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AR-008-938

DSTO-TR-0072

A Portable Transmission Vibration Analysis System for the S-70A-9 Black Hawk Helicopter

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

The prototype portable transmission vibration analysis system developed by AMRL for the Black Hawk helicopter is described in detail, including the results of flight trials conducted at RAAF Base Edinburgh during July 1993. The results of these trials have proved the concept of the system and laid the foundations for the future development of smaller and lighter systems.

Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Aeronautical and Maritime Research Laboratory
GPO Box 4331
Melbourne Victoria 3001 Australia

Telephone: (03) 626 7000
Fax: (03) 626 7999

AR No. 008-938
SEPTEMBER 1994

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EXECUTIVE SUMMARY

The main transmissions of the Black Hawk helicopters operated by the Australian Army are maintained on-condition, that is they have no fixed overhaul life based on their operational hours. At present the condition of a transmission is monitored solely by the built-in magnetic plug chip detectors in the oil scavenge lines. Limits are set on the number of warnings from these detectors that are allowable before the transmission must be removed from the helicopter for overhaul.

Application of vibration analysis to the Black Hawk transmission will provide an additional means of detecting the onset of damage and the prevention of possible catastrophic failure. Vibration analysis has the potential to detect faults before they start to produce significant quantities of wear debris plus the ability to detect those faults that produce no wear debris at all, such as fatigue cracks in gears.

This report describes a prototype portable vibration analysis system for the Black Hawk that was developed at the Aeronautical and Maritime Research Laboratory (AMRL) to demonstrate the application of AMRL developed vibration analysis techniques on this aircraft. The system is based around a portable personal computer with internal anti-aliasing filter and analogue-to-digital converter cards plugged into the expansion bus. It acquires vibration data from three accelerometers mounted on the transmission while in flight and then processes and analyses this data on the ground.

The system was successfully test flown by the Aircraft Research and Development Unit (ARDU) at the Royal Australian Air Force (RAAF) Base Edinburgh in July 1993. Some teething faults were identified but these have now been rectified. Further development has been proposed including miniaturisation of the system to make it easier to use in the field.

Authors

D.M. Blunt

Airframes and Engines Division

Mr Blunt graduated from the University of Western Australia in 1989 with a Bachelor of Engineering (Mechanical) degree with first class honours. He commenced employment with the Aeronautical Research Laboratory in 1990 and spent two years on the engineer rotation scheme. Since 1992 Mr Blunt has been working in the field of gearbox fault detection using vibration analysis. During this time he has been involved with the development of vibration analysis technology for various Australian Defence Force aircraft gearboxes. These gearboxes include the main transmission of the Black Hawk and Seahawk helicopters, and the reduction gearbox of the Allison T56 turboprop found in the P3C Orion and C130 Hercules.

B. Rebbechi

Airframes and Engines Division

Mr Rebbechi graduated in 1969 with a Bachelor of Engineering (Mech) from the University of Melbourne. He commenced employment in the Turbine Design and Applied Research Group at the Aeronautical Research Laboratory in 1970, and in 1976 he received a Degree of Master of Engineering Science from Monash University. Since then, he has worked in the areas of aircraft cabin cooling, and machine dynamics, particularly with reference to gear dynamic load prediction and measurement. In 1989, he was attached for 15 months to the NASA Lewis Research Center, Cleveland Ohio, as a visiting researcher. He is currently managing several tasks related to helicopter gearbox vibration monitoring and engine vibration analysis, at the Aeronautical and Maritime Research Laboratory

B.D. Forrester

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Mr. Forrester has been working at Aeronautical Research Laboratory since November 1981. From 1987 to the present he has been involved in the areas of fault detection by vibration analysis and the development of signal processing techniques. He is responsible for providing consultancy to the Royal Australian Navy in the field of vibration monitoring of helicopter transmission components, developing and applying new vibration analysis techniques, the development of automated vibration analysis systems, and the training of defence force personnel in the applications of vibration analysis.

K.W. Vaughan

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Mr Vaughan commenced employment with the Aeronautical Research Laboratory in 1973 as an Electronic Instrument Maker with Engineering Facilities Division. Since 1980 he has been working as a Technical Officer in the field of aircraft flight trials instrumentation and fault detection using vibration analysis. During this time he has been involved in extensive fault detection investigations both in the laboratory and on many Australian Defence Force aircraft. These include the engines and associated transmissions of the Black Hawk, Sea King and Wessex helicopters, and the F/A 18, F111, CT4 and Hercules aircraft..

Contents

1. Introduction

This report describes a prototype portable vibration analysis system that has been developed to provide conceptual demonstration of a vibration monitoring system for the Black Hawk helicopter transmission. This transmission is operated on-condition, with no fixed overhaul life, and consequently there is scope for the use of various condition monitoring techniques to detect the onset of damage and hence prevent catastrophic failure.

Vibration analysis is a powerful condition monitoring tool which can supplement the existing burn-off magnetic plug chip detectors in the main transmission assembly. Vibration analysis is particularly useful in detecting faults, such as fatigue cracks, that may not produce sufficient quantities of wear debris to be detected by chip detectors.

The system described here is based on a portable 486 personal computer and associated signal conditioning hardware, and is capable of airborne operation. It can also be used on other aircraft transmissions or rotating machinery by loading alternative software. The system acquires and analyses vibration signals from accelerometers mounted on the main transmission assembly using techniques developed by the Aeronautical and Maritime Research Laboratory (AMRL). These techniques have been used in another vibration analysis system operated by the Royal Australian Navy (RAN) for a number of years and have successfully detected a number of faults in the Wessex and Sea King helicopter transmissions [Ref. 1-3].

The system was test flown in an Australian Army Black Hawk helicopter at the Royal Australian Air Force (RAAF) Base Edinburgh in July 1993 by personnel from the Aircraft Research and Development Unit (ARDU) [Ref. 4].

2. System Features

A photograph of the portable vibration analysis system is shown in Figure 1. The system is primarily designed for use with the main and tail rotor gearboxes of a helicopter transmission, however, it could be utilised to measure and record vibration data from other mechanical systems.

The features of the currently installed vibration analysis software are described below. The software is primarily based on the computation and analysis of synchronous signal averages but standard spectral analysis is also available. Other techniques can be included by the addition of more software.

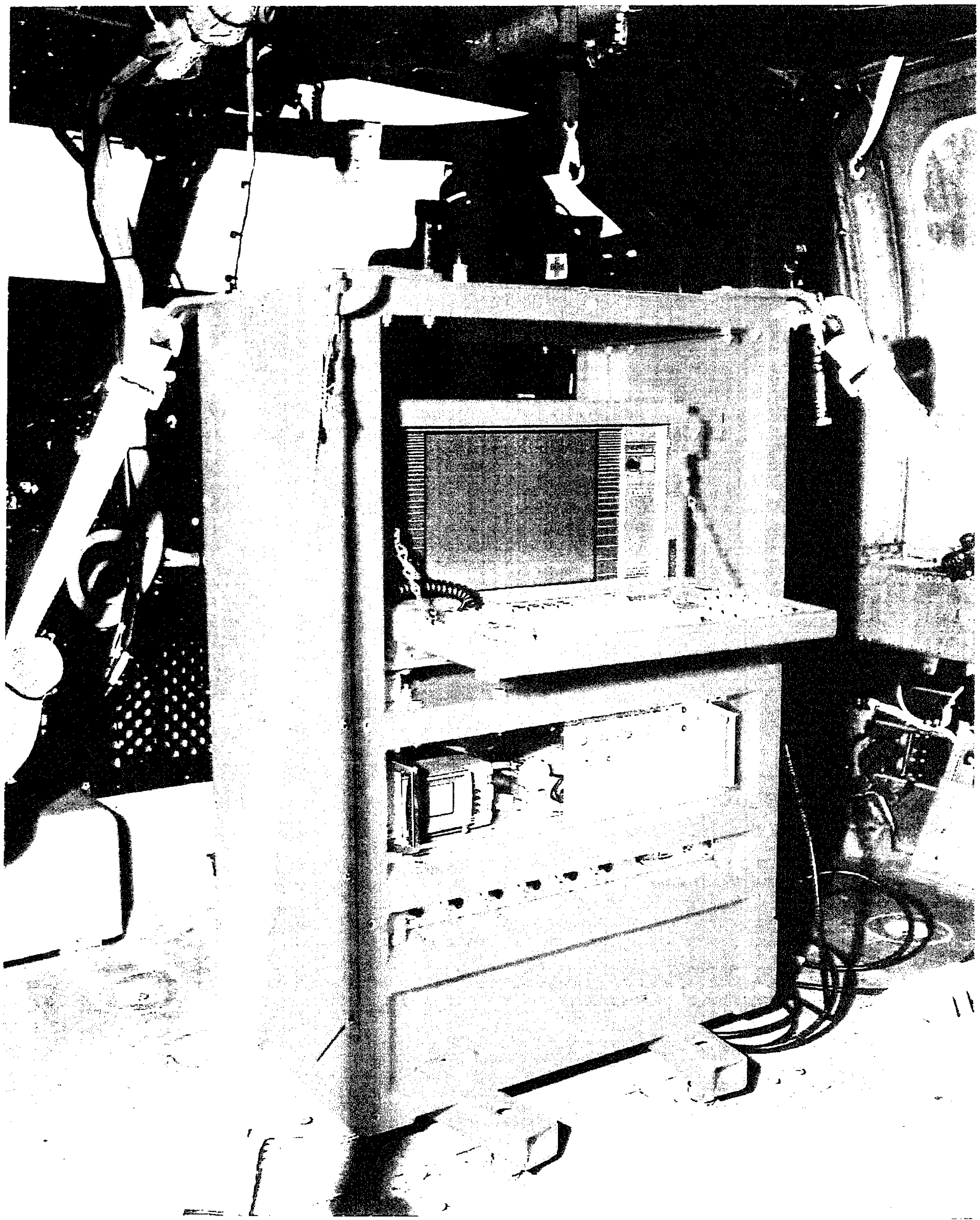

Figure 1. Portable Vibration Analysis System
(Photograph courtesy of ARDU)

2.1. Spectral Analysis

Spectral analysis is one of the basic vibration analysis tools that identifies the various component frequencies present in a vibration signal. The system incorporates programs based on the Fast Fourier Transform (FFT) that capture and display power spectra on the computer screen. Sample rates (up to 250 kHz), sampling periods, and anti-aliasing filter settings (1 Hz to 25 kHz) can be altered to adjust the frequency resolution and the display utilises three different types of cursors; normal, harmonic and sideband.

2.2. Synchronous Signal Averaging

Synchronous signal averaging effectively allows the vibration due to a particular shaft within a gearbox to be extracted from the overall vibration signature. It is based on the principle that the vibration coming from a shaft, and all the components fixed to and rotating with the shaft, will only contain frequencies that are harmonics of the shaft rotational frequency.

Signal averaging, illustrated in Figure 2, is performed by dividing a continuous vibration signal into segments exactly one shaft period in length, and then ensemble averaging a large number of these segments, usually several hundred. This reinforces the frequencies synchronous with the shaft period, ie. the shaft frequency harmonics, while attenuating the non-synchronous frequencies. The resulting signal average is a vibration signal exactly one shaft rotation in length containing that part of the overall vibration signal coming from the shaft of interest.

In order to divide the signal into these segments a timing signal from the shaft, or some shaft directly geared to it, is required. This is provided by a tachometer signal, which in the case of the Black Hawk helicopter, is derived from the AC generator as it is directly geared into the main transmission.

The signal averaging technique adopted in the portable vibration analysis system is as follows.

1. The vibration and tachometer signals are simultaneously sampled at the same rate.
2. The tachometer signal frequency is computed. This is done by counting the number of samples between successive signal zero-crossings, ie. the points where the tachometer signal makes a positive transition through zero volts.
3. The vibration data is digitally re-sampled to synchronise the sample rate to the shaft of interest. The re-sampling algorithm uses the information from (2) above plus the gear ratio of the tachometer to the shaft of interest to interpolate between the original vibration samples to produce an exact integer number of samples, N, per revolution of the shaft.

4. The signal average is computed. Sequential blocks of N points of the re-sampled vibration data from (3) above are ensemble averaged to produce the signal average. That is, the first points of each block are averaged to produce the first point of the signal average, the second points of each block are averaged, etc.

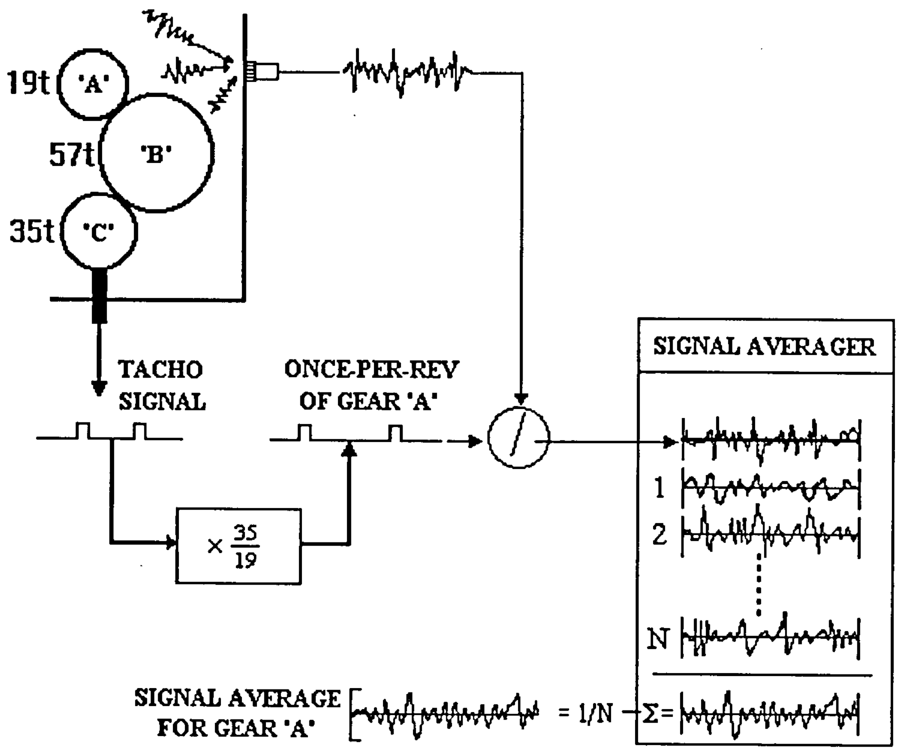

Figure 2. Signal Averaging Technique

Extracting the vibration from a particular shaft through the signal averaging technique requires that all the other shafts in the gearbox are rotating at frequencies that are non-synchronous with the shaft of interest. If there is more than one shaft rotating at the same frequency, or harmonic or sub-harmonic of this frequency, the signal average will contain vibration signals from these shafts as well. This can be minimised to a certain degree by selective placement of the vibration transducers. For example, the input modules of the Black Hawk transmission contain identical gears and so a separate transducer is used for each module.

Helicopter transmissions, including the Black Hawk's, usually incorporate epicyclic gear trains to handle the high torques and large reduction ratios. The planet gears in these gear trains all rotate at the same frequency causing a similar signal average separation problem. This is also complicated by the transmission paths between the planet gears and a transducer mounted on the gearbox casing varying as the planets rotate about the sun gear. Computing a standard signal average in this case produces a composite signal average of all the planet gears. This makes it difficult to detect faults on the planet gears as a small fault on one gear will be masked by the remaining healthy gears.

The portable vibration analysis system however, incorporates a program that uses a windowing technique to "separate" the planet gear signal averages. In this technique the vibration from a transducer positioned on the ring gear housing is considered to contain more vibration from the planet currently passing the transducer than from the other planets. Consequently, windowing the vibration signal as each planet passes the transducer, and assigning that part of the signal to the planet in question, effectively separates the planet gear vibration signals.

2.3. Synchronous Signal Average Analysis Methods

While some faults can be detected by visual inspection of the signal average for irregularities in the meshing pattern, this technique is not effective until the fault is at an advanced stage. Enhancement techniques are used to improve the sensitivity of fault detection and enable fault indices to be derived from the signal average.

The enhancement techniques available on the portable vibration analysis system allow various features of the signal averages to be extracted and graphically displayed.

a) Residual Signal The residual signal is the signal average with all the known vibration frequencies removed (ie. the gear mesh frequencies and other recognised regular frequencies) [Ref. 5]. It gives an indication of the energy in the signal average that cannot be attributed to known vibration sources. Areas of localised energy in the residual signal are indicative of localised faults such as tooth damage. The RMS of the residual signal normalised by the RMS of the signal average is a general fault index.

b) Narrow Band Analysis Narrow band filtering a signal average around a dominant gear mesh harmonic provides a method of analysing the tooth mesh modulation. Removing the dominant mesh frequency from the filtered signal and enveloping gives a function directly related to the amplitude and phase modulation of the tooth mesh [Ref. 6]. This function is sensitive to localised modulation effects such as those produced by tooth cracks.

c) Polar (Bullseye) Plot This is a derivative of the narrow band filtering described above where a signal average is narrow band filtered about a dominant gear mesh harmonic, and then demodulated about that frequency to give a complex vector [Ref. 7]. The magnitude and phase of this vector respectively represent the amplitude and phase modulation of the gear mesh and can be displayed on a polar, or bullseye, plot. This plot is divided into concentric circular regions representing good (inner green region), warning (middle yellow region), and danger (outer red region). A bullseye plot can be regarded as a fingerprint for the gear in question, and responds to changes in the meshing pattern.

d) Wigner-Ville Plot The Wigner-Ville distribution gives an estimate of the energy distribution in both phase and frequency simultaneously [Refs. 8 and 9]. This can be used to locate deviations in the meshing behaviour of the gears. It has the advantage of requiring no filtering of the signal, as do (a), (b) and (c) above, yet can highlight small changes in the meshing pattern of the gears which cannot be seen in an unenhanced signal average. Its main disadvantage is that it requires expert interpretation.

Fault detection using the above techniques can be further enhanced by fault index trending. A number of fault indices can be calculated during the signal processing required for the above techniques, each of which is indicative of a particular range of faults. Several fault indices will usually be calculated from one signal average, and trending these indices over a period of time is an effective way of detecting changes in the vibration signature caused by faults. A list of typical fault indices can be found in Appendix A.

3. Hardware Description

The portable vibration analysis system is based around a 486 personal computer and some associated signal conditioning and data acquisition hardware. A schematic diagram of the system is shown in Figure 3.

The system has the capacity for up to six vibration input channels and one tachometer signal channel, which is used for synchronous signal averaging (see section 2.2.). At present only three vibration channels are in use (the dashed lines represent the unused channels), but the remaining channels are easily available by the addition of more cabling. The tachometer signal is derived from the 115 V 400 Hz aircraft power through a voltage dividing network that reduces the voltage to 0.5 V.

Lists of the hardware components, AMRL drawings, and masses are shown in Tables 1, 2 and 3. A detailed description of each item is given in the following sections.

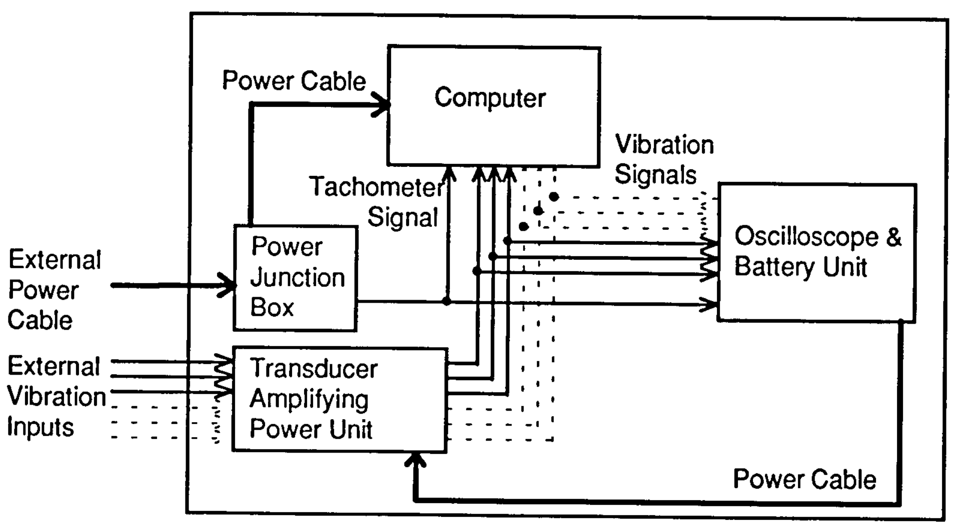

Figure 3. Portable Vibration Analysis System Schematic

Table 1. Hardware List

Number	Description
1×	Equipment Rack
2×	Mounting Beams
1×	Portable Computer with Internal Anti-Aliasing Filter and ADC Cards
1×	Oscilloscope and Battery Unit
1×	Transducer Amplifying Power Unit
1×	Power Distribution Box
1×	External Power Cable
	Internal Cabling
1 to 6×	Transducers / Transducer Brackets / Transducer Cables

Table 2. AMRL Drawing List

Drawing No.	Title
63543-A0	Black Hawk Instrumentation Rack, Framing Details
63545-A2	Seahawk Instrumentation Rack, Anchor Plate - Details
65055-A0	Dolch Cover, Cover
65056-A1	Dolch Cover, Tray
65057-A1	Dolch Cover, Base Plate
65216-A1	Black Hawk Instrumentation Rack, Mounting Beam Detail
65235-A1	Black Hawk Vibration Monitoring System, Block Diagram & Cable Diagram
65301-A3	Black Hawk Transducer Bracket (Recess)

Table 3. Major Component Masses and Centres of Gravity

Item	Mass (kg)	Centre of Gravity (mm above base of rack)
Rack - empty	27.0	309
Computer and Housing	15.3	623
Oscilloscope and Battery Unit	10.0	313
Transducer Amplifying Power Unit	3.0	200
Tie-down Brackets	3.0	853
Rack with all Equipment	58.3	414

3.1. Equipment Rack

The equipment rack is constructed from welded 32×32×3 mm 6063-T5 square section aluminium alloy tubing with corner webbing of 6 mm thick 5005-H34 aluminium alloy plate. The overall rack dimensions are 850×575×365 mm. Three sets of internal shelf cross-members are spaced 141, 226 and 396 mm from the bottom of the rack. The shelves are bolted to the top faces of the shelf cross-members and are made from 3 mm 5005-H34 aluminium alloy plate. Four tie-down anchor plates made from 6 mm steel plate are bolted to the top corners of the rack. There are 1.6 mm 5005-H34 aluminium alloy covers for all sides of the rack for protection of the contents during transportation.

The equipment rack has been subjected to, and passed, 20 G load testing without restraining straps attached to the tie-down anchor plates, as detailed in Appendix B. The restraining straps were only used during the flight tests to provide additional restraint.

3.2. Mounting Beams

Two mounting beams manufactured from 6063-T5 50×40×5 mm aluminium are bolted to the base of the equipment rack and are used to mount the rack on the aircraft cabin floor. See section 4.1.1. for details of the Black Hawk installation.

3.3. Portable Computer with Internal Anti-Aliasing Filter and ADC Cards

The computer is encased in a housing manufactured from 2.5 mm 5005-H34 aluminium alloy sheet bolted to a 5 mm base plate made from the same material. Both are lined with acrylonitrile foam rubber. The base plate is mounted on four L64-AA-10 Barry Mount vibration isolators bolted to the top shelf of the rack.

The computer is a Dolch Model DP486-33E portable with a 200 Mb hard disk and six EISA expansion card slots. Three full length slots are spare for user purposes and two of these are occupied by the anti-aliasing filter and analogue-to-digital converter (ADC) cards. The computer is powered from the aircraft 115 V 400 Hz power supply and draws a maximum of 1.7 Amps.

The anti-aliasing filter card is a sixteen channel Onsite Instruments Techfilter. It is a low-pass switched capacitor filter with a programmable cut-off frequency range of 1 Hz to 25 kHz (increments vary from 1 Hz for frequencies up to 250 Hz, 10 Hz for frequencies from 250 Hz to 2500 Hz, and 100 Hz for frequencies above 2500 Hz). It has single ended or differential inputs; AC or DC coupling; gains of 1, 10, 100, or 1000; and filter or bypass modes; all of which are selectable on a per channels basis. The input/output range is ±5 V.

The analogue-to-digital converter card is a Data Translation DT2821-G-8DI. This card has eight differential analogue inputs that are multiplexed into a single programmable gain amplifier, with gains of 1, 2, 4 and 8, and are sampled with a 12 bit ADC. The maximum ADC input range is ±10 V at a gain of 1 which can be reduced to ±5 V by a jumper on the card. The ADC has a gap free dual channel direct memory access (DMA) throughput of up to 250 kHz. The card also has two digital-to-analogue converters (DAC) and sixteen lines of digital input/output that are not utilised in this application.

In the current configuration the tachometer and first three vibration channels are connected to the first four Techfilter card input channels. The first eight output channels of the Techfilter are connected to the eight analogue inputs channels of the DT2821-G-8DI. The Techfilter is operated in differential input, AC coupled mode with a gain of 1 on all channels. All the vibration channels are filtered, but the tachometer signal is not as it contains only one low frequency component. The programmable amplifier on the ADC card is used to boost the signal amplitude to make best use of the ADC resolution (ie. keep the signal amplitude as large as possible while not exceeding the ADC range).

3.4. Oscilloscope and Battery Unit

The middle shelf is occupied by the oscilloscope and battery unit. The unit contains a rechargeable nickel cadmium battery to power the transducer amplifying power unit, and a Tektronix portable two channel storage oscilloscope (Model 214) that contains its own rechargeable battery. At present two signal inputs are connected to each oscilloscope channel (the tachometer signal and three vibration signals) and are selected using toggle switches. The batteries are recharged by an external charger that runs off 240 V 50 Hz.

3.5. Transducer Amplifying Power Unit

The lower shelf supports the transducer amplifying power unit. It is a PCB Piezotronics (Model 483A08) six channel device for powering and amplifying low impedance quartz transducers of the constant current integrated-circuit-piezoelectric (ICP) type. The unit supplies the transducers with an adjustable driving current of between 2-20 mA, and has a signal amplification range of 0-100 with a maximum output of ±10V. The unit is powered by the rechargeable battery described in section 3.4.

3.6. Power Distribution Box

The power distribution box is bolted to the rear of the rack between the top and middle shelves. Its dimensions are 120×100×35 mm, and it has one input and two output connectors. Its function is to supply power to the computer plus a tachometer signal for signal averaging purposes.

The 115 V, 400 Hz nominal, aircraft power is supplied to the distribution box via the external power cable, and is internally split between the output connectors for the computer power supply and the tachometer signal. The computer is supplied with 115 V, while the tachometer signal is derived through a voltage dividing network that reduces the signal to 0.5 V. A 5 A circuit breaker provides short circuit protection to the aircraft avionics.

See AMRL drawing 65235-A1 for a wiring diagram and details of connector types.

3.7. External Power Cable

This cable supplies 115 V aircraft power to the power distribution box. Power is drawn from one phase of the three phase supply and does not exceed 1.7 Amps. See AMRL drawing 65235-A1 for details.

3.8. Internal Cabling

The internal cabling consists of all the cables which interconnect the various modules. This includes, amongst others, the computer power cable, and the tachometer and vibration signal cables. See AMRL drawing 65235-A1 for details.

3.9. Transducers / Transducer Brackets / Transducer Cables

The system will support transducers of the constant current integrated-circuit-piezoelectric (ICP) type. See section 4.1.2. for details of the accelerometers, brackets and cables used in the Black Hawk installation.

4. Flight Trials

The portable vibration analysis system was flight tested in an Australian Army Black Hawk helicopter by AMRL and Aircraft Research and Development Unit (ARDU) personnel at RAAF Base Edinburgh over the period of July 1 to July 5, 1993. The objective of these tests was twofold:

a) to test the equipment under flight conditions and ensure that it acquires valid data; and

b) to acquire base-line vibration signatures for the Black Hawk helicopter transmission.

The aircraft installation, flight tests, and results are detailed below.

4.1. Aircraft Installation Details

The portable vibration analysis system was installed on a Black Hawk aircraft, tail number A25-206. A sketch of the main transmission, and a diagram of the drivetrain, can be seen in Figures 4 and 5. The transmission serial numbers are listed in Table 4, and the gear details can be found in Table 5.

Table 4. Transmission Serial Numbers for A25-206

Component	Serial Number	Hours
Left Engine	EE213251	557.4
Right Engine	EE213252	557.4
Left Input Module	26403587	557.4
Right Input Module	26403586	557.4
Main Module	52500049	557.4
Intermediate Gearbox	00501727	557.4
Tail Rotor Gearbox	00601438	116.0

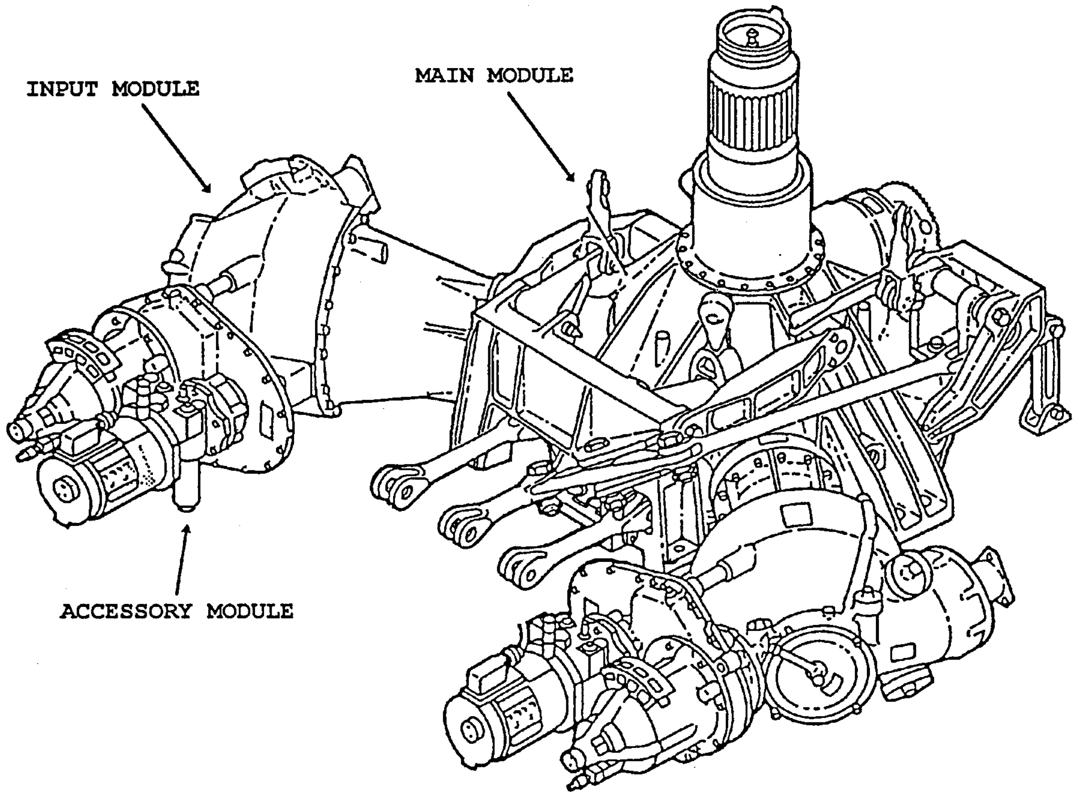

Figure 4. Black Hawk Main Transmission

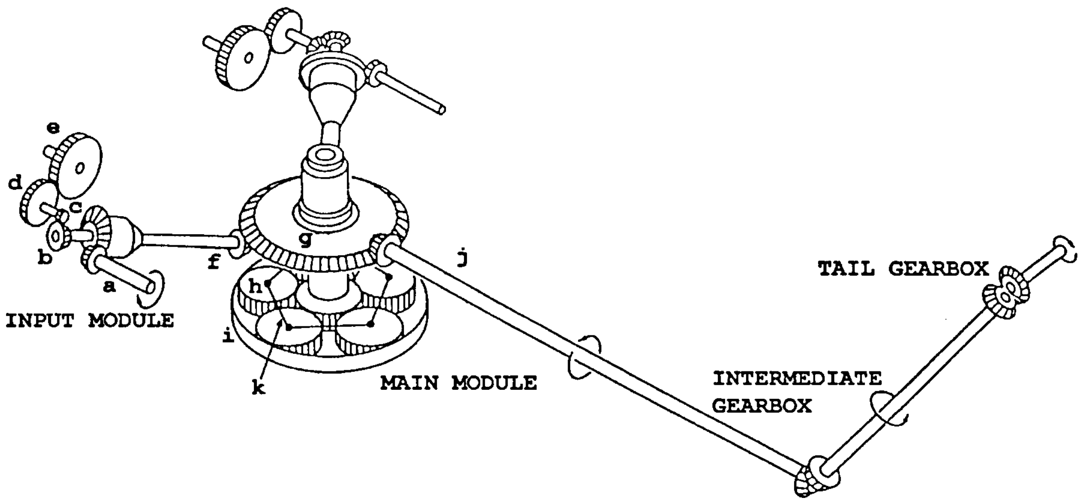

Figure 5. Black Hawk Drivetrain

Table 5. Black Hawk Main Transmission Details

Shaft	RPM	Gear	Teeth	Mesh Freq(Hz)
Input Module				
a High Speed Input Shaft	20900	Input Pinion	22	7663
b Input Gear Shaft	5748	Input Gear	80	7663
		Accessory Drive Take-off	76	7281
c Accessory Drive Shaft	11806	Accessory Drive Gear	37	7281
Accessory Module				
d Generator Drive Shaft	11806	Hydraulic Drive Take-off	56	11019
e Hydraulic Drive Shaft	7186	Hydraulic Drive Gear	92	11019
Main Module				
f Combining Pinion/Quill Shaft	5748	Combining Pinion	21	2012
g Crownwheel Shaft	1207	Lower Crownwheel Gear	100	2012
		Upper Crownwheel Gear	75	1509
		Sun Gear	62	980
h Planet Gear (wrt Carrier)	708	Planet Gear	83	980
i Ring Gear	0	Ring Gear	228	980
j Tail Drive Shaft	4115	Tail Take-off	22	1509
k Planet Carrier/ Main Rotor	258	Lube Pump Take-off	152	654
Lube Pump Drive Shaft	3268	Lube Pump Drive Gear	12	654

4.1.1. Equipment Rack

The equipment rack was bolted to the two mounting beams, which in turn were secured to the cabin floor by Kinedyne 33116 stud fittings bolted to the beam ends. The rack was positioned behind the pilot seats facing the rear of the cabin as shown in Figure 6, and required the removal of the cabin seating in this area. Ratchet type webbing straps were attached to each of the tie-down brackets bolted to the top of the rack, and were secured to the cabin floor using Kinedyne 32326 ring fittings. The system was operated by an AMRL staff member sitting in a seat directly behind and facing the rack at the location marked by an X in Figure 6.

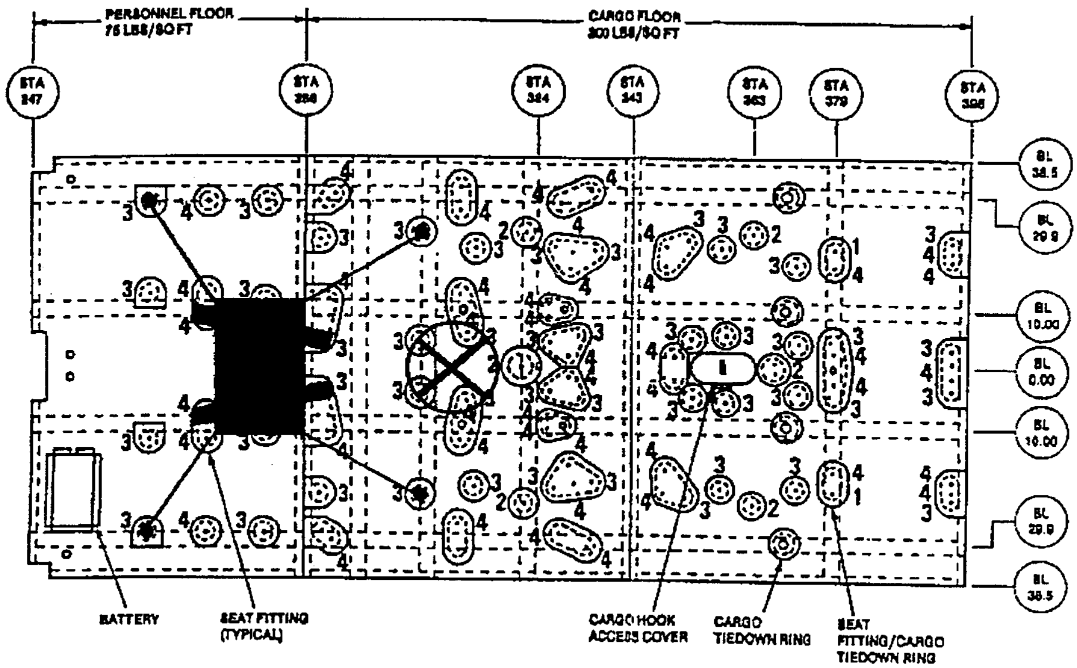

Figure 6. Location of Equipment Rack in Black Hawk

4.1.2. Transducers, Brackets and Cabling

Three Endevco model 7251-10 accelerometers were used to monitor the main transmission: one on each of the input modules, and one on the main module sump near the epicyclic ring gear (see Figures 7 and 8). Transducer brackets manufactured from mild steel as per AMRL drawing 65301-A3 were used for each location, and Brüel & Kjær AC0005 standard teflon coated coaxial cable was used to connect the transducers to the transducer amplifying power unit. Cable details can be found in AMRL drawing 65235-A1.

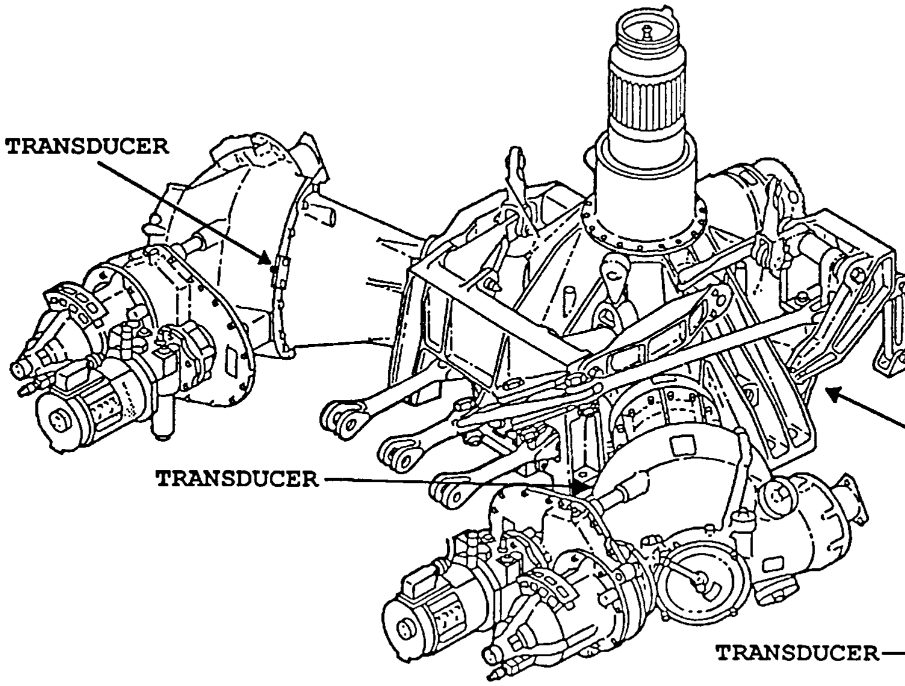

Figure 7. Transducer Locations

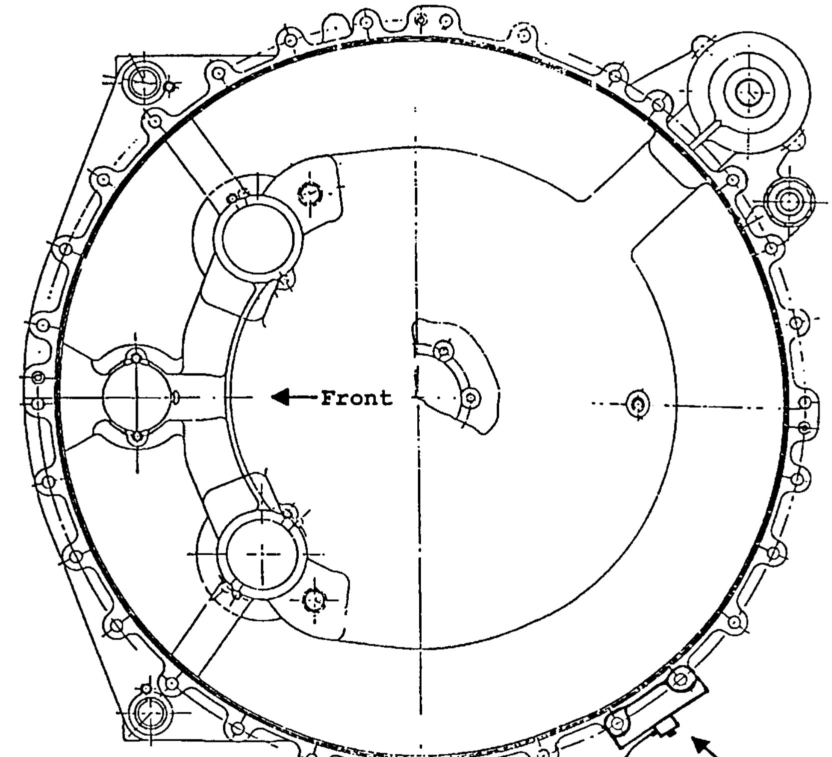

Figure 8. Main Module Transducer Location (Main Module Sump as Viewed From Above)

4.1.3. Power Cable

The external power cable was connected to the 115 V 400 Hz receptacle in the cabin roof above the rack location. Cable details can be found in AMRL drawing 65235-A1.

4.2. Data Acquisition and Signal Average Parameters

The vibration data acquisition from the Black Hawk gear box was split into five sections:

1. Left input module
2. Right input module
3. Main module fixed axis gears
4. Main module epicyclic gears
5. Main module epicyclic gears – extended length (as for 4. above but with a longer sampling time for longer planet gear separation signal averages).

The data acquisition and signal average parameters used are shown in Tables 6 and 7. They were determined by the following requirements.

a) Shaft and Gear Mesh Frequencies Where feasible sample rates were set to allow resolution of at least three harmonics of the highest gear mesh frequency in the section in question.

b) Signal Averaging Requirements Where feasible enough data was captured to allow signal averages to be calculated over at least 400 shaft cycles of the slowest speed shaft in the section in question.

c) Memory Requirements Combined sample rates above ~20 kHz can cause data acquisition errors when the data are written directly to the hard disk. A RAM disk overcomes this problem but the maximum size of the DOS RAM disk is 4 Mb and this imposes an upper limit on the size of the raw data files acquired at high sample rates. The overriding consideration however, was to allow as many raw data files as possible to be stored on the hard disk by keeping their sizes to the minimum required. Generally, this was below 3 Mb except for those intended for extended planet gear separation signal averaging.

Table 6. Data Acquisition Parameters

Label	Section	Sample Rate (Hz)	Time (sec)	Filter Cut-off (Hz)	File Size (Mb)
A	Left Input Module	70,000	10	25,000	2.8
B	Right Input Module	70,000	10	25,000	2.8
C	Main Module Fixed Axis Gears	25,000	25	7,700	2.5
D	Main Module Epicyclic Gears	10,000	60	3,300	2.4
E	Main Module Epicyclic Gears (Extended Length)	10,000	600	3,300	24.0

Table 7. Signal Average Parameters

Signal Average	Data Acq.	Points	Averages	Ratio to Tacho
Input Pinion	A or B	512	400	185 / 209
Input Gear (Quill Shaft)	A or B	1024	407	37 / 152
Generator Drive	A or B	512	988	1 / 2
Hydraulic Drive	A or B	1024	1064	7 / 23
Combining Pinion (Quill Shaft)	C	512	400	37 / 152
Crown-wheel	C	1024	462	777 / 15200
Tail Take-off	C	512	450	58275 / 334400
Lube Pumps	C	512	456	152551 / 1102000
Planet Carrier (Ring Gear)	D	2048	249	24087 / 2204000
Sun Gear	D	1024	456	44289 / 1102000
Planet Gears	D or E	1024	456	1372959 / 45733000

4.3. Flight Tests

The system was tested in one ground run and two flights. Since it was powered from the aircraft 115 V 400 Hz supply, it was not switched on until this supply was switched from the auxiliary power unit to the main AC generators. This was done to protect the system from voltage spikes or current surges that may occur in the switch-over.

In all three tests, data acquisition was the only function carried out while the system was in the aircraft. The computer was removed from the system for all processing and analysis operations to keep the time spent in the aircraft to a minimum. In future some processing could be performed in the aircraft, depending on time requirements but detailed analysis is more easily accomplished out of the aircraft.

4.3.1. Ground Run (1/7/93)

The aircraft main rotor was brought up to 100% speed with flat blade pitch for a period of five minutes during which time the system was checked.

The accelerometer and tachometer signals were individually examined using the Tektronix oscilloscope and found to be satisfactory. They were then visually compared with the signals entering the computer by using an "oscilloscope" program which visually displayed the signals available at the analogue-to-digital converter. Following this, sample data were acquired from each transducer, processed and analysed to ensure the signals were not corrupted.

All system functions were found to be operating correctly.

4.3.2. Flight 1 (2/7/93)

A post flight summary and the data acquired during this flight are shown in Tables 8 and 9.

Table 8. Flight 1 Post-Flight Summary

Aircraft:	A25-206	**Location:**	Edinburgh
Zero Fuel Weight:	13250 lbs	**All up Weight:**	15570 lbs
Start Fuel:	2320 lbs	**End Fuel:**	1310 lbs
Stores:	Nil·/ Nil ESSS	**Configuration:**	Clean
Take-off Time:	1044	**Land Time:**	1139
ATIS:	"B", QNH 1019, OAT +15°C, Wind 020/15 gutsing 25		
Weather:	CAVOK, moderate turbulence		
Aircrew:	ARDU: Ross, Barlow, Thomson.		

Table 9. Flight 1 Data Acquisition

Serial	Description	Data*	Time	OAT	Alt.	Torque	NR
1	Hover	A,B,C, D	1045 - 1051	14°C	140'	L 61% R 61%	100%
2,3,4	Level Accelerations	A,B,C	1057 - 1059	8°C	3000'	L 100% R 100%	100%
5	Level Flight - Long Range Cruise	A,B,C, D,E	1108 - 1118	8°C	3000'	L 62% R 63%	100%
6	Level Flight - Max Continuous Torque	A,B,C, D,E	1119 - 1132	9°C	3000'	L 100% R 100%	100%

* Data column indicates the vibration data acquired as per the labels listed in Table 6.

4.3.3. Flight 2 (5/7/93)

A post flight summary and the data acquired during this flight are shown in Tables 10 and 11.

Table 10. Flight 2 Post-Flight Summary

Aircraft:	A25-206	**Location:**	Edinburgh
Zero Fuel Weight:	13250 lbs	**All up Weight:**	15400 lbs
Start Fuel:	2200 lbs	**End Fuel:**	1000 lbs
Stores:	Nil / Nil ESSS	**Configuration:**	Clean
Take-off Time:	1009	**Land Time:**	1106
ATIS:	"D", QNH 1023, OAT +13°C, Wind 090/5 - 10		
Weather:	CAVOK, nil turbulence		
Aircrew:	ARDU: Ross, Barlow, Thomson.		

Table 11. Flight 2 Data Acquisition

Serial	Description	Data*	Time	OAT	ALT	Torque	NR
1,2,3	Level Accelerations	A,B,C	1010 - 1015	8°C	3000'	L 100% R 100%	100%
4	Level Flight - Max Continuous Torque	A,B,C, D,E	1015 - 1032	8°C	3000'	L 100% R 100%	100%
5a	Level Flight @ 60% Torque	A,B,C, D	1033	8°C	3000'	L 60% R 60%	100%
5b	Level Flight @ 70% Torque	A,B,C, D	1036	8°C	3000'	L 70% R 70%	100%
5c	Level Flight @ 80% Torque	A,B,C, D	1039	8°C	3000'	L 80% R 80%	100%
5d	Level Flight @ 90% Torque	A,B,C, D	1042	8°C	3000'	L 90% R 90%	100%
5e	Level Flight @ 100% Torque	A,B,C, D	1045	8°C	3000'	L 100% R 100%	100%
6	Manoeuvres @ 500' Above Ground Level	A,B,C	1050	12°C	500'	L&R 55-80%	100%

* Data column indicates the vibration data acquired as per the labels listed in Table 6.

4.4. Results

Due to the large amount of data gathered, most processing was carried out at AMRL after the trials. Examination of the data at RAAF Base Edinburgh consisted of:

a) checking the signals had not gone over scale, or dropped out;

b) examining the spectra from each accelerometer to check that the expected frequencies were present; and

c) computing test signal averages of selected shafts from each gearbox module.

Using these checks, only the following two problems were identified during the initial post processing.

1. After the first flight it was discovered that the signal from the main module accelerometer had gone over scale in three raw data files ('C' serial 4, 'C' serial 5, 'E' serial 5). This was found to have been caused by a fault in the auto-gain procedure of the data acquisition program that set the programmable ADC gain one step too high (2 instead of 1).

Rather than modifying the procedure, it was bypassed and the ADC gain was preset to 1 to ensure no recurrence of the problem. The software fault has since been rectified.

2. After the second flight some signal drop-out was found approximately 85% of the way through a 600 second data file ('E' serial 4). It would appear that this was caused by a disk write error, such as the heads skipping, as both the tachometer and vibration signals dropped out for exactly the same period of time. The most likely cause of this would be excessive vibration, but as this was the only occurrence it was considered a one-off event and unlikely to pose a significant obstacle to further data acquisition.

The subsequent, more detailed, post trial analysis at AMRL did uncover one more problem. It would appear that all three vibration signals had been slightly clipped by the anti-aliasing filter as a result of the incoming vibration signals marginally exceeding the maximum filter input range of ±5 V. This can only have been caused by the transducer amplifier gains, set to give a sensitivity of 100 mV/g, being slightly too high. In future, a more appropriate sensitivity would be 75 mV/g or 50 mV/g.

This last fault was not detected during the flight trials as the signal distortion introduced by the clipping was small and did not manifest itself in the computed test signal averages. While the distortion may have unknown effects on the more sensitive fault detection algorithms, it is not so severe as to preclude useful information being extracted from the vibration signals. For example, the following aspects can still be approximated.

a) The signal amplitudes to expect.

b) The gear mesh and other regular frequencies to expect in the signal averages.

c) The relative magnitudes of the frequency components present in each signal (ie. the relative strengths of the gear mesh harmonics).

Due to the large amount of data gathered in these flight tests, only a representative sample of the processed data is presented here. The following sections illustrate some typical program output and are direct screen dumps from the computer. Note that the clock times shown in this output are 30 minutes ahead of those shown in section 4.3. because the computer clock was on Melbourne rather than Adelaide local time.

4.4.1. Left and Right Input Pinion Signal Averages

Figures 9 to 12 show the signal averages and spectra of the left and right input pinions computed from raw data files 'A' and 'B' of serial 5a, flight 2. The fundamental gear mesh frequency of 22 shaft orders (these gears have 22 teeth) is predominant in both, with a much smaller second harmonic at 44 shaft orders. The other frequencies are not immediately identifiable but the 25 shaft order component in the left input pinion signal average may be a ghost frequency, ie an effect caused by slight tooth profile errors generated during manufacture. A similar 25 order component has been previously identified with the 80-tooth input gear, ie. the mating gear to the input pinion, of a UH-60A transmission. This was traced back to a 25:1 reduction ratio in the gear grinding machine used in the manufacture this gear [Ref. 10]. The components at 6 shaft orders may be related to the flexible coupling that connects the input shaft to the engine drive shaft. This coupling has six connection points.

Bullseye plots of the gear mesh frequency modulation are shown in Figures 13 and 14. A pass band of 22 shaft orders about the fundamental gear mesh frequency was used in each case. The left input pinion signal average has larger frequency components in this pass band than the right and is the reason why the bullseye plot of the left input pinion is not so tightly centred as the bullseye plot of the right input pinion.

4.4.2. Planet Carrier (Ring Gear) Signal Averages

Figures 15 and 16 show the signal average and spectra of the planet carrier (ring gear) signal average computed from raw data file 'C' serial 5e, flight 2. The planet pass modulation (5 planets) is clearly visible in the signal average, while its spectrum shows the gear mesh frequency (228 shaft orders) attenuation and asymmetrical sidebands characteristic of an epicyclic gear train [Ref. 11].

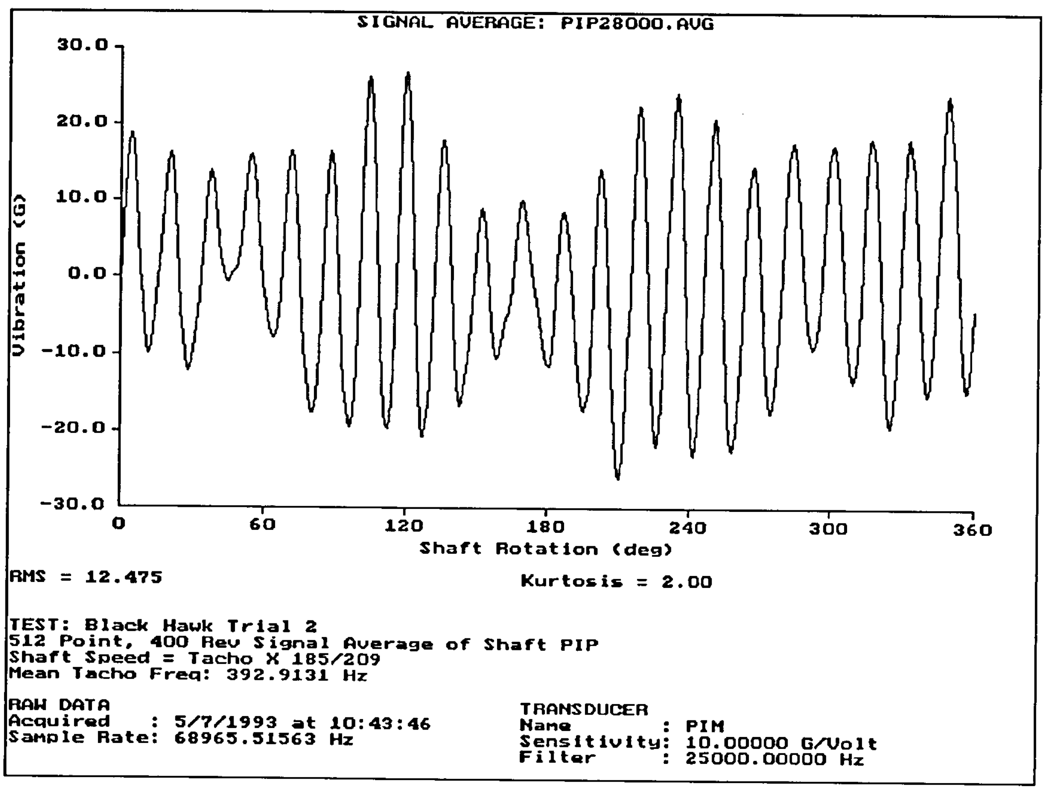

Figure 9. Left Input Pinion Signal Average

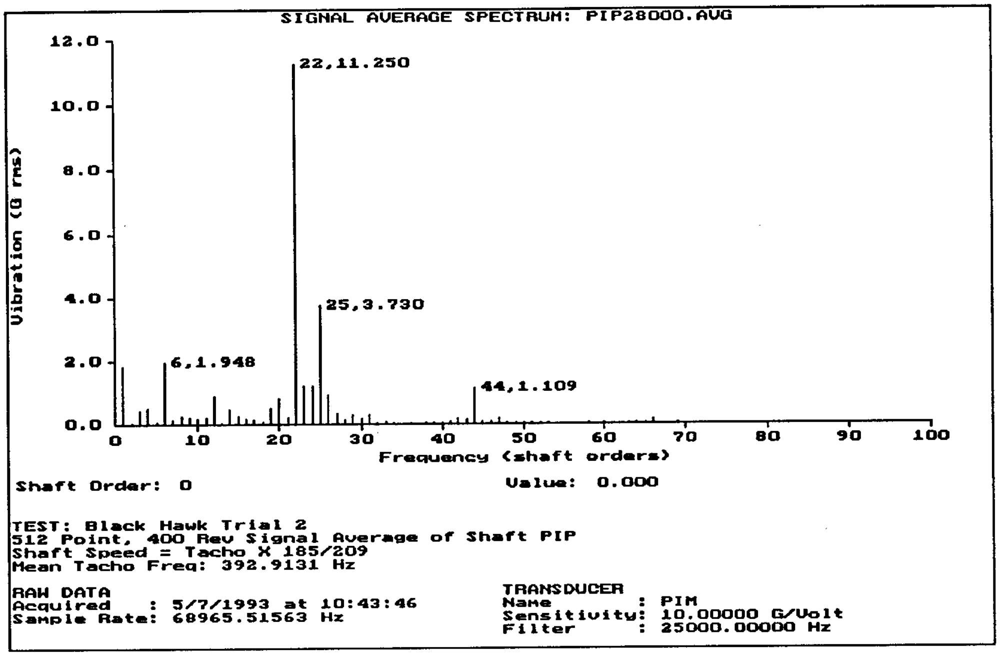

Figure 10. Left Input Pinion Signal Average Spectrum

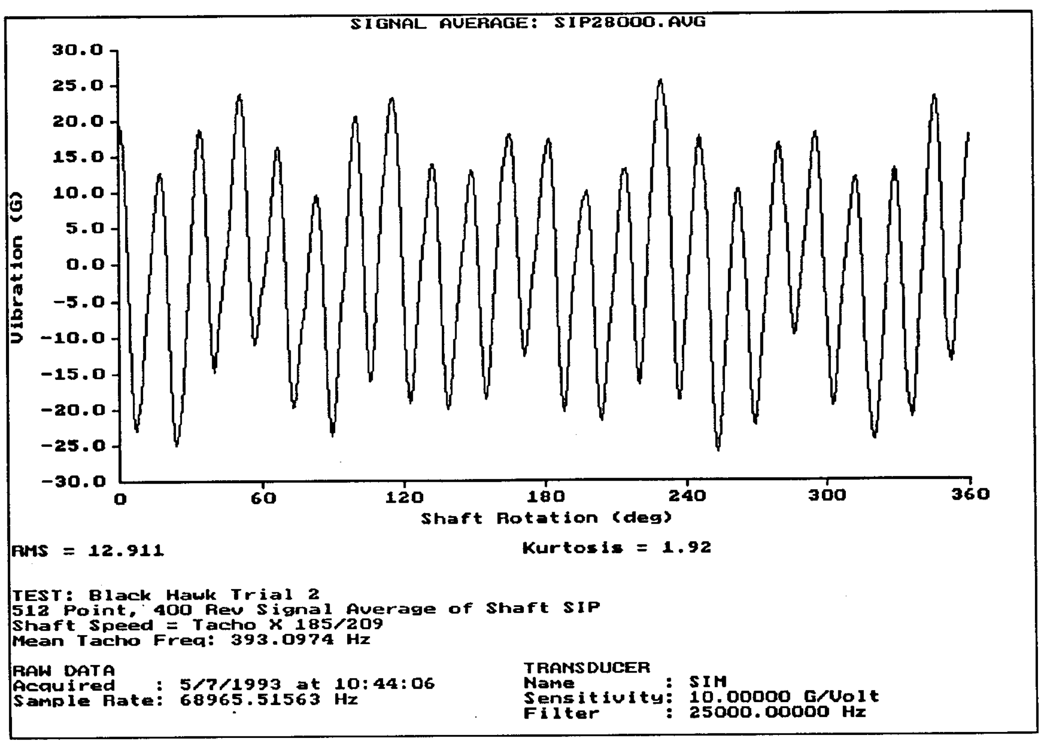

Figure 11. Right Input Pinion Signal Average

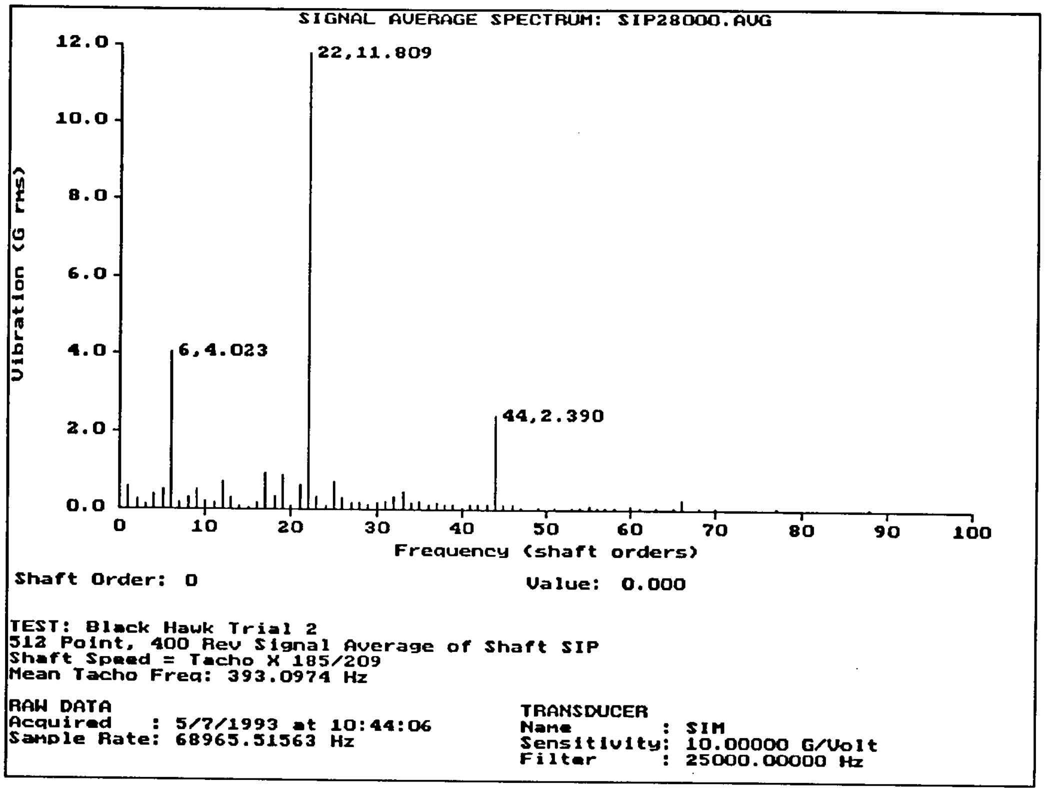

Figure 12. Right Input Pinion Signal Average Spectrum

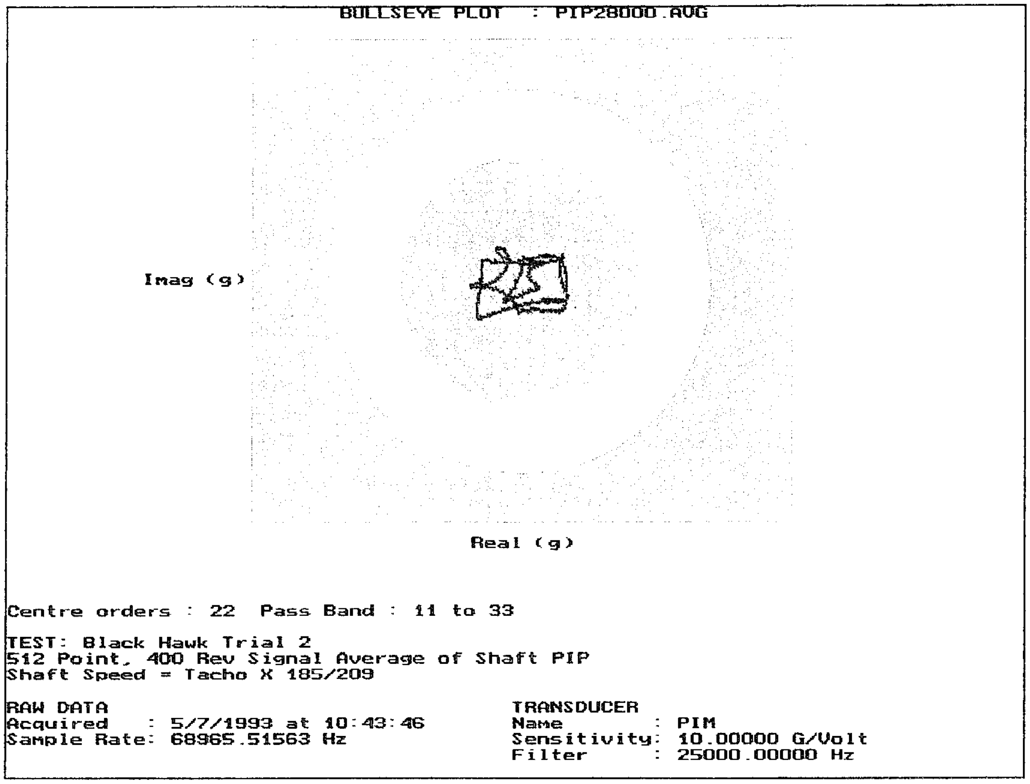

Figure 13. Bullseye Plot of Left Input Pinion Gear Mesh

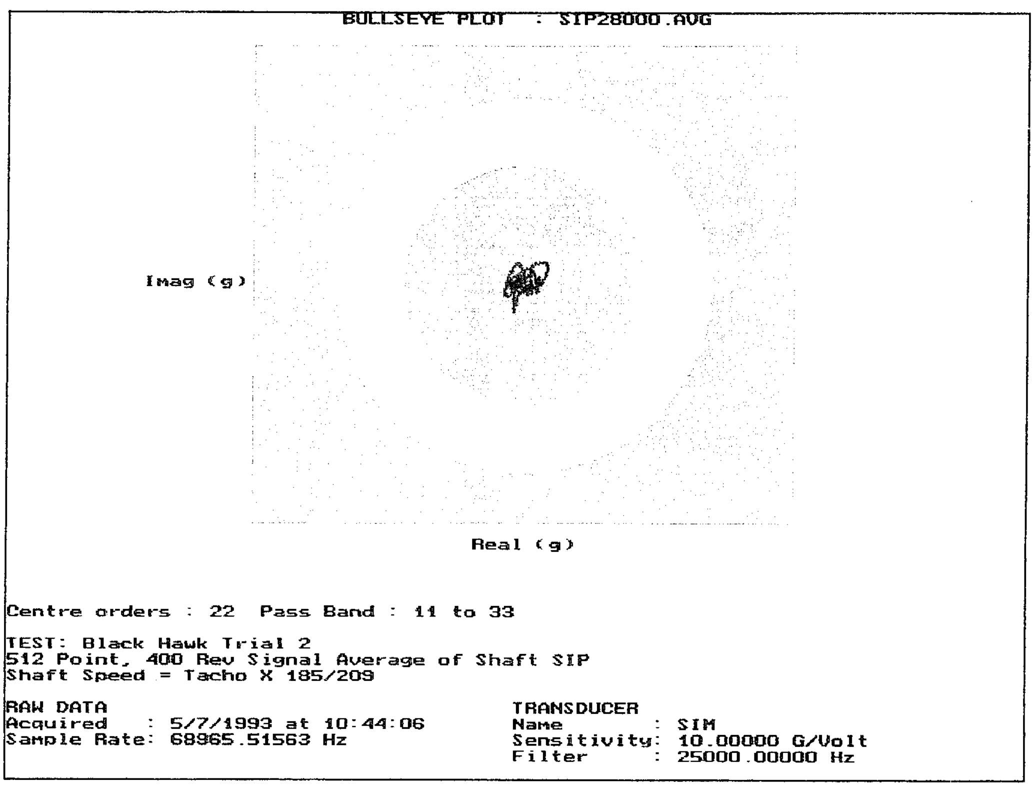

Figure 14. Bullseye Plot of Right Input Pinion Gear Mesh

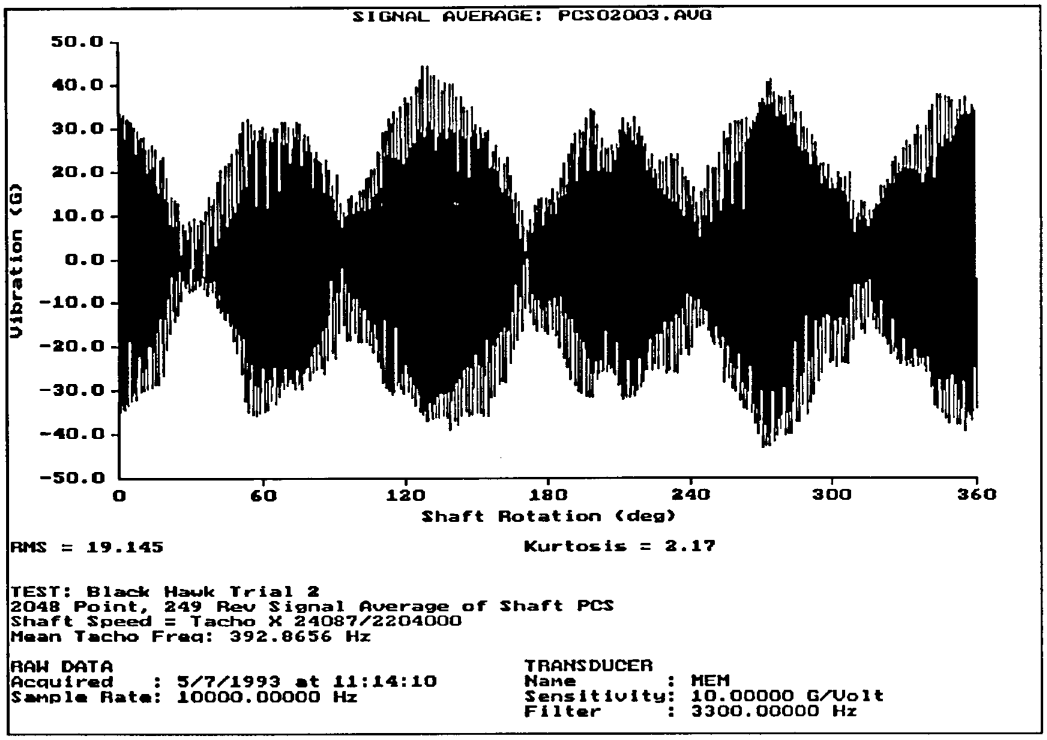

Figure 15. Planet Carrier (Ring Gear) Signal Average

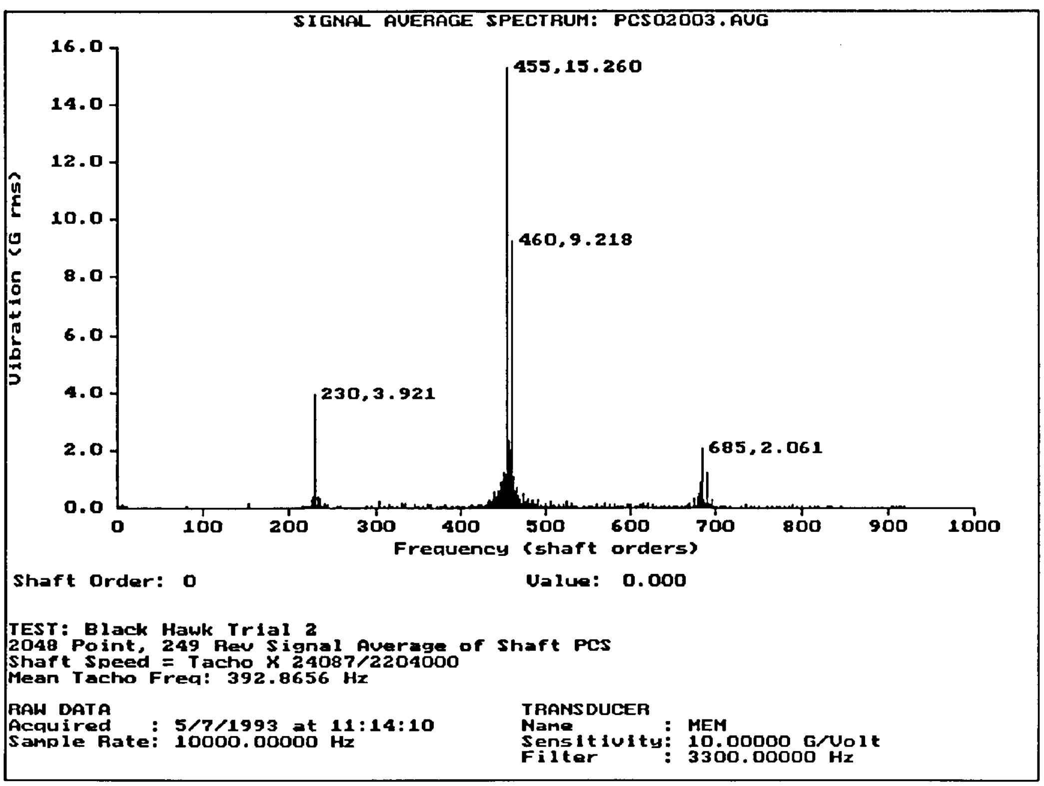

Figure 16. Planet Carrier (Ring Gear) Signal Average Spectrum

5. Concluding Remarks

The prototype portable transmission vibration analysis system has been successfully flight tested in a Black Hawk helicopter. Vibration data were acquired under several flight conditions from three accelerometers mounted on the main transmission. The vibration data were then processed on the ground to produce example signal averages for all the shafts within the transmission. Three operational faults were found:

a) a software fault in an automatic gain setting procedure;

b) evidence of signal drop-out in one data file; and

c) slight signal clipping caused by the anti-alias filter.

All the faults were not serious, but fault (c) may have introduced some unknown effects into the resulting signal averages. As the fault was discovered post-trial, the measurements could not be repeated to determine this. All the faults have since been rectified, and are not expected to cause further problems.

6. Future Development

The system described here is a prototype developed to demonstrate and prove the concept of an in-flight vibration analysis system. Miniaturisation of this system to enable its deployment on routine operational sorties is seen as a logical next step. This should not prove to be difficult as the core of the vibration analysis system is the 486 PC. Most of the signal conditioning equipment external to the PC could be incorporated onto a circuit board that could be inserted into a vacant PC expansion bus slot. All power for the system could then be drawn from the aircraft supply eliminating the need for batteries, and the oscilloscope function could be performed by the PC. Along with this miniaturisation, there is a need for development of ground-station processing capabilities.

7. Acknowledgements

The authors wish to acknowledge S.A. Dutton who was involved with various aspects of the design and development of the portable vibration analysis system.

8. References

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Appendix A

Example Fault Indices

(B = balance fault index; A = alignment fault index; G = general fault index; L = local fault index)

B1 Shaft frequency amplitude.

A1 Amplitude of 2 × shaft frequency.

G1 RMS of signal average.

G2 RMS of residual signal divided by RMS of the signal average. A measure of the energy in the signal average that cannot be attributed to known frequency components.

G3 Peak level of the narrow band envelope divided by the RMS of the mesh harmonic. A measure of the maximum deviation of the modulated signal amplitude from the pure mesh harmonic amplitude. Used as a general damage indicator.

L1 Residual signal kurtosis. A measure of the energy localisation in the residual signal. Used as an indicator of tooth damage.

L2 Kurtosis of the narrow band envelope. A measure of the localised modulation effects of the tooth meshing pattern. Used to indicate tooth cracks.

L3 Kurtosis of the instantaneous frequency (derivative of the phase) of the modulated signal. Extremely sensitive to phase changes such as those caused by tooth cracks, but restricted to a limited number of cases due to instabilities caused by impulsive events.

Appendix B

Equipment Rack Load Test

Nature of test

Non-destructive static load test conducted by the Structures Experiment Group, AMRL, 11/5/93.

Test Method

The rack was mounted on a test bed in the same manner as the aircraft installation (see Attachment 1), but *without* the cargo restraining straps attached to the tie-down brackets. This consisted of bolting the rack mounting beams to two 102 x 51 mm steel channel sections (7.6 mm flange thickness) that were in turn secured to the test bed. A space of approximately 5 mm was provided between the mounting beams and the channel section by washers to prevent the beams receiving support from the channel sections. These washers were of approx the same diameter as the Kinedyne stud fasteners to be used in the aircraft.

Horizontal loads were applied to the rack to simulate the forward, rearward and lateral restraint criteria set out in the Black Hawk S-70A-9 flight manual. Note that the absence of restraining straps results in a more severe loading condition than can be expected in the aircraft, where straps were used, due to the reaction forces to the overturning moments. The vertical restraint criteria were not tested as it was calculated that the horizontal load tests would generate greater loads than those required for vertical restraint. In addition, the restraining straps used in the aircraft installation would provide more than adequate vertical restraint.

The cargo restraint criteria listed in the S-70A-9 flight manual are:

Forward	20 g
Rearward	20 g
Lateral	18 g
Vertical	10 g (Up) 20 g (Down)

Loading

The test loads were applied using the mechanism shown in Figure B1 which split the load into two components. The upper component simulated the computer load and was applied to the C of G of the computer through a bracket bolted to the top shelf of the rack. The lower component simulated the combined loading of the rack and the rest of the equipment. It was applied through a channel section clamped across the rear of the rack at the height of their combined C of G (excluding the computer). The masses of the computer, rack and equipment, and their C's of G above the base of the rack are listed in Table B1.

Table B1. Masses & Centres of Gravity

Item	Mass (kg)	Centre of Gravity (mm above base of rack)
Computer and computer housing	15.3	623
Oscilloscope and battery unit	10.0	313
Transducer amplifying power unit	3.0	200
Tie-down brackets	3.0	853
Rack - empty	27.0	309
Rack with all equipment except computer	43.0	340
Rack with all equipment	58.3	414

The rack was subjected to a load equivalent to 20g in both horizontal directions (see Figure B2) to provide the option of mounting the rack laterally, should this be necessary in the future. The maximum applied load was:

$$F_{G_g} = G \times g \times m$$

$$F_{20_g} = 20 \times 9.81 \times 58.3 = 11{,}438N$$

The maximum load was sustained for a period of one minute.

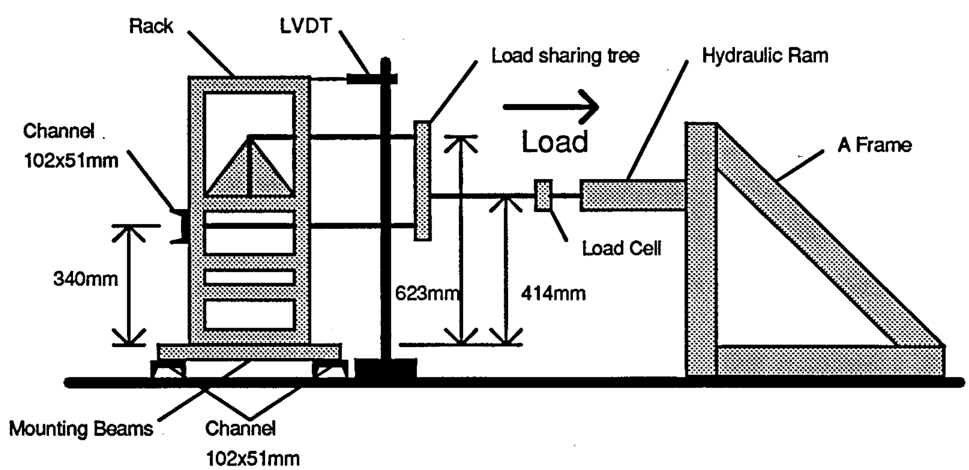

Figure B1. Loading Mechanism

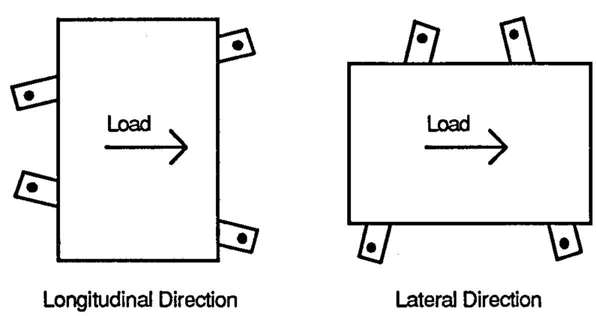

Figure B2. Loading Directions

Instrumentation

The horizontal deflection of the rack under the applied load was measured by two LVDT transducers attached to the upper corners of the rack, and the applied load was measured with a load cell (see Figure B1).

Results

The load-deflection curves for the tests are shown in Figures B3 to B5, and the raw data is listed in Attachment 2. Two tests were conducted in the longitudinal direction because in the first test the higher loads could not be maintained due to the A frame (see Figure B1) sliding along the test bed. This was rectified by tightening the bolts securing this frame.

Neither the rack, nor the mounting beams, nor the securing bolts failed during all three tests. The only identifiable deformation was some slight dimpling, less than 1 mm deep, of the mounting beams under the bolt heads where they were secured to the rack. This may account for the slightly non-linear behaviour of the load-deflection curves, and the non-zero deflections upon release of the loads. There was no corresponding dimpling of the rack members under the nuts due to the presence of squares of reinforcing mild steel (see Attachment 1). The dimpling could be reduced by using similar reinforcement under the bolt heads.

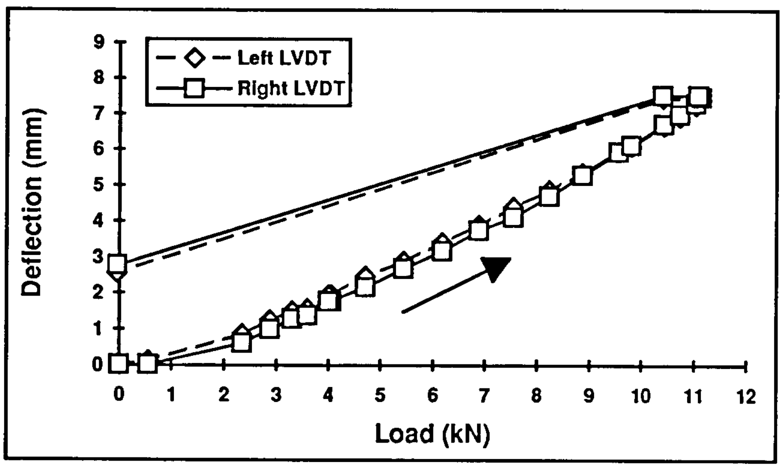

Figure B3. Longitudinal Test 1

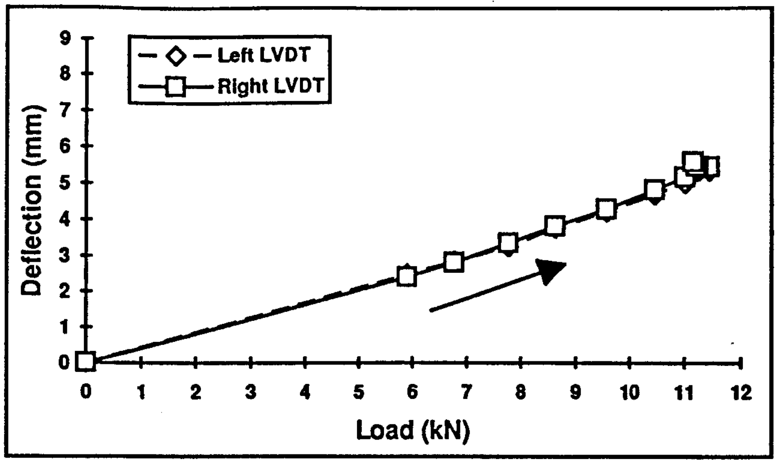

Figure B4. Longitudinal Test 2

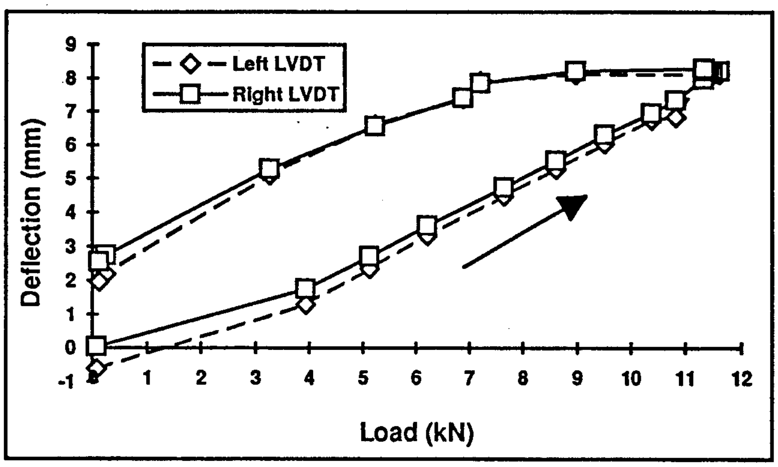

Figure B5. Lateral Test

Attachment 1

Aircraft Mounting Details of Black Hawk Equipment Rack

- The equipment rack is to be bolted to two aluminium mounting beams (AMRL Drawing No. 65216-A1) using AN4-34A bolts, AN960-416 washers, and MS21044-N4 nuts. Bolt heads are to bear against the mounting beams, and nuts against the rack members. There should be clearance between the bolt heads and the cabin floor. Squares of 0.125 in thick mild steel, length 32 mm, with a ϕ6.5 mm hole in the centre, are to be placed under the nuts to share the load more evenly across the member.

- The rack is to be mounted in the cargo area as shown in Figure B6. The computer and other equipment should face the rear of the cabin. The rear ends of the mounting beams are to be fastened to the floor studs at STA 273.0, BL 8.00 left and BL 8.00 right, and the forward ends at STA 289.50, BL 55.43 left and 5.43 right, using Kinedyne 33116 stud fittings and MS21044-N6 nuts.

- Cargo straps are to be attached to the tie-down brackets on all four top corners of the rack and lashed to Kinedyne 32326 ring fittings attached to floor studs at STA 264.25, BL 28.00 left and 28.00 right, and STA 306.0, BL 22.62 left and BL 22.62 right. See Figure B6.

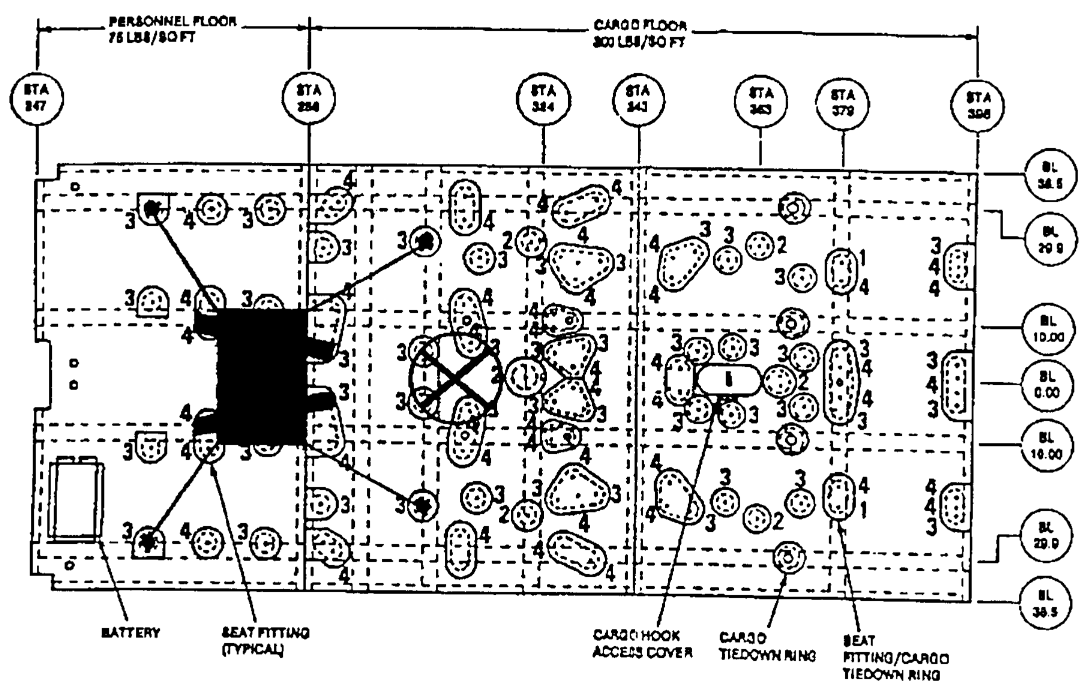

Fig B6. Rack Mounting Location

Attachment 2

Raw Data

Longitudinal Test 1

HP Data Acquisition
Static test of BHawk Equipment Rack
The time is 21:57:37
The date is 07/05/93

Time	L.LVDT	R.LVDT	LOAD	EXCN	l.lvdt	r.lvdt	load
HH:MM:SS	V	V	V	V	mm	mm	kn
21:57:44	-0.28958	0.28577	0.000147	9.9697	0	0	-0.00016
21:57:56	-0.25917	0.28761	0.000677	9.9697	0.120454	0.007049	0.566071
21:58:47	-0.07267	0.44504	0.002342	9.9697	0.859169	0.610163	2.34522
21:59:51	0.026784	0.54656	0.002842	9.9697	1.253118	0.999086	2.879069
22:00:54	0.087708	0.61984	0.00324	9.9697	1.494438	1.279822	3.303841
22:01:16	0.10478	0.64877	0.003507	9.9697	1.56206	1.390653	3.589409
22:01:46	0.2019	0.74688	0.003943	9.9697	1.946752	1.766512	4.055205
22:02:24	0.20184	0.74691	0.003896	9.9697	1.946515	1.766627	4.00542
22:02:47	0.3352	0.85119	0.004554	9.9697	2.474754	2.166124	4.708281
22:03:37	0.44061	0.98876	0.005234	9.9697	2.892283	2.693155	5.434966
22:04:08	0.57224	1.1154	0.005932	9.9697	3.413669	3.178313	6.180774
22:04:57	0.69519	1.2619	0.006593	9.9697	3.900674	3.739554	6.886092
22:05:35	0.81898	1.3577	0.007205	9.9697	4.391006	4.106564	7.540771
22:06:12	0.94033	1.5127	0.007846	9.9697	4.871674	4.700369	8.22547
22:06:47	1.0631	1.6663	0.008443	9.9697	5.357965	5.28881	8.862735
22:07:24	1.2158	1.8367	0.009095	9.9697	5.96281	5.941613	9.559186
22:10:21	1.2498	1.8828	0.009323	9.9697	6.097484	6.118222	9.802554
22:10:52	1.3904	2.0352	0.009911	9.9697	6.654401	6.702066	10.43106
22:11:29	1.4565	2.106	0.010184	9.9697	6.916223	6.973301	10.72293
22:11:54	1.5336	2.1879	0.010475	9.9697	7.221616	7.28706	11.03382
22:12:25	1.5776	2.2354	0.01057	9.9697	7.3959	7.469033	11.13531
22:12:38	1.5859	2.2489	0.010508	9.9697	7.428776	7.520751	11.06907
22:13:02	1.5857	2.2494	0.009881	9.9697	7.427984	7.522667	10.39879
22:15:05	0.35446	1.0077	0.000109	9.9697	2.551042	2.765714	-0.04059

Longitudinal Test 2

HP Data Acquisition
Static test of BHawk Equipment Rack
The time is 22:29:12
The date is 07/05/93

Time	L.LVDT	R.LVDT	LOAD	EXCN	l.lvdt	r.lvdt	load
HH:MM:SS	V	V	V	V	mm	mm	kn
22:29:28	0.27527	0.77849	0.000172	9.9697	0	0	0.000139
22:29:52	0.90263	1.4043	0.005698	9.9697	2.484973	2.397478	5.903967
22:30:08	0.99327	1.5133	0.006505	9.9697	2.843998	2.815057	6.766118
22:30:18	1.0939	1.6502	0.007447	9.9697	3.242593	3.339521	7.77228
22:30:29	1.2237	1.7746	0.008248	9.9697	3.756731	3.816097	8.628341
22:30:41	1.3413	1.896	0.009125	9.9697	4.222545	4.281181	9.564848
22:30:52	1.456	2.0348	0.009963	9.9697	4.676872	4.812924	10.46022
22:31:02	1.5394	2.1261	0.010476	9.9697	5.007219	5.162694	11.00818
22:31:12	1.6219	2.2034	0.010881	9.9697	5.334001	5.45883	11.44085
22:31:43	1.6219	2.2079	0.010706	9.9697	5.334001	5.47607	11.25389
22:32:02	1.622	2.2079	0.010659	9.9697	5.334398	5.47607	11.20368
22:32:29	1.6374	2.2369	0.010612	9.9697	5.395397	5.587169	11.15347

Lateral Test

HP Data Acquisition
Static test of BHawk Equipment Rack
The time is 14:13:52
The date is 04/05/93

Time	L.LVDT	R.LVDT	LOAD	EXCN	L.LVDT	R.LVDT	LOAD
HH:MM:SS	V	V	V	V	mm	mm	kN
14:13:58	-0.15583	0.01109	7.15E-05	9.9696	-0.617	0.042	0.076
14:18:31	0.32831	0.45927	0.003683	9.9696	1.300	1.759	3.935
14:21:13	0.59526	0.70737	0.004797	9.9696	2.358	2.710	5.124
14:21:43	0.83932	0.94351	0.005814	9.9696	3.325	3.615	6.211
14:22:16	1.1345	1.2368	0.007147	9.9696	4.494	4.738	7.635
14:22:51	1.3357	1.4477	0.008055	9.9696	5.291	5.546	8.605
14:23:16	1.5279	1.6494	0.008891	9.9696	6.052	6.319	9.499
14:23:46	1.7066	1.8172	0.009711	9.9696	6.760	6.962	10.374
14:24:11	1.7296	1.9177	0.010128	9.9696	6.851	7.347	10.820
14:24:42	2.051	2.0835	0.010601	9.9696	8.124	7.982	11.325
14:25:29	2.0511	2.1478	0.010858	9.9696	8.124	8.228	11.600
14:25:50	2.0511	2.1479	0.010752	9.9696	8.124	8.229	11.487
14:26:18	2.0511	2.1479	0.010688	9.9696	8.124	8.229	11.418
14:26:41	2.0511	2.1479	0.010649	9.9696	8.124	8.229	11.377
14:26:59	2.0511	2.1662	0.010614	9.9696	8.124	8.299	11.339
14:27:16	2.0511	2.1497	0.008393	9.9696	8.124	8.236	8.967
14:27:36	1.9977	2.0499	0.006729	9.9696	7.913	7.853	7.188
14:27:45	1.8656	1.9346	0.006433	9.9696	7.390	7.411	6.872
14:27:58	1.667	1.7133	0.004895	9.9696	6.603	6.564	5.230
14:28:10	1.2936	1.3824	0.003046	9.9696	5.124	5.296	3.254
14:28:25	0.55728	0.71924	0.000223	9.9696	2.207	2.755	0.238
14:28:35	0.49646	0.66643	0.000111	9.9696	1.966	2.553	0.118

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PAGE CLASSIFICATION
UNCLASSIFIED

PRIVACY MARKING

DOCUMENT CONTROL DATA

1a. AR NUMBER	1b. ESTABLISHMENT NUMBER	2. DOCUMENT DATE	3. TASK NUMBER
AR-008-938	DSTO-TR-0072	SEPTEMBER 1994	91/063

4. TITLE

A PORTABLE TRANSMISSION VIBRATION ANALYSIS SYSTEM FOR THE S-70A-9 BLACK HAWK HELICOPTER

5. SECURITY CLASSIFICATION (PLACE APPROPRIATE CLASSIFICATION IN BOX(S) IE. SECRET (S), CONF. (C) RESTRICTED (R), LIMITED (L), UNCLASSIFIED (U)).

DOCUMENT	TITLE	ABSTRACT
U	U	U

6. NO. PAGES

42

7. NO. REFS.

11

8. AUTHOR(S)

D.M. BLUNT, B. REBBECHI
B.D. FORRESTER and K.W. VAUGHAN

9. DOWNGRADING/DELIMITING INSTRUCTIONS

Not applicable.

10. CORPORATE AUTHOR AND ADDRESS

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GPO BOX 4331
MELBOURNE VIC 3001 AUSTRALIA

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14. DESCRIPTORS

UH-60a helicopters
Transmission (mechanical)
Vibration analysis

15. DISCAT SUBJECT CATEGORIES

010301
1309

16. ABSTRACT

The prototype portable transmission vibration analysis system developed by AMRL for the Black Hawk helicopter is described in detail, including the results of flight trials conducted at RAAF Base Edinburgh during July 1993. The results of these trials have proved the concept of the system and laid the foundations for the future development of smaller and lighter systems.

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16. ABSTRACT (CONT).

17. IMPRINT

AERONAUTICAL AND MARITIME RESEARCH LABORATORY, MELBOURNE

18. DOCUMENT SERIES AND NUMBER	19. WA NUMBER	20. TYPE OF REPORT AND PERIOD COVERED
DSTO Technical Report 0072	43421F	

21. COMPUTER PROGRAMS USED

22. ESTABLISHMENT FILE REF.(S)

M1/9/34

23. ADDITIONAL INFORMATION (AS REQUIRED)