written to disk with all of the analysis results. The HIDS program is in the process of determining alarm limits and algorithm sensitivities to achieve this goal and level of integration.

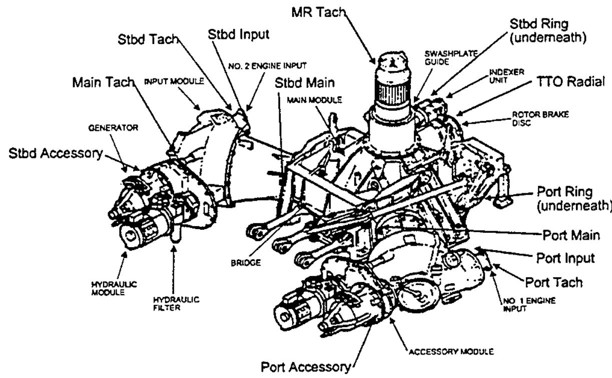

Fig. 3. Accelerometer Locations on Input and Main Modules.

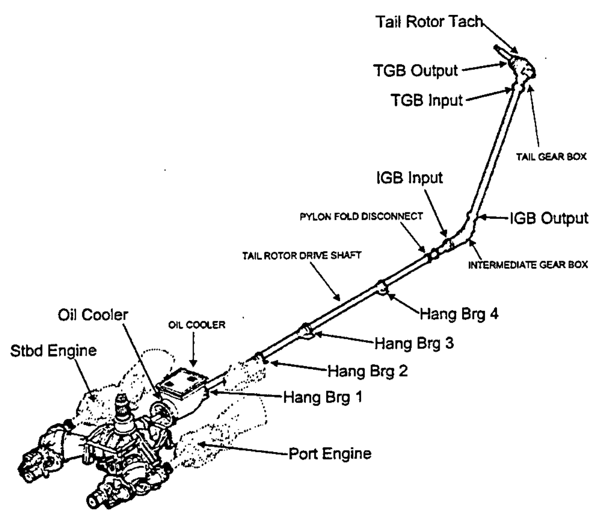

Fig. 4. Accelerometer Locations on the Tail Drive System.

Rotor Track and Balance: The ROTABS system promises to negate the need for on-board trackers and utilize higher order mathematics and a significantly larger data set to resolve the adjustments required to keep the rotor system in track and balance. ROTABS does not collect or use track data to compute rotor adjustments. ROTABS adjustments are computed from vibration data collected by the HIDS (Helicopter Integrated Diagnostic System) installed on the aircraft, using six accelerometers at three locations within the fuselage. These transducers are arranged as follows: A single-axis device sensing vertical vibration, and a two-axis device sensing vertical and lateral acceleration, both attached to the bulkhead immediately behind the pilot and copilot. One is located near the copilot's left shoulder, while the other is near the pilot's right shoulder. A three-axis device sensing vertical, lateral, and fore/aft vibration is located on the cabin ceiling just aft of the vibration absorber, roughly on the centerline of the fuselage. The system simultaneously acquires six accelerometer channels and then processes them simultaneously and resolves the corrections using transfer function from a training data set including pitch rod sensitivity, hub weight sensitivity, and tab bend sensitivity. On other aircraft types the system has demonstrated the ability to maintain track limits while simultaneously optimizing vibration in 6-degrees-of-freedom at 1/rev and selected harmonies thereof. Main and tail rotor track and balance accelerometers on the aircraft are recorded as part of the vibration data set. They will be processed at the pilots command and automatically in predetermined flight regimes for trending. Adjustments will be recommended by the groundstation upon completion of a flight test. Raw vibration data is stored for algorithm training and validation.

Groundstation: The HIDS groundstation houses maintenance, pilot, and engineering windows to support complete health and usage functionality. Tools are provided for parts and maintenance tracking, rotor track and balance, mechanical diagnostics, flight parametric data and flight regime replay, pilot flight logs, and projected component retirement times. During a flight data download, the groundstation calculates flight regimes from downloaded parametric data, and updates life usage on pre-selected serialized components in a data base upon aircraft data download. Functions to trigger usage based maintenance and component replacement are designed into the system. Historical data replay provides regime, event and exceedance information along with all aircraft parameters for the entire flight. Pilot control inputs are displayed along with all aircraft parameters for the entire flight. Pilot inputs are recorded along with other parameters which is essential for understanding events during a flight. The ground station has been shown to reduce the paperwork associated with daily operations and to direct maintenance personnel to the faulty component identified by diagnostics.

Description of the Test Cell

The NAVAIRWARCENACDIVTRENTON Helicopter Drive System Test Facility has been described in detail (Ref. 3). The test cell uses aircraft engines to provide power to all of the aircraft drive systems except the rotors. Power is absorbed through both the main rotor mast and tail rotor shaft by water brake dynamometers. The main rotor shaft is loaded in bending, tension and torque to simulate flight conditions. There is a speed increasing gearbox between the main rotor mast and the water brake which raises the main rotor speed by a factor of 32. This allows water brakes to extract up to 8000 shaft horsepower (SHP). The complete aircraft lubrication system is used with the oil cooler, oil cooler blower and blower drive shaft part of the system assembly. The tail drive system is installed and power is extracted from the tail at operating speed. The tail water brake can extract up to 700 SHP.

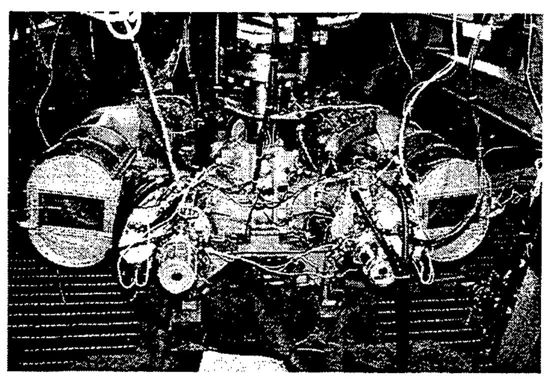

Fig. 5. Main Transmission Assembly including Accessories.

The tail drive system installation allows balance and alignment surveys on the blower, tail drive shafts and disconnect coupling. Aircraft viscous damper bearing assemblies support the installation. The length of the test cell limits the number of tail drive shafts, so two of the aircraft shafts are not installed. The test cell also supports the aircraft accessories. Generators and hydraulic pumps are mounted on the accessory gearboxes and loaded to simulate aircraft operation (see Figure 5). This is a significant capability, especially when diagnostics using vibration acquisition is the test objective. Vibration signatures collected from NAVAIRWARCENACDIV-TRENTON test cell include frequency content from all dynamic components of the loaded power drive system. The complex signal is representative of the aircraft environment.

Since this cell has the ability to operate all the aircraft mechanical systems together, the diagnostic system can record all the component "signatures" to a data base. This data base can then be interrogated to determine system health, and system performance rather than a diagnostic evaluation of a single component or fault. This is a significant improvement over single component regenerative rigs that tend to have two gearboxes that generate the same frequencies (and cross-talk) bolted to a single stand and none of the adjacent mechanical systems.

Aircraft Installation

The HIDS installation is the first health and usage monitor with advanced gearbox diagnostics to be placed on-board a US military helicopter. The system has a menu driven cockpit display (see Figure 2) for pilot information/interface. The KT-1 usage monitor is built on an open architecture, STD-32 bus housed in a 1/2 ATR short box, which has unused slots for future integration of selected KT-3 functions. Download from the KT-1 is accomplished via the data transfer unit (DTU) Type II PCMCIA card. The KT-3 vibration analysis system is housed in a large vibration isolated chassis with removable hard drives and a full VME chassis. This system is necessary for the development program to acquire all of the raw data that generates an airborne warning or alarm for either confirmation of the fault, or development of additional algorithms that identify a data problem that resulted in a false alarm. A significant benefit of this system is the comprehensive database, which is a powerful resource for diagnostic development. This system, although conspicuous in appearance, is being reduced to a set of cards in the 1/2 ATR KT-1 after successful demonstration of the required diagnostics, i.e., optimization of the number of simultaneous channels, gain control and processing.

Evaluation

The SH-60 was selected for this program since it offered the best availability of test assets and highest potential for support due to the large fleet of aircraft between the Navy, Army and Coast Guard. The NAVAIRWARCENACDIVTRENTON drive system includes two General Electric T700 engines, the main transmission, oil cooler and the tail drive system .

Test Objectives

To insure a comprehensive test effort, the planning for this test program included support from individuals and organizations involved with the design of the H-60 aircraft and diagnostic systems. The team developed and documented the program plan (Ref. 3). All seeded fault test planning is discussed with Sikorsky drive system engineering prior to execution. Team discussions led to the objectives and test sequence summarized below.

1. Demonstrate operation of an integrated diagnostic system for tracking usage of the helicopter power drive train.

2. Evaluate the ability of the diagnostic system to identify localized faults in an entire drive system.

3. Quantify the level of signal for a known defect size to develop operational limits and trending for the SH-60 drive system.

4. Evaluate the diagnostic algorithms for cracked gear fault identification and sensitivity.

5. Evaluate the diagnostic systems ability to identify a degraded performance engine and damaged engines removed for cause.

6. Evaluate the diagnostic systems sensitivity to defects and faults in tail drive shafts and bearings.

7. Evaluate the diagnostic systems sensitivity to bearing defects in gearboxes.

8. Evaluate the diagnostic systems ability to identify oil cooler blower faults.

9. Evaluate variability of data across flight regimes (including torque and weight variations).

10. Evaluate sensor placement sensitivity for the various defects. The objective is to minimize the total number of sensors required to identify faults large enough to require maintenance action and to increase robustness via use of secondary sensors.

11. Determine ambient temperature affects on the diagnostics.

12. Support The Technical Cooperation Program (TTCP) in evaluating new and emerging technologies in diagnostics.

13. Evaluate the potential for detecting misalignment, bad pattern and improper shimming during assembly that may be the cause of premature damage in mechanical systems.

14. Develop seeded fault data library that can be used to evaluate systems in the future without repeating the test program.

15. Verify ROTABS rotor track and balance.

16. Demonstrate automated engine health monitoring by automating the Health Indication Test (HIT) check and implementing a real time engine performance algorithm.

17. Evaluate as many currently available propulsion and power drive system diagnostic technologies as possible in test cell 8W and assess their relative effectiveness.

18. Evaluate the data collected on-board the aircraft with the test cell data to validate the pertinence of test cell proven algorithms for use on-board an aircraft.

19. Categorize diagnostic results with respect to aircraft flight regime to define optimized system acquisition and processing requirements.

20. Demonstrate automatic acquisition of mechanical diagnostics an ROTABS via flight regime recognition.

21. Demonstrate real time, on-board analysis and health assessment of drive system gears, shafts, and bearings.

22. Demonstrate flight data replay and structural usage functions in groundstation.

23. Demonstrate ability of the diagnostics to reduce component "false removals" and trial and error maintenance practices.

24. Demonstrate methods that improve the accuracy of component condition assessment and reduce false alarms.

Test Plans

Testing of the diagnostic system has been divided between two Navy activities that can exercise as much of the entire diagnostic system as possible. The NAVAIRWARCENACDIVTRENTON Helicopter Transmission Test Facility (HTTF) and NAVAIRWARCENACDIVPAX aircraft both operate the entire propulsion and power drive system during testing. Test plans maximize the return on investment when the system is evaluated in a single test vehicle.

1. Usage Monitoring KT-1: Usage monitoring requires continuous measurement and recording of a number of parameters that directly or intentionally relate to the fatigue life determination of critical mechanical and structural components. Evaluation of the usage data products and ground station is primarily accomplished through the demonstration and use of the system. Accuracy of the signals compared with aircraft cockpit parameters, and proper operation of exceedance and event functions have been documented. Production specification requirements for minimum acceptable functionality will be the primary product.

2. Vibration Monitoring and Diagnostics: Reliable fault identification from vibration signatures is a well documented, but difficult task. In many test cases, the researcher has been able to show that a given process can successfully identify a fault in a small scale test. Production use in complicated systems that have varied operational parameters with time has proven to be much more difficult to implement without false alarms and missed detections. In order to maximize the potential benefit of the HIDS program, early program decisions drove the diagnostic system to be a state-of-the-art data collection and processing system, with the intention of acquiring the raw data, and using it as a foundation to allow rational selection and evaluation of diagnostic parameters such as data rate, sample length, degree of redundancy required, etc., and also to identify the anomalies that result in inconsistent system performance. The KT-3 and NAVAIRWARCENACDIV-TRENTON test cell have been combined to create a unique mechanical diagnostics laboratory.

NAVAIRWARCENACDIVTRENTON began acquiring seeded fault assets at the program inception. These parts had been removed from the overhaul process for discrepancies and were set aside for test rather than scrapped. This provided a tremendous cost savings by avoiding purchase of good parts for artificially seeded fault specimens, while supplying naturally created faults for test. Sikorsky Aircraft parts from prior bench qualification tests are also available for test. These parts are "bench test only" assets since they experienced over-torque conditions during test. The program has over two full sets of Not For Flight Asset (NFFA) gearboxes. The spares can be implanted with faults while another gearbox is tested. The testing initially concentrated on the tail drive system to verify the TII/BFG diagnostic system operation and performance. Subsequent testing has been performed on all drive system components, including artificially implanted and naturally occurring faults. The test conditions have consisted of sequentially varying power settings throughout the normal range of operation. It is essential to understand the sensitivity of the diagnostic algorithms as a function of changing aircraft power. Ambient temperature variation effects are included in the analysis. The first data set from each run is taken before the oil warms up at low torque to obtain a data base that can be compared to flat pitch maintenance ground turns for troubleshooting.

Test runs to evaluate component assembly (i.e. build-up variation) requires gearbox disassembly, assembly and test sequences without changing any parts. All four of the input and main gearbox assemblies in the data base were tested for sensitivity to bolting being loosened, housings jacked apart, and then reassembled with the same components.

System Installation

The HIDS system is capable of accommodating multiple configurations. NAVAIRWARCENACDIVTRENTON test cell and aircraft 162326 installations are the same for a majority of the inputs. The aircraft has many additional parameters that are not present in the test cell, such as flight parameters including altitude, airspeed, pitch, roll and heading. Also, the aircraft system measures fuel quantity while the test cell system measures fuel flow. Aircraft 162326 was made available for instrumentation in the spring of 1994 and the entire system was installed by 1 August 1994. The initial installation was completed with a majority of parameters in good operation and a system that functioned and passed installation acceptance tests. Several modifications have been incorporated since the commissioning. Performing checkout of system functionality at NAVAIRWARCENACDIVTRENTON tested the aircraft system changes, and many of the aircraft discrepancies were found to be in areas where the aircraft was different from NAVAIRWARCENACDIVTRENTON. The interface documentation was updated and validated accordingly. In March of 1997, the next generation HIDS system (with improved KT-1) was installed on PAX aircraft 804 for continued analysis and development.

Vibration Data Analysis

The HIDS program is correlating the seeded fault test data acquired in the NAVAIRWARCENACDIVTRENTON test cell to the NAVAIRWARCENACDIVPAX flight data. The diagnostic system user interface and its ability to detect faulty components in a full drive system are being evaluated using NAVAIRWARCENACDIVTRENTON data. The operational characteristics, rotor track and balance and user interface are being evaluated at NAVAIRWARCENACDIVPAX.

Data is recorded at both sites using the same acquisition system, sensors, mounting, and accelerometer locations. The data sets are digital records, recorded simultaneously on all channels at 100,000 samples per second for 30 seconds. This system is believed to exceed the requirements for a total onboard health and usage monitoring system. However, by exceeding the requirements for data acquisition under known conditions, HIDS will provide the rationale to specify the minimum system requirements needed to achieve the low false alarms and complete functionality goals. This system can store and analyze large amounts of meaningful raw data and has significant value when new aircraft types or newly overhauled aircraft require a new baseline.

The TII/BFG diagnostic system has a comprehensive scientific development environment that aids the user in evaluating and tuning diagnostic system performance. Trending of indicators and adjustment of limits is a useful part of the system, and the flexibility to add and develop new algorithms is also noteworthy. This ability makes it possible to review and modify the processing in the ground station to optimize on-board system performance.

The HIDS program, by taking advantage of these tools for diagnostic system development and verification has an excellent opportunity to properly bound the operational issues that have limited the successful implementation of currently available health and usage monitoring system. Extensive analysis and algorithm development of the baseline and fault raw data continuously improves the performance of the system through scientific understanding of the mechanics of the helicopter, and through detailed study of the events that have resulted in false alarms. By utilizing the database, HIDS has been able to develop and validate quality assurance routines that identify maintenance required to the diagnostic system rather than an on-board alarm.

Two means of collecting vibration data are being implemented at HTTF. The TII/BFG diagnostic system saves raw digital data, while Metrum VHS digital tape recorders are used for making parallel raw data tapes. The test cell does not provide the airframe inputs or the rotor pass vibration inputs, but these frequencies are relatively low compared to the engine and gearmesh frequencies. The impact of this limitation on component- specific algorithms is restricted to the lowest speed components.

Rotor System Track and Balance/Diagnostics

Rotor Track and Balance using ROTABS has shown the ability to prescribe all necessary adjustments for rotor track and balance without the need for multiple flights or the use of optical trackers. The potential benefit obtained by eliminating the need for a tracker solves the operational and reliability issues associated with a full time on-board tracker. When extensive rotor changes are made, current RT&B systems use the tracker during ground turns to adjust the track to acceptable limits, then fly to balance. HIDS will investigate if ROTABS can similarly reduce track to acceptable values after major rotor system maintenance. Concurrently, flight testing will be performed to determine the capability of ROTABS and a tracker to detect rotor system faults. This program will provide valuable demonstration to help resolve the tracker issue for day-to-day rotor smoothing to improvement in aircraft comfort (pilot fatigue), airframe aging and avionics life.

Other Support

The Team approach has been utilized to develop, plan and support the HIDS effort. The propulsion and power drive system community as well as the diagnostics community have been heavily involved in determining what to demonstrate and how to put it to the test. SH-60 design engineers from the Naval Air Systems Command (NAVAIR), NAVAIRWARCENACDIVTRENTON, Naval Aviation Depot (NADEP), Cherry Point, NC, Army Aviation and Troop Command (ATCOM), St. Louis, MO, Aviation Applied Technology Directorate, Ft. Eustis, VA and Sikorsky Aircraft, Stratford, CT have participated in planning the NAVAIRWARCENACDIVTRENTON test cell efforts that are used to baseline and then challenge the diagnostic system. Diagnostic engineers from the same organizations have participated in program planning and system design reviews. Not for Flight Assets (NFFA) have been collected from Sikorsky, NADEP Pensacola, FL, NADEP North Island, CA, NADEP Mayport, FL, Corpus Christi Army Depot, Corpus Christi, TX and the Coast Guard for test.

Accomplishments

Accomplishments Summary

The KT-1 COTS hardware and software has been successfully installed and operated in both the NAVAIRWARCENACDIVTRENTON test cell and NAVAIWARCENACDIVPAX aircraft Bureau Number (BUNO) 162326 and 164176. The HIDS aircraft is flying with engine algorithms and recording cockpit instrumentation, control positions and alarm panel indications. The cockpit display can notify the pilot when there is an exceedance and the ground station reiterates those exceedances during data download into the ground station. The system has functioned as a flight data recorder providing a complete history of the flight. The ground station tracks serialized part numbers and times, correlates maintenance performed and part change data, and has a variety of report and plotting options. The system has continued to improve towards, and provide valuable data for, defining the specification of a production Navy system.

The KT-1 usage monitor and maintenance tracking system is also being used in the test cell to track what faulted components were run on any given day. The system has a list of all gear and bearing serial numbers which we can correlate to the faults. All component changes are tracked chronologically and the files are maintained by the test cell mechanics.

The KT-3 32 channel simultaneous sampling vibration acquisition have proved to be reliable and robust for both test stand and flight activities. The system recorded data in aircraft BUNO 162326 as a not-to-interfere secondary test. The hardware installation required that the system be stood on end to fit into the aircraft during the initial installation, and later was moved from the front of the aircraft to the rear. Data has been acquired from three airframes for the main gearbox and one aircraft for the entire system. A total of 85 hours of flight and 254 data sets have been recorded on aircraft 326. The helicopter drive system test facility at NAVAIRWARCENACDIVTRENTON has operated for 396 hours of diagnostic system evaluation. Seven main gearboxes, seven input modules, two accessory modules, three intermediate gearboxes, four tail gearboxes and six engines have been tested and 31 faults have been run in the test cell. Extensive investigation into signal quality, and gain control has provided good confidence of the data acquisition quality. The analysis has provided a significant diagnostic capability for the detection of degraded components.

The data library consists of over 2000 sets of 32 channel simultaneous acquisitions of raw time series data with tachometers and accelerometers recorded together. This allows for time domain and frequency domain analysis to be performed post flight.

Compliance with Objectives

1. Demonstrate operation of an integrated diagnostic system for tracking usage of the helicopter power drive train. The capability to track the usage

of drive system components is illustrated in the Figure 6 histogram display generated by the groundstation. A composite distribution of main transmission and engine torque during three flights is shown.

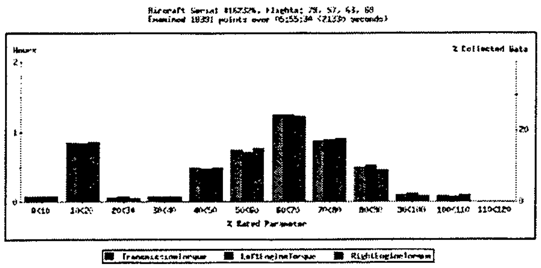

Fig. 6. Life Usage Tracking Window.

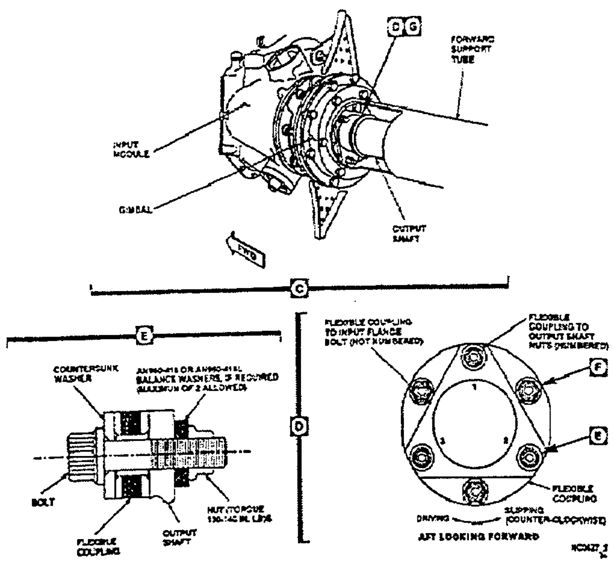

Fig. 7. High Speed Shaft Interface.

2. Evaluate the ability of the diagnostic system to identify localized faults in an entire drive system. The HIDS system has demonstrated the ability to identify localized faults on a number of H-60 drive system components. The engine high speed shaft/input module interface (see Figure 7) has been a problem area, where the difficult to inspect Thomas Coupling disc pack has suffered several failures. The Figure 8 engine high speed shaft (with cracked Thomas Couplings) was removed from the fleet and tested at Trenton. Figure 9 illustrates baseline test data with good driveshafts, and the degraded component installed at the starboard engine location for one acquisition at run number 31. The HIDS system detects the fault and isolates it to the starboard side. This provides a rationale for providing a cockpit alert for critical, rapidly degrading components. The HIDS system also detected a fleet removed input module suspected of being an every-other-tooth gearmesh candidate. These gearboxes were emanating a strong tone at one-half the normal gearmesh frequency, and it was believed this tone was contributing to premature removals of the mating T700 engines due to torque reference shaft wear. Figure 10 exhibits a gear health indicator (algorithm) of such a component tested at Trenton which shows baseline and fault (run numbers 149 through 170) data.

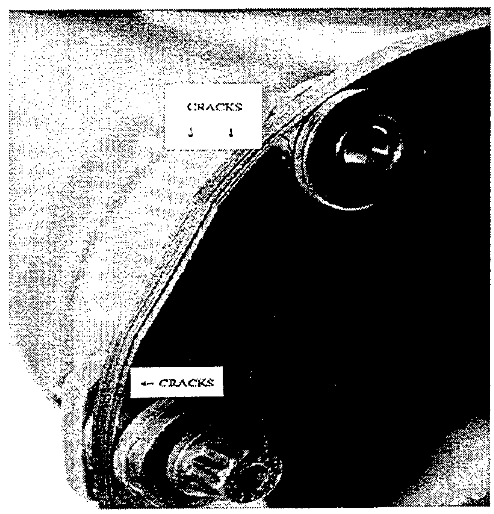

Fig. 8. Cracked Thomas Coupling.

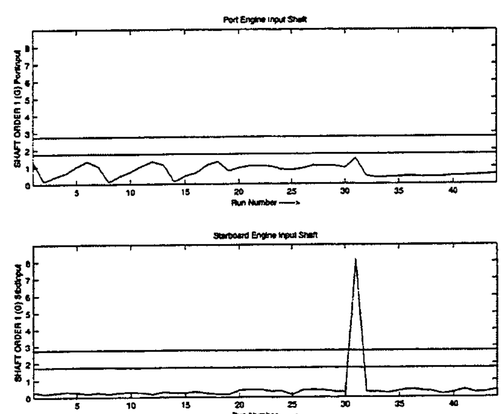

Fig. 9. Degraded Shaft at Position 31.

3. Evaluate the diagnostic algorithms for cracked gear fault identification and sensitivity. A critical part of the HIDS program is to demonstrate the detection of catastrophic gear faults. The most serious of which are root bending fatigue failures.

Depending upon gear design, this type of crack can either propagate through the gear tooth causing tooth loss, or through the web causing catastrophic gear failure and possible loss of aircraft. A means used in the helicopter community to promulgate this type of investigation is to weaken the tooth by implanting an Electronic Discharge Machine (EDM) notch in the gear tooth root. This action creates a localized stress concentration at the tooth root in an effort to initiate a crack. The HIDS team had previously attempted this test on other gear teeth, but with no success. Discussions with the transmission design departments at Agusta Helicopters and Boeing Helicopters assisted us in determining optimum notch placement. Figure 11 is a cutaway of the SH-60 intermediate gearbox. Two EDM notches (.25" Length x 006" Width x .040" Depth) were implanted along the length of the intermediate gearbox (IGB) gear tooth root by PH Tool of New Britain, PA. The location of the notches is critical as they were implanted where the gear tooth root bending stress is greatest.

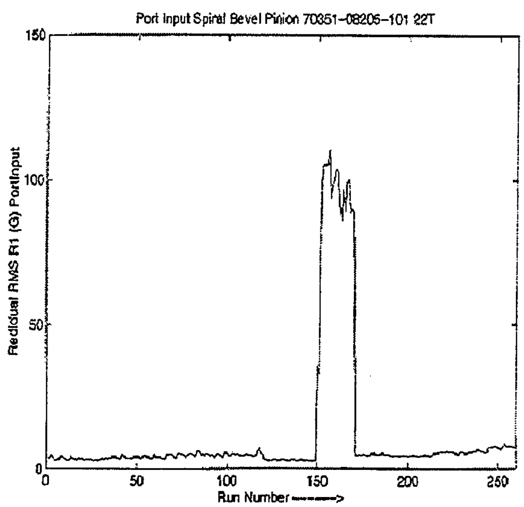

Fig. 10. Response for Half Gearmesh Anomaly.

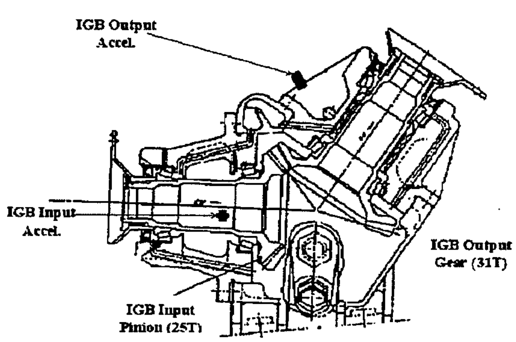

Fig. 11. SH-60 Intermediate Gearbox Cutaway.

Fig. 12. Cracked Intermediate Gerabox Pinion.

The test was run at 100% tail power for a total of 2 million cycles, when testing was terminated prior to gearbox failure when a gross change in the raw FFT spectra was observed on the HP36650 Spectrum Analyzer. Subsequent to test termination the gearbox was disassembled and inspected. The input pinion's faulted tooth exhibited a crack initiating from the tooth root and extending through the gear web and stopping at a bearing support diameter. Figure 12 exhibits the subject pinion at the end of the test. There is a void at the toe end of the notched tooth where a large section of the tooth broke off, and a through web crack extending to the bearing support diameter. No indication from the gearbox chip indicator was observed.

A review of the diagnostic results shows the TII/BFG model based algorithms successfully detect the presence of the gear tooth fault. Figures 13, 14 and 15 respectively exhibit "Component Condition" and the early and late responding health indicators from which it was derived. After indicating a healthy gear for roughly 267 minutes (most acquisitions were acquired 15 minutes apart), the indicator levels raised steadily for the next 139 minutes, thereafter exhibiting sharp changes in level until test termination at 548 minutes (Ref. 4 discusses indicator results of another pinion tooth fault). Test results illustrated an EDM notched tooth behaves much like adjacent teeth until the part is fatigued and a crack develops. The crack effectively weakens the tooth in bending,

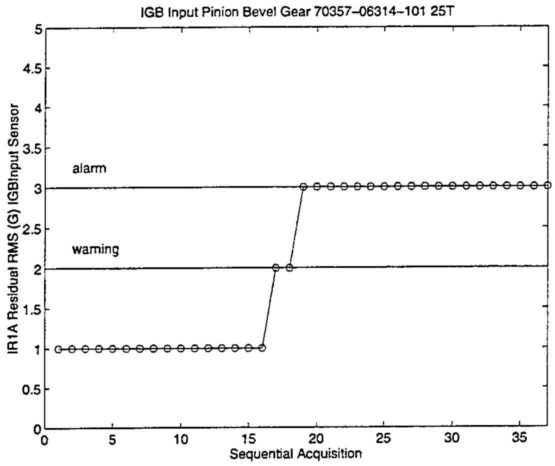

Fig. 13. IGB Pinion Component Condition.

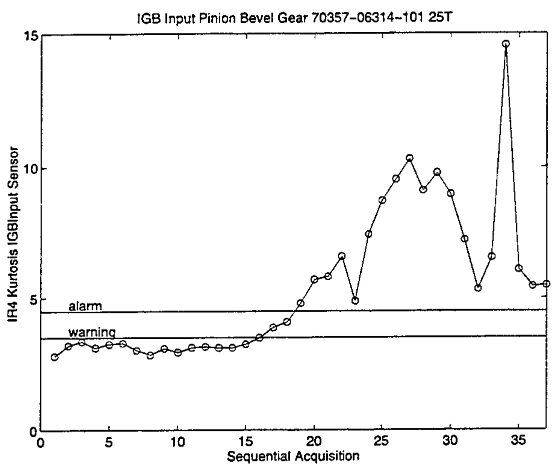

Fig. 14. Early Responding Health Indicator.

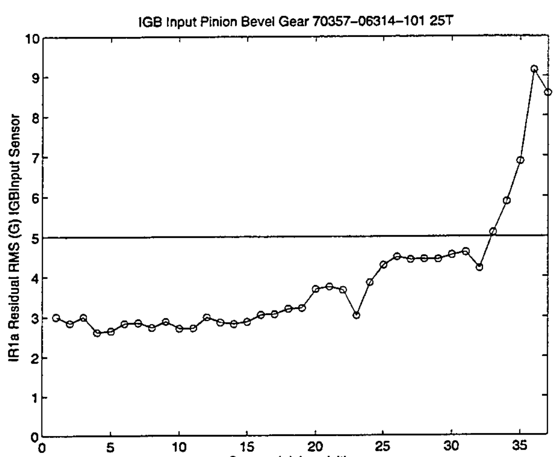

Fig. 15. Late Responding Health Indicator.

causing the faulted tooth to share load unequally with adjacent teeth. Depending upon the crack path, other dynamic anomalies are manifested. Also, synchronous averaging techniques employed in model based diagnostics can "filter out" non-synchronous vibration providing a health determination of a specific component.

A root bending fatigue propagation test was repeated on a main transmission input pinion. This test promised to be a more challenging effort for several reasons. First, the main transmission module is a larger and more complex system than the intermediate gearbox. The background noise is greater and the fault is located deep inside a larger housing. The gear form was also different. The intermediate gearbox pinion has a large web, where the main module pinion teeth are closer to the shaft centerline and therefore has a great deal of support at the tooth root. These observances made, the HIDS team determined to investigate the crack propagation properties of the more robust gear form.

Two EDM notches were implanted in the root of one geartooth and run for 12 million cycles at 110% power, removed and inspected, and then tested for another 10 million cycles. After 12 million cycles, small cracks less than 2mm in length emanating from the notch corners were present. Figure 16 exhibits the pinion after another 10 million cycles. A large part of the faulted tooth has broken off, and a crack propagated the length of the part forward (toe end), and aft (heel end) to the bearing support. No indication from the gearbox chip indicator was observed.

Fig. 16. Main Transmission Input Pinion Crack.

Figure 17 shows an indicator response for the test. Run numbers 1-206 are data from the first gearbox build, and run numbers thereafter from the second. It is interesting that key fault response indicators reached only half the level as for the IGB fault. Speculatively speaking, this may be due to the fault being deeper inside the gearbox, but is most probably due to the other main module pinion emanating "healthy" synchronous gearmesh tones and masking indicator response.

It is presumed the steep increase can be attributed to either the gear tooth breaking off, or the crack propagating through the web. It is indeed impressive that these components held together considering their condition and the loads transmitted.

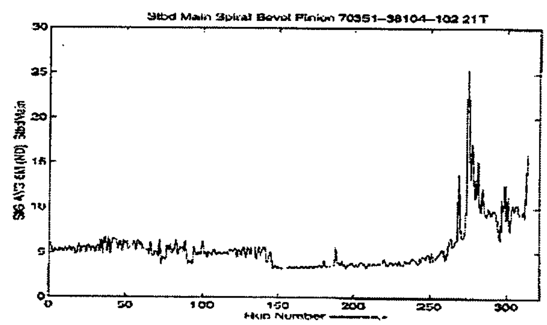

Fig. 17. Response to Main Module Pinion Fault.

These tests demonstrated (1) the HIDS diagnostic algorithms successful early detection of root bending fatigue failures, (2) chip detectors are unreliable for the detection of classic gear failures caused by root bending fatigue, (3) H-60 drive system components are particularly robust, and (4) root bending fatigue cracks on gear tooth forms such as the main module pinion can propagate through the web (vice only the tooth) to a catastrophic condition.

4. Quantify the level of signal for a known defect size to develop operational limits and trending for the SH-60 drive system. As discussed above, the IGB root bending fatigue failure provided excellent results in component fault detection and condition assessment. Figures 13, 14 and 15 exhibit the gear "Component Condition" indicator, and two gear health indicators which determine the component condition. The IR4 Kurtosis indicator provides early warning of a local gear tooth anomaly, and the IR1a indicator is excited as the gear tooth crack has propagated to a severe condition. These indicators could therefore be integrated into the diagnostics package as early warning and impending failure indicators respectively.

5. Evaluate the diagnostic systems ability to identify a degraded performance engine and damaged engines removed for cause. Two USCG T700-GE-401C engines were removed from the fleet and provided to Trenton for engine algorithm investigation. Engine serial number 366497 was removed from the fleet at approximately 25 degrees C off specification, and serial number 366622 approximately 45 degrees off of spec. Results from these tests showed the algorithm provided a constant, reliable value at powers between 60-90% (see Figure 18). Considerable data scatter was present, and a smoothing algorithm was recommended. The air data correction (.95 exponent) also appeared to cause divergence at low ambient temperatures, and an exponent of .65 provided improved results (see Figure 19). The algorithm values however estimate the engine performance for both engines to be 20-30 degrees C below actual, suggesting a bias correction is required.

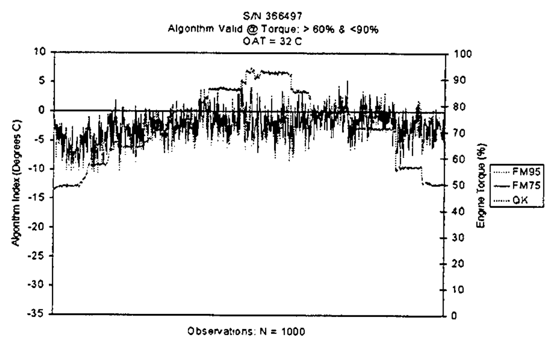

Fig. 18. T700 Engine Algorithm Results.

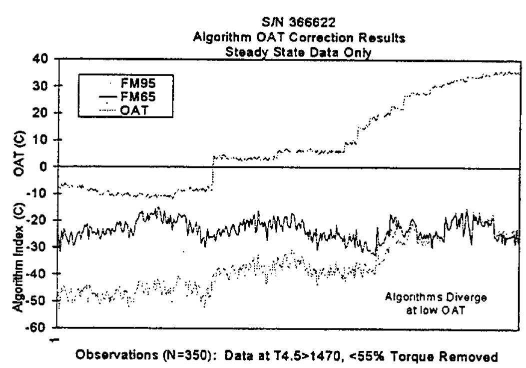

Fig. 19. Algorithm Correction Results.

6. Evaluate diagnostic system sensitivity to defects and faults in tail drive shafts and bearings. Hanger bearing assemblies are used to support the helicopter tail drive shaft. The main components of the assembly consist of a grease-packed sealed ball

bearing that is pressed into a viscous damper bladder and supported by a housing that mounts to an air-frame interface. The bearing is expected to be lightly loaded since it doesn't support any significant radial or axial loads, though those imposed from imbalance and misalignment occur in-service. Figure 20 shows the hanger bearing assembly and associated accelerometer installed at the number 2 location in the tail drive system. Since the viscous damper is in the vibration transmission path, there was concern it would inhibit the transmission of high frequency tones from the bearing to the vibration sensor.

A fleet removed hanger bearing with a very light click was installed in the HTTF. There was considerable opinion that the click was due to dirt in the bearing. 12.7 drive system operating hours were accumulated and 129 data points were acquired. Figure 21 shows a representative envelope spectral plot for the fleet rejected hanger bearing.. A fault clearly exhibits itself by the strong tones at frequencies specific to the inner and outer race defect frequencies and also at shaft speed. By comparison, fault-free hanger bearings did not generate bearing defect frequencies. The Figure 22 indicator is derived from the information contained in the spectral plot, and presents data from four different bearings which were installed in the #2 hanger bearing location. Data from the fleet rejected bearing is easily identifiable between run numbers 199 through 325. Note that the viscous damper attenuation concern did not materialize

Post test inspection of the bearing revealed that the inner ring was fractured as shown in Figure 23. Also, the bearing was found to have about 1.5 grams of grease remaining, which is within the range normally found in bearings operating to their 3000 hour overhaul life. Hanger bearings with inner race fractures have been known to eventually purge all the grease through the fracture leading to overheating, seizure, and loss-of-aircraft.

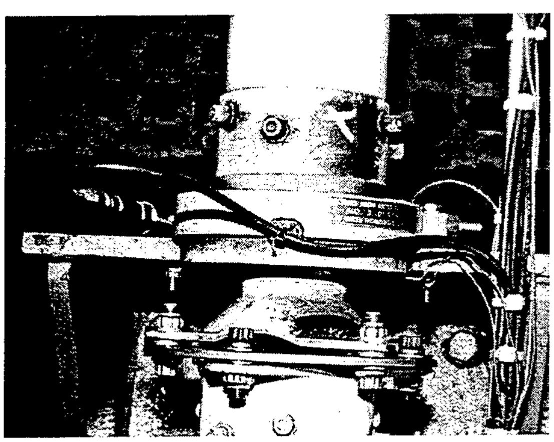

Fig. 20. Hanger Bearing Assembly.

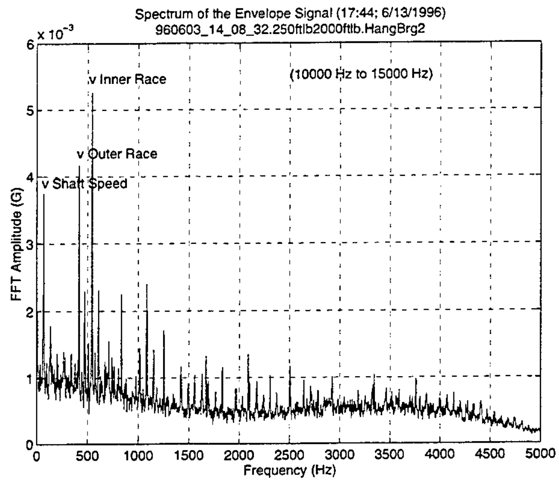

Fig. 21. Rejected Hanger Bearing Spectral Plot.

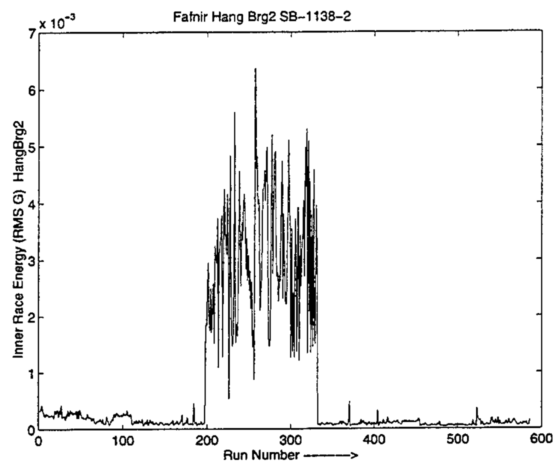

Fig. 22. Hanger Bearing Inner Race Energy.

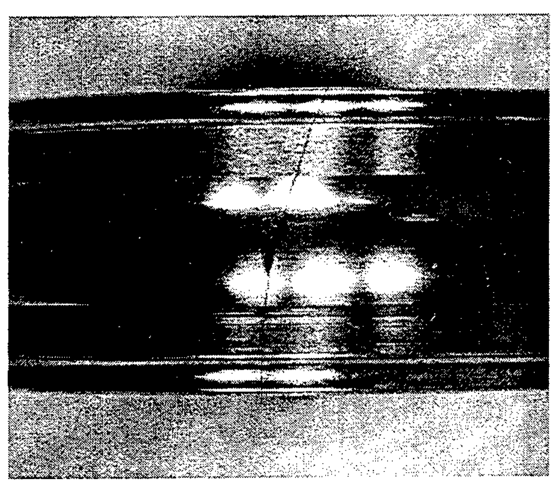

Fig. 23. Post-Test Condition of Hanger Bearing.

7. Evaluate the diagnostic systems sensitivity to bearing defects in gearboxes. The spalled integral raceway bearing (P/N SB 2205) is the most common dynamic component cause for gearbox removal in the H-60 community. This fault is particularly challenging as it is located deep inside the main transmission, (see Figure 24) suggesting it would be difficult to detect. Figure 3 illustrates the SH-60 main transmission system and respective vibration accelerometer locations. The Figure 25 fleet rejected component was installed in the Trenton test facility starboard location. Bearing condition for the starboard and port main accelerometer locations are presented in Figures 26 and 27 respectively. The starboard main condition indicator toggles into the alarm position when the fault is implanted at acquisition number 254 and reverts back to the okay position when the fault is removed at acquisition number 300. The port main indicator is also sensitive to this fault because the sensor is located on the same structural housing member, and is rotated about 90 degrees around the housing from the starboard main sensor. The port indicator serves as a confirmation of the starboard condition. Enveloped kurtosis is the main indicator used to evaluate bearing condition for this fault. One of the keys to obtaining meaningful results with this technique is to envelope an appropriate frequency range. The frequency range used in this analysis was determined analytically as well as experientially. Figures 28 and 29 respectively exhibit the Kurtosis values of the primary (stbd main) and secondary (port main) sensors for the bearing SB-2205 fault.

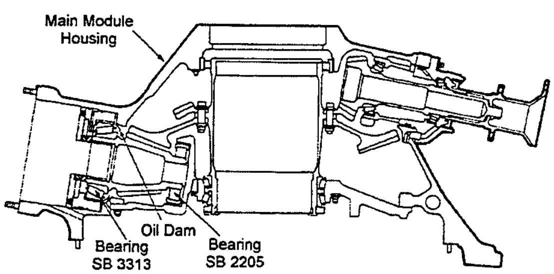

Fig. 24. Locations of SB-2205 and SB-3313 Bearings in the Main Module.

8. Evaluate the diagnostic systems ability to identify oil cooler blower faults. This test was recently performed by deliberately imbalancing the blower by attaching weights to the fan blades. The imbalance did not manifest itself in the data and recent conversations with Sikorsky Test Group suggest insufficient imbalance was implemented during the test.

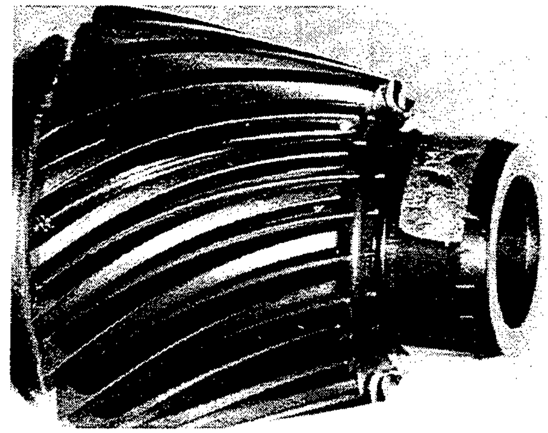

Fig. 25. Main Module Input Pinion with Spalled Integral Raceway Bearing SB 2205.

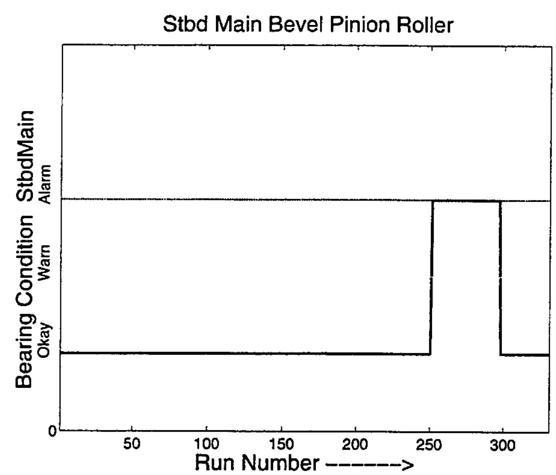

Fig. 26. SB 2205 Condition Call from Starboard Sensor.

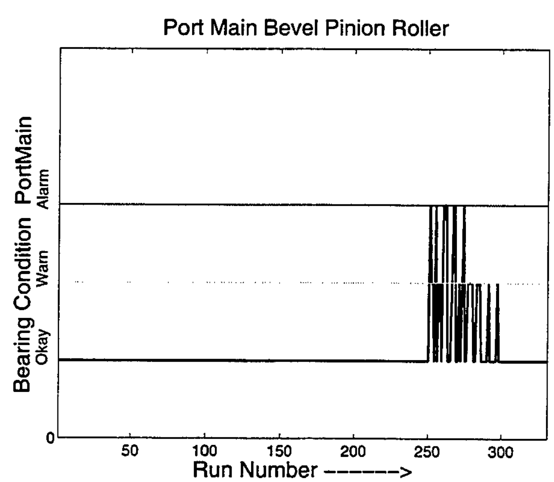

Fig. 27. SB 2205 Condition Call from Port Sensor.

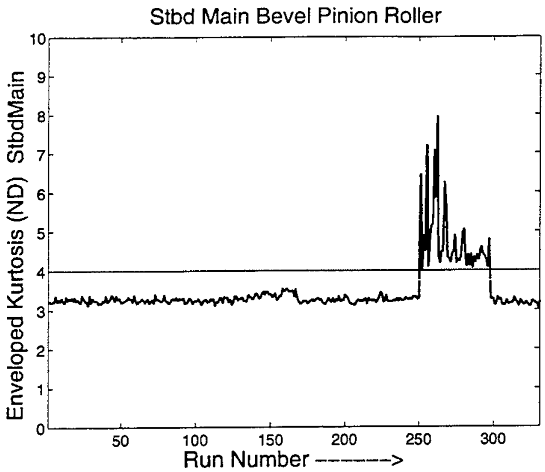

Fig. 28. SB 2205 Starboard Main Kurtosis Trend.

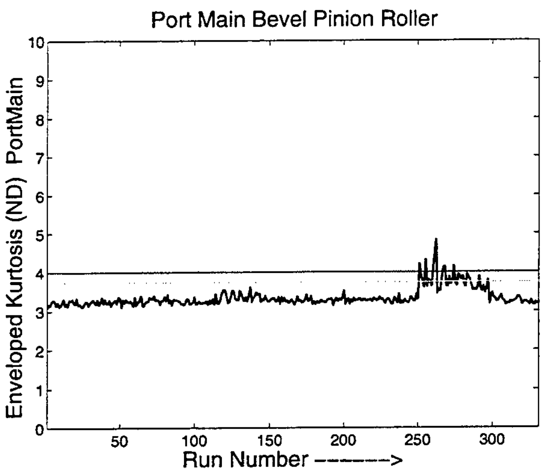

Fig. 29. SB 2205 Port Main Kurtosis Trend.

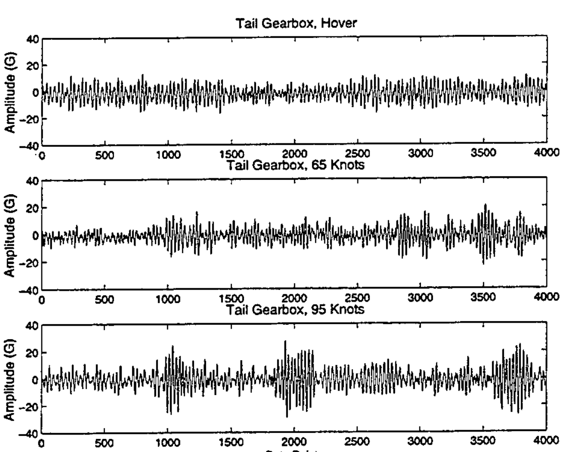

Fig. 30. Dissimilarity of Tail Gearbox Time Series Data for Various Flight Regimes.

9. Evaluate variability of data across flight regimes (including torque and weight variations). Figure 30 exhibits time domain tail gearbox vibration data at different flight regimes. There is considerable difference in the signal between forward flight and hover. This introduced considerable scatter in the algorithm indicators. It was determined a large main rotor 4/rev component (rotor wash) is interacting with the tail pylon in forward flight, which is causing this data instability. This and other flight regime nuances are being investigated.

10. Evaluate sensor placement sensitivity for the various defects. The objective is to minimize the total number of sensors required to identify faults large enough to require maintenance action and to increase robustness by verifying use of secondary sensors. The test of bearing SB 2205 provided an interesting study for sensor placement. At the time of test, the stbd main was the primary sensor for the stbd SB-2205 bearing, and the stbd input sensor was the secondary. Test results however showed otherwise. Figure 31 shows that the enveloped kurtosis of the stbd input sensor does not respond to the fault, whereas the port main sensor does (see Figure 29). Based on results from this test, the port main sensor was then mapped as the secondary sensor for the stbd SB 2205 bearing.

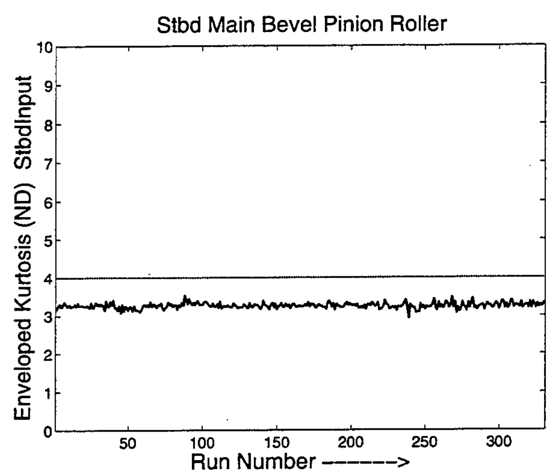

Fig. 31. SB 2205 Starboard Input Kurtosis Trend.

11. Determine ambient temperature effects upon diagnostics. The Trenton HTTF is capable of operating at temperatures from +20F to 100F. Many test configurations were tested at this temperature range. Also, data was acquired immediately upon reaching test conditions and prior to the gearbox reaching operating temperatures. For no-fault data, data acquired during cold temperatures fall within the existing "ambient" distribution. Figures 14 and 15 exhibit a

knee in the upward trend at approximately 360 minutes (acquisition 23), during the IGB cracked pinion test. This data point was the first of the day, acquired before the gearbox reached operating temperature.

12. Support The Technical Cooperation Program (TTCP) in evaluating new and emerging technologies in diagnostics. As stated, the HIDS team has coordinated with AMRL and the UK MOD to share test hardware, data, results, and engineering expertise. Digital vibration data acquired on wide band Metrum tape recorders was provided to the UK MOD for use as evaluation criteria in a recent RFP for HUMS systems on the Chinook helicopter. Tapes have also been provided to the Australian Aeronautical Maritime Research Laboratory (AMRL) for diagnostic evaluation and development. Tapes have also been provided to Sikorsky Aircraft in a reciprocate agreement in exchange for implanting faults at their overhaul facility. As stated previously, the HIDS team has coordinated with AMRL on the evaluation and development of engine performance algorithms. The oil debris monitoring evaluation was also coordinated with TTCP.

13. Evaluate the potential for detecting misalignment, bad pattern and improper shimming during assembly that may be the cause of premature damage in mechanical systems. Misalignment and imbalance testing have been performed on a number of drive system components. Specifically, the engine high speed shaft/input module assembly has been investigated under these conditions and findings were documented (Ref. 5). Other similar tests (some naturally occurring) were recorded. Gearbox gear pattern shim surveys were also performed. Test results are pending data review.

14. Develop seeded fault data library that can be used to evaluate systems in the future without repeating the test program. The HIDS program has provided a wealth of knowledge and understanding of the implementation of mechanical diagnostics. Though not immediately quantifiable, the HIDS testing has identified many optimized test methods and fleet implementation issues. Though not eliminating the need of seeded fault testing for other drive systems, the scope of work can be more precise and reduced. For the Integrated Mechanical Diagnostics Commercial Operational Savings and Support Initiative (COSSI), the HIDS data is being distributed to various institutions to develop and evaluate transmission planetary system gear and bearing algorithms.

15. Demonstrate ROTABS rotor track and balance. Four trials of ROTABS were undertaken to investigate the ability of the ROTABS concept to effect adequate control of blade track and balance. The aircraft used for these trials was a Sikorsky SH-60B, Bureau Number 162326. All operations were conducted at Patuxent Naval Air Station under the auspices of NAVAIR. The vibration and track data presented in this paper were recorded by a standard U.S. Navy Vibration Analysis Test Set (VATS) installed in the aircraft for these tests. VATS records vertical vibration at the same locations (copilot's left shoulder and pilot's right shoulder) as the single and dual-axis ROTABS sensors.

VATS vibration data are displayed as "A + B", and "A - B". These terms refer to the mean [more precisely, (A + B)/2] and difference (A - B) of the 1P vibration at the two locations near the pilot and copilot. Using rigid-body terminology, "A + B" is a measure of the vertical motion of the fuselage at the pilot's and copilot's seats, while "A - B" is a measure of the rolling motion of the fuselage about a longitudinal axis. VATS also collects blade track data from a line-scan camera aimed out of the left-side window of the aircraft. This camera is held and operated by a member of the crew. Data was collected at the following conditions: (1) on the ground, (2) Hover Out-of-Ground Effect (HOGE), (3) 120 knots, (4) 140 knots and (5) maximum forward velocity (VH).

Single Pitch Rod Adjustment Test

Table 1 shows Rotor Track and Balance (RTB) vibration and track data for the initial flight.

Table 1. RTB Data for Initial Flight

	A-B (ips)	A+B (ips)	Track (in)
Ground	0.16	0.19	1.0
HOGE	0.19	0.12	0.8
120 kts	0.15	0.25	1.5
140 kts	0.13	0.24	1.0
VH	0.06	0.21	1.2

After this flight, the Pitch Control Rod (PCR) on the blue blade was extended 10 clicks. The vibration and track data collected during the flight following this adjustment are shown in Table 2.

Table 2. RTB Data after Blue PCR Extension

	A-B (ips)	A+B (ips)	Track (in)
Ground	0.46	0.22	2.8
HOGE	0.60	0.26	2.8
120 kts	0.37	0.69	3.6
140 kts	0.43	0.78	4.7
VH	0.53	0.84	4.5

Table 3 shows the vibration and track data recorded during the flight following the implementation of the ROTABS adjustments. In every operating regime the vibration is greatly reduced, and with the exception of VH, is lower than recorded before the rotor was thrown out of balance by extending the pitch rod. The ROTABS adjustments reduced the track spread from a maximum of 4.7 inches to 2.3 inches.

Table 3. RTB Data after ROTABS Adjustments

	A-B (ips)	A+B (ips)	Track (in)
Ground	0.13	0.11	1.2
HOGE	0.08	0.05	1.2
120 kts	0.06	0.10	2.0
140 kts	0.06	0.10	2.0
VH	0.16	0.21	2.3

Single Tab Bend Test

Following this flight the tab on the red blade was bent down 10 mils. The vibration and track data collected during the flight following this adjustment are shown in Table 4.

Table 4. RTB Data after Red Tab Bend

	A-B (ips)	A+B (ips)	Track (in)
Ground	0.31	0.03	2.1
HOGE	0.25	0.10	1.7
120 kts	0.14	0.34	4.3
140 kts	0.19	0.45	5.2
VH	0.38	0.61	5.9

Based upon the vibration recorded by KT-3 during this flight, the ROTABS computed adjustments were made. The vibration and track data taken during the confirmation flight are shown in Table 5. Again the vibration is greatly reduced in all operating regimes. The track spread is reduced from 5.9 inches to 3.3 inches.

Table 5. RTB Data after ROTABS Adjustments

	A-B (ips)	A+B (ips)	Track (in)
Ground	0.10	0.05	1.4
HOGE	0.07	0.08	1.3
120 kts	0.04	0.08	2.1
140kts	0.07	0.24	2.8
VH	0.15	0.21	3.3

Based upon the vibration data collected during this flight, a second set of ROTABS corrections were computed and made. The vibration and track spread recorded on the flight following the implementation of these adjustments are shown in Table 6.

Table 6. Second ROTABS Adjustment RTB Data

	A - B (ips)	A + B (ips)	Track (in)
Ground	0.16	0.21	1.6
HOGE	0.05	0.08	1.3
120 kts	0.04	0.10	2.2
140 kts	0.07	0.14	2.0
VH	0.08	0.21	2.7

Equal Pitch Rod Changes on Opposing Blades (Track Split) Test

As the third trial, a pair of equal pitch control rod adjustments on opposing blades, in this case the red and yellow blades, were implemented. The pitch rods on these blades were both lengthened 10 clicks.

Balanced changes of this sort have minimal or no effect on vibration at odd shaft orders (1P, 3P, and so on). They do affect vibration of even shaft orders (2P, 4P, etc.), and throw out the blade track.

Table 7 shows only the track spreads before and after the adjustments and after the ROTABS corrections. In all cases, the 1P vibration was less than 0.2 ips before and after all adjustments.

Table 7. Track Spread Summary

	Prior to PCR Adjustments	After PCR Adjustments	ROTABS Corrections
Ground	1.0	2.0	0.7
HOGE	1.1	2.4	0.8
120 kts	1.5	3.7	2.5
140 kts	1.1	4.0	2.3
VH	1.7	3.6	2.0

Paired PCR and Tab Bends (Track Split) Test

The fourth trial consisted of a paired set of PCR extensions and tab bends. The pitch control rods on the yellow and red (opposing) blades were extended 8 clicks, and the tabs on the same two blades were bent up 10 mils. Four flights were conducted including two sets of ROTABS corrections. Table 8 shows the track spreads recorded on these flights.

During this trial as well, the 1P vibration was substantially unaffected by the adjustments, and on all flights was less than 0.2 ips.

Table 8. Paired PCR and Tab Bends

	Before Change	After Change	First ROTABS	Second ROTABS
Ground	0.7	2.4	2.1	1.5
HOGE	0.8	2.7	1.7	1.4
120 kts	2.5	4.7	3.3	2.0
140 kts	2.3	4.3	3.3	2.0
VH	2.0	3.9	3.1	3.1

ROTABS was able to keep vibration within limits (below 0.2 ips) on all tests and track spread within limits except for the track split paired adjustments (3.0-3.3 mils). Test results reflect the coupling between blade flapping and rotor vibration particular to this specific type of helicopter as well as the accuracy with which specified blade adjustments can be implemented using approved methods and procedures.

16. Demonstrate automated engine health monitoring by automating the HIT check and implementing a real time engine performance algorithm. See item 5 above.

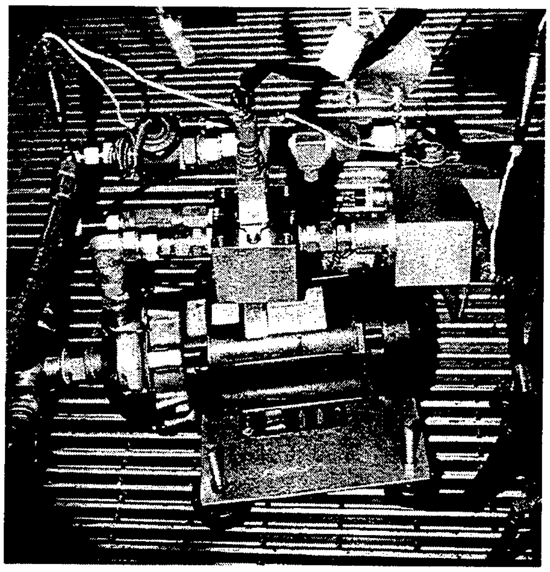

Fig. 32. Test Rig for Oil Monitoring Evaluation.

17. Evaluate as many currently available propulsion and power drive system diagnostic technologies as possible in test cell 8W and assess their relative effectiveness. Engineering evaluation testing of Stress Wave Analysis, Electrostatic Engine Exhaust Monitoring, Inductive Oil Debris Monitoring, Quantitative Oil Debris Monitoring, Optical Oil Debris Monitoring, and Acoustic Emission have been done in parallel with HIDS testing evaluation at Trenton. Two of these efforts are US Army SBIR efforts. As a means to evaluate the IDM and QDM MKII oil debris monitoring systems simultaneously, a modified main transmission lubrication scavenge apparatus was provided by Vickers Tedeco (See Figure 32). The system attaches to the main transmission module at the normal chip detector location and a positive displacement pump adds sufficient head to pump the oil through an external plumbing arrangement. Sump oil enters the pump, IDM, QDM MKII, and finally the production main module chip detector and returns to the transmission. A fine mesh screen is included to capture particles that are not captured by the QDM MKII and main module magnetic detectors. The Figure 25 main transmission input pinion with a spalled integral bearing raceway was used as a tool to generate debris for the evaluation. This test (Ref. 6) found the fault generated particles much smaller (5-20 microns) than what a typical bearing fault (>100 microns) is known to produce. This evaluation provided sensitivity and performance information.

18. Evaluate the data collected on-board the aircraft with the test cell data to validate the pertinence of test cell proven algorithms for use on-board an aircraft. As part of the HIDS program, drive system vibration data was acquired on 22 and 23 May and 30 August 1995 from SH-60 BuNo 164176 at NAVAIRWARCENACDIVPATUXENT. Data was also collected on two other SH-60 aircraft using the same data acquisition system. The data was acquired primarily to support a next generation diagnostic effort based on neural network technology and designated the Air Vehicle Diagnostic System (AVDS) program. The intent was to acquire raw vibration data on fault-free aircraft to use as a means for baselining the neural network process. For aircraft BuNo 164176 a total of 46 separate acquisitions were taken at several different flight conditions including ground turns, hover in-ground effect, hover out-of-ground effect, straight and level and descent. Torque ranged from 28-100%. Approximately one month after the May data had been acquired from BuNo. 164176, HIDS project personnel were informed that the aircraft had a history of setting off the main transmission chip detector light. The chip detector events prompted an analysis of vibration data collected from BuNo. 164176 using HIDS diagnostic algorithms. The same analysis was also conducted on one of the other aircraft , namely BuNo. 162326, to provide a baseline for comparison to aircraft BuNo. 164176. Representative envelope spectral plots of baseline and faulted aircraft data are shown in Figures 33 and 34 respectively. The fault clearly exhibits itself by the strong tones at frequencies specific to the main bevel pinion tapered roller bearing (SB 3313) both in the test cell and the aircraft. The Roller Energy indicator for the aircraft data is displayed in Figure 35.

The analysis clearly indicated a fault in the rolling elements of the starboard main bevel input pinion tapered roller bearing, P/N SB 3313 (see Figure 24 schematic for location) and represented a safety-of-flight concern. Further confirmation of fault location was provided by chip elemental analysis, conducted by Sikorsky Aircraft, which determined that the chips were CBS 600 steel indicating that this bearing was one of several possible sources of the chips. Based on the analysis, the HIDS team strongly recommended that flight operations on aircraft BuNo. 164176 cease and the main gearbox be removed and sent to NAVAIRWARCENACDIVTRENTON for installation and continued testing in a test cell environment to provide a comparison to flight test data (see Figure 36 for test cell data). Moreover, the urgency to remove the gearbox from service was a result of the HIDS team assessment that the presence of the oil dam (P/N 70351-38124-101), adjacent to the bearing was a barrier to chip migration thereby (1) preventing the chip detector from indicating the true severity of the failure development and (2) creating a reservoir of chips which may act to increase the failure progression rate. Action was taken to comply with the recommendation. Subsequent teardown and inspection confirmed that 13 of the 23 rollers in the bearing were severely spalled as shown in Figure 37. Inspection revealed a large amount of debris harbored by the oil dam, confirming the HIDS team suspicion that the oil dam acted as a chip reservoir.

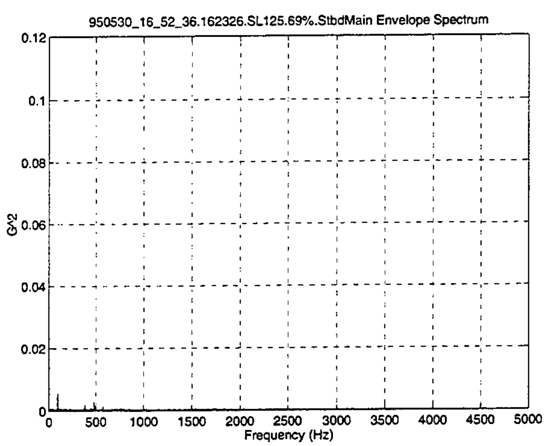

Fig. 33. Baseline Spectrum for Bearing SB 3313.

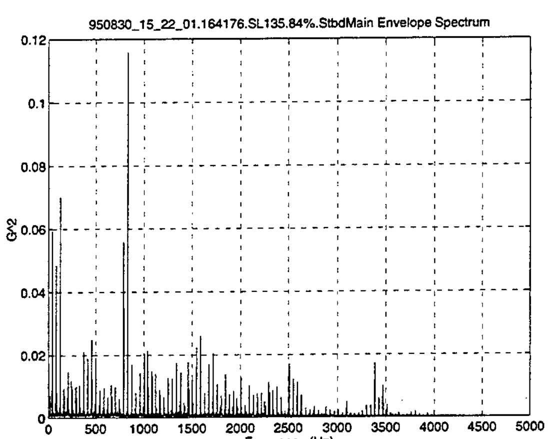

Fig. 34. Fault Spectrum for Bearing SB 3313.

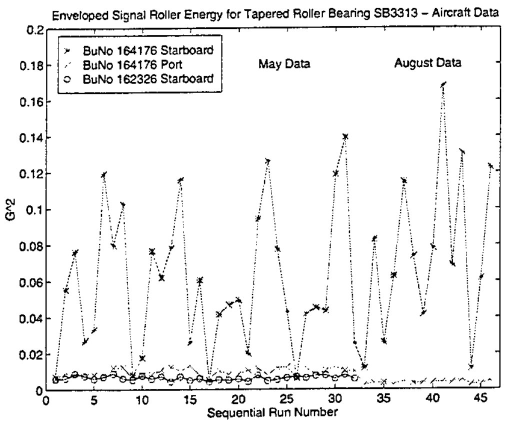

Fig. 35. Enveloped Signal Roller Energy for Bearing SB 3313, Aircraft Data.

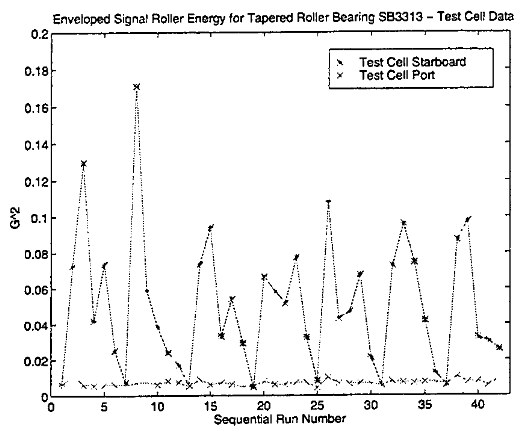

Fig. 36. Enveloped Signal Roller Energy for Bearing SB 3313, Test Cell Data.

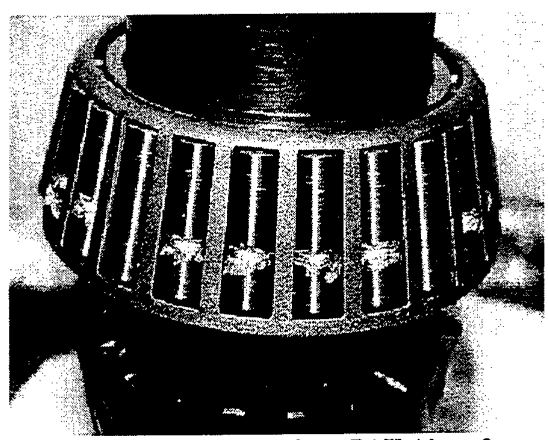
Fig. 37. SB 3313 Removed from PAX Aircraft.

19. Categorize diagnostic results with respect to aircraft flight regime to define optimized system acquisition and processing requirements. Review of Figures 35 and 36 reveals a great deal of scatter in the

value of the faulted bearing indicator. This is due to the differences in flight regime and torque. A fault must be loaded to excite a discrete frequency, and a determination of what regimes produce satisfactory results is needed.

20. Demonstrate automatic acquisition of mechanical diagnostics and ROTABS via flight regime recognition. Automatic acquisition via regime recognition of drive system diagnostics data and rotor track and balance data have been demonstrated.

21. Demonstrate real time, on-board analysis and health assessment of drive system gears, shafts, and bearings. The real time data acquisition and analysis for all channels was demonstrated in the test cell in May 1995, and in the aircraft in May 1997. The KT-3 system was found to have a hardware processing limitation on the Shamrock quad DSP which prevented it from calculating the optimum length of data for bearing analysis for all aircraft bearings in parallel. This shortfall has been overcome during the H-53E Early Operational Assessment by the implementation of a Pentium processing board on the second generation KT-3.

22. Demonstrate structural usage functionality in groundstation. Figure 38 is a view of the groundstation window which the HIDS team and BFG have worked to develop. By using flight regime recognition and structural usage calculations, component damage can be calculated in near real time. A rotor system component with flight regime, flight hours, and damage assessment to date is displayed.

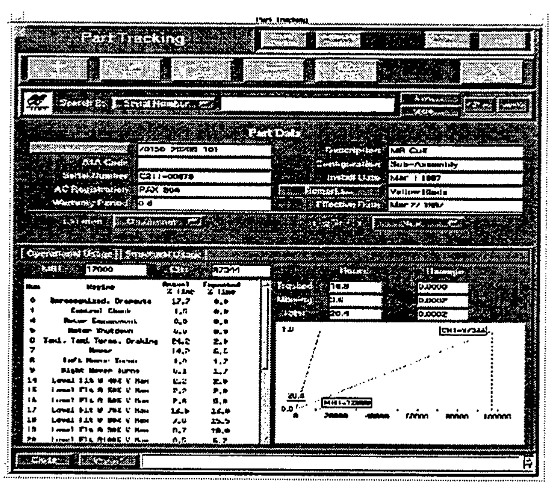

Fig. 38. Groundstation Window.

23. Demonstrate the diagnostics ability to reduce component "false removals" and trial and error maintenance practices. Several fleet removed components which were tested at Trenton were found to be fault free. Four hydraulic pumps removed for oil pressure problems were found to operate normally in the Trenton test cell. An input module removed for chip generation was tested. No debris was generated, and the diagnostics indicated a healthy component. Subsequent teardown inspection at Sikorsky revealed no dynamic component degradation.

24. Demonstrate methods that reduce false alarms and improve component condition assessment. Numerous indicators have been developed to quantify health of the drivetrain components. Rather than use each of these indicators in isolation, practicing data fusion can derive additional benefit. Multivariate Analysis is currently under investigation and has been shown to increase robustness of condition calls. Tighter control limits can be established by taking advantage of underlying correlation among the indicators while developing a composite indicator that changes by orders of magnitude in the presence of a fault.

Conclusions and Recommendations

1. This collaborative effort has provided significant benefit to the US, Australia and UK, in the form of a rich vibration database, diagnostic reports and integrated HIDS lessons learned.

2. The U.S. Navy has taken an aggressive approach in the evaluation and validation of propulsion and power drive system diagnostics through the HIDS effort.

3. Raw digital time series data files are a valuable asset for evaluating the performance of diagnostic algorithms, and are necessary to identify system problems that result in false alarms. The data allows for development of system built in test features to negate potential false alarms, and provide system maintenance direction.

4. Technology to monitor and diagnose aircraft systems exists today, but reliable vibration diagnostics requires the capability to record raw data for baseline development of aircraft types to establish production system algorithms and thresholds. Raw data collection capability and detailed analysis prior to release of aircraft from overhaul is a necessary part of system development and fleet support.

5. Testing needs to continue in the HTTF to expand the database and refine the correlation of defect

size to algorithm output level for alarm threshold settings on the SH-60 and H-53E. Continue refinement of vibration diagnostic algorithms and QA/QC routines and implement into aircraft system. Expanded testing to include the following:

(a). Testing of fleet gearboxes rejected for vibrations or chips. Support from the Class Desk and Depot has been coordinated for identification and testing of components.

(b). Continue testing of EDM notched gears and bearings for fault propagation testing at HTTF.

6. NAVAIRWARCENACDIVPAX needs to continue flying the HIDS system to continue evaluation of functional capabilities while developing recommendations and requirements for a fleet system.

(a) Ongoing work is required to improve correlation of engineering diagnostic outputs with component conditioning to effect meaningful fleet information and recommended actions.

(b) Expand diagnostic system data base for regime recognition and structural usage monitoring algorithms for the H-60.

(c) Validation and implementation of ROTABS technology in flight test aircraft. Survey other aircraft to expand database. Recommend procuring portable ROTABS system for aircraft survey to expand database. Maintenance procedures to minimize functional check flights need to be developed, allowing for regular rotor system improvement without maintenance down time. Small adjustments to the system on a regular basis is the maintenance concept that could negate the need for a dedicated functional check flight.

(d) Altitude flight testing and validation of T700 Power Performance Index algorithm to expand the data base for additional refinement of the on-board monitor of performance.

7. Expand system demonstration to leverage off the HIDS propulsion and power drive efforts to include the additional functions required by a fleet health monitoring and maintenance system, i.e. logistics and structures.

(a) Add an automated NALCOMIS interface that will update upon HIDS system download into the ground station. Expose fleet maintenance and NAESU personnel to capabilities for development of fleet friendly interfaces and functions. Incorporate the existing H-60 Integrated Electronic Technical Manuals (IETM) and develop a connectivity between maintenance actions recommended by diagnostics and the procedure in the IETM.

(b) Utilize the existing data acquisition system which records all of the required parameters for regime recognition and structural usage monitoring by including algorithms to calculate these functions in the HIDS system demonstration.

8. Testing for vibration analysis evaluation and validation in the NAVAIRWARCENACDIV-TRENTON HTTF has provided a tremendous foundation for a thorough understanding of the vibration characteristics and transmissibility between dynamic components of the SH-60 drive system. Future HTTF test efforts should require vibration databases to be established using the KT-3 raw vibration data system. Upgrade the HTTF to allow for testing of the CH-53E at full power. Provide vibration test facilities at overhaul as a quality assurance check and initial aircraft baseline for when the component is installed. These data records will provide component level baseline prior to installation on the aircraft.

9. Demonstrate groundstation interface with USCG Aircraft Computerized Maintenance System.

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Developments in Non-Intrusive Diagnostics for Engine Condition Monitoring

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Abstract
Knowledge of the condition of a gas turbine engine is essential for both flight safety and cost effective operations, particularly in the military environment with severe operating conditions, critical missions and limited fleets. One option is for military operators to look for new engine condition assessment tools. However, these tools must be practical for use on an operational base or at least in an overhaul centre, if real benefits are to be seen. Non-intrusive sensors using thermal radiation and spectroscopic analysis appear as promising technologies. The Institute for Aerospace Research of the National Research Council of Canada is working with the Canadian Department of National Defence to assess the effectiveness of these two, engine condition monitoring methods. The real-time, online capabilities of these two methods are of particular interest. Results of bench and implanted fault studies are shown for the infrared thermography study, demonstrating fault isolation in a test cell environment. Limited implanted fault tests with actual turbine rubs in a J85 turbojet are also reported to demonstrate early promising results for the use of spectroscopy. Field usage assessments are a key part of the overall project; some details are given of the use of the thermography tool at an overhaul centre and also on the flight line.

1.0 Introduction
In recent years, the National Research Council of Canada (NRC) has worked together with the civilian and military staff of the Canadian Forces (CF) to conduct relevant short and longer term research and development for gas turbine propulsion systems. In general, the goals have been to reduce life cycle costs and to maintain or improve safety.

To achieve these goals, the major emphasis for the Propulsion Laboratory of NRC has been to integrate effort in two initiatives. The test technology initiative aims to improve and validate methods and equipment for assessing the performance of propulsion system components. The second, complementary initiative is in system diagnosis. There the aim is to take validated measurements and infer the physical or functional condition of components and to do that with a known confidence level (Bird, 1994). In some cases, this confidence assessment depends on comparisons to fault libraries, compiled from laboratory tests or field data (MacLeod et al., 1992).

One aspect of the integration of the test and diagnosis technology studies has been the recognition of a promising contribution for non-intrusive methods. This paper is intended to provide both a background and a status report for NRC's efforts in this area. First, this paper identifies the need for new methods for operational engines. Next, infrared thermography and spectroscopy are selected from promising, existing or emerging technologies. Details are then given for current studies and results with these methods. Application needs for field usage are discussed. Finally, near term plans, recommendations and opportunities are covered.

2.0 Identification of the Need
Gas turbine engines are mission critical components of many air, marine and ground vehicles.

To the already large inventory of engines, projections for the 1997 to 2006 time frame are for an increase of more than 50,000 turboprops and turboshafts. The total value of these additions alone is forecast at more than $US110 billion (Franus and Opdyke, 1997).

These data give a clear view of the substantial initial investment for an operator. The full cost of ownership includes several overhauls, each at a significant fraction of the first cost. In many cases, the overhaul needs will vary depending on the actual service seen by the engine and aircraft. The on-condition maintenance schemes devised to address this situation require the identification of significant degradation in an installed engine. Often this degradation will occur in the physical condition of the gas path components before measurable performance losses are evident.

Reviews of overhaul records yield details of actual engine degradation modes that are useful to identify condition assessment requirements (Bird, 1988):

a) fan/compressor casing rubs, sometimes covering up to 90 degrees circumferentially,
b) labyrinth or honeycomb seal rubs,
c) combustor liner cracks and fretting around mounting points, and
d) turbine tip rubs and trailing edge loss.

In all of these cases, costly and potentially dangerous damage is accompanied by the loss of metallic particles into the air stream of the operating engine. The expected duration of these events may range from seconds to many hundreds of hours. In all cases, knowledge of the existence, location, duration and extent of the damage would provide important information to engine maintainers and life cycle managers.

2.1 Program Goal

This program is to assess available or emerging technology for non-intrusive monitoring of the condition of gas turbine engines by operators. To be relevant to operators, the methods must show promise for use in test cells and/or on the flight line. Technology demonstration and validation must include operation on a real engine with relevant, actual faults.

3.0 Relevant Technology

Thanks to the results of many dedicated industry and government efforts, the gap is narrowing between technology that functions only in a laboratory and that which can be applied in the field. National and international initiatives like space programs have provided the technical and financial stimulus for new science and for 'tools' relevant to the monitoring of gas turbine operations.

Surveys of measurement technology capabilities are essential to evaluate possible benefits and development or demonstration needs. In response to the challenges presented by the next generation of advanced controls, Barkhoudarian et al. (1993) have assessed measurement needs and available or emerging technology. While they were primarily interested in rocket and hypersonic propulsion systems, they did recommend a number of technologies (with associated applications) such as:

a) Development ready: spectrometry -emission and absorption (8), ultrasonic tomography (4), and several other optical sensors (1 to 3); and
b) Research-type: optical gas diagnostics (17), gas anemometer (5), exoelecton fatigue detector (3) and acousto-optic flaw detector (3).

General reviews of non-intrusive methods have been prepared by Breugelmans (1993, 1994). Detection of a particle's electrostatic charge has been demonstrated as a promising technology (Fischer, 1988). However, this effective detection method may be limited in the identification of actual elements. Review of these methods and other sources by MacLeod et al. (1994) and Paradis (1997) were the preliminary steps in the selection of infrared thermography and spectroscopy, respectively, as development projects at NRC. Some details of the background for these two non-intrusive methods are given in the following sections, before the discussion of the individual project achievements in sections 4 and 5.

3.1 Infrared Thermography

IR methods have been applied for more than 25 years, although most often for aerodynamic research (Gartenburg and Roberts, 1992). Gas turbine applications have occurred more recently, in two main areas. External casing temperatures have been measured cost-effectively over large areas (Mahulikar, 1992 and Burns 1994). To aid or frustrate detections, observability of exhaust plumes has also been an important stimulus for developments (Sully et al., 1996 and Breugelmans, 1993,1994).

Infrared thermography offers the capability to remotely map thermal patterns, measuring radiation at thousands of points simultaneously. Typical refresh rates of 30 Hz are compatible with gas turbine transient performance changes. Detectors are available in different wavelength ranges for cold end components or cases (8 to 12 μm) and hot end or plume studies (3 to 5 μm).

With available IR cameras, metal and gas spectra can be distinguished by the use of flame filters. However, calculation of the metal temperature depends on applying an emissivity value to the measured radiation energy data. In practice this may be difficult unless there is a reference thermocouple in the field of view or the surface condition of the metal is constant. For example, external casings can be painted with high temperature, high emissivity, flat black paint.

Based on this background and these applications, infrared thermography was identified as a technology to assess for possible use as an engine condition monitoring tool. The details of this investigation are presented in section 4. The second initiative in spectroscopy is presented in the next section to highlight these complementary efforts.

3.2 Spectroscopy

Non-intrusive methods based on spectral emissions have been used for both industrial (Wittmann, 1983) and for propulsion systems. Relevant liquid, solid and hybrid rocket engine applications were detailed in a preliminary survey and assessment at NRC (Paradis, 1997). Emission spectroscopy was identified as the method in most of these applications.

Exhaust plume sampling applications of emission spectroscopy have been particularly effective (Hudson et al., 1994). Condition monitoring of the critical Space Shuttle main engine has been a stimulus for the development of methodology and hardware. Tejwani et al., (1992, 1993) demonstrated the capability of this method to identify metallic components injected into the combustion chamber during liquid rocket engine tests. Concentrations were 2 to 50 parts per million (ppm) for single elements like chromium, nickel, manganese, aluminum, cobalt and iron. A spectral range of 300 to 420 nm was employed with a resolution of 0.25 nm. Manganese was detected at levels as low as 0.05 ppm and clear identifications were also made for iron, chromium and nickel. The same tests also simulated alloys, e.g. Incoloy, Inconel, and Hastelloy, at similar concentrations. Unambiguous identification of these alloys proved more difficult because most shared the readily detected, common elements. Some automated methods were proposed for improving the identification of alloys.

Spectroscopy has also been widely used as a means of detecting the presence and concentrations of pollutants (Hilton and Lettingham, 1998). Regulatory requirements have driven the need for such emissions monitoring. Gaseous pollutants like nitrous oxides, carbon monoxide and carbon dioxide have been the targets. Recommended practices have been produced which detail methods, accuracies and calibration procedures (SAE, 1990).

However, recent applications for gas turbine engines use low cost, non-spectroscopic sensors (Schubert et al., 1996 and Snyder and Neulicht, 1996). These applications also use one minute sampling averages to derive functional correlations of measured emissions (concentrations of 50 to 4000 ppm) to readily measured engine performance parameters, e.g., specific humidity, barometric pressure, inlet air temperature, exhaust gas temperature and compressor discharge pressure. Accuracies of 2 to 7% were achieved (Snyder and Neulicht, 1996). Although this result is not a direct use of spectroscopy, it demonstrates an important gas turbine application where the practical systems are traceable to such technology.

Based on this background and these applications, spectroscopy was identified as a technology to assess for possible use as an engine condition monitoring tool. The details of this investigation are presented in section 5.

4.0 Progress with Infrared Thermography

Early feasibility studies began at NRC to measure thermal patterns at temperatures relevant to gas turbines. Emphasis on hot end components focussed efforts on temperatures in the 500 to 1000 K range. The intent was to demonstrate the feasibility of the techniques first on bench tests and then on actual fleet engines. These tests have been supplemented by gathering field data from fleet engines to establish engine-to-engine variations that would affect field applications.

In addition, conceptual designs have been prepared for a fibre optic probe to replace thermocouples in critical installations. Details of the thermography studies only are presented in the following sections.

4.1 Bench Tests

Preliminary work began with an investigation of possible limitations inherent in commercially available IR cameras (Mulligan et al., 1996). Atmospheric transmissivity, reflectivity, emissivity and response were investigated. Bench tests covered particular studies with the following results:

a) Sampling errors: Imaging a heated, black, aluminum block with a reference thermocouple indicated standard deviations of about 2 K or 1%.

b) Viewing angles and surface condition: For viewing angles less than 50 degrees, high emissivity values were biased less than 2%, and at angles up to 80 degrees the change was only 6%. For low emissivity (shiny) surfaces, the emissivity bias for angles less than 60 degrees was 4%.

c) Metal and gas temperatures: Metal temperatures measured over a narrow IR band (unaffected by carbon dioxide emissions) matched thermocouple readings within 3.5%, the expected accuracy of the camera system. Gas energy levels could also be measured. However, since emissivity measurements or calibrations for typical gas flows are difficult to obtain, gas temperature estimation was not possible.

In conclusion, operating parameters for IR energy measurements were identified and accuracies quantified. Metal temperature methods were developed. An image subtraction technique was devised to separate gas energy signatures from metal energy signatures taken with flame filter.

4.2 Engine Fault Tests

Extensive tests have been conducted with a T56 turboshaft engine, by imaging the thermal patterns in the turbine exhaust flow (Mulligan and MacLeod, 1997). Several component faults identified at the overhaul contractor were implanted in the engine installed in a sea level test cell, as shown in Figure 1.

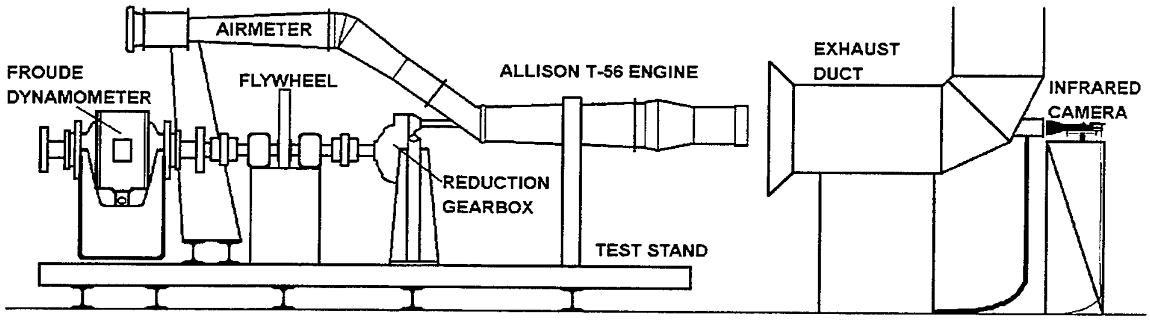

Figure 1. Engine/Imager Installation (from Mulligan and MacLeod, 1997)

Extensive software development was required for image processing. Methods were developed to account for biases introduced by ambient temperature differences between tests. Additionally, software was devised to handle variations in the calibration of the bank of detectors in the Hughes 7300 Thermal Video system. This analysis software allowed pixel-by-pixel comparisons of images with and without faults at selected power settings.

IR image identification of faults was compared to a conventional method using only the engine turbine inlet thermocouples. The following faults were investigated:

a) *Fanning fuel nozzle:* Images with installed nozzles giving spray angles of 109 and 119 degrees were compared to nominal nozzles with a 106 degree spray angle. The IR method detected significant temperature differences (> -8 K) in 3 of 6 test conditions while the conventional method failed to detect any change. Figure 2 shows a difference image.

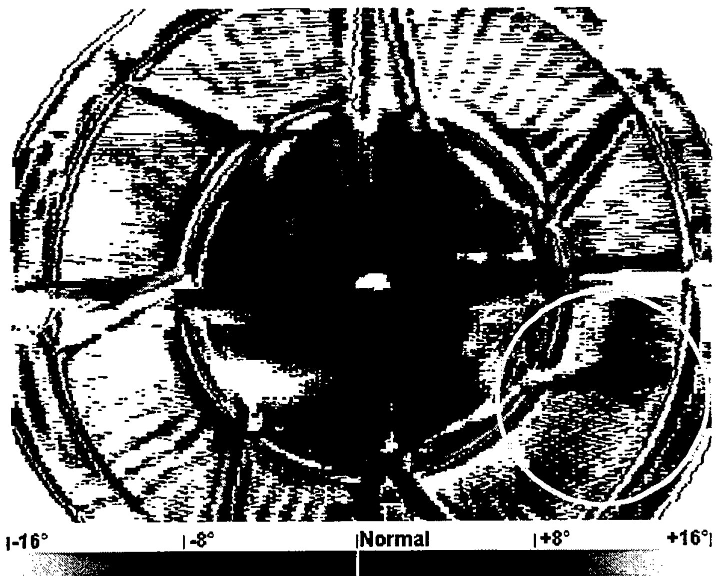

Figure 2: Fuel Nozzle Fault-Fanning Pattern (Mulligan and MacLeod, 1997)

b) *Streaking fuel nozzle:* Images with streaking nozzles installed were compared to those with nominal nozzles. The resulting hot spots were detected by the IR methods from the significant temperature differences (11 degrees). The IR methods detected this fault in 11 of 12 cases; the thermocouple method found 3 of 12 implanted faults. Figure 3 shows a sample difference image.

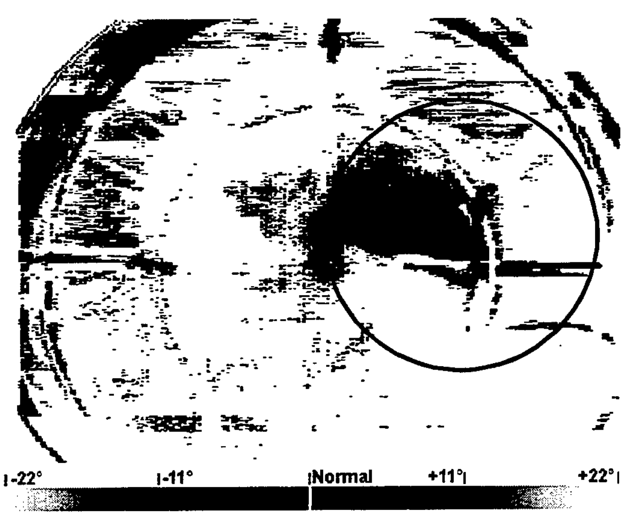

Figure 3: Fuel Nozzle Fault- Streaking Pattern (from Mulligan and MacLeod, 1997)

c) *Damaged combustor can:* Deformed combustor cans were detected by the IR system in 3 of 6 cases. During the same tests, no changes could be detected with the thermocouple system.

d) *Turbine inlet guide vane damage:* Burned and bowed inlet guide vanes were not detected by either the IR system or the thermocouples.

e) *Unserviceable turbine inlet thermocouple:* Both shorted and open thermocouples were installed. The expected change in fuel flow scheduled by the fuel control resulted in a change in image intensity. However, the analysis software in accounting for ambient temperature changes normally eliminates such changes. Therefore, this fault was not detected by the IR system.

In conclusion, significant differences were detected by the IR system and associated image processing software for several faults relevant to field use of the T56 engine. Hot and cold spots were readily quantified both in magnitude and in size, in a test cell environment.

4.3 Field Tests

While the library of healthy and faulted images has been collected and validated for a test cell environment, these tests were based on one gas generator. The current phase of the project has seen a complete IR system installed in a production test cell at the CF overhaul agency, Standard Aero Ltd. The aim of this phase of the project is to gather data on a sample of fleet engines to assess the variability of baseline and faulted patterns across a fleet and over a wide range of ambient temperatures. In addition, since images will be gathered before and after overhaul, new fault images should be added to the existing library.

The second part of the field test phase is the imaging of installed T56 engines, right on the flight line. A mounting apparatus has been constructed to fix the camera at a safe but useful distance behind a C130 aircraft. Preliminary images have already been gathered. The intent is to capture images from several engines over an extended period of time. Normal and abnormal engine degradation data are anticipated. CF operational staff will also assess the needs for introduction of IR tools into service.

5.0 Progress with Spectroscopy

In our initial survey (Paradis, 1997), no evidence was found of the application of spectroscopy to gas turbine engines. This initial study identified some of the limitations of the method for a gas turbine application. For example, rocket motor exhaust temperatures are typically more than 3000 K compared to gas turbine temperatures of 1000 K. Consequently, gas turbine exhaust would have a very small population of upper energy level metallic atoms, which would give insufficient emissions without an external energy addition.

Detection will also depend on the size and number of particles present. Limited information was available on the particles that result from engine gradual degradation or discrete damage events. The NRC survey found that particles in the gas path should be less than 1 µm (Boyle, 1996 and CRC, 1977). Boyle's work also suggests that concentrations of particles would be of the order of 10^9 particles/hr/square inch. Paradis (1997) hypothesises that these findings suggest that the total mass of ejected material might be 10^{-5} g/s for events of 5 to 30 ms duration. With typical engine airflow, this would only provide concentrations of less than parts per billion (ppb). These events and those with duration of one second or more appear to be at the threshold of the capability of available spectroscopy equipment.

Investigations have also shown the feasibility of vapourization techniques suitable for these particle sizes and for the relatively low gas temperatures in a gas turbine, outside of the primary combustion zone. Paradis (1997) identified lasers and plasmas capable of vapourizing particles up to 30 µm with local temperatures of 6000 to 10000 K. DC plasma torches used for metal coating have also been identified as feasible vapourization tools (Wittmann, 1983). Recently, Moreau et al. (1995) have studied the temperature, velocity and diameter of metallic particles at

380 to 550 m/s by sensing thermal radiation in a practical plasma torch.

NRC in-house activities have sought to extend these promising findings (Mulligan and MacLeod, 1998). A series of engine and bench tests have been supplemented by a recent activity to characterize particle sizes from rub events. Details are provided in the following sections.

5.1 Sampling Tests

Initial feasibility tests were planned with a J85 turbojet test engine to determine the capture efficiency of proposed sampling methods. Practical, single point probes cover nominally only 0.003 to 0.03 percent of the internal compressor and turbine flow areas of interest. The sampling method was to draw a known flow from the engine through fine filters (Environment Canada, 1993). These filters could then be analyzed off-line with a specialized, high accuracy mass spectrometer at NRC's Institute for Chemical Processes and Environmental Technology.

Consequently, it was necessary to first establish whether reasonable amounts of material could be captured. Initial tests with a rare earth element added to the fuel failed to detect this element. It was suggested that the particles were vapourized in the combustor before reaching the sampling probe in the turbine exit.

Another aspect of the sampling problem was the identification of contributions from the ambient air streams entering the engine and also entering the cell exhaust. Measurable levels of zinc, silicon, nickel and cadmium were detected in the ambient air. It was found that these levels increased with the engine running because of the high, induced airflow in the test cell. It was determined that establishing the ambient levels of the elements of interest was difficult with the current sampling methods. Consequently, it was decided to try to induce real damage events and then look for changes, not absolute levels, in the measurements of the sampled elements.

5.2 Preliminary Engine Fault Tests

Typical engine damage or degradation occurs when turbine blades rub on the shroud seals. Since these seals are relatively cheap and easy to replace, a procedure was devised to mechanically deform the seals, nominally 1mm, before installation. Engine tests were conducted with sampling at idle and 70% of design rotor speed. Mulligan and MacLeod (1998) found increases in chromium, nickel, molybdenum and cobalt in the turbine exhaust and test cell exhaust samples. These species are component materials for the seals and blades. These results qualitatively agree with the loss in mass of the seals (40 mg).

A second series of engine tests sought to confirm these encouraging results and better quantify the actual changes. An additional probe was installed downstream of the compressor to measure the incoming particles either in the ambient air or generated in the compressor. In all cases, samples were extracted from the engine under iso-kinetic conditions: the flow rate of the sampling pumps was set to match the engine airflow at that probe's location. In this way, sampling would be complete over the flow area covered by the probe.

Four different power settings were used with the J85 engine, again with dimpled seals. A sample was taken during rollover to idle to detect any start-up rubs. A second sample was taken at idle, nominally to capture the ambient air sample, assuming that the rub event was finished. The third sample covered the 10 second period after a rapid acceleration to 95% power. Two, five minute samples were then taken at this high power after slow accelerations from idle (when the filters were changed).

Results from the isolation of nickel and chromium are shown in Figures 4 and 5. The concentrations of the samples collected on the filters were determined by a careful laboratory technique (Mulligan and MacLeod, 1998) by the spectroscopy specialists at NRC's Institute for Chemical Processes and Environmental Chemistry. The particles attributed to the rub are indicated by the difference between the compressor exit and turbine exit probes. Although the overall concentrations are small, they are significant within the repeatability and accuracy of the mass spectrometer used.

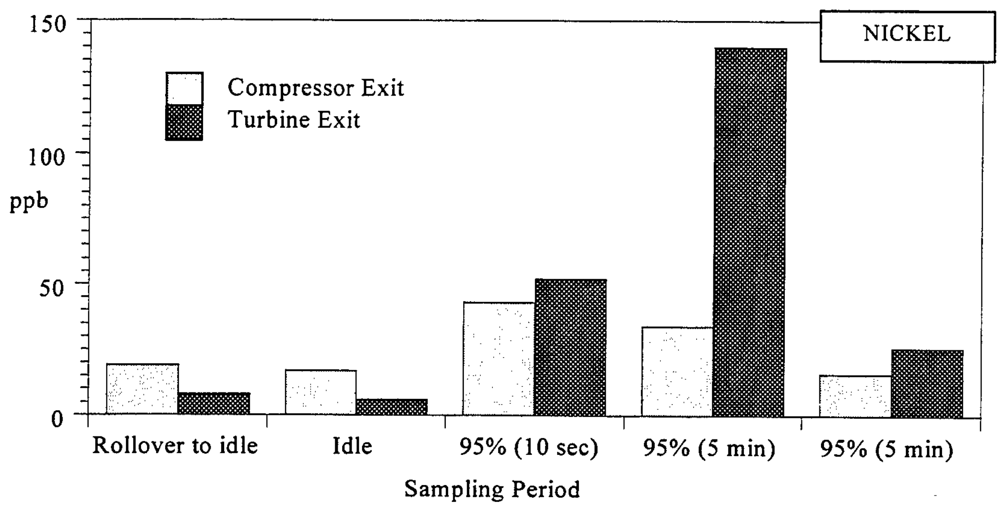

Figure 4: Nickel Concentration Results for Compressor and Turbine Exit Probes

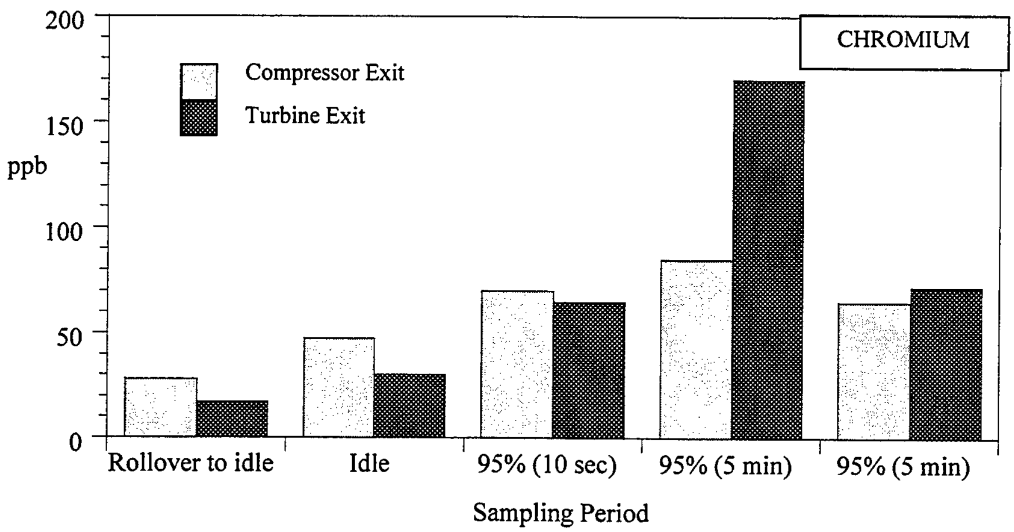

Figure 5: Chromium Concentration Results for Compressor and Turbine Exit Probes

The generally higher levels in the last three samples compared to the idle samples are likely caused by the higher airflow at the 95% power setting. Some measure of the sample-to-sample repeatability may be associated with the levels for samples when no rub is expected, i.e., the second and fifth samples, nominally 25 ppb for nickel and 50 ppb for chromium. Considering this ambient level, the increases seen for the fourth sample appear significant.

Seal mass losses were measured at 160 mg, following the complete test. These seals were 47% nickel and 22% chromium which would mean some 75 mg and 35 mg respectively of these metals were ejected into the exhaust gases. When the concentrations of nickel and chromium are converted to mass, based on the measured sampling area of the associated probes, the total collection is estimated at 6 mg, which is about a 5% collection efficiency. Considering all of the elements, some 32 mg were estimated as collected, or a 20% collection efficiency. These results indicate the feasibility of detecting events, like rubs, with spectroscopic methods.

5.3 Particle Characterization

To apply spectroscopic methods on-line appears most easily done through emission spectroscopy. This approach would require an external energy source and detectors (Paradis, 1997). To optimize the selection of available vapourization sources (Moreau et al., 1995), knowledge is required of the particle sizes and distributions from relevant events.

An existing NRC abradable seal rig was used as the first effort to characterize event particles. The pump-driven, filter-based sampling system used for the engine tests was adapted to capture particles from the rub of a titanium wheel on samples of the engine seal. Particles were transferred from the filter paper (0.2 to 5 μm mesh) to carbon tape for analysis in a scattering electron microscope (SEM). Figure 6 shows the spectral analysis of a particle, clearly indicating the chromium and nickel content.

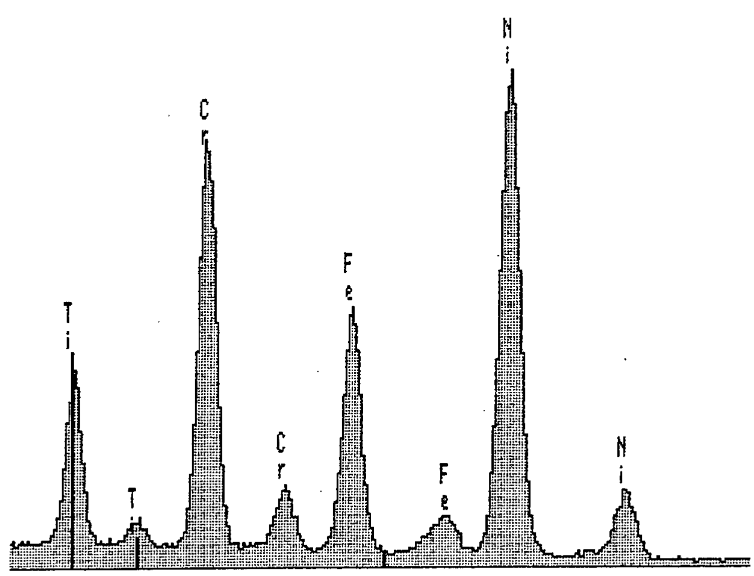

Figure 6: SEM-Measured Spectrum of a Seal Rub Particle

6.0 Applications for Field Use

A specific discussion on application issues is important to guide our efforts towards systems that can be used in the field. Installations in overhaul test cells or on portable carts for flight line use appear to be reasonable objectives. Already, spectroscopy-based sensors have seen on-board application on the space shuttle rocket engine (Bickford et al., 1991).

Infrared Thermography: Certain equipment is readily available. IR cameras with calibration methods and digital recording interfaces are commercially available. Installations downstream of engines will require silicon windows to ensure low losses (<1% loss) and a cleaning apparatus. An air jet system has been successfully implemented in an NRC test cell. The actual acquisition of data may be based on pre-selected, engine exhaust temperature settings. However, intelligent image processing software will be necessary to account for changes in ambient conditions and to perform image comparisons and to identify fault conditions.

Spectroscopy: Practical vapourization devices may be coupled with simple and robust probes with airflows provided by the internal pressure of the engine. Engine bleed flows of 100 l/min have been used to date and these should be practical for sampling in most cases. Exposure times will need to be selected to detect events, although 0.5 s has proved adequate (Tejwani et al., 1992). It will likely be necessary to assess the content of trace metals in commonly available fuel to set threshold values for event detection. Automated spectral analysis approaches will be needed to select key wavelengths from the measured emissions.

7.0 Plans

Both aspects of this non-intrusive monitoring program continue to be active areas of research and development at NRC. Program objectives continue to include validation and assessment for field use. National Defence aerospace engineering specialists are key players in the field data gathering and in the assessment of needs for possible field applications. The main efforts planned are described in the following sections.

7.1 IR Thermography

Further effort is planned and approved for extending the applicability and validity of the current method:

a) Gather field data from pre- and post-overhaul engines at Standard Aero Ltd. to quantify real fleet variations across actual ranges of ambient temperature.
b) Gather field data from installed engines on selected C130 aircraft during actual service use.
c) Extend the validated fault image library with field data.
d) Monitor detector and optics component costs to continue development of an IR probe to replace/augment standard thermocouples.

7.2 Spectroscopy

Planned work is aimed at establishing the feasibility and associated development parameters for the practical use of this technology by:

a) Characterize rub and other relevant damage particles by size distribution through the use of rigs such as the NRC abrasive seal rig.
b) Repeat engine rub tests to quantify the mass of particles generated by relevant short and long term events.
c) Establish a particle ingestion rig to optimize vapourization and optical detection components.
d) Demonstrate on-line event detection and quantification.

8.0 Recommendations and Opportunities

The background and rationale have been presented for two non-intrusive, condition monitoring projects at the National Research Council. The strength of the effort is in the multi-disciplinary teamwork that has capitalized on the contributions from scientists, engineers and operators. The progress of the work towards useable tools for engine operations would benefit from the following:

a) Continued teamwork between measurement scientists, sensor developers, engine operators and system integration specialists;
b) Rig development to optimize detector and processing equipment prior to engine test; and
c) Engine tests of relevant degradation events, both short and long duration to characterize these faults and validate automated fault detection tools.

9.0 Acknowledgements

The financial support of the National Defence Air Vehicle Research Section, as well as the moral support of Bob Hastings and his staff is gratefully acknowledged. Jim MacLeod initiated both of these efforts and is responsible for important contributions throughout the program. Dedicated efforts by National Defence DGAEPM and ATESS military staff have made the data gathering and assessments possible. Drs. Ralph Sturgeon and Alan Steele of NRC provided essential expertise, specialized equipment and most of all, their time. Key contributions have also been made by guest workers at NRC, Paul-Francois Paradis and Fabrice Catoire. Colin MacKenzie and David Chow provided their knowledge and experience to the particle characterization work. Valuable assistance was also provided by a number of students, sponsored by the Women in Engineering and Science program.

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HEALTH AND USAGE MONITORING SYSTEM FOR THE HAWK AIRCRAFT

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Abstract

This paper describes the Health and Usage Monitoring System for the Hawk aircraft supplied to the Royal Australian Air Force.

British Aerospace MA&A placed a contract upon AMS for the development of a HUMS with the following functionality:

(a) Avionics equipment health monitoring.

(b) Flight data recording in crash protected memory.

(c) Cockpit voice data recording in crash protected memory.

(d) An airframe fatigue monitoring system.

(e) Low cycle fatigue monitoring of the engine.

Health Monitoring is conducted by the sampling and storage of avionics equipment built-in test data. When a failure occurs the relevant environmental data is stored which allows detailed analysis of failure conditions on the aircraft.

In addition, failure discretes as asserted by the OBOGS are monitored and stored by the HUMS.

Airframe Usage Monitoring is conducted by sampling and processing of strain gauges mounted at key locations within the aircraft.

Engine Usage Monitoring is conducted by the sampling and processing of key engine parameters sampled from engine and aircraft sensors.

The HUMS consists of a Data Acquisition Unit, a Crash Survivable Memory Unit, a Flightline System and a Desktop System.

The Data Acquisition Unit samples, processes and stores data from sensors and aircraft equipment. It formats and transmits flight data to the Crash Survivable Memory Unit. All stored data is transmitted to the Flightline System during upload and download operations at the aircraft flightline.

The Crash Survivable Memory Unit receives formatted flight data frames for the Data Acquisition Unit and samples voice data from the Cockpit Audio Management Unit and stores this data in crash protected memory. The unit

provides storage for 10 hours of flight data and 1 hour of voice data.

The Flightline System acts as a temporary storage medium for fatigue, maintenance and flight data to be downloaded to the Desktop System. The Flightline System can also upload relevant configuration data originating from the Desktop System to the Data Acquisition Unit. Calibration of strain gauge channels as well as calculation of strain gauge channel offsets is conducted utilizing the Flightline System.

The Desktop System is a commercial off-the-shelf Personal Computer. The aircraft and engine component configuration is maintained on the Desktop System. The Desktop System allows updating of configuration parameters as well as airframe and engine fatigue databases. Calculation of airframe and engine components life consumed as well as remaining life is executed and displayed at the Desktop System.

Table of Contents

1 Hawk HUMS Introduction

The primary objective of Health Monitoring is to detect deviations from normal performance of flight critical aircraft systems at the earliest possible time so that catastrophic failures can be prevented. Health Monitoring also aims at lowering maintenance cost of aircraft through early prevention of secondary damage and monitoring of degradation trends over time.

Usage Monitoring is directed at the accurate recording of actual usage of life limited aircraft components. This allows prediction of remaining component life and moving away from scheduled maintenance actions to on-condition maintenance, resulting in cost saving without compromising flight safety.

The HUMS designed for the Hawk Lead-In Fighter Aircraft implements usage monitoring of the airframe as well as the engine with the full co-operation of the airframe and engine original equipment manufacturers. The potential benefits of actual usage monitoring (Reference 1) is shown in Figure 1.

Airframe fatigue monitoring is carried out by the measurement of direct loads from strain gauges installed onto the airframe. Algorithms supplied by British Aerospace MA&A are implemented in software to calculate the Fatigue Index of the airframe.

Engine parameters are monitored continuously and Low Cycle Fatigue is calculated by means of a Rolls-Royce Military Aero Engines supplied algorithm.

2 Principles of Health Monitoring on the Hawk Aircraft

The Mission Computer supplies Initiated Built-in Test (IBIT), Power-up Built-in Test (PBIT) and Continuous Built-in Test (CBIT) results of the avionics equipment to the on-board equipment.

The IBIT, PBIT and CBIT results are stored with relevant environmental data on occurrence of a failure. The environmental data is defined as flight data that can aid in the analysis of failures of avionics equipment. A total of 4096 failure messages can be stored on-board before a download is required.

The failure messages are downloaded to the off-board equipment, where they are analysed in detail.

During downloading of data from the on-board equipment only the equipment that failed are automatically displayed by the Flightline equipment.

3 Principles of Usage Monitoring on the Hawk Aircraft

Accurate usage monitoring of the airframe and the Rolls-Royce Adour Mk871 engine is carried out by the Hawk HUMS.

3.1 Airframe Usage Monitoring

Airframe usage monitoring is carried out on the following individual components:

a) Front fuselage.

b) Rear fuselage.

c) Centre fuselage.

d) Wing.

e) Tailplane.

f) Fin.

Data sampled from the strain gauge channels is processed and the peaks and valleys are extracted and stored by the on-board equipment. These peaks and valleys are downloaded to the ground equipment.

At the ground equipment peak and valley data is used to form range pairs. These range pairs are scaled and applied to S-N curves and a Fatigue Index is calculated. The airframe Fatigue Index database is updated with downloaded data.

The life consumed on every component is monitored accurately and held in a database for analysis and updating.

3.2 Engine Usage Monitoring

The on-board equipment will accurately sample and store the following parameters related to engine fatigue monitoring:

a) Turbine Gas Temperature.

b) High Pressure Spool Speed.

c) Low Pressure Spool Speed.

d) Outside Air Temperature.

e) Indicated Airspeed.

f) Altitude.

This data is downloaded to the off-board equipment. At the off-board equipment the data is processed using OEM supplied algorithms. From the raw data Low Cycle Fatigue Counts are calculated on every major component within the engine. The Fatigue Index and thus the life consumption are updated within the database on the ground equipment.

4 Maintenance of Strain Gauges.

Airframe fatigue is monitored by the use of conventional strain gauges. These gauges are installed on the aircraft as Wheatstone bridges to form Strain Gauge channels.

Unfortunately, the maintenance of the functions of strain gauges (Reference 1) on the aircraft can be problematic. To alleviate this problem two courses of action have been undertaken by British Aerospace MA&A and AMS. The first action is the installation of backup gauges on the aircraft and the second action is accurate monitoring of the health of strain gauge channels.

The HUMS on-board equipment will automatically verify the health of the strain gauge channels by monitoring of the following:

a) Strain gauge channel open circuit.

b) Input voltage exceedance.

c) Strain gauge channel short circuit.

d) Low activity on a strain gauge channel.

e) Excessive chatter on a strain gauge channel.

f) Excessive number of data spikes on a strain gauge channel.

Strain gauge channel health is analysed on ground equipment where decisions on strain gauge channel health is made. When a faulty strain gauge channel is detected the back-up channel will be switched into the system.

5 Hawk HUMS System Design

The architecture of the Hawk HUMS is shown in Figure 2.

The main functions of the Data Acquisition Unit are as follows:

a) Record airframe fatigue data.

b) Record engine parameters.

c) Store avionics BIT data.

d) Sample Flight data.

e) Transmit flight data to CSMU.

f) Download HUMS data.

g) Upload configuration data.

The main functions of the Crash Survivable Memory Unit are as follows:

a) Record flight data.

b) Record cockpit audio data.

The main functions of the Flightline System are as follows:

a) Upload HUMS data from the DAU and download HUMS data to the DTS.

b) Upload flight data from the CSMU and download flightdata to the DTS.

c) Upload configuration data from the DTS and download data to the DAU.

d) Perform calibration upon strain gauge channels.

e) Display high level avionics equipment and HUMS failure data.

The main functions of the Desktop System are as follows:

a) Upload HUMS and flight data from the FLS.

b) Upload and store in a database strain gauge channel calibration data.

c) Download configuration data to the FLS.

d) Update all databases with uploaded data.

e) Calculate airframe and components fatigue indexes.

f) Calculate engine and components fatigue indexes.

g) Manage aircraft, airframe and engine configuration.

h) Display of HUMS information.

i) Display of Flight Data.

6 Hawk HUMS Subsystems.

This paragraph supplies the characteristics within the Hawk HUMS subsystems.

6.1 Data Acquisition Unit Characteristics

The DAU interfaces to the MIL-STD-1553B avionics bus. This bus supplies flight data and avionics equipment BIT data. All HUMS related failure data are output on the bus by the DAU.

Interfacing capabilities of the DAU are as follows:

a) Capability to supply +10V excitation voltage to 21 strain gauge channels.

b) Samples data from 21 strain gauge channels at rates ranging from 1024 Hz to 1 Hz. (Sampling rates are configured by software).

c) Capability to supply +5V excitation voltage to 9 potentiometers.

d) Samples data from 9 potentiometers.

e) Samples data from 16 input discretes.

f) Samples data from 5 analogue differential input channels.

g) The DAU can assert 8 output discretes.

h) Samples data from 3 direct interfaces to the Engine Control Panel.

The DAU transmits fatigue data to the FLS at a rate of 10 Mbit/s.

The DAU transmits configuration data (as well as receiving data) to the FLS at a rate of 19,7 kBaud.

Memory capacity for the storage of configuration data is 2 Mbyte and the memory capacity for storage of fatigue data is 176 Mbyte.

The DAU processor extracts peak and valleys from sampled strain gauge channel data. Every detection of a peak or valley will trigger a sampling and storage of all strain gauge channels as well as selected flight data. Peak and valley data is stored in 20 Mbyte of non-volatile memory.

The DAU processor samples all relevant engine parameters at a rate of 8 Hz and stores this data in 16 Mbyte of non-volatile memory.

All detected HUMS failure data and all relevant configuration data is stored in 256 Kbyte of non-volatile memory.

Avionics BIT failure data is received as an event driven message and stored in 256 Kbyte of non-volatile memory.

The DAU housing is a standard ½ ATR configuration with circular military external connectors.

6.2 Crash Survivable Memory Unit Characteristics.

The CSMU is a ruggedised version of the SCR500 series of recorders supplied by British Aerospace Systems and Equipment.

It receives flight data from the DAU at 128 words/s and has the capacity to store 10 hours of flight data in a cyclic buffer. Voice data is supplied by the Cockpit Audio Management Unit and has the capacity to store 1 hour of voice data in a cyclic buffer.

All data is stored in crash protected memory according to EUROCAE ED55 and ED56A standards.

Data storage capacity is 128 words/s for flight data.

6.3 Flightline System Characteristics

The FLS is based on an off-the-shelf ruggedised personal computer. The weight is less than 7 kg and can be easily carried by one person.

The FLS interfaces to the DAU and CSMU on-board the aircraft via standard serial Ethernet, RS232 and RS422 interfaces.

The FLS computer is based on 133 MHz Pentium technology and has the capability to store 2 Gbyte of data on a removable hard disk.

6.4 Desktop System Characteristics.

The DTS hardware is based upon commercial off-the-shelf personal computers. An Interface Unit is installed into the PC so that the FLS can be connected to the DTS with the same interfacing as used on the aircraft. The DTS will also supply +24 VDC to the FLS.

The DTS MMI is implemented using a Windows-based environment. The MMI allows operator inputs via standard controls.

The DTS allows selection and updating of the airframe fatigue, engine fatigue and flight data databases. The fatigue data, maintenance data and configuration data for one or more squadrons are stored in a number of tables in a relational database.

Configuration management of aircraft information relating tail numbers to airframe engine component serial number are maintained by the DTS. All configuration relating to strain gauge offsets and calibration data are centralised at the DTS. The DTS will relate DAU units installed to aircraft tail numbers enabling verification of data before any database is updated.

Data corruption is prevented by Cyclic Redundancy checks on all data before any database is updated.

The DTS has special data archiving capabilities for long term storage of fatigue data.

7 Conclusion.

The HUMS developed by AMS for the new generation Hawk Mk127 Lead-In-Fighter, is an excellent example of a fully integrated HUMS. Full integration of both health and usage functionality is achieved by having these functions synchronised with the flight data as required for the CSMU. On older generation systems, these two functions were not integrated, on the correlation between the flight data and the classical HUMS function were not provided for. This obviously enhances the capability for trouble shooting or fault finding on the aircraft.

A further feature of this system is the integration of several functions into the DAU which previously were performed by separate LRU's. This obviously have a cost and mass benefit and will save on logistic support cost in the long-run.

The development of a HUMS has shown that a practical operational loads monitoring system using strain gauges can be implemented on production aircraft. This is made possible by correct installation procedures, installation of back-up gauges and the accurate monitoring of strain gauge health on-board the aircraft.

The HUMS allows accurate calculation of airframe and engine life consumption. The system is designed for ease of operation. Display of fatigue data is in graphical format and can easily be interpreted by the operator.

The system is versatile in that it can easily be adapted for different types of aircraft.

8 Acknowledgement

AMS would like to acknowledge the support and design guidance of British Aerospace MA&A with regards to the HUMS development.

9. List of References

Usage Monitoring Working Group Report to the HHMAG, January 1994.

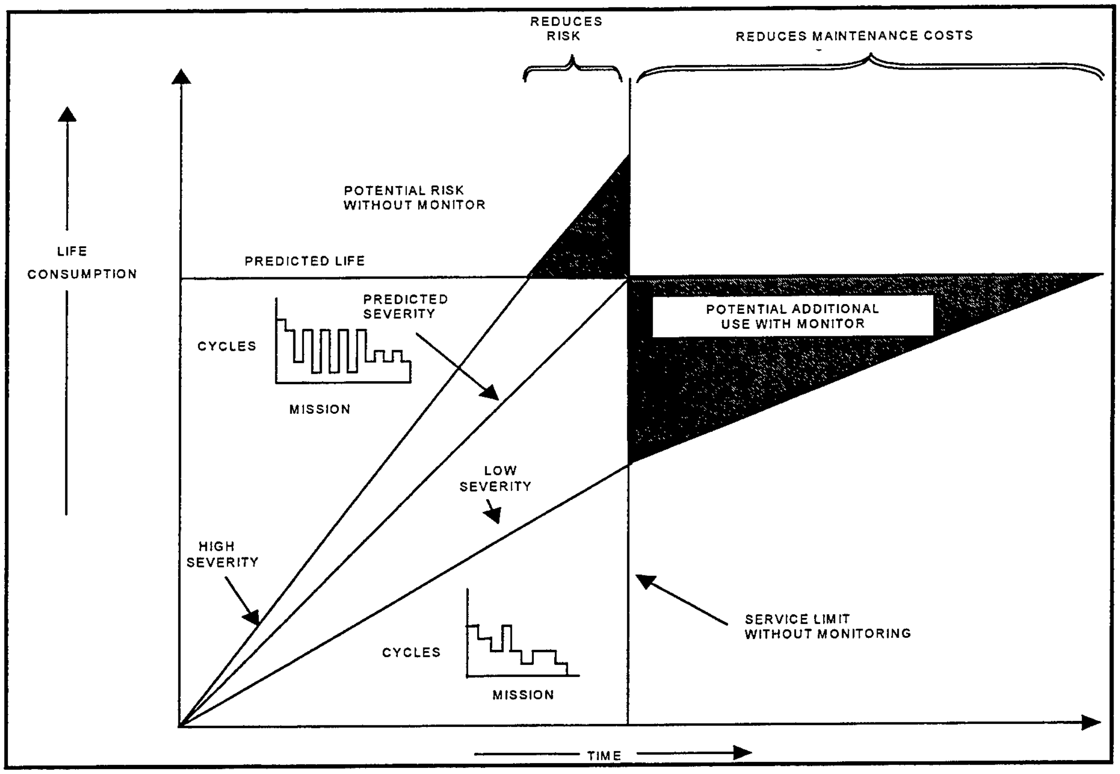

Figure 1 : Potential Benefits with Actual Usage Monitoring

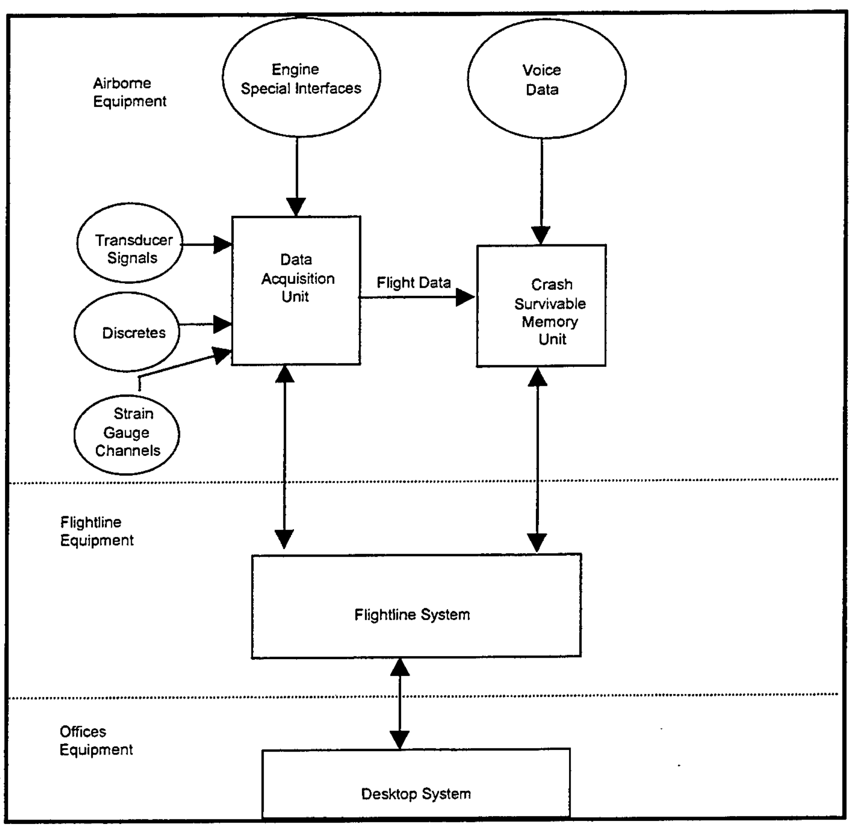

Figure 2 : Hawk HUMS Architecture

List of Abbreviations

AMS	:	Analysis Management & Systems (Pty) Ltd
ATR	:	Air Transport Racking
BIT	:	Built-in Test
CBIT	:	Continuous Built-in Test
CSMU	:	Crash Survivable Memory Unit
DAU	:	Data Acquisition Unit
DC	:	Direct Current
DTS	:	Desktop System
FLS	:	Flightline System
HHMAG	:	Helicopter Health Monitoring Advisory Group
HUMS	:	Health and Usage Monitoring System
IBIT	:	Initiated Built-in Test
LRU	:	Line Replaceable Unit
MA&A	:	Military Aircraft and Aerostructures
MMI	:	Man Machine Interface
OBOGS	:	On-Board Oxygen Generation System
OEM	:	Original Equipment Manufacturer
OLM	:	Operational Loads Monitoring
PBIT	:	Power-up Built-in Test
PC	:	Personal Computer

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19. ABSTRACT

Over the last 10 years, helicopter Health and Usage Monitoring Systems (HUMS) have moved from the research environment to being viable systems for fitment to civil and military helicopters. In the civil environment, the situation has reached the point where it has become a mandatory requirement for some classes of helicopters to have HUMS fitted. Military operators have lagged their civil counterparts in implementing HUMS, but that situation appears set to change with a rapid increase expected in their use in military helicopters.

A DSTO-sponsored Workshop was held in Melbourne, Australia, in February 1999 to discuss the current status of helicopter HUMS and any issues of direct relevance to military helicopter operations.