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**BASIC GUIDELINES FOR PERFORMANCE  
MONITORING OF SHIPBOARD MACHINERY**

By

**William R. McWhirter, Jr.**

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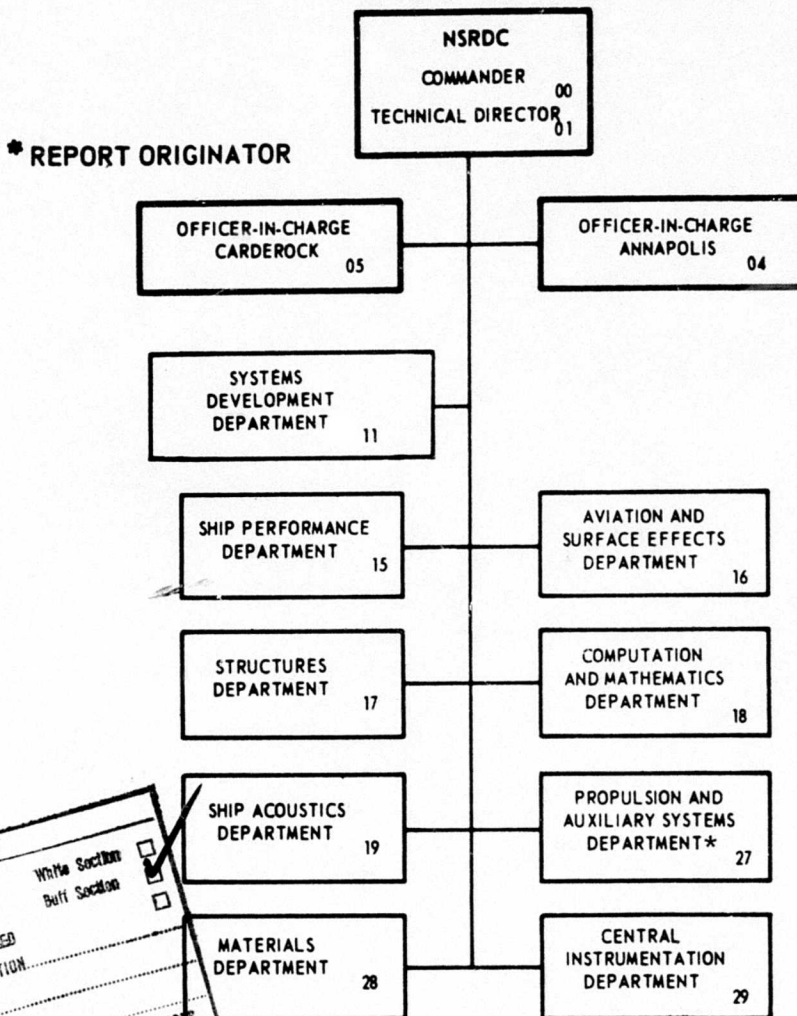
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BASIC GUIDELINES FOR PERFORMANCE MONITORING OF SHIPBOARD MACHINERY

The Naval Ship Research and Development Center is a U. S. Navy center for laboratory effort directed at achieving improved sea and air vehicles. It was formed in March 1967 by merging the David Taylor Model Basin at Carderock, Maryland with the Marine Engineering Laboratory at Annapolis, Maryland.

Naval Ship Research and Development Center  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report provides the necessary basic guidelines to conduct an effective Shipboard Machinery Performance Monitoring Program. Such a program will develop a propulsion and auxiliary machinery monitoring system capable of providing, via central processor, to the Watch Supervisor, information on machinery operational status and machinery maintenance requirements. An annotated bibliography of feasible monitoring techniques and related literature is included. (Author)		

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## ADMINISTRATIVE INFORMATION

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## LIST OF ABBREVIATIONS

AADC	- All application digital computer
AFB	-
AIDS	- Airborne Integrated Data Systems
ATE	- Automatic test equipment
CASREP	- Casualty report
CATS	- Centralized Automatic Test System
DAC	- Data analysis computer
° C	- Degree, Celsius
DD&P	- Detection, diagnosis, and prognosis
etc.	- And so forth
HP	- High pressure
Hz	- Hertz
IATS	- Integrated Automatic Test System
i.e.	- For example
IMAC	- Integrated Machinery Automatic Concept
IMMP	- Integrated Maintenance and Modernization Plan
LP	- Low pressure
LVDT	- Linear variable differential transformer
MCA	- Machinery Condition Analysis
MFPG	- Mechanical Failures Prevention Group
MG	- Motor generator
NC	- Numerical control
NVMA	- Noise-Vibration Monitor Analyzer
ORMS	- Operational Readiness Monitoring System
ORTS	- Operational Readiness Test System
PAC	- Process data acquisition computer
PTA	- Performance Test Approach
rpm	- Revolutions per minute
SEM	- Standard Electronic Module
SMPMS	- Shipboard Machinery Performance Monitoring System
SW	- Seawater
SSTG	- Ship service turbogenerator
TEAMS	- Test, Evaluation, and Monitoring System
VIDEC	- Vibration Analysis and Deviation Concept
LEDs	- Light emitting diodes

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## GLOSSARY\*

Active Sensor - A sensor requiring a source of power in addition to that of the signal being measured.

Active Testing - The process of determining equipment static and dynamic characteristics by performing a series of measurements during a sequence of known operating conditions. Active testing requires an interruption of normal equipment operations, and it involves measurements made over the range of operation.

Aliasing - An error which sometimes occurs in digital frequency analysis, where a signal can appear to contain frequencies which, in fact, are not there at all. This error is due to improper signal sampling.

ATE - An abbreviation of the term "automatic test equipment."

Automatic System - A system in which the operations are performed by electrically controlled devices without the intervention of operators.

Automatic Test Equipment - An equipment that is designed to automatically conduct analysis of functional or static parameters and to evaluate the degree of performance degradation and perform fault isolation of unit malfunctions. The decision making, control, or evaluative functions are conducted without reliance on human intervention.

Automation - The investigation, design, development, and application of methods of rendering processes automatic, self-acting, or self-controlling.

BITE - An abbreviation of the term "built-in test equipment."

Built-in Test - A test approach using built-in test equipment or self-test.

Built-in Test Equipment - Any device which is functionally separate from, but permanently connected to, the prime equipment and used for the express purpose of testing the prime equipment.

\*Definitions for many of the terms identified in this glossary have been taken from either Military Standard 1309A: A Definition of Terms for Automatic Electronic Test and Checkout, 12 Apr 1972 or Schlereth, F. H., (Ed), "Glossary of Terms Used in the Identification and Prediction of Mechanical Failure," Mechanical Failures Prevention Group Interim Tech Rept 1, ONR, Arlington, VA, AD-721 354, 10 Jan 1971



Channel - A path along which signals can be sent.

Complex Test Point - A test point at which the parameter of interest is present only when stimulated or activated by means of the ATE Program.

Computer-Controlled Tester - A tester in which the logic required to execute the test program is provided by a computer (central processing unit).

Condition Monitoring - The monitoring performed to assess the material state of equipment(s) by measurement of selected static and dynamic physical characteristics.

Corrective Maintenance - Maintenance performed to restore a failed or degraded equipment. It includes fault isolation, repair, or replacement of defective unit(s), alignment, and checkout.

Data (Real and Applicable) - Those data about real, operating equipment that is similar enough to subject equipment to be applicable to the design of maintenance programs or monitoring systems for the subject equipment.

Data Reduction - The process of transforming masses of raw or experimentally-obtained data, usually gathered by instrumentation, into useful, ordered, or simplified intelligence.

Degradation - The act of impairing in respect to some physical property.

Detect - To sense the occurrence of a specific statistic or an obscure event.

Detection Equipment - An equipment used to implement a decision rule concerning the occurrence of an obscure event.

Diagnosis - The art or act of identifying a condition from its signs and symptoms.

Diagnostic - Pertaining to the detection and isolation of a malfunction or fault.

Diagnostic Phenomenon - A physical event or condition reflecting or relatable to the mechanical or structural condition of an equipment component.

Diagnostic Routine - A logical sequence of tests designed to locate a malfunction in the unit under test.

Diagnostic Sensitivity - A measure of a technique's ability to sense changes in the mechanical condition of an equipment component at an early stage of degradation.

**Diagnostic Technique** - A failure detection method directed at a specific diagnostic phenomenon. A diagnostic technique consists of sensing, data processing, and data analysis techniques.

**Diagnostic Test** - A test performed for the purpose of isolating a malfunction in the unit under test or confirming that there is a malfunction.

**Effective Incipient Failure Detection** - That technique which will reliably detect the pending failure of a unit or system before that system fails.

**Failure** - A malfunction that causes degradation or complete loss of equipment performance.

**Failure Detection** - Implies that a failure mode has been identified, a signal has been identified, and a detection criterion has been specified.

**Failure Effects** - The consequence of failure.

**Failure Mode** - The ways in which units, equipments, and systems deteriorate, malfunction, and can be considered to have failed.

**Failure Path (Malfunction Path)** - The path of secondary effects connecting a mechanical condition change of other components possibly terminating in equipment failure.

**Fault** - A degradation in performance due to detuning, maladjustment, misalignment, failure of component(s), and so forth.

**Fault Detection** - One or more tests performed to determine if any malfunctions or faults are present in a unit.

**Fault Indicator** - A device which presents a visual display, audible alarm, and so forth, when a failure or marginal condition exists.

**Fault Isolation** - Tests performed to isolate malfunctions or faults to a line replaceable unit.

**Fault Symptom** - A measureable or visible abnormality in an equipment parameter.

**Feedback** - (1) The return of a portion of the output signal of a circuit or device to its input. (2) A timing signal used as a self-test feature in an automatic test system to verify that a control instruction has been executed before proceeding to the next control instruction.

**Incipient Failure** - A condition wherein the first signs of failure become apparent by acceptable means of detection.

**Information Retrieval** - The methods and procedures for recovering specific information from stored data.

**Instrumentation** - Includes all those devices (electrical, mechanical, magnetic, chemical, optical) used to test, observe, measure, monitor, alter, generate, record, calibrate, manage, or control physical properties, movements or other characteristics.

**Integral Test Equipment** - Test equipment that uses some of the prime equipment's circuitry (such as power from the power supply of the prime equipment) and is physically located within and permanently wired to the prime equipment. Connections to the signals and voltages to be measured are made through permanently wired internal leads and selector switches.

**Line Replaceable Unit (LRU)** - A unit which is designated by the "Plan for Maintenance" to be removed upon failure from a larger equipment/system in the operational environment.

**Maintenance** - Activity intended to keep equipment (hardware) or programs (software) in satisfactory working condition, including tests, measurements, replacements, adjustments, repairs, program copying, and program improvement. Maintenance can be either preventive or corrective.

**Maintenance Monitoring** - The monitoring performed to determine when corrective maintenance actions are required.

**Manual Test Equipment** - Test equipment that requires separate manipulations for each task (for example, connection to signal to be measured, selection of suitable range, and insertion of stimuli).

**Module** - A physically independent assembly whose boundaries are determined by easy replacement as reflected by the applicable maintenance policy.

**Monitor** - To check the operation and performance of an equipment or system by sampling the result of the operation.

**Monitoring** - The continuous observation of diagnostic phenomena for an indication of a change of such phenomena reflecting a change in the mechanical condition of an equipment component.

**Noise** - The difference between a waveform and the signal; noise is generated in the sensor, the transmission medium, the receiver, the filter, and the display.

**Observable** - Waveform, signal, or signature.

**Off-Line** - As it pertains to ATE, (1) operation of input/output and other devices not under direct control of a device, as

a central processing unit; (2) peripheral equipment operated outside of, and not under control of the system.

Off-Line Testing - Any method of testing in which the unit under test has been removed from its operational environment.

On-Condition Maintenance - The maintenance performed on a non-scheduled or nonroutine basis determined by the material condition of subject equipment(s).

On-Line - (1) Operation of an input/output device as a unit of the system under programmed control of that system; (2) monitoring and testing in a noninterfering manner while the prime equipment is in normal operation use.

On-Line Testing - Any method of testing which allows the unit under test to be tested in its operational environment.

Passive Sensor - A sensor requiring no source of power other than the signal being measured.

Passive Test - A test conducted upon an equipment or any part of such equipment, when the equipment is not energized. This is also called a "cold test."

Performance Monitor - A device which continuously or periodically scans a selected number of test points to determine if the unit under test is operating within specified limits. This device may include provisions for insertion of stimuli.

Performance Monitoring - The monitoring performed to (1) detect a performance degradation; (2) predict failures, (3) isolate faults, and (4) predict maintenance requirements for subject equipments by processing measurements of selected static and dynamic characteristics.

Periodic Check - A test or series of tests performed at designated intervals, to determine if all elements of the unit under test are operating within their designated limits.

Peripheral Equipment - Equipment external to a basic unit; for example, a tape unit is peripheral equipment to a computer.

Pickup - A sensing device that converts a sound, vibration, pressure, or other form of intelligence into corresponding electrical signals.

Preventive Maintenance - Tests, measurements, replacements, adjustments, repairs, and similar activities carried out with the intention of preventing faults or malfunctions from occurring during subsequent operation. Preventive maintenance is designed to keep equipment and programs in proper operating condition and is usually performed on a scheduled basis.

Prime Equipment - An equipment or system that is to be monitored.

Prognosis - The art or act of predicting a future condition on the basis of present signs and symptoms.

Program - An organized sequence of instructions, commands, and data which causes a machine to execute some desired function.

Quantitative Testing - Testing that monitors or measures the specific quantity, level, or amplitude of a characteristic to evaluate the operation of an equipment. The outputs of such tests are presented as finite or quantitative values of the associated characteristics.

Readiness Test - A test specifically designed to determine whether an equipment or system is operationally suitable for a mission.

Real-Time Testing - The testing of events which are simultaneous with the events.

Self-Test - A test or series of tests performed by a device upon itself, which shows whether or not it is operating within designated limits. This includes test programs on computers and automatic test equipment which check out their performance status and readiness.

Self-Test Capability - The ability of a device to check its own operation. The degree of self-test is dependent on the ability to detect and isolate faults.

Semiautomatic System - A system in which the operations combine manual and automatic features so that a manual operation is required to supply the actuating influence which causes the automatic feature to function.

Semiautomatic Test Equipment - Any automatic testing device which requires human participation in the decision-making, control, or evaluative functions.

Sensor - A device used to provide an observable related to a condition of interest; i.e., a device transducing physical quantities into (usually) electrical form.

Signal - A manifestation of an event containing information of interest.

Signature - A frequently used term usually referring to some characteristic of a waveform which is related to a condition of interest. A signature is that combination of signals of some known condition of subject equipment(s).

**Signature Analysis** - Usually refers to the act of analyzing variations in that combination of signals indicative of some known condition of subject equipment(s).

**Simple Test Point** - A test point at which the parameter of interest is continuously present.

**Sonic Analysis** - Usually refers to the act of analyzing the spectral content of the sound emanating from an operating equipment.

**Static Test** - (1) A test of a nonsignal property, such as a voltage or current, of an equipment or of any of its constituent parts, performed while the equipment is energized; (2) a test of a device in a stationary position as a means of testing and measuring its reactions.

**Supervisory Control System** - A system in which an arrangement for the selective control of remotely located units by electrical means is performed over one or more common interconnecting channels.

**Test** - A procedure or action to determine under real or simulated conditions the capabilities, limitations, characteristics, effectiveness, reliability, or suitability of a material, device, system, or method.

**Test Analysis** - The examination of test results to determine whether the device is in an operationally ready state or not, or to determine the reasons for or location of a malfunction.

**Test Equipment (Checkout Equipment)** - Electric, electronic, chemical, optical, mechanical, hydraulic, or pneumatic equipment, either automatic, semiautomatic, manual, or any combination thereof, which is required to perform the test or checkout function.

**Test Point** - A convenient safe access to an equipment, system, or circuit so that a significant quantity can be measured or introduced to facilitate maintenance, repair, calibration, alignment, and checkout.

**Test Procedure** - A document that describes step-by-step the operations required to test a specific unit within a specific system.

**Time-Controlled Maintenance (Hard Time Limit)** - The maintenance performed on a scheduled or routine basis determined by time-in-service of subject equipment(s).

**Tolerance** - The total permissible variation of a quantity from a designated value.

Transducer - A device which converts energy from one form to another.

Trend Analysis - A means to determine if a signal is changing in some predictable manner, such as increasing in magnitude with respect to time.

Unit Under Test - Any equipment, system, subsystem, assembly, subassembly, component, and so forth, undergoing testing.

Vibration Analysis - Usually refers to the act of analyzing the spectral content of structureborne vibratory motions of an operating equipment.

Vibroacoustic Phenomena - Those phenomena of sound including its production, transmission, and effects as related to mechanical vibration.

Virtual Test Point - A point in the prime equipment about which information is known by virtue of processing information from actual test points.

Waveform - Usually a voltage-time record of a sensor output. A waveform may or may not contain a signal. A signal must be carefully described and identified. A signal is related to a failure which is impending or has occurred. The definition of that which constitutes a failure must be carefully identified before a signal can be identified.

## INTRODUCTION

### BACKGROUND

The Navy spends large amounts of time and money maintaining ship machinery systems. This required maintenance is undesirably increasing because of the size and complexity of the ship systems/equipment. At present, most maintenance is performed on a planned, calendar schedule where it is possible (and quite probable) that infrequently used equipment will be unnecessarily overhauled, and the consequences of unreliable "open and inspect" procedures will often produce more damage than improvement.

Concurrently, manpower costs are escalating. This is forcing the Navy to reduce manning levels on ships and to automate critical ship functions that may be supervised by a small crew. These requirements and the importance of considering machinery degradation originated in a memorandum (OP97A, Ser 138P97 of 1 November 1972) from Director, Ship Acquisition and Improvement Division to Chief of Naval Operations; a letter from Chief of Naval Operations (OP987D, Ser 349P987 of 2 November 1972) to Chief of Naval Material; and another memorandum from Naval Operations (OP987D, Ser 741-72 of 30 October 1972) to Chief of Naval Operations.

Ultimately, automation will control the naval ships of the future. To achieve this, it will be necessary to develop a propulsion and auxiliary machinery performance monitoring system that will conveniently provide:

- Machinery operational status.
- Machinery maintenance requirements.

Machinery performance monitoring will make it possible to attain the benefits of ship automation, manning reduction, and improved continuity of operation.

A number of ongoing programs within the Navy, other government agencies, domestic industries, and foreign governments and industries are involved in periodic machinery monitoring. Many of these attempts have been successful and are potentially valuable for the Navy's requirements. They require adaptation, however, for an automated shipboard machinery performance monitoring system.

It is the purpose of this document to provide the basic guidelines required for those investigators who will be called upon to pursue the detailed equipment investigations, monitor system hardware development, and formulate the system software necessary in an effective shipboard machinery performance monitoring system.



## APPROACH

Monitoring may be defined as the continuous observation of diagnostic phenomena for an indication of any change that might reflect a change in the mechanical condition of an equipment, system, or component. It will allow maintenance to be performed on the basis of condition, providing maintenance on a nonscheduled or nonroutine basis, determined by the material condition of the equipment.

Monitoring can be employed for different desired results. Maintenance monitoring can determine when and where corrective actions are required. Condition monitoring can assess the material state of equipments by measurement of selected static and dynamic physical characteristics. Performance monitoring will detect performance degradation, predict failures, isolate faults, and predict maintenance requirements for equipments by processing measurements of selected physical parameters.

Monitoring can be employed, also, to enforce energy conservation measures and maintain high system operating efficiencies, to promote safety, and increase machinery longevity.

In order to determine guidelines for shipboard machinery performance monitoring, it has been necessary to review other efforts in this domain (refer to table 1). The "historical" programs include such manually-oriented systems as: the SSBN Shipyards Maintenance Monitoring and Support Program, the MCA\* Program, the Navy Oil Analysis Program, the "Chapman Number" Acoustic and Vibration Measurement Program, and its more recent relative, the Surface Ship Vibration Analysis Program.<sup>1</sup> Two other programs, also, belong in this category. The PTA Program for surface ships identified alternatives to periodic disassembly for selected equipment and developed improved test procedures. The IMMP Program developed more precise and expanded definitions of intermediate maintenance tasks to extend overhaul cycles for SSN's, borrowing from the SSBN program when possible.

Programs employing semiautomatic types of systems that are in development for current or future applications include the NVMA Program and the IATS Program for the TRIDENT submarine; the VIDECON Program onboard the American President Lines Ship, S.S. PRESIDENT JOHNSON; the Shipboard Machinery Maintenance Monitoring Program aimed at FF/DE 1052 class; the Diesel Engine Condition Monitoring Program being developed by the DD&P Technical Committee of the MFPG; the CATS developed at NELC; and the Propulsion Monitor and Display System Program utilizing the TEAMS technique.

<sup>1</sup>Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

\*Definitions of abbreviations appear on page i.

**TABLE 1  
PROGRAMS CONCERNING  
SHIPBOARD MACHINERY PERFORMANCE MONITORING**

Program Title	Technique Sophistication	Objective	Cognizant Activity
Shipboard Machinery Performance Monitoring Program	Automatic	Complete automation of shipboard machinery operation	NAVSEA 0331 NAVSEC 6141 & 6732B DTNSRDC 2731
Ship System Maintenance Monitoring and Support Program	Manual to semiautomatic	Extend overhaul cycle for SSBN's	NAVSEC 6107
Machinery Condition Analysis Program	Manual	Elimination of unnecessary repair work and identification of equipment most in need of repair	NAVSEC 6141B NAVSECPHILADIV 6732B
Navy Oil Analysis Program	Manual	Identification of potential malfunctions or equipment degradation	NAVSEA 0494
Noise-Vibration Monitor Analyzer Program	Semiautomatic	Automatic noise and vibration monitoring by shipboard personnel (TRIDENT)	NUC 603
Integrated Automatic Test System Program	Semiautomatic	On-line performance monitoring, trend analysis, and corrective fault isolation data for selected system/equipments (TRIDENT)	NELC 3500
Vibration Analysis and Deviation Concept System Program	Semiautomatic	Central automated on-line monitoring of performance and material condition.	MARAD 930
Surface Ship Vibration Analysis Program	Manual	Elimination of necessity to periodically open and inspect machinery, monitoring by ship's force	NAVSEA 0494
Chapman Number Acoustic and Vibration Measurement Program	Manual	Ship silencing and quality assurance in machinery overhaul by tenders	NAVSEA 037
Shipboard Machinery Maintenance Monitoring Program	Manual to semiautomatic	Improved shipboard maintenance resulting in reduction of maintenance personnel, tasks, material, and failures (FF/DE 1052 class)	DTNSRDC 2784
Diesel Engine Condition Monitoring Program	Semiautomatic	Diagnostic maintenance system for LST diesel engines	NAVSEC 6146B
Centralized Automatic Test System	Semiautomatic	Improved material readiness - avoidance of unnecessary disassembly	NAVSEC 6178B
Propulsion Monitor and Display System Program	Semiautomatic	An automated monitoring and display system for ship's propulsion plant (FF/DE 1078 class)	NAVSEC 6178B
Automatic Test Equipment Management and Technology Program	Semiautomatic to automatic	To establish guidelines for selection standardization, application, and logistic support of ATE	NAVMAT 036T NAVSEA 981E NAVELEX 4804

Design and planning data for an automatic shipboard monitoring and control system for a ship's engineering system were also available for review. This computer-controlled system is called the IMAC.<sup>2</sup> This concept extends the concepts of the AEGIS ORTS to automatic ship machinery control and performance monitoring.

A highly automated control and monitoring system is being installed in a new series of Italian missile frigates, equipped with two aeroderived LM 2500 type gas turbines.<sup>3</sup>

## CANDIDATE EQUIPMENTS FOR PERFORMANCE MONITORING

Shipboard machinery systems were examined to determine equipment/components that are critical to ship operation and are the greatest consumers of maintenance resources. Examples of such equipment are:

- Propulsion turbines, either steam or gas turbine.
- Diesel engines.
- Forced draft blowers for steam driven ships.
- Reduction gears.
- Ship service turbogenerator sets.
- Freshwater and saltwater pumps.
- Lube oil pumps.
- Air compressors.
- Steering system.
- Hydraulic pumps.

Less critical equipments were also examined to resolve which would be amenable to performance monitoring. Some of these include:

- Refrigeration system compressors.
- Air-conditioning compressors.
- Distilling plants.
- CO<sub>2</sub> scrubbers.

From these investigations, a list of shipboard machinery that would be candidates for performance monitoring was compiled (see table 2). This table was compiled from Fleet maintenance data and lists of pertinent machinery from maintenance and performance monitoring technical documents. Machinery is presented as components of major ship systems for a more logical format. There is great emphasis on steam-powered-ships' machinery in the list, this is due to the preponderance of such ships in the Fleet. It should be noted, however, that propulsion machinery for gas turbine and diesel engine ships is likewise candidate for performance monitoring.

**TABLE 2**  
**LIST OF CANDIDATE SHIPBOARD MACHINERY FOR**  
**PERFORMANCE MONITORING**

Item	Ship System	Equipment	References*	
1	Various Steam Generating System	All rotating machinery	A, G	
2		Boilers	B, D, E, F, I	
3		Forced draft blowers	A, B, C, D, E, H, I	
4		Fuel oil service pumps	A, C, D, F, I	
5		Fuel oil filters/strainers	I	
6		Fuel oil heaters	I	
7		Main feed pumps	A, B, C, D, E, F, G, H, I	
8		Feed booster pumps	A, B, C, G, H, I	
9		Automatic combustion and feedwater controls	B	
10		Fuel oil transfer pumps	A, C, G	
11		Feedwater stage heaters	D	
12		Deaerating feed heaters	D	
13		Regenerative air heaters	D	
14		Prime Mover System (steam turbine or gas turbine)	Propulsion turbines	A, B, C, D, F, G, H, I
15		Reduction gears	A, B, C, D, F, G, H, I	
16		Lube oil coolers	I	
17		Lube oil filters/strainers	I	
18		Lube oil purifiers	A, B	
19		Lube oil pumps	A, G, I	
20		Line shaft bearings	A, D, E, G, I	
21		Main thrust bearings	D, E, G	
22		Propellers and shafts	E	
23		Ship's Electrical Service System	60 Hz turbogenerators	A, B, C, D, F, G, H, I
24			400 Hz generator sets	A, B, C, F, G, H, I
25			Diesel generators	A, B, D, F
26	Lube oil system turbogenerator		I	
27	Condensate System	Main condensate pumps	A, B, D, G, H, I	
28		Turbogenerator condensate pumps	A, F, G, I	
29		Main condensers	B, D, F, I	
30		Turbogenerator condensers	I	
31		Main and turbogenerator air ejectors	I	
32		Freshwater drain tanks	I	
33		Freshwater drain pumps	A, B, D, G, I	
34		Deaerating feed tanks	I	
35		Auxiliary gland condensers	I	
36		R&E feedwater tanks	I	
37		High-pressure drain system	I	
38	Seawater Circulating System	Main condensers	I	
39		Main circulating pumps	A, C, D, G, H	
40	Freshwater System	Saltwater circulating pumps	A, G,	
41		Distiller feed pumps	A, G	
42		Distilling plants	D, F, G, I	
43		Potable water pumps	A, G	
44	Lubricating Oil System	Lube oil service pumps	A, B, C, D, F, G, H, I	
45		Lube oil coolers and filters/strainers	Recommended	
46	Compressed Air System	Low-pressure air compressors	A, B, C, D, E, H, I	
47		High-pressure air compressors	A, B, C, D, E, G, H, I	
48		Air dehydrators	F	
49		Ship Control System(s)	A, B, C, D, F	
50		Steering gear	B	
51		Fin stabilizer	A, C, G	
52	Refrigeration System	Hydraulic pumps	Recommended	
53		Hydraulic oil coolers	Recommended	
54		Hydraulic oil filter/strainers	Recommended	
55		Hydraulic oil supply tanks	Recommended	
56	Air Conditioning System	Refrigeration compressors	A, B	
57		Evaporators	Recommended	
58	Habitability System	Air conditioning compressors	A, B, F, G	
59		Air conditioning chill water pumps	A, F, G	
60	Deck Machinery Systems	CO <sub>2</sub> scrubbers	G	
61		Fans and blowers	A, G	
62		Electrohydraulic winches/controls (Stream)	E, F	
		Elevators and conveyors	C, E, F	

TABLE 2 (Cont)

Item	Ship System	Equipment	References
63	Miscellaneous	Vacuum pumps	D
64		M-G sets	A
65		Fire and flushing pumps	A,B,C,D,E,H
66		Saltwater service pumps (auxiliary SW, trim, drain)	A,D,G,
67		Prime pumps	A,G
68		ASROC circulating pumps	A
69	Various	Magazine sprinkler systems (ASROC)	E,F
70		Valves; fluid: air, gas, steam, freshwater, saltwater, hydraulic oil, etc.	Recommended
		(control, regulating, servo, etc.)	

\*Key for References:

- A - Surface Ship Vibration Analysis Program<sup>4</sup>
- B - Shipboard Machinery Maintenance Monitoring Program<sup>5</sup>
- C - Machinery Condition Analysis Program<sup>6</sup>
- D - Vibration Analysis and Deviation Concept Program<sup>7</sup>
- E - Detection, Action and Response Technique (DART)<sup>8</sup>
- F - Fleet Machinery Maintenance Notes<sup>9</sup>
- G - Noise-Vibration Monitor Analyzer Program<sup>10</sup>
- H - Ship Overhaul and Maintenance Study by Harbridge House<sup>11</sup>
- I - Propulsion Monitor and Display System (TEAMS)<sup>12</sup>

Important machinery data will require confirmation for individual equipment/component testing for SMPMS. Existing sources of data that can assist in corroborating this subsequent testing are:

- 3M Program, NAVSEC, Mechanicsburg Division.
- Detection Action and Response Technique Program, NAVSEA, Fleet Support Directorate.
- Machinery Condition Analysis data bank, NAVSEC, Philadelphia Division.
- SSBN Ship System Maintenance, Monitoring, and Support Program Data Bank, DTNSRDC, Annapolis.
- Noise-Vibration Monitor Analyzer Program data bank.
- Surface Ship Vibration Analysis Program data.
- Shipboard Manning and Automation Project Office, DTNSRDC, Annapolis, contracted studies.
- Individual equipment manufacturers data.

Plus the individual equipment/system performance investigation testing.

## FEASIBLE MONITORING TECHNIQUES

A search was conducted to investigate applicable techniques for machinery monitoring. A wide spectrum of techniques was considered, techniques with broad application, specialized techniques, even esoteric or proprietary techniques. Only those techniques that in past experience have been employed in relevant monitoring situations with successful results were considered for this report, see appendixes A through G.

These monitoring techniques involve multivariate considerations. Parameter-Isolation techniques can determine exactly what machine parameters or physical characteristics are easily adapted for monitoring. This is based on "signature analysis." Any operating system has a mechanical, electromagnetic, or chemical "signature." Any change in this signature indicates incipient failure before any external signs appear.<sup>13</sup> Parameter-Isolation techniques include physical characteristics such as:

- Motion and vibration.
- Pressure.
- Temperature.
- Flow.
- Force, torque, and strain.
- Power.
- Efficiency.

Beginning with the domestic commercial airlines introduction of maintenance monitoring of jet engines using normal, in-flight instrumentation to detect degradation, signature-analysis techniques have been extended to utilize bearing and gear vibration spectra to determine condition and predict incipient failures in rotating machinery. Other techniques involve thermal signatures (direct-sensing and noncontacting, infrared thermography); chemical signatures (vapor monitoring, salinity measurement, spectoscopy and X-ray fluorescence for determining wear debris in lubricants); and electromagnetic energy signatures (transients from induction motors and solenoid actuators and induced eddy currents for material flaw detection). More recently, methods have been devised that use inexpensive friction monitoring equipment to signal the need for maintenance action or confirm the satisfactory mechanical condition after rework or relubrication by measuring electric motor coastdown time from de-energizing to stop.

Other major categories of techniques are failure simulation techniques utilizing systems mathematical models; testing techniques such as wear testing; measurement techniques including

commercial measurement systems, automated instruments, and sensors. Sensor technology is improving rapidly due to the application of integrated circuit technology to the sensing elements. Prediction techniques for malfunction and failure and systems integration techniques are necessary, too. Several successful prediction techniques employ pattern recognition methods for prognosis. Systems integration will be facilitated by the application of microprocessors and other large-scale-integrated-circuits in data acquisition and signal conditioning roles. This will allow control of the monitoring system to be more distributed and permit the use of "less-than-ideal" sensors, which would be compensated by preprogrammed microprocessors.

In selecting any of the proposed techniques, it is mandatory for the investigator to verify that a correlation exists between a monitored variable or the employment of a specific technique and actual equipment condition. The investigator should ask himself about a specific technique, "Does it offer potential rewards in monitoring machinery performance?"

#### POTENTIAL FOR APPLICATION OF SIMULATION/FAILURE ANALYSIS MODELS

An investigation was made to determine the potential for implementing systems simulation models; this was based on an assessment of previous attempts at failure analysis simulation. It is anticipated that a complete computer simulation program for the monitoring system will provide the basis for checkout of the prototype software package.

Pertinent simulation and failure analysis models for machinery systems include maintenance models for control and surveillance of deteriorating systems;<sup>14</sup> probabilistic maintenance models for failing equipment;<sup>15</sup> and systems effectiveness measurement models such as system reliability and availability, system mean-up-time, and probability of system repair.<sup>16</sup> In reliability theory, the concept of increasing failure rate distributions plays a large part. From a failure distribution function of a particular machine, a corresponding failure rate can be defined; this can easily be extended to a group of machines with known failure distributions or to a system that has a known failure distribution. A simple optimal maintenance policy can be formulated for a machine (group of machines or system) where the necessary failure distribution function describes the deterioration of the piece of machinery at each monitored condition or inspection.<sup>15</sup> It is assumed that any machine with an increasing failure rate distribution deteriorates with age and is more likely to fail the older it gets.

Also, mathematical models for the on-line diagnosis of unrestricted faults in sequential systems, such as digital logic and computers,<sup>17, 18</sup> may be adaptable for machinery systems failure analysis. These models should also prove helpful for monitoring system self-test routines and fault isolation.

Simulation models for failure analysis of individual equipments and components were also considered. As can be seen above, probabilistic maintenance models can be employed for individual machines. Other appropriate techniques include methods for determining the degree of friction wear on machine parts and cybernetic diagnostic models of mechanical equipment exhibiting vibroacoustic phenomena.<sup>19</sup> The latter models are applicable to such equipment as metal-working machines, piping systems, and structures.

Equipment/component vibration-response models can be formulated by modal analysis techniques and by computing mechanical impedance. Such modeling can, when done in conjunction with vibration testing or monitoring, determine and predict dynamic performance and assist in isolating faults.

Enough examples of previous successful mathematical modeling attempts exist to conclude that failure analysis simulation for machinery systems is feasible.

#### SYSTEMS INTEGRATION

Systems integration considerations are paramount in optimization of monitoring system design to determine machinery performance and condition from the monitored parameter data and in providing required machinery status information for the Watch Supervisor in the most direct manner. As has been stated, the monitoring system will continuously observe specific diagnostic phenomena (i.e., vibration, temperature, flow, etc.) for an indication of change in the mechanical condition of the equipment. The specific capabilities of the Shipboard Machinery Performance Monitoring System would permit:

- Displaying plant status.
- Determination of plant capability.
- Indication of off-normal condition.
- Detection of performance degradation.
- Failure prediction.
- Diagnosis of failures.
- Isolation of faults.
- Anticipating maintenance requirements.
- Scheduling maintenance.
- Recording performed maintenance.



- Maintaining machinery history.
- Providing data for off-ship analysis.

The hardware and software solutions to these problems must be melded together in a workable manner. This is the problem of systems integration.

It is expected that ATE techniques will be implemented. Automatic test for machinery monitoring systems is a logical extension of state-of-art ATE for sophisticated electronic systems. The ATE techniques will be required to provide the rapid detection, diagnosis, and prognosis for necessary fault identification and isolation. To determine and select test points on prime equipment and system interface requirements for shipboard machinery monitored by ATE, investigators should consult MIL STD 1326 (NAVY). This document should guide the overall application of ATE for the SMPMS.

It will be necessary for monitoring system equipment vendors to adhere to and comply with the SEM Program, formerly Standard Hardware Program, for system electronics.<sup>20</sup> A continuous effort should be made to limit complexity and cost to ensure the reliability and availability of the monitoring system itself!

The machinery performance monitoring system will have to interface with other ship monitoring systems. Developments should be coordinated with the ORMS Program<sup>21</sup> as it progresses. Automatic test equipment to be employed in the SMPMS shall comply with Naval Material Command Instruction 3960.4A of 26 December 1973, which implements policy and responsibility for ATE and other similar equipment (see table 1). This will facilitate the utilization of established data banks for ATE and diagnostic systems.<sup>22</sup>

Systems integration will also have to adapt and ameliorate previously formulated concepts for automatic/semiautomatic test and monitoring systems for shipboard machinery. Systems that merit consideration include:

- Centralized Automatic Test System.
- Noise-Vibration Monitor Analyzer.
- Integrated Automatic Test System.
- Vibration Analysis and Deviation Concept.
- Propulsion Monitor and Display System.
- Integrated Machinery Automation Concept.

Each of these systems has features that would appear to solve specific difficulties in piecing together a performance monitoring system; no one, alone, provides all the necessary

capabilities for this requirement, however. The IMAC system approaches the automated machinery system goals. It does not attack the problem of employing the individual dedicated monitoring techniques required for all of a ship's machinery systems.

The Shipboard Machinery Performance Monitoring System, as it is presently conceived (see figure 1) will be capable of providing plant status-maintenance schedule commands to the operator, diagnosis of pending problems, and prognosis of future failures. The sensors and transducers will be located at various selected points throughout the machinery system. Practically all of these devices will develop analog output signals as a function of their input-measured parameters. The number and type of sensors will be optimized to provide the necessary machinery-monitoring scope with a minimum of monitoring system complexity.

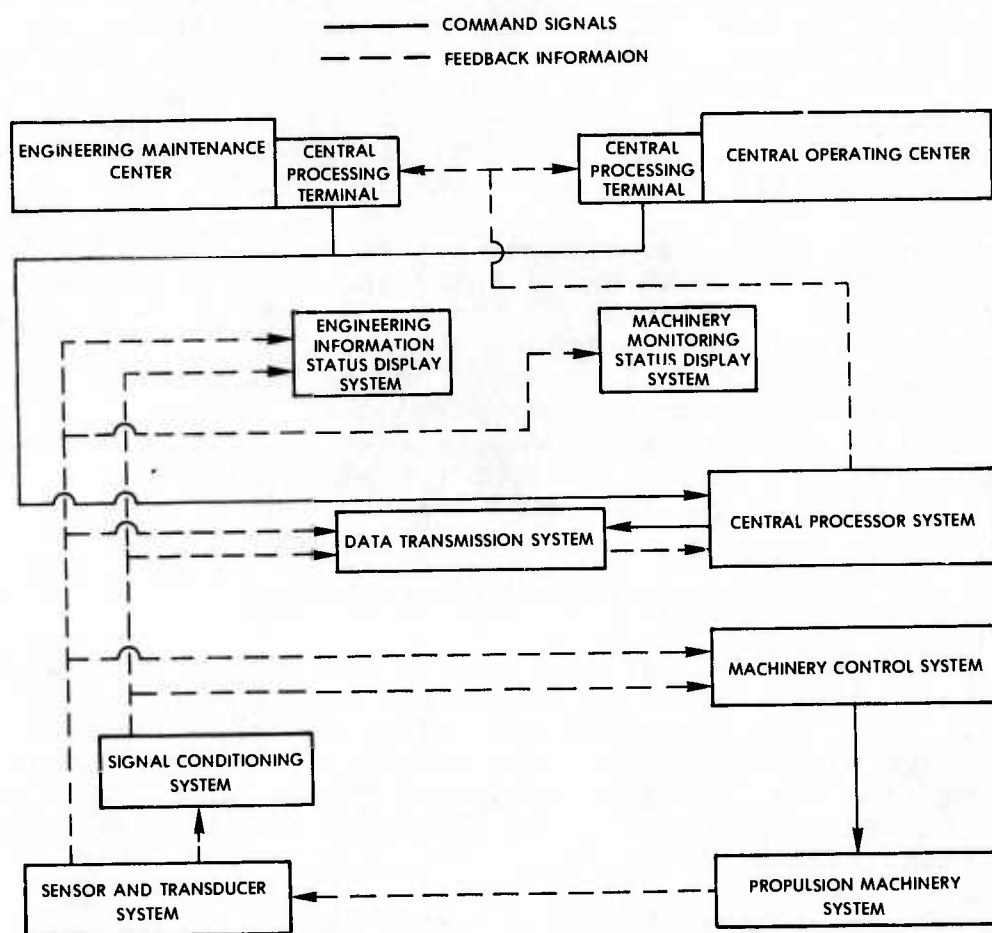


Figure 1  
Automatic Machinery Performance Analysis System  
Concept, Information Flow Chart

The signal conditioning system is composed of processor elements which perform computation based on input information received from its transducer(s). The computation performed may be for purposes of scaling or biasing, or for combining signals, as in the case of computation of shaft power as a function of measured torque and speed.

The purpose of the data transmission system is to collect and distribute information from the sensing of signal conditioning system to the various peripheral components of the monitoring system, along with identifying "tag" signals. It should be considered that a shipboard data multiplex system will likely be implemented, but fiber optical data transmission techniques should also be considered.<sup>23</sup>

The central processor terminal provides the interface between the Watch Supervisor and the central processor. Using these devices, the central processor will be able to present the various data generated as a result of routine procedure, specific demands made by the Watch Supervisor, or predefined requirements for emergency procedures. The terminals will also provide the facility to permit operator requests for central-processor-generated information, as well as allowing the Watch Supervisor to modify certain processor functions such as alarming at varied levels. The terminal will also be the input device for the type of information that would not be available to the central processor through its data acquisition system.

The central processor system will be capable of providing all information processing and display that is required for the successful one-man monitoring of the space. Under normal operations, monitoring is accomplished automatically without Watch Supervisor intervention. During off-normal or emergency conditions, automatic procedures used to reduce these anomalies will be generated by the central processor but tempered by the Watch Supervisor. It is anticipated that the all application digital computer (AADC) will be considered for the central processor application.

#### CONCLUSIONS FOR BASIC GUIDELINES

A list of criteria for guidance in evaluating the specific systems to be investigated in detail has been compiled (see table 3). This list comprises the guidelines that individual investigators will require for monitoring system development. Concerning item 4 in table 3, equipment manufacturers and their vendors will have to provide base line performance test data on new equipment such as rotating and reciprocating machines. Also, it is quite likely that manufacturers will have to provide "built-in" sensors as an integral part of their equipment.<sup>24</sup>

TABLE 3  
CRITERIA FOR GUIDANCE IN EVALUATING  
SPECIFIC SYSTEMS TO BE INVESTIGATED

1. High maintenance equipment.
2. Critical equipment.
3. Availability of previous test and operating data.
  - a. Successful Navy program data corroboration.
  - b. Successful non-Navy program data corroboration.
4. Availability of technical expertise on newly developed equipments being introduced into the Fleet.
5. Safety considerations.
6. Applicability of MIL STD 167-1 (SHIPS): Mechanical Vibrations of Shipboard Equipment.
7. Energy utilization (savings).
8. Availability of desired/required sensors.
9. Validation of selected techniques.
10. Systems integration compliance with MIL STD 1326 (NAVY): Test Points, Test Point Selection, and Interface Requirements for Equipments Monitored by Shipboard On-Line Automatic Test Equipment.
11. Continuous or periodic monitoring for selected parameter.
12. Processor data storage space required.
13. Trend presentation/machine history.
14. Ability to interface with damage control, central control, and casualty control systems and any operational readiness monitoring system onboard ship.
15. Integrable with laboratory prototype performance monitoring system for propulsion and auxiliary machinery.

Regarding item 6 in table 3, shipboard equipment that conforms to MIL STD 167-1 is generally found to perform its functions satisfactorily aboard ship, and equipment for which

compliance to this standard has been waived is likely to experience failures induced by vibrations in shipboard service.

For item 8 in table 3, it is essential to consider sensor reliability, for what good is a monitoring system when it ceases to hear, see, or feel?

Goals for incipient failure detection should include determining the ability to predict "time to failure" with high confidence level and the diagnostic capability for fault location. The key to efficient fault diagnosis is the ability to rapidly isolate each fault.

#### RECOMMENDATIONS

The successful implementation of an integrated machinery monitoring system development program will require additional investigations to include:

- A list of recommended equipment to be monitored, including newly developed equipments being introduced into the Fleet.
- Identification of major machinery failure modes.
- Identification of recommended monitoring techniques.
- Requirements for new or improved sensors.
- A preliminary integration plan for a laboratory evaluation machinery performance monitoring system.

It is only through the implementation of such an integrated program that the benefits of automation combined with an automated monitoring system be fully realized.

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## APPENDIX A

### GENERAL TOPICS

#### Performance Monitoring and AIDS Seminar Notebook

S. Tenenbaum, Editor

Aero Data, Inc., Syosset, NY

April 1975, 600 pages

This notebook comprises the text of a presentation on performance monitoring and Airborne Integrated Data Systems (AIDS) made in April 1975 at Montreal, Canada. A definition of a performance monitoring system is presented, and the objectives attainable by such systems are discussed.

Key elements of performance monitoring systems are reviewed, as well as various ways in which these elements can be assembled and organized to achieve the desired monitoring system objective.

An historical development of performance monitoring systems is included. A brief description of some current programs including case histories, the VIDECA experience, military air transport detection analysis system, and an electric power utility case history is presented. Future trends for performance monitoring systems are indicated.

#### Condition Monitoring, Trend Analysis, and Maintenance Prediction for Ship's Machinery

W. DeJong

Netherlands Ship Research Centre TNO, Delft, The Netherlands,  
Engineering Department Report 190M

April 1974, AD-923 389, 22 pages

"This survey of literature reviews the state-of-the-art with regard to Condition Monitoring, Trend Analysis and Maintenance Prediction Techniques for ship's machinery installations and the utilization of computers in this field, i.e. as far as these new developments have been reported in technical journals, symposium papers, and other publications.

"The main objectives of the application of these techniques and the possible effect on maintenance systems are discussed. In particular, the following subjects are dealt with:

- i. Condition Monitoring, Trend Analysis and Maintenance Prediction systems for main diesel engines based on the monitoring of the combustion chamber processes and using specially developed as well as conventional

sensing devices to measure temperatures of cylinder liners and covers, piston ring behavior, cylinder pressures, fuel injection timing and similar parameters. This part is predominantly based on reports describing recent developments which take place in Scandanavia, particularly Norway.

ii. Vibration Monitoring techniques and their possible use for Condition Monitoring, Trend Analysis and Maintenance Prediction. This part is based on practical and theoretical studies and experiments mainly carried out in the U.S.A. and using vibration monitoring and analyzing equipment for all types of rotating machinery such as turbines, gearings, compressors, pumps, etc.

It is further indicated that quite a few firms, particularly engine builders and makers of monitoring equipment and computers are actively engaged in developing such systems. In the conclusions, it is stated that a widespread use of Condition Monitoring, Trend Analysis and Maintenance Prediction Techniques on ships may be expected within the next 5 to 10 years." (Author)

"Quo Vadis Automation"

George F. Quittner

IEEE Transactions on Industrial Electronics and Control Instrumentation

Volume IECI-21, Number 4

November 1974, pages 215-221

This paper provides a state-of-the art overview of automation, differentiating between automation and continuous automatic control. The author emphasizes industrial manufacturing applications and details standardized information signals, non-contact sensors, and how computers affect automation for continuous, pseudo-continuous, and batch automated processes.

"U. S. Naval Machinery Automation Concepts"

M. R. Hauschildt and L. B. Ward

Naval Engineers Journal

April 1973, pages 41-63

"This paper briefly outlines the present centralized machinery plant control practices in the U. S. Navy for steam, gas turbine and diesel plants. The level of automatic control existent in the more advanced ships today is described.



"Problems existing with present automated machinery designs are discussed with some recommended solutions.

"Present conceptual automated machinery designs are discussed with some recommended solutions.

"Present conceptual automated machinery plant control systems for current ship designs are described, together with applicable control concepts. An examination of practical control system design alternatives available for such warships today are presented.

"Considerations regarding the ultimate practical level of automation for naval machinery are postulated for the future.

"Advantages in accepting 'on-line' digital control of naval machinery in a combatant ship are discussed with an exposition of the side benefits to be gained in utilizing this method of control.

"Predictions relating to the impact of 'on-line' digital computer control of naval machinery in the Fleet and the eventual advantages of such a control scheme are related. The interface relationships with personnel training, rate structure, and maintenance philosophy are discussed."  
(Authors)

"New Ship Automation"

J. J. Dor and J. E. Lidiak  
Naval Engineers Journal  
August 1974, pages 51-63

"This paper examines the principal monitoring and control requirements of machinery and other non-electronic systems on new Navy ships. Measureable parameters and control functions are defined. An automated system design concept is developed. Principal hardware and software modules are identified. The advantages of centralized automatic control and monitoring of ship's engineering systems are demonstrated in terms of reducing manpower, ease of operation, ease of maintenance, greater equipment safety and improved system efficiencies and performance.

"The advantages of standardized and centralized ship's automation are profound. Computer facilities store and process all of the

critical checks on ship's service and performance. Checks and balances are provided to ensure that operating procedures are conducted rapidly, accurately, and without errors of omission or commission. Computer control counteracts the tendency for skill requirements to increase as a function of equipment complexity. It extends operating scope and efficiency of the skilled technician. It minimizes the need for meters and other manual instrumentation. It provides consistent performance independent of individual operator skills. It facilitates a maintenance schedule based on condition rather than time, hence, is more effective and reliable. It enables one system to support a whole class of tactical equipment with expandability to adapt to future needs." (Authors)

"Efficient Manpower Utilization Through Shipboard Automation, Integration and Good Ship Design"

VADM F. H. Price, Jr., USN  
Naval Engineers Journal  
February 1974, pages 61-64

In an address to the Joint Naval Engineering Associations Annual Technical Symposium ("Utilization of Manpower," Washington, D.C., 28 September 1973), the author states that utilization of manpower is one of the most critical problems facing the Navy today. The aspects of this subject are discussed as they relate to shipboard automation, integration, and efficient ship design.

"Essential Manning - Its Impact on Destroyer Design, Operation and Maintenance"

LCDR W. L. Fulton, II, USN  
Naval Engineers Journal  
June 1974, pages 79-96

"The 'Essential Manning Concept' examines the potential for a dramatic reduction in manning aboard the 1980 generation of destroyers.

"This concept considers the transfer of technology from a variety of fields and addresses innovations in design, operation, and maintenance of these future escorts. It investigates, within a broad framework, the feasibility of significant changes which can simultaneously reduce manning and improve military capability." (Author)

"The Navy and Reduced Shipboard Manning"

R. A. Gaites

Naval Engineers Journal

December 1974, pages 73-80

"It has been estimated that manpower costs consume 55% of the life cycle costs of a ship, and that by 1975 these costs will be 65% of the Navy's budget. Manpower reduction has become a necessity, if the procurement dollar is to survive. The Chief of Naval Operations (CNO) has directed that efforts to reduce ship manning be given priority and has appointed an OPNAV Coordinator for Shipboard Manning Reduction.

"Merchant shipping has been operating automated ships with reduced crews for over ten years. It is not uncommon to find unmanned engine rooms and two or three man bridge watches. Crews may work one shift per day with week-ends and holidays off.

"This paper goes on to summarize recent efforts in the U. S. Navy carried out by a Joint Fleet/Laboratory Team and sixteen Fleet Units. It also discusses the Navy's short and long range programs in this area. The main thrust of the short range program will be to automate the engine room and integrate the bridge of a DE 1052 Class ship. Long range efforts will culminate in a 12 man destroyer-type ship by the late 1980's.

"The paper concludes that construction costs of a highly automated ship will certainly be greater than those presently configured ships, and that the procurement dollar may not be alive when the Navy is ready to spend it. The point is made that such a ship could be constructed today using the knowledge accumulated by our NATO Allies and a great deal of off-the-shelf technology.

"A 'bare-bones' plan is presented for the development of a demonstration ship and a pilot support system. It is argued that such a program would be an efficient vehicle for the accumulation of much experience, and that it would exhibit to the Congress the Navy's resolve to reduce costs substantially." (Author)

Logistics and Technology: Some Thoughts about Future Military Implications (U)

R. M. Paulson and T. T. Tierney  
The Rand Corporation, Santa Monica, CA  
Report P-4597  
March 1971, AD-738 045, 13 pages

"Logistics, the creation and support of military capability, and technology, the application of scientific knowledge to the industrial arts, are mutually interactive. Logistics uses technology to improve its service. Technology requires logistics to assure its sustained support. New technology will permit almost unlimited development of applications in logistics command and control. Such advances permit even higher goals of system reliability to be set, perhaps to the point where systems are virtually failure proof. Ideally, system logistics would stop when the system was delivered to the user." (Authors)

"The Maintenance Engineering Process - A Vital Link Between Designer and Fleet Support"

M. L. Hendrickson and T. J. Marcucilli  
Naval Engineers Journal  
February 1974, pages 84-94  
(Paper presented at 10th Annual Technical Symposium, Association of Senior Engineers, Naval Ship Systems Command, Washington, D.C., March 1973)

"This paper discusses the Maintenance Engineering Analysis (MEA) as performed in support of a major ship acquisition process. A major impetus is to demonstrate how the MEA can be utilized better to provide a direct data link between the design agent and the logistic support community to enhance Fleet operational effectiveness. A description of the overall MEA process is provided and several examples are used showing the type of design improvements realizable through an integration of the MEA process into the early stages of ship system design." (Authors)

"Demand Oriented Maintenance"

J. B. Gayle and R. D. Enlow  
Plant Engineering  
October 4, 1973, File #5533, pages 134-134

"In planning major maintenance jobs, the basic question that must be answered is: 'Should equipment which is apparently in satisfactory operating condition be periodically torn down and overhauled?' And if the answer is yes, how often should this be done?"

"Ideally, maintenance should be carried out on a 'Demand Oriented' basis - when equipment approaches failure, it should be checked out and the necessary repairs made. This approach requires a continuous, rigid inspection program for all machinery, but, in the long run, the method will generally pay off because maintenance activities can be performed most efficiently with a minimum of waste in labor, materials, and time." (Authors)

Airline/Manufacturer Maintenance Program Planning Document  
Reliability and Maintainability Committee  
Air Transport Association of America, Washington, D. C.  
Document MSG-2  
March 1970, 27 pages

Airline and manufacturer experiences in developing scheduled maintenance programs for new aircraft have shown that more efficient programs can be developed through the use of logical decision processes. Historically, the initial scheduled maintenance program has been specified in maintenance review board documents. This document is intended to facilitate the development of initial scheduled maintenance programs. The remaining maintenance, that is nonscheduled or nonroutine maintenance, is directed by the findings of the scheduled maintenance program and the normal operation of the aircraft. The remaining maintenance consists of maintenance actions to correct discrepancies noted during scheduled maintenance tasks, nonscheduled maintenance, normal operation, or condition monitoring.

An Index of Non-Electronic Systems for Naval Vessels  
P. B. Perry and J. G. Dinmick  
Naval Ship R&D Center, Annapolis Division, Annapolis, Md.,  
ELECLAB Report 149/68  
May 1968, 100 pages

"This Technical Note catalogs and indexes ship systems and their major components falling in the nonelectronic, nonordnance category." (Authors)

"Integration of Modern Machinery Systems"  
J. W. Abbott  
Naval Engineers Journal  
June 1973, pages 65-84

"With the advent of gas turbine prime movers for both propulsion and electric power generation, new methods of optimizing thermal efficiency are needed if weight and cost limits are to be achieved by new ship designs without sacrificing operational capability. The balance of primary power generation from fuel and secondary power generation utilizing other

energy media must be reviewed. Where once the basic shipboard energy conversion was Bunker C fuel into steam within a large boiler, using steam as the energy medium for all power and heating use, we now have machinery systems that convert fuel into energy at several subsystem levels, i.e., propulsion, electric power, auxiliary steam, and so forth. The design challenge for today's machinery system engineer is to optimize thermal recovery from fuel much the same as economizers etc. that were used in previous steam plant designs. This can be done by making one system dependent upon another for its source of energy. However, the design constraint demanded by Navy combatant ships is that operational flexibility, vulnerability protection and reliability/maintainability/availability goals for each dependent system must be maintained should the primary energy source system fail.

"This paper presents an engineering approach to generating and evaluating alternative machinery designs within the structure of a set of ship design criteria categories. These categories are defined and examples of machinery system design objectives given. A design process is then proposed which includes determination of energy requirements, identification of alternate energy generation/conversion hardware and verification of adequate energy supply under all operating modes. Discussion is given to the importance of selecting the proper energy medium (fuel, electricity, steam, etc.) for each functional service if energy generation and energy absorption are to be efficiently matched. An evaluation approach is then presented which compares total performance of candidate designs on a system-level basis.

"Finally, the paper describes two recent ship designs where integration of machinery systems has taken place: the Canadian DDH-280 Class Destroyer and the U. S. Navy DD-963 Class Destroyer. Elements in the trade-off studies for these ships are reviewed and design advantages discussed." (Author)

"DD 963 Power Plant"

D. A. Rains  
Marine Technology  
January 1975, pages 1-24

"Gas turbines were selected as the main and auxiliary power plants for the new DD 963 Class ships, which is a departure from previous designs for U. S. Naval power plants. This paper describes the DD 963 power plant design, including propulsion and supporting auxiliary machinery." (Author)

"Prospects in Naval Gas Turbine Power Plant Machinery"

D. A. Rains  
Naval Engineers Journal, Volume 87, Number 2  
April 1975, pages 126-138  
(Paper presented at ASNE Day 1975, American Society of Naval Engineers, Washington, D.C., May 1975)

"The naval machinery engineer should be constantly alert to possible design improvements as new technology becomes proven. There are many improvements and innovations currently in development by industry and government. Selections from these many new approaches may be incorporated during the evolution of a particular ship design, or may become available earlier as new ship requirements evolve.

"Prospects for improved gas turbine naval power plant technology that will be available to meet future ship needs are described. New high performance gas turbine engines, machinery maintenance monitoring techniques, improved propulsors such as high skew propellers, waterjets, and pumpjets, advanced speed control and speed reduction devices, combined cycle plants (gas/steam), new fuels, improved anti-icing techniques, and superconducting electric drive machinery are discussed. Potential applications of this machinery technology are described to demonstrate how design change is an important part of the professional life of the naval machinery engineer." (Author)

Status Information Proposed for Presentation to a Submarine  
Conning Officer at a Command-Control Console Simulated by the  
Submarine Safety Monitor System

G. S. Murphy, M. E. Death, and C. C. Hall

Naval Ship R&D Center, Annapolis Division, Annapolis, Md.,

ELECLAB Report 21/68

July 1968, 82 pages

"The conning officer of a submarine requires knowledge of the current status of the ship's subsystems and the effect changes in the status have upon the operational situation.

"In a study conducted under the FRISCO Program, a comprehensive list of functions required of the conning officer for various missions and phases was prepared. Requirements were then derived to effect fulfillment of each function. These requirements were summarized as follows: weapons status, operations summary, and systems status.

"The Submarine Safety Monitor System was used to evaluate the concept of presenting status information of the submarine conning officer in an experiment at the U. S. Navy Submarine School, New London, Connecticut. Some minor modifications to the Submarine Safety Monitor System were necessary to present the status information requirements as listed." (Authors)

Status Information Requirements of Shipboard Control Personnel  
Concerned with Non-Electronic Systems

P. B. Perry and J. G. Dimmick

Naval Ship R&D Laboratory, Annapolis, Md., ELECLAB Report 1/69

March 1969, 49 pages

"The information requirements of some of the shipboard system and subsystem controllers, which will be associated with Centralized Automatic Test System are established. The basic requirements are derived from the duties of those personnel as prescribed by U. S. Navy Regulations (1948). The specific information requirements of the officer of the deck (OOD), the engineering officer of the watch (EOOW), and the damage control assistant are outlined. The origins, transmission methods, retrieval methods, and use intervals during all conditions of readiness for each item of information which is presently available to the OOD and the EOOW are tabulated." (Authors)



Outline Description of A Ship Status System for Escort Vessels  
P. B. Perry, J. G. Dimmick, and M. E. Death  
Naval Ship R&D Laboratory, Annapolis, Md., ELECLAB Report 3196  
October 1969, 48 pages

"This report, the third in a series, describes a shipboard system composed of a digital computer, sensors, output terminals, recorders, and interface equipment which will automatically collect, process, record, and disseminate information describing the status of nonelectronic shipboard systems. Problem areas are identified and recommendations made for their solution." (Authors)

"The Design Requirements for an Unattended Engine Room Steam Propulsion Plant"

W. G. Bullock and F. D. Yonika  
Marine Technology  
April 1972, pages 205-215

"This paper is a summary of a report prepared by the Office of Ship Construction to provide a base reference document from which a detailed design for an automated steam propulsion plant will be developed for unattended engine room operation. As the design details are developed, it may be anticipated that some of the concepts and preliminary design requirements discussed herein may be modified and/or changed to reflect these developments." (Authors)

## APPENDIX B

### PARAMETER-ISOLATION TECHNIQUES

#### Technical Diagnostics of Machines

V. P. Lints

Army Foreign Science and Technology Center, Charlottesville, VA

Report FSTC-HT-23-1381-72

June 1972, AD-746 559, 39 pages

"Machinery Diagnostics is a new, rapidly growing branch of machinery science. This report describes diverse methods of machine diagnostics used to permit diagnosis of parts of complex machinery and its uses in testing materials." (Author) Translated from Russian.

#### "Signature Analysis: Product Early-Warning System"

F. J. Lavoie

Machine Design

23 January 1969, pages 150-160

"Every operating system has a mechanical, electromagnetic or chemical 'signature'. Any change in this signature indicates incipient failure, long before any external signs become evident. With the sophisticated monitoring techniques now being developed, catastrophic system failures could soon be a thing of the past." (Author)

#### "Analyzing Malfunctions in Plant Equipment"

E. M. Stolberg

Plant Engineering

5 October 1972, pages 101-103

The plant engineer who is alert to signs of equipment weakness and takes preventive measures can save thousands of maintenance dollars in reduced production equipment downtime, improved product quality, and continued utility services.

Some of today's tools, instruments, and procedures for accurate troubleshooting are highly sophisticated and expensive; however, other techniques are simple, inexpensive, and quite effective in detecting and preventing expensive machinery failures.

Nondestructive Evaluation Technique Guide

A. Vary

NASA Lewis Research Center, Cleveland, OHIO

NASA Report SP-3079

September 1973, N73-31441, 105 pages

"Seventy nondestructive techniques for evaluating materials and structures are described in a single guidebook. A standardized format facilitates comparison of their merits and limitations for solving problems.

"The nondestructive techniques described in the guidebook permit measurement of physical properties, composition, and structures, and reveal or infer hidden flaws. Each technique is described on a single page under six headings: method, principles, objectives, applications, limitations, and references. Schematic diagrams complement the text. Techniques are classified in a modified form of the classification system adopted by the National Materials Advisory Board (NMAB) Ad Hoc Committee on Nondestructive Evaluation. Additional categories have been included to cover advanced techniques.

"The guide includes an index of flaw types and a tabulated guide to the use of nondestructive evaluation techniques. Alternative technique names are cross-referenced." From NASA Tech Brief B74-10122, November 1974.

"The Particles of Wear"

D. Scott, W. W. Seifert, and V. C. Westcott

Scientific American, Volume 230, Number 5

May 1974, pages 88-97

"When the parts of a machine wear, they shed tiny bits of metal. A new method of analyzing such particles clarifies the process of wear and can give early warning of the failure of a machine." (Authors)

The Investigation and Interpretation of the Nature of Wear Particles

V. C. Westcott and J. L. Middleton

Trans-Sonics, Inc., Burlington, MA

March 1974, AD/A-003 553, 92 pages

"The particles of wear recovered and analyzed from more than 200 oil samples using Ferrographic techniques. Oil samples from controlled component tests and from field operating systems were analyzed. The

particles have been classified by morphology and material and have been related to the wear mechanisms. The character of the particles which occur during normal operation is discussed. When the machine starts to fail not only does the amount of particulate matter increase, but some unique types of particles are generated. These types are shown to be related to specific modes of wear and can be used to determine the location of the failure." (Authors)

Studies of the Nature of Wear

V. C. Westcott, D. Scott, J. L. Middleton, and R. A. White  
Trans-Sonics, Inc., Burlington, MA  
October 1974, AD/A-003 548, 62 pages

"It was shown that spherical particles which are found in fatigue cracks of rolling contact elements, i.e. bearings and gears, are not formed in fatigue cracks generated, by translational cyclic stress. A 'Contact Wear Machine' was developed to simulate conditions near the pitch line of gears. Test specimens are a simple cylinder and a rectangular anvil. Contact loads and the ratio of sliding motion to rolling motion may be varied. Experiments have been run using Armco 17-4 PH and EN-8 (SAE 1040). Ferrograms made from oil samples taken during the experiment with Armco 17-4 contained a large number of spheres prior to the appearance of typical gear fatigue particles. The tests using EN-8 also produced typical gear fatigue particles, but no spheres. The fatigue pits found on the test specimens have the same apparent morphology as those found on gears." (Authors)

"Oil Analysis in Perspective"

R. S. Miller

Office of Naval Research, Arlington, VA

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"Is oil analysis primarily a detector of failure or a tool to be used to improve reliability and to reduce the incidence of failure? This paper stresses the need to know the systems characteristics before oil analysis requirements of I.C. engines, aero gas turbines, and hydraulic systems. The paper concludes with a discussion of why assumptions that work well in one system are not necessarily appropriate for another." (Author)

"Oil Analysis - A Maintenance Management Tool"

J. D. Guite, Jr.

NAVSEA Journal

November 1974, pages 14-18

"Lubricating fluid is the life blood of oil-wetted mechanical systems. Just as a doctor samples a patients blood to determine the health of his patient and to describe medication as required, the oil analyst in the laboratory examines oil samples for predicting incipient failures of equipment, improving equipment operational availability and reliability, and reducing unnecessary maintenance actions. Oil analysis is based on the concept that under certain conditions and within certain limitations, the interval conditions of any enclosed mechanical system can be evaluated by the spectrometric and physical analysis of fluid samples from the system. Oil analysis can provide a sound maintenance management tool for equipment operators." (Author)

"Tri Service Oil Analysis Research and Development Program"

P. B. Senholzi

Department of the Navy, Washington, D.C.

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"The objective of the Tri Service Oil Analysis Research and Development Program is to define correlations between wear particles characteristics and respective oil wetted component wear surfaces. These correlations will provide a firm technical base for utilization of oil analysis as a diagnostic technique.

"Laboratory bench testing constitutes the initial phase of the research effort. Oil wetted components are subjected to bench testing in closed loop lubrication systems. Periodic monitoring of the component oil wetted wear surfaces is conducted throughout testing. Oil specimens are sampled regularly during testing and wear particle characteristics and parameters are thoroughly categorized. Correlations are then defined between surface wear and wear particulate parameters.

"The second phase of the research program consists of applying laboratory

results in actual field situations. Control field equipment test groups have been established and are being monitored for oil samples and failure data. Laboratory developed correlations are applied to those control groups for verification." (Author)

"Simple Detector for Oil Contamination"

J. E. McAlister

Instruments and Control Systems

October 1974, page 81

In oil-fired steam power plants, where there is a closed fuel-oil-service-heater steam-system, there can be a problem with fuel oil contamination in the condensate. A simple device to detect oil in water is presented.

Spectrometric Oil Analysis-Principles and Practice

C. A. Waggoner

Defence Research Establishment Pacific, Victoria, B.C., Canada

Report DREP-71-A

March 1971, AD-885 561, 45 pages

"Spectrometric oil analysis is a system of preventive maintenance applicable to oil-lubricated components in mechanical equipment. The system is based primarily on the assumption that the extent of wear at the surfaces of lubricated internal components is a function of their physical condition, and that is reflected by the kind and content of metals in the used oil, which result from either particle transfer or dissolution. Under normal conditions wear rate, and thus metallic contamination, is assumed to be minimal and relatively uniform. However, in the event that surface defects arise, a tendency towards increased wear is to be expected and, concurrently, increased metallic contamination of the lubricating oil should become evident. Detection of abnormal contamination is accomplished by the quantitative analysis of lubricating oil samples for specific metals at regular intervals. There 'time lapse' analyses provide indirect information on the cumulative wear of components of different alloy composition and on the rate of wear, thereby permitting prediction of the possibility of mechanical failure."  
(Author)

The Application of Some Chemical Techniques to the Assessment of  
Wear in Oil-Washed Systems

M. Freegarde and B. J. Webb

Admiralty Materials Laboratory, Poole, England, U.K.

Report AML/5/74

May 1974, AD-923 717, 8 pages

"An examination has been made of some chemical changes that result when wear takes place in machinery lubricated by OX38 oil. Wear products containing iron are present as a mixture of metallic iron and  $Fe_3O_4$  shortly after release but no correlation between the proportions of each and the mode or degree of wear can be found. On standing, the wear products slowly dissolve in the worn lubricant at a rate that reflects the severity of the wearing conditions applied during preparation. This effect arises from depletion of antioxidants followed by a breakdown of the lubricant to release acids. A test to measure the degree of anti-oxidant depletion has been developed and is suggested for general evaluation and exploitation as a means of giving warning of the onset of rapid wear."  
(Authors)

Mechanical Failure Warning System for Hydraulic and Lubrication  
Systems

F. C. Jones

K-West Company, Westminster, CA, Bulletin 9-73

April 1974, 9 pages

This bulletin describes an oil debris monitoring system which can provide early warnings of transmission, air compressor, and engine failures. The system is comprised of a small, inexpensive indicating screen and an electrical readout which gives the user warnings of impending bearing or seal failure. The sensors will electrically indicate the buildup of particles (aluminum, steel, magnesium, brass, etc.) as well as strain these particles from the lube oil system. Magnetic plugs and oil strainers can most probably be removed from lube oil systems and more diagnostic information can be obtained by using "indicating screens."

"Bearing Contact Resistance as a Diagnostic Aid"

R. L. Smith

Shaker Research Corporation, Albany, NY

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"Electrical contact resistance signals have been useful in diagnosing the relative 'health' of operating bearings. Preliminary results of analysis indicate that it is

possible to tell more about the condition of bearings than has been possible in the past; even when operating. Common bearing conditions which provide distinct spectrum displays while operating are:

- Non-sphericity of balls, rollers, and raceways.
- Flat spots, rough areas, or unfinished surfaces.
- Worn or degraded bearing surfaces.
- Insufficient bearing lubricant film thicknesses.
- Unstable ball or roller retainer operation.
- Dynamic component overloading."

(Author)

"Ultrasonics Checks Bridge for Fatigue"

Editorial Staff

Instruments and Control Systems

June 1974, pages 26-28

Five nondestructive inspection techniques were selected for experimental investigation to appraise their relative applicability for inspecting in-service steel highway bridges for fatigue cracks. Each technique was assessed according to minimum size crack detectable (in welds, in mechanical joints, beneath the surface) and the degree of discrimination of the technique; influence of environment and other parameters related to field adaptability including vibration, temperature, power required, safety requirement accessibility required, and surface preparation required; factors related to the necessary instrumentation to implement the technique, including complexity, adaptability to automation, degree of operator skill for interpretation, and potential for development.

The investigation of ultrasonic techniques showed that they offered the best overall potential for development into usable equipment for detecting fatigue cracks in steel bridges.

Feasibility Study of Semiautomated Ultrasonic System for Flaw Detection in Metal Castings

G. D. Giacomo and M. L. Foster

Naval Applied Science Laboratory, Brooklyn, NY

Report NASL-IED-13-PR-3

September 1968, AD-839 296L, 57 pages

"This report describes the feasibility of scanning portions of complex shapes (metal



castings) automatically by a prototype ultrasonic system and recording synchronously the ultrasonic flaw information by chart readout. The system has been tried on a hollow hemispherical steel casting with a radius of curvature of 8-1/2 inches and a wall thickness of one inch. The casting had artificial holes of various depths (1/4 in. to 3/4 in.) and diameters (1/8 in. to 1/4 in.), drilled from the inside surface. The probe scanning was performed by a hydro-tel while the casting was immersed in water. The C-scan chart records show good definition of the holes in their actual size. The feasibility of ultrasonically inspecting castings of complex shapes has been demonstrated." (Authors)

The above-mentioned hydro-tel is a milling machine that was used as the probe positioning unit. It was utilized as an expedient to keep costs within fund limitations.

"Flaw Detection by Mechanical Resonance"

Editorial Staff

Mechanical Engineering

October 1974, page 44

Standard nondestructive tests of the weld quality of tubes and bars fastened to base plates are expensive and time consuming. Present techniques, including ultrasonics, are not sufficiently accurate to detect very small critical flaws in high strength alloys. A quick, reliable method has been developed for testing weld quality by means of vibration resonant frequency analysis. This technique is based on the analysis of varying frequency scan applied to measured samples. Any changes in resonant frequency harmonics detected in the samples then are used to indicate the size of the fault. From NASA Tech Brief B73-10440.

"Optical Methods Measure Qualities"

D. J. Abel

Instruments and Control Systems

April 1975, pages 25-29

"Over the past two decades, as machinery and processes have become more complex and the need to inspect and control more vital, optical instruments have come into wider use. When you can't reach it or touch it, an optical system may be the only way to measure a critical variable." (Author)

Examples of application include inspecting jet engines for wear or defects without tearing them down and using infrared thermometry for noncontact temperature measurement.

"Radioactive Line Keeps an Eye on Machinery Wear"

Editorial Staff

Machine Design

January 23, 1975, page 48

This system is a real-time monitor which is being used to measure erosion, corrosion, ablation, and wear on a wide range of materials in various configurations. It measures wear on moving parts while the wear is actually occurring, even in inaccessible or hostile environments. A line of radioactive atoms is formed by training a high-energy proton beam on the outer wall of the component to be monitored. A nuclear radiation detector measures the radioactivity in the line; a decreasing signal converts to real-time wear data.

"Radiation Monitor has Linear Output"

P. Prazak and LT W. B. Scott, USAF

Electronics

March 20, 1975, page 117

A monitoring system consisting of a commercial silicon diode detector plus two operational amplifiers provides an output voltage that is linearly proportional to radiation intensity. The small size of the diode probe permits the accurate mapping of a radiation fields of high energy X-rays and Gamma rays, as may be found in nuclear propulsion plants.

"Energy Signature Measures System Changes"

S. J. Bailey

Control Engineering

October 1973, pages 45-46

An instrument that records and manages frequency data detected on the electrical power infeed to a machine captures transient data and displays it for comparison. It detects trends in operation deviation from the norm, and preprocesses frequency spectra for later detailed computer analysis. The basic function is to aid in determination of frequency components whose telltale variation from proper to improper operation make them helpful in performing automatic machinery monitoring. This is especially applicable for electric motors and other mechanical output devices with electrical inputs.

Checkout of Turbine Engine Foreign Object Damage

J. E. Bridges and R. B. Schwab

IIT Research Institute, Chicago, IL

Report IITRI No. E6106

May 1969, AD-863 197, 130 pages

"Since operation of a turbine engine which contains Foreign Object Damage (FOD) may result in either fatigue failure of damaged parts or possible catastrophic failure of the entire engine, the detection and assessment of the damage severity as well as the com-

pressor's operational status condition is important. On the other hand, premature overhaul of the engine, based only upon visual inspection of the first-stage and second-stage blades, results in considerable unnecessary expense in overhaul costs and spare replacement engines. In attempting to solve this problem, an exploratory model system was designed and fabricated based upon detection techniques developed by previous work. This system employs Eddy-current detectors which are mounted in the compressor shroud above the blade tips. These detectors monitor blade tip curl, blade-to-blade spacing, and blade twist during in-flight or flight-line operational inspection of the engine which are indicative of FOD. Tests were run on a J-47 and a J-57 compressor which contained simulated FOD to demonstrate the system's capability for measuring geometric deformation of the blade tips beyond the normal blade tolerances. In conjunction with the hardware aspect of the program a cursory survey was conducted on several currently used turbine engine compressors to determine the nature of actual FOD and the problems involved with mounting the detectors on the compressor. An extensive survey of actual FOD experienced in specific engines for the engineering application of the above model system is recommended for future work."  
(Authors)

Radio Engineering Method for Determining the Degree of Wear of Machine Parts

V. S. Vergunov, O. G. Korol, and T. I. Lyasjenko  
Foreign Technology Division, Wright-Patterson AFB, OH  
Report FTD-HT-23-181-74  
September 1973, AD-768 059, 6 pages

During the operation of a machine in the process of deterioration the products of wear of the ferromagnetic parts of the machine drop into the lubricating oil. In this work the authors propose a new method for the analysis of oil to determine the content of iron in it. It is based on a change in the quality factor (Q) of an induction coil, into which a test tube with the investigated oil has been placed. A quality-measuring device is used to determine the effective quality factor of the induction coils by direct reading. (Translated from Russian.)

"Listening to Magnetic Fields Can Be Useful, As Well As Fun"

C. R. Graf

Electronics

September 5, 1974, page 127

Magnetic fields created by an alternating current are radiated by many electrical and electronic devices including power transformers and motors. A simple sensing circuit provides the capability to listen to sounds created by machinery.

On-Board Hydraulic System Monitor Study

Oklahoma State University, Fluid Power Research Center, Stillwater, OK

OSU-FPRC Report 3M5

December 1973, AD-779 468, 49 pages

"The purpose of the OSU-MERDC hydraulic specification program is to develop industrially acceptable test procedures and requirement specifications relative to the performance of hydraulic components and systems to facilitate the military's buy-commercial approach. Although the program has been aimed toward components and systems for future 3000 psi operating pressure levels, it was intended that the test procedures be applicable to any pressure level." (Author)

System For Measuring Transients in Fluid Flow

D. J. Pearson

NASA Ames Research Center, Moffett Field, CA

Ames Research Center Contract ARC-10852

Ames Research Center Reference TSP 74-10217

This paper details a system to measure fluid-flow transients in small fast-acting electrically actuated valves so that performance of the valves can be determined as a function of voltage-applied, pressure, temperature, presence of particulates, number of actuation cycles, and time. The system employs an electro-optical monitor. From NASA Tech Brief B74-10217, November 1974.

Valve Degradation Detector

N. H. Doshi

NASA Ames Research Center, Moffett Field, CA

Ames Research Center Contract ARC-10850

Ames Research Center Reference B74-10117

This paper reveals a technique to determine corrosive degradation of a valve while it is in service. Using a pair of thermal sensors, it can detect changes in surface roughness or the presence of corrosive layers at the junction of a poppet and seat by measuring temperature gradients created across the junction by a small heat source. From NASA Tech Brief B74-10117, November 1974.

"Monitor Particle Streams for Moisture"

T. Tanaka and H. Nakajima  
Instruments and Control Systems  
July 1974, pages 67-68

In automatic processes, critical variables must be measured continuously to provide information to the control system. Among these critical variables, moisture content is one of the most difficult to measure. This article relates moisture content in particle streams to changes in electrical capacitance for flows of solid particles such as silica gel in process control situations.

"A New Automated Laboratory Salinometer"

Dr. T. M. Dauphinee and H. P. Klein  
Sea Technology  
March 1975, pages 23-25

This article describes an improved technique for automatically measuring the salinity of seawater. The instrument employs continuous flow of the sample under low air pressure (to avoid bubble formation) with the flow coming from the original sample bottle. A high-precision controlled temperature bath and heat exchange maintains the sample and standard at a precisely defined temperature during analysis, thus avoiding the need for temperature compensation.

A square wave is the comparison technique used to continuously compare the conductivity of seawater sample at the defined temperature with an internal reference. Readout provides the ratio of the conductivity of the sample to that of standard seawater.

Fail-Safe Fire Detection System

E. T. Bloam  
Lewis Research Center, Cleveland, OH  
Lewis Research Center Report LEW-12238

This paper explains the operation of a fire detection control system used to monitor an aircraft engine. The system continually monitors its own integrity and automatically signals any malfunction and separately signals a fire in any zone being monitored. From NASA Tech Brief B74-10078, August 1974.

"Plate-Out Timer Capsule Is Easy Way to Monitor Equipment"

Editorial Staff  
Product Engineer  
April 1975, page 18

For time-controlled maintenance conditions, a solid-state timer module with LED indicator (the alerting maintenance monitor) can be used to monitor machine-operating time and to provide preventive maintenance monitoring of individual machines.

"Real-Time Trouble Shooter"

Editorial Staff

Mechanical Engineering

February 1973, page 41

The article examines "videostrobe," a new technique to monitor and analyze machines while they operate at high speed. The portable system consists of a strobe light, a video camera, a video and sound recorder, and a TV monitor. A detailed image of the operating equipment can be recorded and played back immediately in slow motion to detect malfunctions and anomalies such as improper "gear-meshing" and gear cracking.

"Circuit Monitor Motor Speed and Warns of Impending Failure"

D. K. DeSilva

EDN Magazine

April 5, 1974, pages 65-67

An electronic circuit described in this article illustrates the feasibility of a device that will predict, as well as detect, centrifugal blower failures. The circuit magnetically senses the rotational speed of the blower motor and provides distinctive outputs to tell whether the speed is normal, low (warning), or zero (blower not operating). From IBM Technical Disclosure Bulletin, Volume 16, Number 6, November 1973.

Engine Health Monitoring for the Gas Turbines in Royal Naval Ships

A. V. Cooke

8 pages

American Society Mechanical Engineers Paper 75-GT-24  
(Paper presented at the Gas Turbine Conference, ASME, Houston, TX, March 1975)

"Details are given of an integrated engine health monitoring (EHM) program for use by the staffs of Royal Naval Ships primarily aimed eventually at engine removal 'on condition' rather than on fixed overhaul life. The logic behind the choice of particular EHM methods is given followed by a description of the data collection and analysis procedures. Emphasis is placed on fault diagnosis, using formal charts to reduce the time and effort involved." (Author)

"Gas Turbine Engine Diagnostic Test Results Utilizing Gas Path Analysis Techniques"

R. Stenberg

U. S. Army Aviation Systems Command, St. Louis, MO

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"Extensive testing on AVCO Lycoming T53L-13 turbo-shaft engines has yielded data

showing detectable discrimination between good and degraded engines. Measurements were made utilizing standard UH-1H cockpit sensors. Testing was conducted at AVCO Lycoming in test cells and at Ft. Rucker, AL, in carefully selected flight profiles engines were verified as good through a complete teardown and rebuild cycle. After sufficient baseline data was accrued on good engines, degraded gas flow parts were implanted in the engines and the test profiles repeated both in cell and in flight.

"The thermodynamic model analysis considers inputs from the measurable parameters and calculates dependent variables, such as compressor and turbine efficiencies. Changes in these dependent variables are an indication of engine degradation and can be utilized by Army maintenance personnel in reducing troubleshooting and inspection time and aiding in maintenance decision making concerning engine removals at the first level of maintenance." (Author) Results of gas path analysis on test data are shown and discussed.

Airborne Engine Condition Analysis Instrumentation

W. J. Harris, H. K. Ziebarth, J. D. Chang, and J. Kukel  
AiResearch Manufacturing Company, a Division of Garrett Corporation, Los Angeles, CA

Report CB-70-6657-4

June 1971, AD-887 922L, 282 pages

"The AECAI program is directed at the conceptual and functional definition of an exploratory model of an airborne engine condition analysis instrumentation (AECAI) system. The exploratory system that is to be developed is intended to detect incipient degradation and failure of propulsion system components and permit engine shutdown, or other actions, and deterministic replacement or repair prior to substantial engine failure. The system is to monitor instrumented propulsion system component parameters, analyze parameters that indicate significant changes in the condition of the components, and provide output indications of detected deterioration. Ground processing equipment may be required for subsequent, more detailed analysis of recorded data. Thus, the desired result is an integrated system that will provide continuous monitoring of propulsion system condition status, displaying and recording only abnormalities due

to incipient malfunctions, and indicating when repair action of specific types should be initiated." (Authors)

Gas Turbine Engine Health Analysis Under Transient Operating Conditions for Application to an On-Board Monitoring System

J. R. Esser and S. F. Krafluk

Emerson Electric Company, St. Louis, MO

Report RPO-1014-1

March 1971, AD-883 278L, 11 pages

"A study was conducted to determine if the 'health' of an operating jet engine could be determined during the transient operating mode. This study was conducted as part of the preliminary work necessary for the design and development of an on-board Navy jet fighter engine monitoring system. The ultimate objective of the on-board system will be to analyze the health of the engine in real-time and inform the pilot of the condition of the engine(s). This study concentrated on evaluating the gas path parameters since these parameters are responsive indicators of the majority of the causes of Navy engine removals. The transient analysis investigated in this study indicated that parameter repeatability during the engine transient is adequate to verify specification performance. Also, gas path related anomalies can be detected through transient analysis; and corrected accuracy and sensitivity necessary for baseline establishment and performance comparison. The inclusion of transient analysis with steady state analysis in a real-time on-board monitoring and analysis system will expand the mission coverage and provide an immediate performance check prior to takeoff as a result of a snap acceleration to takeoff power." (Authors)

"Compressor Instrumentation Systems"

J. B. Arant and W. A. Crawford

Instrumentation Technology

April 1974, pages 46-51

"Large turbine-driven centrifugal gas compressors - to 40,000 hp with speeds to 11,000 RPM - are vulnerable to catastrophic failure, so compressor control systems have become increasingly sophisticated. For such machines, the article discusses lube oil systems, mechanical and thermal parameters,



surge suppression and turbine speed control with various governor schemes. Case histories are examined to show the value of troubleshooting large turbine compressor systems with instruments that monitor system 'health'." (Authors)

"Automatic Inspection and Diagnostic System for Army Tactical Vehicles"

A. Chalfin and G. R. Staton

IEEE Transactions on Aerospace and Electronic Systems

Volume AES-2, Number 3

May 1966, pages 291-302

"A tactical system designed to inspect and diagnose malfunctions in all Army tactical vehicles including jeeps, trucks, and tanks is known as Ready Multipurpose Automatic Inspection and Diagnostic System (READYMAIDS). The laboratory model developed to prove the feasibility of design is discussed together with design problems such as instrumenting a vehicle without modifications. The system uses a small digital computer in addition to switching, measurement and loading devices. These devices are integrated into small transportable units. Results to date, problem areas, and possible solutions are described."  
(Authors)

"On Vehicle Mobility Measurement and Recording System"

F. K. Chin, General American Transportation Corporation, Miles, IL  
R. Watts, Army Tank Automotive Command

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"A prime long term goal of the U. S. Army is to field, maintenance-oriented diagnostic equipment which will improve reliability and reduce cost associated with keeping vehicles operational. An important part of making diagnostic equipment viable is the establishment of baseline levels on a well operating vehicle so an adequate automatic judgment of the operational status of a vehicle under test can be made.

"This paper describes an on-going U. S. Army Tank Automotive Command, Maintenance/Product Assurance Directorate program directed at establishing such levels for the M35 truck. The program uses technology previously developed for the M151A2, 1/4 Ton Utility Truck. The current work involves instrumenting an M35A2, 2-1/2-Ton Cargo Truck with on-

board transducers, signal processing, and tape recording equipment, and running the vehicle 20,000 miles with various 'seeded' and 'unseeded' components in both idle and running modes. The data is computer analyzed to establish 'good' and 'bad' levels for diagnostic reference purposes." (Authors)

"How Does Your Engine Run?"

K. Arthur and W. C. Vesser  
Instruments and Control Systems  
September 1974, pages 81-83

"Organizations that operate large numbers of heavy-duty engine drive units (diesel) have adopted, with considerable success, a maintenance program that incorporates many features of aircraft trend-analysis programs. This program monitors engine performance without shutdown. It detects, identifies and evaluates pre-malfunction signatures for their effect on future operation so that management can schedule part replacements for periods when shutdowns have the least effect. As a result, outages between major overhauls are virtually eliminated." (Authors)

"Varying Reference Pressure Monitors Engine Output"

Editorial Staff  
Electromechanical Design, Volume 19  
May 1975, page 40

A monitoring technique and measuring circuit are presented for obtaining a performance parameter of internal combustion engines: cylinder pressure.

Predictive Maintenance of Heavy-Duty Engines Through Pre-Malfunction Waveform Analysis

W. C. Vesser  
American Society of Mechanical Engineers Paper 74-Pet-34  
9 pages  
(Paper presented at Petroleum Mechanical Engineering Conference, ASME, Dallas, TX, September 1974)

"Maintenance costs for heavy-duty engines (diesel) have risen sharply in terms of both personnel and lost production time. The gas pipeline industry and many small electric power utilities have made a direct attack on the problem by applying simple instrumentation techniques. The use of lightly modified conventional equipment and the introduction of a new maintenance philosophy have yielded significant improvements and

substantial economic benefits. This paper describes the instrumentation problem and one of the solutions to this problem."  
(Author)

"Feasibility of a Diesel Engine Condition Monitor"  
M. B. Peterson

Wear Sciences, Inc., Scotia, NY  
(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"A study has been conducted by a task force of MFPG to define for the Navy the advantages to be gained in developing a diagnostic system to replace the present maintenance practices on the propulsion systems of the LST 1179 Class ship. The study consisted of determining the maintenance experience with this propulsion system and what drive-system parameters would be measured to accurately define engine performance and detect malfunctions. Based upon this information a potential diagnostic system has been proposed and costed. Based upon the assembled maintenance experience the cost savings and other advantages of such a system are proposed." (Author)

"Diagnostic for Refrigerator Car Diesel Generating Sets"  
R. F. McKee

Pacific Fruit Express Company, San Francisco, CA  
(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"Railroads are turning to space-age technology to help protect valuable shipments of meat, vegetables, and other perishables. New types of electronic analyzers will help keep the diesel engines aboard refrigerated railroad cars operating properly. The Railroad Owned Refrigerator Car Committee have developed the requirements for testing refrigerator car diesel generating sets.

"An on-board monitor system automatically spots potential diesel malfunctions while the train is in transit. Read out can grow from the initial annunciator to wayside scanning. The diesel engine diagnostic analyzer incorporates modern signal processing and computer diagnostic techniques, and has memory capacity to accommodate a large 'library' of diagnostic routines. Faults are

detected with response data processing routines which look for differences between normal or reference values and the actual measured and calculated values. The analyzer will operate in a service shop or railroad yard environment." (Author)

"Measurement of the Visible Light Spectrum in I.C. Engine Cylinders"

J. M. Marrs

Tektronix, Inc., Beaverton, OR

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"The rapid spectral measurement of light emitted from mechanical devices such as internal combustion engines allows one to correlate the spectra, with various parameters such as load, fuel mixture, internal temperature and possibly chemical processes. The Tektronix 7J20 Rapid-Scan Spectro-Radiometer can make such measurements essentially in real time and being compact and portable allow measurements in unusual circumstances."

(Author) The measurement process is discussed.

"Turbomachinery Clearance Indicator"

Editorial Staff

Instrumentation Technology

October 1974, page 52

In the testing of high-speed turbomachinery, it is necessary to measure the clearances between the tips of the rotating blades and stationary shroud. The article explains a low cost measuring system capable of measuring blade-to-shroud clearances of turbines and compressors with accuracy of  $\pm 0.001$  inch. The circuit was developed at NASA Lewis Research Center, Cleveland, OH. From NASA Tech Brief B73-10411.

"Monitoring Rotating Machinery"

Editorial Staff

Mechanical Engineering

February 1973, page 40

The article describes a technique developed by NASA Ames Research Center, Moffett Field, CA, that provides both vibration or stress data and a rotational reference point with only one magnetic pickup for monitoring rotating machines. From NASA Tech Brief B72-10179.

"Noise Analysis: A Maintenance Indicator"

K. A. Bowen and T. S. Graham  
Mechanical Engineering  
October 1967, pages 31-33

A preventive maintenance program for submarine machinery is explained. The monitored parameters for this program are the structureborn noise and vibration emanating from operating machines.

"Origins of Noise"

L. D. Mitchell and G. A. Lynch  
Machine Design  
May 1, 1969, pages 174-178

"Narrow-band frequency analysis with a constant-bandwidth filter may be time consuming, but from it you can learn a great deal about the causes of noise. For example, you may trace frequencies and frequency clusters in a spectrum to geometry and operating effects, or you may find the 'ghosts' of faulty manufacturing equipment." (Authors)

"Machinery Noise May Indicate Loss of Efficiency and Severity of Dynamic Stresses"

A. C. Underwood and W. J. Graff  
Journal of Engineering for Industry, Transactions of ASME  
May 1971, pages 703-709  
American Society of Mechanical Engineers Paper 70-WA/Pet-2  
(Paper presented at Winter Annual Meeting, ASME, New York, NY, November 1970)

"The general consensus about industrial noise is that it may have harmful effects on hearing, is at best a nuisance, and therefore should be absorbed or alleviated. Although not as universally recognized, noise represents an excellent medium for evaluating machine performance. Energy expended in unwanted machine motion or vibration results in noise and reduces the useful output of the machine. It is generally true that for uniform machine operation the condition of least noise corresponds to minimum loss in efficiency and minimum wear. Information from several industrial situations is presented in support of using noise data to help control the loss of efficiency and assess the severity of dynamic stresses in machine parts." (Authors)

"Analyzing the Sounds of Trouble"

R. E. Herzog  
Machine Design  
September 6, 1973, pages 128-134

"An unbalanced rotor, a defective bearing, or a noisy gear often signal a serious design fault. You can identify the offending member, quickly and accurately by analyzing the unique noise frequencies generated by these parts." (Author)

Nuclear Power Plant Diagnostics Using Fourier Analysis Techniques

M. C. Plummer  
Nuclear Services Corporation, Campbell, CA  
Hewlett-Packard Application Note 140-7  
15 pages

"This note describes application of Fourier analysis techniques to nuclear power plant diagnostics. Reactor core measurements discussed include: (a) Detection of core component vibration, (b) Detection of core motion, (c) Detection of departure from nucleate boiling. Other reactor plant measurements discussed include: (a) Measurement of vibrations of rotating machinery, (b) Seismic measurements, and (c) modal analysis of vibrating pipes." (Authors)

"On Line Monitoring of An Operating Nuclear Reactor With Acoustic Emission Instrumentation"

H. Dunegan  
Endevco Corporation, San Juan Capistrano, CA  
(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"By way of introduction this presentation briefly reviews the work completed relative to the use of acoustic emission technology to ascertain the structural integrity of pressure vessels. Programs completed have included both periodic hydrotest and on-line monitoring.

"This report discusses the work now in-process on characterization by acoustic emission techniques of the materials used in nuclear reactors. Two specific problems are being investigated, the attenuation and dispersion of the acoustic emission signals as a function of distance in a thick plate, and the effects of oxidation on the amplitude of acoustic emission signals from a growing

crack. Low cycle fatigue tests under typical operating conditions are being conducted, as well as long term static tests in both inert atmosphere and air to determine the effects of oxides on the acoustic emission signals. In addition, a large thick plate is being used to study the attenuation and dispersion of signals injected into the plate as a function of distance and frequency.

"System approaches for on-line monitoring are outlined and equipment design concepts presented. The ultimate purpose of this technology is that of on-line monitoring of an operating reactor to detect, locate, and quantify any growing defects." (Author)

Practical Applications of Acoustic Emission

H. L. Dunegan

Dunegan/Endevso Corporation, San Juan Capistrano, CA

Technical Report DE-74-5

April 1974, 15 pages

"This report presents acoustic emission data from three different applications areas: (1) proof test monitoring of pressure vessels by use of multiple channel acoustic emission instrumentation; (2) monitoring of aircraft for fatigue crack growth and structural failure; and (3) monitoring of the burn rate of solid propellants by acoustic emission techniques." (Author)

"Acoustic Emission: A New Testing Method Requires No Scanning"

P. J. Brennan

Instruments and Control Systems

January 1975, pages 21-22

"Acoustic emission is a new nondestructive testing method for detecting defects and deformations in materials and structures. This method is based on the phenomenon that many materials emit acoustic pulses under load, if elastic forces are released by plastic deformation. A well known example of this is the so-called 'tin-cry' emitted during the plastic deformation of tin. In this case the acoustic signals are so strong that they are audible without any equipment; modern AE instruments, on the other hand, are sensitive enough to detect even minor dislocation phenomena in metals." (Author)

Auxiliary Machinery Noise and Vibration Measurements for  
DE-1040, DE-1052, and DEG-1 Ocean Escorts

R. Y. Chapman

Naval Submarine Base New London, Groton, CN  
Technical Report 236-71, NAVSHIPS 0940-007-1010  
August 1971, 67 pages

"For several years Forces Afloat has conducted noise and vibration measurements on board submarines to monitor changes in vibration levels in auxiliary machinery. These several years of experience have proven that changes noted in measured levels of vibration in auxiliary machinery can be associated with auxiliary machinery performance degradation. In every place where changes quickly detected and prompt corrective action was accomplished, ship readiness was maintained.

"This structureborne noise monitoring program is now introduced to the DE-1040, DE-1052, and DEG-1 Class Ocean Escorts encompassing the experiences gained by the submarine ship silencing program." (Author)

Machinery Vibration Seminar Notebook

R. H. Badgley, Editor

Mechanical Technology, Inc., Latham, NY  
January 1975, 450 pages

Vibrations are a major cause of operational problems in rotating machinery. This notebook provides:

- A fundamental understanding of rotating machinery vibrations.
- An awareness of available tools and techniques for analysis and diagnosis of rotating-member vibration problems.
- An appreciation of how these techniques are applied to correct such vibration problems.

Sections devoted to vibration instrumentation and signature analysis describe techniques to detect and diagnose impending machinery vibration-related breakdowns.

"Mechanical Failure Forecast by Vibration Analysis"

J. J. Hvillum

Technical Review, B & K Instruments, Inc., Cleveland, OH  
Number 2  
1967, pages 3-12

"The article describes various methods of mechanical failure forecasting by means



of vibration measurement and analysis. Starting with a brief discussion of the importance of obtaining a measure for the growth in mechanical wear of production machinery, different vibration analysis methods which may be used to obtain such a measure are outlined. It is shown that an analysis in the form of a frequency spectrum of the vibration of various points on some machinery, the analysis being performed at regular time intervals, can give a good indication of wear.

"Finally two examples are given of factories which utilize the described principles and where the number of breakdowns has been reduced considerably since the methods of failure forecasting were introduced. It is estimated that the increase in production obtained in this manner has paid for the measuring equipment in less than six months."  
(Author)

This technique is especially suited to detecting degradation in rotating machinery bearings.

"Vibration-An Indicating Tool"  
R. L. Baxter and D. L. Bernhard  
Mechanical Engineering  
March 1968, pages 36-41

Vibration is being studied and charted, as a guide both for preventive maintenance and acceptance of new machinery. Vibration is a useful tool to detect the presence of mechanical trouble in its early stages of development. It is known that different troubles cause vibration in uniquely different ways. This article describes vibration tolerances for certain machine tools and general rotating machinery.

Vibration Monitoring

J. M. Shea  
American Society of Mechanical Engineers Paper 69-PEM-9  
9 pages  
(Paper presented at Plant Engineering and Maintenance Conference, ASME, Pittsburg, PA, April 1969)

"Vibration monitoring of critical plant equipment is growing very rapidly. It behooves the plant engineer to thoroughly understand the simplicity as well as the complexity of monitoring machinery vibration. This paper outlines the many considerations that must be made prior to the design, fabrication and installation of vibration monitor-

ing systems for optimum protection of rotating machinery." (Author)

Vibration Monitoring and Analysis as Maintenance Tools

R. H. Nittinger

American Society of Mechanical Engineers Paper 70-PEM-2

(Paper presented at Plant Engineering and Maintenance Conference, ASME, Forth Worth, TX, March 1970)

5 pages

"Vibration monitoring and analysis of vibration are fast becoming required tools in the maintenance of rotating equipment. Plant managers, plant engineers, and others responsible for the operation of these machines should thoroughly understand the uses and benefits that are available through the proper understanding of, and belief in, data which this equipment can furnish." (Author)

This technique is applicable to rotating machinery, such equipment includes electric motors, gears, compressors, turbines, pumps, etc.

Vibration Velocity Measuring Program

S. Maten

American Society of Mechanical Engineers Paper 70-PEM-27

(Paper presented at Plant Engineering and Maintenance Conference, ASME, Forth Worth, TX, March 1970)

11 pages

"Vibration velocity measurements on running machinery are giving instant readout of the energy-levels to which the internal equipment components are subjected. At various determined levels, fatigue will eventually cause failure. The permissible velocity levels for most rotating equipment are, for all practical purposes, about the same regardless of their operating speed. This paper describes the advantages of vibration velocity monitoring, velocity monitoring, and velocity spectrum analysis as an aid to start-up inspection, maintenance, and operation of mechanical equipment in industrial plants." (Author)

"A Shipboard Trial of Vibration Analysis Equipment to Determine Mechanical Performance"

R. E. Ellis; H. J. Goodfried; C. H. Gross, Jr.; and E. T. St. Germaine

(Paper presented to the Chesapeake Section of Society of Naval Architects and Marine Engineers, Washington, D.C., September 1970)

"In order to determine the feasibility of employing a vibration data acquisition and analysis system in a shipboard preventive maintenance program, the Maritime Administration undertook a one-year project aboard two cargo liners. Utilizing vibration analysis techniques developed for industrial use, a program of periodic measurements of engine room rotating machinery was instituted. Vibration velocity measurements were recorded by portable battery powered instruments. Biweekly readings were recorded, plotted and compared by the ship's engineers for indications of developing trends and maintenance/overhaul decisions. The accumulated data were reviewed in detail and specified recommendations for more frequent checks of equipment developing failure trends and maintenance actions warranted were provided to the ship's Chief Engineer.

"Conclusions reached as a result of the project are discussed, as well as current engineering underway to utilize the output from this experience, along with a 'deviation' method of preventive maintenance scheduling, for the first shipboard application of a computer aboard a ship of the subsidized fleet." (Authors)

"Measurement and Analysis of Machinery Vibration"

W. Tustin

Chemical Engineering Progress, Volume 67, Number 6  
June 1971, pages 62-69

This article provides the principles of operation of a manufacturing or process plant machinery vibration monitoring system. It includes information on types of sensors, electronic signal processing systems, and vibration identification and tolerances. The author concludes that since it is possible to predict what the vibration of the final equipment assembly will be under standard test conditions, vibration sensing systems should be adjusted after the machine is operating in its final location.

"Machinery Vibration Monitoring and Analysis Techniques"

R. L. Fox  
Sound and Vibration  
November 1971, pages 35-40

"Machinery vibration monitoring programs involve personnel training, machinery selection and check points to be monitored, establishment of vibration level criteria, scheduling of tests, and recording of pertinent data. Instrumentation systems and operating techniques for manual monitoring, automatic monitoring and machinery vibration analysis are reviewed." (Author)

"Vibration Measurement Gives Early Warnings of Mechanical Faults"

R. Monk  
Process Engineering  
November 1972, pages 135-137

As machines get larger, repair costs become greater. The author explains how vibration measurements may be used to detect incipient failure and enable downtimes to be reduced to a minimum.

"The Measurement of Vibration as a Diagnostic Tool"

T. Carmody  
Transactions of Marine Engineers, Volume 84  
1972, pages 147-159

"A brief introduction into the use of the vibration measurement technique as a machinery defect diagnostic tool is given. Details of different types of measuring systems and methods of application are discussed, as well as some case histories." (Author)

Establishing Machinery Condition at Start-Up Through Vibration 'Baseline' Analysis

J. M. Shea and J. B. Catlin  
American Society of Mechanical Engineers Paper 72-PET-13  
9 pages  
(Paper presented at Petroleum Mechanical Engineering and Pressure Vessels and Piping Conference, New Orleans, LA, September 1972)

"During the critical period of machinery start-up incipient mechanical defects can be detected through vibration 'baseline' analysis. Machinery vibration 'Baselines' (signatures) established at start-up become the foundation for predictive mainten-

ance programs using vibration as the key to machinery condition. This paper presents several cases of vibration 'baseline' analysis of specific machines at start-up using both conventional and 'real-time' technology." (Authors)

"Improved Maintenance of Machinery Through 'Baseline' Vibration Measurements"

J. B. Catlin

Journal of Engineering for Industry, Transactions of ASME  
November 1973, pages 913-918

(Paper presented at Plant Engineering and Maintenance Conference,  
Baton Rouge, LA, October 1972, ASME Paper 72-PEM-1)

"The purpose of this paper is to present a method for increasing the value of vibration analysis as a tool in the maintenance of machinery. The method, termed 'baseline' method, is described and the use of various types of vibration measuring instruments and data recording explained. Seven steps involved in setting up a baseline program are discussed with information provided as to specific measurement and technique. Various applications of the method, designed to expand the usefulness of vibration analysis, are also outlined."  
(Author)

"The Relationship Between Machinery Vibration Levels and Machinery Deterioration and Failures"

B. Lundgaard

Marine Technology

January 1973, pages 22-29

(Paper presented at Meeting of Society of Naval Architects and  
Marine Engineers, Pacific Northwest Section, November 1971)

"The paper proposes the use of periodic vibration monitoring as a diagnostic maintenance tool. For a small initial investment, the monitoring program will provide in most cases an early warning of impending equipment failure. Vibratory frequency is used to determine the nature of a malfunction, while the amplitude history indicates the seriousness of the problem. This information is useful in determining when to overhaul a machinery item and how extensive the overhaul should be." (Author)

Shipboard Vibration Monitoring as a Diagnostic/Maintenance Tool

C. A. Bowes

Endevco Corporation, San Juan Capistrano, CA

Endevco Technical Paper TP 257

(Paper presented at International Symposium on Marine Engineering, Tokyo, Japan, November 1973)

"The generally poor correlation between the condition of machinery health and hours of operation is a significant problem for time based maintenance systems. This problem can be overcome with maintenance systems which use knowledge, obtained with instrumentation, regarding the actual condition of machinery health. Knowledge of the vibration characteristic of a machine is particularly useful in determining its condition, and the instrumentation of a machine to obtain this knowledge is relatively easy and inexpensive. The majority of this paper is concerned with the nature of machinery vibration, where it should be measured, how the raw data should be analyzed, and how the results should be interpreted. A brief discussion of the current trends in vibration instrumentation is given at the conclusion." (Author)

"Vibration Monitoring for Machine Protection"

R. B. Randall

Bruel & Kjaer Instruments Inc., Cleveland, OH

B & K Application Note 12-052

12 pages

For valuable mechanical equipment, it pays dividends to monitor the vibration level continuously both to give forewarning of impending breakdown and to allow or effect shutdown before catastrophic failure occurs. This is particularly applicable for unattended machines. A description and explanation of industrial vibration monitoring systems is included in this note.

Mechanical Vibrations of Shipboard Equipment (Type I-Environmental and Type II-Internally Excited)

Military Standard 167-1 (SHIPS), 1 May 1974

"The purpose of this standard is to establish requirements for vibrations of Naval equipment including machinery.

"Shipboard equipment which conforms to the requirements of MIL-STD-167 is generally found to satisfactorily perform its function aboard ship.

"Equipment for which compliance with MIL-STD-167 is not specified or is waived is likely to experience failures induced by vibration in shipboard service."

"Measure Machinery Vibration"

A. B. Kaufman

Instruments and Control Systems

February 1975, pages 59-62

"All machines vibrate, no matter how well they are designed and assembled, and it has been found in industrial practice that good correlation exists between the characteristic vibration signatures of machines and their relative condition. The selection of location for the vibration sensor and the direction of measurement is the single most critical factor in machinery vibration monitoring and analysis." (Author)

The Rationale of Monitoring Vibration on Rotating Machinery in Continuously Operating Process Plant

E. Downham and R. Woods

American Society of Mechanical Engineers Paper 71-VIBR-35

8 pages

(Paper presented at the Vibrations Conference, ASME, Toronto, Canada, September 1971)

"This paper presents a factual discourse on the problems associated with vibration monitoring of continuously operating, process machinery. The shortcomings of existing vibration criteria are discussed with reference to operational experience and case studies on chemical process plants operated by Shell Chemicals U. K. Ltd and with particular regard to the wide variations in machine frame impedances which have been measured on a representative number of machines used for ethylene and propylene production. A technique is described which enables bearing impedances to be measured quickly and safely on operational machines on site. The information thus obtained is used in conjunction with operational levels to interpret general vibration criteria in a more realistic manner, having regard to the dynamic characteristics of particular machines. The philosophy of machine wear diagnosis in relation to prediction of component failure is discussed with a view to the extension of running periods between overhaul and to enable predictions to be made of replacement component

requirements prior to dismantling machines, and thereby reduce overhaul periods. This philosophy is being applied at present to a number of operational machines, and details of the results to date are given. Finally, the type of monitoring system required to provide this additional information, as well as providing the conventional day-to-day alarm facility is discussed." (Authors)

Signature Analysis of Plant Equipment

G. B. Kellum

American Society of Mechanical Engineers Paper 71-PET-14  
(Paper presented at Petroleum Mechanical Engineering with Underwater Technology Conference, ASME, Houston, TX, September 1971)

"There often appears to be an important gap between equipment manufacturers and equipment users in the area of analytical instrumentation. Experience indicates that a relatively minor investment in complete system investigation and installation of on-stream analysis capability can return major dividends through increased production and decreased maintenance loss. This paper is intended primarily to illustrate, through field experience, results which may be obtained through comprehensive signature analysis of critical plant equipment. Comprehensive signature analysis can be a powerful tool in reducing unexpected machinery failures. Each case history discussed here resulted in substantial savings to equipment users because they were able to schedule corrective action and concentrate on a particular problem source. Further development of analysis techniques is needed to make results more quantitative and, thus, more predictive. Analysis can be greatly improved by incorporation of analytical instrumentation in system designs." (Author)

The Octave Band Vibration Analyzer as a Machinery Defect Indicator

C. A. W. Glew and D. C. Watson

American Society of Mechanical Engineers Paper 71-DE-47  
13 pages  
(Paper presented at the Design Engineering Conference, ASME, New York, NY, April 1971)

"The Canadian Armed Forces have developed an effective machinery defect indicator by the use of vibration analysis. Periodically, the vibration signal from each principal bearing



on all machines is measured and analyzed by the use of a portable octave band vibration analyzer, compared with the normal levels pertaining to that point. The resultant fault diagnosis is used in conjunction with the planned maintenance schedules to determine the machinery overhaul procedures. It is considered that this technique could be applied to any industrial machinery maintenance operation responsible for a number of similar machines." (Authors)

"Octave Band Monitoring Reduces Random Failures of Machinery"

L. Morley  
Process Engineering  
March 1973, pages 105-106

Vibration monitoring has gained wide acceptance in the process industries as a way of detecting incipient machine failure. The author describes two lesser known techniques of vibration analysis: 1/2 and 1/3 octave band monitoring.

"New Tool for Vibration Analysis"

J. E. Borhaug and J. S. Mitchell  
Hydrocarbon Processing, Volume 51  
November 1972, pages 147-151

This article deals with the determination of mechanical characteristics of machines used in chemical plants by using frequency spectrum analysis. The following topics are discussed in some detail: Frequencies of interest, waveform analysis, spectrum analysis in the frequency domain signature plot, misalignment, and cracked turbine blades. Several low- and high-frequency spectra for different machines are presented as examples.

"Dynamic Analysis for Machine Design"

W. Hawkins, Jr.  
Sound and Vibration, Volume 7  
March 1973, pages 4-14

The design engineer, production man, or operator of complex high-speed equipment must identify and accurately measure each component that contributes significantly to the dynamic behavior of the machinery. Such a detailed analysis of machinery dynamics is now possible and is becoming commonplace both in quieting and maintaining existing equipment and in the design phase of products. Dynamic analysis can be divided into several phases based on the responsibilities of different departments of the manufacturer: (1) design engineering of individual components; (2) design analysis and evaluation of the complete product; and (3) quality control of production units.

"Dynamic Analysis: A New Maintenance Technique"

W. M. Hawkins  
Power Engineering  
January 1974, pages 46-48

"Dynamic analysis often enables the engineer to pinpoint vibration problems quickly without tearing down equipment. This technique is the key to detailed examination of operating machinery, especially complex units and systems. One benefit is reduced shutdowns for maintenance. Another is the ability to detect deterioration of performance early enough to avoid emergency shutdown. A third is focusing attention on components that are in serious trouble without disassembling whole units for visual inspection." (Author)

"Real-Time Spectrum Analysis of Machinery Dynamics"

A. C. Keller  
Sound and Vibration  
April 1975, pages 40-48

"Narrowband, real-time spectrum analyzers have been available for almost ten years. Their applications have included speech analysis, improving the design of guitars, observing muscle response to a known stimulus, and analyzing space craft performance. Perhaps nowhere, however, have the benefits of on-line processing and cause and effect analysis been more fully realized than in the monitoring and diagnostic detection of rotating machinery vibration characteristics. The following discussion details some of the ways in which this powerful tool is used for design, production, maintenance and overhaul of operating machinery." (Author)

Vibration Analysis of Rotating Machines

Honeywell Signal Analysis Operation, Hauppauge, NY  
Technical Note D-2526 1273

This tech note explains the use of a Honeywell SAICOR real-time, time-compression spectrum analyzer in detecting machinery faults in on-line operation. There are tables listing applicable machinery amenable to vibration monitoring and vibration troubleshooting symptoms.

Evaluation of Machinery Characteristics Through On-Line Vibration Spectrum Monitoring

R. E. Kerfoot, L. T. Hauck, and J. E. Palm

American Society of Mechanical Engineers Paper 73-GT-68

11 pages

(Paper presented at Gas Turbine Conference, ASME, Washington, D.C., April 1973)

"The purpose of this paper is to explore the application of state-of-the-art instrumentation for vibration monitoring and analysis in a growing industry. The subject is immense and cannot be covered in its entirety by this paper. It is hoped that useful information is provided for those interested in acquiring this vibration analysis capability or in applying these techniques. This paper contains new material combined with a compilation of technical articles that already exist on the subject. Credit to those authors is duly given."  
(Authors)

"Widened Frequency Range is Improving Today's Machinery Vibration Analysis"

J. E. Borhaug and J. S. Mitchell

Power

March 1973, pages 51-53

Vibration analysis based on frequencies close to shaft operating speed has long proved to be an effective method for diagnosing many industrial-machinery problems. Sudden unexpected failures, however, such as loss of turbine blading, indicate that vibration analysis at shaft rotational frequencies must be supplemented; a wider frequency range is necessary. High-frequency components, normally associated with acoustic energy, include characteristics of rolling element bearing failures, gear-mesh and tooth-load irregularities, and dynamic excitation of nozzles, shrouds, and blades in turbines and compressors. Low-frequency vibrations indicate an existing problem; high-frequency vibration, however, often reveals the dynamic characteristics that can make machines fail catastrophically.

Production Acceptance Testing Using an Improved Acoustic Signature Analysis

R. P. Chen, F. T. Yokota, D. V. Allen, and J. A. Friedericy

Society of Automotive Engineers Paper 730929

7 pages

(Paper presented at National Aerospace Engineering and Manufacturing Meeting, SAE, Los Angeles, CA, October 1973)

"This paper presents the composite exceedance method as an alternative to the more costly broad band Power Spectral Density (PSD) analysis which is the standard

method of acoustic signature analysis for rotating machinery. The composite exceedance is superior to the PSD analysis in that the computational procedure is straight forward and effective without the use of Fourier Transforms and, therefore, lends itself to simple programming, and the information extracted from the vibration data is represented in one master plot, permitting direct evaluation of all 'g' peak levels encountered in terms of the number of occurrences above which they exceed a given level of acceleration. The sensitivity of anomaly detection by the proposed method has been demonstrated in a number of actual cases, one of which is discussed. The data collection methodology and philosophy of the method as they relate to narrow-band Gaussian random processes are also considered." (Authors)

New Machinery Health Diagnostic Techniques Using High-Frequency Vibration

R. F. Burchill, J. L. Frarey, and D. S. Wilson  
Society of Automotive Engineers Paper 730930

8 pages

(Paper presented at National Aerospace Engineering and Manufacturing Meeting, SAE, Los Angeles, CA, October 1973)

"A technique is discussed for generating diagnostic information from the vibration signature of machinery in the high frequency range (up to 100K Hz). The signal generation mechanism is discussed, as well as the diagnostically significant characteristics of the data and a method of extracting this information. Two specific cases are presented utilizing the techniques to illustrate its suitability for many of the common problems encountered in machinery."  
(Authors)

Acoustic Signature Analysis of Space Program Mechanical Devices

D. Kitchel and K. A. Smith

Society of Automotive Engineers Paper 730931

14 pages

(Paper presented at National Aerospace Engineering and Manufacturing Meeting, SAE, Los Angeles, CA, October 1973)

"Predominant features of sound signatures can be related back to operational events occurring within components both for normal and failure mode operation. Engineering analysis permits establishment of a

quantized go, no-go, or caution parameters necessary to make readiness assessment decisions.

"The 'Structure Borne Acoustics' test technique presented in this paper has outstanding potential for this work. Reliability includes accurate detection and diagnosis of the maximum number of faults, with an absolute minimum false alarm rate. Jet engine-bearing monitoring is one example of successful application." (Authors)

"Application of High Frequency Acoustic Techniques for Predictive Maintenance in a Petrochemical Plant"

R. James, Exxon Chemical Co., Houston, TX

B. C. Baird, Boeing Co., Houston, TX

(Paper presented at 22nd Meeting of Mechanical Failure Prevention Group, Anaheim, CA, April 1975)

"Lead times provided by the use of high frequency acoustic instrumentation in detecting incipient mechanical failure, establish this instrumentation technique as an effective tool for performing predictive maintenance. Applications where high frequency acoustic monitoring has provided predictive maintenance data in a typical petrochemical plant and the potential economic impact this can have on the plant's operation are described." (Authors)

"Sonic Analyzer - Case History"

J. L. Frarey

Shaker Research Corp., Albany, NY

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"The paper discusses programs conducted during the 1960's on the sonic analysis of gas turbine engines and helicopter transmissions. Two papers on this subject were given at the first MFPG Meeting in April 1967. The basic detection concept that was employed is discussed as well as the field analyzer that was developed by Curtis-Wright. Results of the programs conducted both in the military and on commercial turbine engines will be briefly discussed. The main emphasis of the paper, however, will be those areas of program planning in which the problems encountered in the 1960's are common with the problems being encountered in today's diagnostic programs. These include:

- Laboratory Versus Aircraft Testing
- Verification of System Accuracy
- Human Factors

"The paper concludes that whether a diagnostic concept has merit or not cannot be evaluated unless the program planned has adequate provision for the above factors."  
(Author)

Refinement of Reject Criteria for UH-1 Sonic Analyzer

W. H. Dawson

Curtiss-Wright Corp., Caldwell, NJ

USAAVLABS Technical Report 69-89

December 1969, AD-866 977, 57 pages

"The purpose of this program was to use additional data to update the original UH-1 aircraft sonic analyzer limits and to determine the advisability of using a common checking engine speed for all models.

"The method involved a full engineering analysis of the original 1967 data plus an approximately equal amount of data obtained on UH-1 helicopters at Ft. Eustis, VA, in 1968.

"Emphasis was placed on selected transmission and rotor tail components including the primary drive gears.

"The work consisted of deleting invalid or questionable data by detailed investigation of component inspection records, maintenance records, RPM locking information, play backs of recorded data, contradictory data, etc., in an effort to assure that only valid representative data was used for limits determination.

"The need for two test tapes to handle all the various models of the UH-1 helicopter evolved from the analysis. The result is sonic analyzer limits for the UH-1 helicopter which should demand considerable respect as to the condition of the aircraft components. Any readings that exceed these limits in the future should not be passed off lightly, but rather should be seriously considered and investigated thoroughly." (Author)

CWEA-4 Sonic Analyzer with UH-1 Helicopter Capability  
W. B. Gray and R. G. Locklin  
Curtis-Wright Corp., Caldwell, NJ  
USAAVLABS Technical Report 68-28  
May 1968, AD-674 198

This report contains complete information on the design and use of the sonic analyzer, mechanical information for various models of the UH-1 aircraft, component frequencies, and sample calculations for this monitoring technique.

The sonic analyzer monitors similar components assemblies for all mechanical devices such as transmissions and gear trains. This report estimates performance limits for mechanical components of the B model helicopter drive train.

Vibration Signal Analysis Techniques

D. R. Houser and M. J. Drossjack  
Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, VA  
USAAMRDC Technical Report 73-101  
December 1973, AD-776 397, 242 pages

"The high cost of helicopter maintenance has created a great deal of interest in the monitoring of the condition of helicopter components. In helicopter power trains, which contain both gears and bearings, the use of vibration signals to detect the condition of these gears and bearings has become of increasing interest in recent years.

"This research program was initiated to investigate the many means of using vibration signals to detect the condition of mechanical components with particular emphasis on gears and bearings in the helicopter power train. An exhaustive literature search was performed in which specific techniques were identified. Several visits were made to people active in the vibration diagnostics field.

"The techniques which were identified as being potentially useful were investigated in detail. The results of this investigation include a presentation of the state of the art of each technique and an analysis via actual helicopter data, test rig data, and a dynamic model simulation. The techniques have been broken down by mathematical function, i.e., time domain and frequency domain, and also by the components being monitored, i.e., gears or bearings. Both mechanically related

and pattern recognition techniques are discussed. An extensive reference listing and a listing of companies and agencies active in diagnostics work are included in this report." (Authors)

"Signal Analysis Techniques for Vibration Diagnostics"

D. K. Houser

Ohio State University, Columbus, OH

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"This paper describes practical mathematical methods including statistical, time and frequency design techniques by analyzing vibration data for diagnostic purposes. Many different vibration diagnostics schemes which have been proposed for the detection of gear and bearing faults will be reviewed. Particular emphasis will be directed toward helicopter power trains." (Author)

"Optimize Your Vibration Analysis Procedures"

C. Jackson

Hydrocarbon Processing, Volume 53, Number 1

January 1974, pages 89-92

Many existing vibration analysis techniques are inadequate. This article shows how to match analysis instruments to machinery behavior knowledge and reduce maintenance costs in the process. The author presents ten case histories in which improved methods of the vibration analysis of various machines in the petroleum industry have brought substantial savings through the purchase of portable and fixed vibration equipment.

"Vibration Monitoring and Warning Systems"

P. Wilhjelm

Technical Review, B & K Instruments Inc., Cleveland, OH

Number 2

1969, pages 26-29

"The criteria of detecting defects in rotating machinery with accelerometers used as vibration detectors is discussed.

"The paper is mainly based on equipment designed to monitor unwanted signals on water and gas turbines and to give alarm when a preset level is exceeded." (Author)



"Engine Vibration Monitoring on the Boeing 747 Aircraft"

C. A. Bowes

Endevco Corporation, San Juan Capistrano, CA

(Paper presented at Sixteenth International ISA Aerospace Instrumentation Symposium, Seattle, WA, May 1970)

"This paper is a discussion of the characteristics and features of the engine vibration monitoring system used as standard equipment on board the Boeing 747 aircraft. This paper presents measurement objectives, the operational and environmental constraints presented by the aircraft, and the system concepts used to meet the objectives within the constraint limits. Included is a discussion of a rugged piezoelectric transducer capable of reliable operation for long periods of time at temperatures up to 900° F, a unique hardline cable assembly for transmission of the transducer signals from the hot section of the engine to the firewall connector, and a state-of-the-art differential charge converter which was the key to overcoming many of the operational difficulties formerly associated with piezoelectric systems in this application."  
(Author)

Quality Evaluation of Automotive DC Motors, Using Real-Time Spectrum Analysis

G. E. Curry and J. J. Anderson

Nicolet Scientific Corp., Northvale, N.J.

Application Note 5, September 1972

(Paper presented at 14th Meeting of Mechanical Failures Prevention Group, Los Angeles, CA, January 1971)

"This paper describes an investigation to establish spectral testing methods for high production volume, low cost, DC motors used in automotive heating and air conditioning systems. Test data were evaluated to establish acceptable noise limits for a specification requiring 100% production testing. The spectral 'noise signatures' were obtained with a Real-Time Ubiquitous Spectrum Analyzer. This approach to diagnostic evaluation provided the testing speed that would be required for on-line production testing.

"For initial evaluation, a total of 22 heater motors and 29 air conditioner motors were tested for spectral content. These motors included units selected at random from completed production lots, as well as

production rejects and motors returned on warranty. The test consisted of the recording of vibration levels for the first 11 orders of rotational frequency. The motors were then ranked in accordance with the quantitative data and compared to the qualitative evaluation previously obtained for motor noise. Very good correlation was obtained between the two evaluations; acceptable vibration levels were established for production line testing. The final system, in connection with a computer, will have the potential capability of regular statistical analysis and diagnosis of defects, as well as 100% production line test capability." (Authors)

"Vibration Measurement on Turbomachinery"

C. Jackson

Chemical Engineering Progress, Volume 68  
March 1973, pages 60-65

Utilizing proximity probes as the vibration measuring technique, the author states that provisions should be made to ensure that vibration monitoring systems for machinery be functioning at equipment start-up. Many failures can occur during this critical period.

Mechanical Signature Analysis for Diagnosis of Reciprocating Engines

F. A. Passanti

General Electric Company, Schenectady, NY  
Report Number 72CRD105  
March 1972, 36 pages

"This report describes a study to determine the feasibility of using mechanical signature analysis to detect incipient malfunctions in combustion engines.

"A one cylinder combustion engine was run in normal conditions with several types of bearing and valve defects inserted. The structure-borne sound from the engine was picked up with an accelerometer, mounted on the crankcase. The accelerometer signal was processed in several ways to extract the engines signature.

"It is shown that the internal condition of the engine can be monitored through an external sensor. Valve timing, tappet clearance, tappet lifting from the cam and probably valve-seat misalignment can be monitored

while the engine is operating; piston-pin and crank-pin bearings can be diagnosed for excessive wear or clearance." (Author)

"A New Approach to Turbomachinery Analysis"

D. Lorio  
Hydrocarbon Processing  
January 1974, pages 105-107

Large process plants containing many rotating machinery systems present a unique data collection and analysis problem. The author describes a mobile analysis unit containing vibration monitors and other instrumentation used to determine machinery and equipment condition at Shell Chemical Company's Houston plant. The analysis unit is primarily designed to be used in conjunction with noncontacting eddy current vibration sensors but is not limited to this type of probe.

"Improved Turbine Operation by Drainage of Steam Systems and Monitoring of Vibration"

M. A. Prohl, J. W. Mann, and B. Siegel  
Marine Technology  
January 1974, pages 34-47

"This paper reviews recent operational problems caused by water induction into propulsion turbines and the resulting heavy vibration. The phenomenon is described as an orbiting vibration of the turbine shaft. Analysis shows the conditions required to produce this result. The steam system is discussed with a view to reducing the opportunities for water induction, and specific recommendations are made to improve drainage. A newly developed vibration monitoring system is described which can be used to reduce turbine speed when very large vibration levels occur." (Authors)

Signature Analysis: Nonintrusive Techniques for Incipient Failure Identification Application to Bearings and Gears

B. Weichbrodt and K. A. Smith  
General Electric Company, Schenectady, NY  
Report Number 70-C-364  
October 1970, 13 pages

Acoustic and vibration signals generated by operating machinery are used to diagnose its internal condition. It is shown how characteristic signatures are electronically extracted from the overall noise and vibration signals. By interpreting these signatures in the light of engineering knowledge of the machinery under study, it is possible to identify incipient failure modes long before final failure. Specific applications to bearing and gear diagnostics are discussed, and it is shown

how the diagnostic process is electronically implemented and automated.

"Mechanical Signature Analysis of Ball Bearings"

A. S. Babkin and J. J. Anderson

Sound and Vibration, Volume 7

April 1973, pages 35-42

(Paper presented at 18th Annual Meeting of Institute of Environmental Sciences, New York, NY, May 1972)

"Mechanical signature analysis procedures are described and then used to detect faults in ball bearings. The test system for driving the bearings and analyzing the resultant vibration signatures is also described. Analyses for bearings with no defects and with a number of known defects are covered." (Authors)

"Analyzing Bearing Vibration"

O. Susolik and J. J. Coy

Machine Design

January 10, 1974, pages 110-111

"Vibration in rolling element bearing is only a part of overall structureborne vibration of machine assemblies. But it is important to analyze this bearing portion because it can become a clue for improvement of machine performance." (Authors)

Design and Fabrication of Prototype System for Early Warning of Impending Bearing Failure

J. Meacher and H. M. Chen

Mechanical Technology, Inc., R&D Division, Latham, NY

MTI Report 74TR34

April 1974, N74-28960, 84 pages

"A test program was conducted with the objective of developing a method and equipment for on-line monitoring of installed ball bearings to detect deterioration or impending failure of the bearings. The program was directed at the spin-axis bearings of a control moment gyro. The bearings were tested at speeds of 6000 and 8000 RPM, thrust loads from 50 to 1000 pounds, with a wide range of lubrication conditions, with and without a simulated fatigue spall implanted in the inner race ball track. It was concluded that a bearing monitor system based on detection and analysis of modulations of a fault indicating bearing resonance frequency can provide a low threshold of sensitivity." (Authors)

Detection of Simulated Journal Bearing Wear Using Vibration Analysis

J. D. Wu

Intern Training Center, Army Materiel Command, Texarkana, TX  
USAMC-ITC Report 02-08-73-005  
May 1974, AD/A-007 142, 84 pages

"This paper examines the sources of vibration in rotating machines. The conversion of machine vibration into an electrical signal by transducers for purposes of measurement and analysis is presented in the first part of the report. These transducers, or vibration pickups, are discussed with regard to their construction and applicability. The second part of this paper investigates the detection of simulated bearing wear in a refrigeration compressor using vibration analysis. For the experiment, connecting-rod bearings in a Dunham-Bush reciprocating compressor were bored oversize to simulate bearing wear. The resulting compressor vibrations picked up by an accelerometer were analyzed to detect changes in the vibration signal. The power spectral density of the vibration signal was computed. The results indicate that an increase in the connecting-rod bearing clearances is detectable in the power spectral density plot of the accelerometer output." (Author)

"A New Technology for Bearing Performance Monitoring"

G. J. Philips

Naval Ship R&D Center, Annapolis, MD

(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"The measurement of ball bearing outer ring displacements is the central feature of a new technology which has been developed for monitoring bearing performance. This paper traces that development and describes experiments which have demonstrated some of the applications the technology is suited for. Included are measurements of operating contact angles of ball bearings, bearing performance during transient thermal environments, transient vibration at start-up and the early detection of faults in bearings.

"The technology advances the state of the art of performance monitoring providing, with a simple instrumentation package, the ability to do the following:

- Supplement quality control of new bearings.
- Detection of bearing faults at the time of their inception.
- Check for improper machinery assemblies and too tight bearing fits.
- Guard against thermal lockup.
- Long-term monitoring of bearing loads.
- Detect bearing surface of lubricant degradation."

(Author)

"Application of a Shock Pulse Technique to Helicopter Diagnostics"  
 J. A. George, T. C. Mayer, and E. F. Covill  
 Parks College of St. Louis University, Cahokia, IL  
 (Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"An investigation has been carried out on the possibility of shock pulse techniques in the detection of failures in helicopter power trains. The standard off-the-shelf SKF Industries Model MEPA-10A was employed to construct shock emission envelopes of shock rate versus shock level. Data was collected from the hangar bearings of the tail rotor drive shaft assembly, the 42° and 90° gear box assemblies and the transmission and mast assemblies as installed on operational UH-1 series helicopters. Further data was obtained on the OH-58 as well as from helicopters at Ft. Rucker, AL, with implanted bearings of known condition. The correlation between the shock emission envelope and degree of degradation as revealed by teardown analysis is described. The shock pulse meter shows promise for its ability to separate those components with normal wear, or the onset of damage from those with severe damage. A system suitable for an operational helicopter environment is described." (Authors)

### Gear Diagnostics and Wear Detection

R. A. Thompson and B. Weichbrodt

American Society of Mechanical Engineers Paper 69-VIBR-10

7 pages

(Paper presented at the Vibrations Conference, ASME, Philadelphia, PA, March 1969)

The important problem of determining the condition of operating gears from externally measured vibration is discussed. It is shown that data reduction by time averaging or "summation analysis" serves to isolate those parts of an externally sensed signal which are periodic from those which are random. Thus, events such as cyclic meshing of teeth become very pronounced in the time-averaged signal, the time averaged waveforms appearing similar to the stress versus time function measured on an instrumented tooth. It is suggested that if the dynamic tooth loads due to wear were known or could be predicted, a wear indication could be inferred from the time-averaged signals.

### The Detection of Wear In Gears

R. A. Thompson and J. R. McCullough

General Electric Company, Schenectady, NY

4 pages

"The ever-growing importance of the gear wear problem, its causes, effects, and how it may result in gear failure, have led to the development of a model for tooth profile wear. One useful outgrowth of the model is that it can lead to methods for measuring wear from externally-sensed gearbox vibrations. This work discusses one such method. It is based on Fourier Analysis. The model predicts that as gear wear increases the ratio of the harmonics to the fundamental of the meshing frequency also increases. Using this result, a conceptual design for a gear-wear monitor is suggested." (Authors)

### Vibration Frequencies Generated by Gear Meshing

Nicolet Scientific Corporation, Northvale, NJ

Application Note 6

October 15, 1972

"A common cause for side-band generation in gear meshing frequencies is the slight eccentricities in the shaft of a gear. During one revolution of a gear, the intensity of the gear-meshing noise or vibration will vary, depending on the run-out in the pitch diameter of the gears. Perfect meshing of gear teeth is possible only if pitch diameters of both gears are in perfect rolling contact." (Author)

Prediction of Vibration Sidebands in Gear Meshes

A. L. Gu and R. H. Badgley

American Society of Mechanical Engineers Paper 74-DET-95

9 pages

(Paper presented at Design Engineering Technical Conference, ASME, New York, NY, October 1974)

"A computer-implemented analysis has been established for predicting vibration sidebands produced by variations in gear parameters, such as centerline distance, tooth transmitted force, and tooth support discontinuities for single gear mesh systems. The sidebands are normally found at mesh frequency harmonics plus and minus integral multiples of the frequency of variation of the gear parameters. The vibration sidebands spectra produced by spiral bevel gear shaft runout, externally imposed tooth mesh force variation, and a decrease in support stiffness over a number of consecutive ring gear teeth have been obtained for gear meshes in the CH-47 helicopter forward rotor drive transmission. This sideband analysis is useful both for designing low-vibration gear systems by properly controlling important gear parameters, and for identifying the existence of several types of gear problems, such as gear runout, drive train resonances, and tooth cracks." (Authors)

Investigation of Gear Dynamics Signal Analysis

M. J. Drosjack, D. R. Houser, and A. C. Tinney

Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Ft. Eustis, VA

USAAMRDL Technical Report 75-1

January 1975, AD/A-006-584, 189 pages

"This study was performed to investigate the dynamic effects encountered at the gear mesh as the result of gear tooth surface faults. For this purpose, a torsional dynamic simulation of a geared system was developed which included provisions to account for the effect of pitting on a gear tooth. Tests were performed with gears which were in good condition and with gears containing manufactured faults. Results of the experiments and simulation were compared, and substantial correlation has been found between the two. Thus, the capability of the simulation to Model A fault on a tooth was substantiated." (Authors)



Identification of Failing Mechanisms Through Vibration Analysis

J. L. Wotipika and R. E. Zelenski

American Society of Mechanical Engineers Paper 71-VIBR-90

12 pages

(Paper presented at Vibrations Conference and International Design Automation Conference, ASME, Toronto, Canada, September 1971)

"The purpose of this study was investigation of a means of machine failure detection which did not rely solely on the time-consuming correlation of machine functional operation with signal waveform. The general vibration characteristics of elemental mechanisms (e.g., cam and follower) were investigated and the effects of certain operating conditions and failures on the vibrations were then determined. The significance of this study does not lie so much in the results pertaining to the specific cam-and-follower investigated but more importantly in the general type of knowledge gained. This type of information can be applied not only to other cam-and-follower types, but also to other mechanisms as has been shown in the design of a probe for the detection of bearing failures. The natural frequencies of the bearing races are calculated, and then an accelerometer mounted in a spring-loaded probe and a filter are used to monitor the levels of these frequencies. The system has proved capable of detecting extremely small race and/or ball damage that could not be found by monitoring the overall vibration level of rotational frequencies." (Authors)

Detection of Incident Machine Failure Through Vibration Analysis

F. H. Schlereth

American Society of Mechanical Engineers Paper 72-DE-55

4 pages

(Paper presented at Design Engineering Conference, ASME, Chicago, IL, May 1972)

"In this paper the need for a close working relationship between the mechanical engineer and the electrical communication engineer is stressed. A glossary of terms is presented which points up some of the language difficulties. An example related to the detection of ball bearing failures is presented, which shows the kind of analysis equipment that is needed for working in the field and shows the results of utilizing this equipment through comparison of sensor output waveforms. The paper concludes

with a recommended procedure for the design of incipient malfunction detection equipment."  
(Author)

"The Effectiveness of Vibration Analysis as a Maintenance Tool"

C. A. W. Glen

Transactions of the Institute of Marine Engineers, Volume 86  
1974, pages 29-51

"The Canadian forces use the portable octave band analyzer as a machinery health monitor as part of their preventative maintenance program on ships and aircraft.

"Velocity measurements are taken near each principal bearing on a machine, on an overall and octave band basis. These readings enable the operator to diagnose rapidly any serious deterioration due to unbalance, misalignment, bent shafts, defective gears or bearings in the machine, because the overall velocity level defines whether a machine is in good condition, or not, and the octave band analysis enables the nature of the fault to be determined.

"To take machinery health measurements, monitoring points are welded at standardized positions on each machine and vibration measurements are taken periodically at specified operating conditions. The state of the machine is determined by comparing these measurements with the machinery norms and with the previous readings at each point. These operations are computerized.

"A cost effectiveness study shows that unscheduled maintenance during refits and machinery breakdowns during operational periods, have been reduced by 45 percent. The reduction of repair costs and the improved ship availability are worth £800,000 per year over a fleet of 20 destroyers." (Author)

APPENDIX C  
MEASUREMENT TECHNIQUES

"Instrumentation '74"

B. M. Oliver, H. Falk, D. C. Loughry, D. Mennie, R. Allen, R. K. Jurgen, M. Eleccion, J. Gerakos, and G. Kaplan  
IEEE Spectrum  
November 1974, pages 44-87

This special report is a compilation of articles on the state-of-the-art in test equipment and instrumentation. Important subjects include future trends for instrumentation, the impact of microprocessors, instrument interfaces, serviceability of test equipment, and new measurement capabilities.

"Instruments '74"

Editorial Staff  
Electronic Design, Volume 22, No. 24  
November 24, 1974, pages 40-145

This is another inspection and review of the state-of-the-art in instrumentation. The highlights include articles on increased use of large-scale-integration-digital-integrated-circuits to improve instrument performance, instrument self-test capability, programmability and compatibility between individual units in instrument systems, signal analyzer improvements for diagnostic systems, and new temperature measurement systems and techniques.

"Technology Update: Instruments"

S. E. Grossman  
Electronics  
October 17, 1974, pages 98-109

"The entry of large-scale integration into instrumentation is now simplifying test and measurements procedures for all users, from the design engineer to production-line personnel. Instruments will 'get smart' increasingly as their manufacturers learn to take advantage of microprocessor chips. Automated networks controlling entire plants will spread rapidly as soon as a standard data bus can be agreed on." (Author)

"Instruments That Think for Themselves"

T. M. Comella  
Machine Design  
June 26, 1975, pages 50-54

A new breed of instrument is taking over certain dedicated tasks that required a minicomputer or programmable calculator.

These instruments have the ability to remember, compute, and control by utilizing microprocessors and other large-scale-integration electronic devices. Typical instruments are digital data analyzers, real-time analyzers, and data acquisition systems. This article provides an overview on the degrees of "instrument intelligence" that are available and the design strategies being used to produce such instruments.

"Improving Instrument Service Factors"

V. Skala

Instrumentation Technology

November 1974, pages 27-30

"A three-year study of almost 5,000 refinery control loops indicates that traditional means of reducing instrumentation downtime, including predictive maintenance, provide only limited rewards. Some improvement can be gotten by concentrating on those few loops identified as particularly poor performers. But the major effort should be directed towards making the maintenance organization more productive by scheduling more efficiently, cutting waiting time for service, and reducing unnecessary inspections. Analysis of statistical maintenance data shows where these improvements are needed most." (Author)

"NAVSEA Test, Measuring and Diagnostic Equipment Program"

C. E. Boucher

NAVSEA Journal

February 1975, pages 42-45

As stated in NAVSEA Instruction 5400.7 of 12 December 1974, test measuring and diagnostic equipment requirements are to be specified in each integrated logistic support plan and shall be compatible with the overall ship plan for use. Such test, measuring, and diagnostic equipment requirements should normally be determined through a maintenance engineering analysis or logistic support analysis of the prime shipboard system and equipment. Requirements are to be considered for the three levels of maintenance: organizational maintenance (ship's force), intermediate maintenance (tenders or repair ships), and depot maintenance (ship repair facilities, etc.).

"Standard Instrument Interface Simplifies System Design"

D. W. Ricci and G. E. Nelson

Electronics

November 14, 1974, pages 95-106

Until recently, sophisticated, cost-effective instruments have been readily available, but their generally incompatible inputs and outputs have forced the system designer to put much effort into interface design. A proposed international interface standard is explained. The standard defines the physical

connector of the interconnection bus, the roles of interconnecting bus wires, the logic conventions, format, and timing of control and data signals. Other factors necessary in a communications link that will be capable of interconnecting instruments and peripherals, such as computer, voltmeters, and card readers, are included. The information presented is aimed at the system designer, to help him utilize the interface by understanding its capabilities and limitations.

"Accuracy in Signal Conversion"

D. W. Devall  
Instrumentation Technology  
March 1975, pages 41-43

"The process of converting a signal from one form to another or amplifying it may introduce errors that subvert the accuracy inherent in a high quality transducer. The author shows how to relate overall system accuracy to specifications for the transducer, signal converter, and instrumentation amplifier; and presents some basic guidelines to minimizing conversion errors."  
(Author)

"Signal Conditioning for Gas Flow Computation"

G. W. Evans  
Instrumentation Technology  
June 1973, pages 38-42

"Orifice flow meters are accepted as the standard for natural gas measurement, and every effect which may influence the indication is taken into account. On-line computation of these flow corrections that let buyer and seller obtain the same answer requires careful consideration of ranges to be handled and of ways to get maximum accuracy out of inexpensive apparatus." (Author)

"Intrinsically Safe System Gages Shipboard Tanks"

J. D. Gagliardi  
Instruments and Control Systems  
November 1974, pages 55-56

Shipboard application of electrical equipment requires consideration of the system's safety as well as its performance. Electrical safety may be assured by use of either explosion-proof enclosures or intrinsically safe systems. The equipment and its associated wiring are incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of hazardous atmospheric mixtures. This article describes techniques that can be employed to ensure intrinsically safe systems for gaging and monitoring of tank

fluid conditions aboard ship. Such systems could satisfy safety requirements for electrical tank gagings of ballast, fuel oil, potable water, and other various liquids.

101 Tech Tips

Reprinted from Instrumentation Technology  
Instrument Society of America, Pittsburgh, PA  
Publication R-119  
59 pages

This booklet is a compendium of successful measurement techniques reprinted from Instrumentation Technology Magazine, an ISA publication. Measurement topics include flow measurement, liquid level instrumentation, temperature measurement, pressure measurements, chemical analysis, strain measurement, cryogenic instrumentation, signal handling techniques, switching techniques, and instrument maintenance.

"Use Low-Cost IR Detectors"

C. S. Molee, M. Muller, and A. Eschbach  
Electronic Design 12  
June 7, 1975, pages 84-87

"Available low-cost infrared detectors give the engineer many sensing options for industrial measurements. With these IR elements and fairly simple signal-conditioning circuitry, you can design reliable and economical measuring instruments for remote monitoring and control.

"Applications range from noncontact temperature sensing of inaccessible targets and remote counting of moving objects and locating optical telemetry paths. IR detectors are also useful to analyze gases, such as engine exhausts based on absorption of infrared radiation." (Authors)

"Composition Transducer Closes Another Control Loop"

S. J. Bailey  
Control Engineering  
April 1975, pages 55-56

"The composition transducer described here is the latest process control building block developed to measure the percentage of a single component in a chemical mix. The output of the transducer can be used as a feedback signal for control, as with flow, temperature, and pressure transducers." (Author)

Overview of Transducers and Sensors for Diagnostics

H. G. Tobin

Society of Automotive Engineers Paper 700495

(Paper presented at Mid-Year Meeting, SAE, Detroit, MI, May 1970)

12 pages

"The wide interest in the development of diagnostic techniques for automotive purposes has led to developments in several areas. These include sensing methods, signal processing methods, and studies of how mechanical systems fail. This paper, concerned with only the first of these categories, presents an overview of sensors with emphasis on the new developments that may be useful in the diagnostic field. Among the parameters which may be measured in automotive diagnostic systems are pressures, speeds, flow rates, temperatures, vibration, and electrical measurements. This paper will discuss various methods by which such parameters can be measured." (Author)

"Sensors in Five Areas are Getting Tinier, Cheaper, and More Precise"

D. Bursky

Electronic Design 15

July 19, 1974, pages 30-38

Sensing transducers are smaller, more accurate, and lower in cost than ever before. Errors of 1% or less are common, while prices are plummeting. The article reveals advances in measurement of temperature, pressure, strain, acceleration, and displacement. A description of an optical flowmeter, employing LEDs and photosensors to determine flow, is included.

"Integration Brings a Generation of Low-Cost Transducers"

A. R. Ziås AND W. F. J. Hare

Electronics

December 4, 1972, pages 83-88

This article describes a new type of pressure transducer. Standard high-volume integrated circuit techniques are used to build, test, calibrate, and package these transducers, and they are priced like ICs. This represents an important breakthrough, considering that transducers have routinely set the price and performance bounds for most electronic measurement systems that must interface with larger mechanical systems.

"Sensors and Transducers: An Update on the IC Invasion"

W. Patstone  
EDN Magazine  
July 20, 1974, pages 32-41

This article provides an overview of the myriad of available sensors, transducers, and their manufacturers. The article focuses on the utilization and application of the new "integrated circuit transducers" which combine sensor, signal conditioning, and amplification in one compact, inexpensive unit. The information presented mainly concerns pressure and temperature sensors, but other sensor information is included.

Fundamentals of Temperature, Pressure, and Flow Measurements

R. P. Benedict  
John Wiley & Sons, New York, NY  
1969, 353 pages

This book is a working reference for practicing engineers involved in measurement of temperature, pressure, and flow rate. It provides a complete review of techniques for making such measurements. Topics are treated in depth, and all necessary data, diagrams, equations, and tables are included.

"Vibrator Sensors for Atmospheric Pressure, Temperature, and Humidity Measurements"

Y. Kagana  
Journal of Acoustic Society of America, Volume 56, Number 5  
November 1974, pages 1644-1649

"Circular vibrator sensors for atmospheric pressure, temperature, and humidity measurements by means of natural frequency change have been developed. Uniform pressure over a circular plate supported at the edge causes an axisymmetric deformation to a quasi-shallow spherical cap, which changes the natural frequency of the plate. A similar deformation effect is achieved with temperature or humidity by employing bimaterial construction for the plate. Change of the natural frequency is linear with atmospheric pressure, temperature, or humidity over a relatively wide range, and the sensitivity is sufficiently high for practical applications. The devices are suitable for telemetering and digital measurement applications." (Author)



Transducers: Temperature and Pressure  
National Semiconductor Corporation, Santa Clara, CA  
Publication Number C50M84  
August 1974, 150 pages

"Progress in solid-state electronics traditionally has brought advances to heretofore non-electronic fields of endeavor. Transduction is not an exception. While mechanical transducers traditionally have been used to measure pressure and pressure-related quantities, the use of electronics - particularly the use of hybrid IC pressure transducers - brings lower cost, higher accuracy and greater versatility than previously available to traditionally mechanical-type measurements."

This handbook details the capabilities of these transducers with application notes and technical briefs. Some of these include temperature control circuits, acoustic applications of pressure transducers, and using pressure transducers as accelerometers and in fluid flow measurements.

"Guide to Temperature Measurement"  
John Fluke Manufacturing Company  
Instruments and Control Systems  
June 1974, pages 47-48

Temperature is the most commonly measured industrial parameter. To sense it properly one must be able to detect changes in, as well as judge the degree of, heat in an object. Temperature can be inferred from a number of other physical properties. For example, changes in pressure or electrical resistance, voltages created at the junction of two dissimilar metals, or the intensity of radiation emitted by an object all depend on temperature. Each specific sensing technique has its own inherent advantages. An examination of these techniques is presented.

"Temperature Sensing"  
L. Blasso  
Instruments and Control Systems  
June 1975, pages 17-20

"To sense temperature accurately, you must be able to distinguish certain changes, as well as judge the degree of heat that an object contains. Variations in temperature result in observable phenomena, such as: changes in pressure or density, a change in electrical resistance, a voltage created at the junction of two different metals, or a change in the intensity of radiation emitted

by an object. Some thermal sensor designs are, in fact, based on these phenomena." (Author)

An overview of state-of-the-art temperature sensing techniques, their respective selection criteria, and typical applications are presented.

Manual on the Use of Thermocouples in Temperature Measurement

R. P. Benedict, Editor

American Society for Testing and Materials, Philadelphia, PA

ASTM Special Technical Publication 470A

March 1974, 252 pages

This manual is a "consolidated sourcebook covering all aspects relating to accuracy, application, and usefulness of thermometric methods," specifically thermocouples. "The contents include principles, circuits, standard electromotive force (emf) tables, stability and compatibility data, installation techniques, and other information required" by the measurement engineer.

"How Accurate are Thermocouples, Anyway?"

D. R. Keyser

Instruments and Control Systems

March 1974, pages 51-54

(Extracted from NAVSECPHILADIV Project A-1055 Final Report: AD-739 684)

"Thermocouples are widely used as temperature sensors but they can be strongly affected by the environment in which they are employed.

"Several studies have attempted to discover the nature of thermocouple drift and aging effects." A standard to determine sensor degradation is presented.

"Applying the Systems Concept to Thermocouples"

R. M. Park

Instrumentation Technology

August 1973, pages 25-31

"The venerable thermocouple is re-evaluated as part of a complete system of temperature measurement. Similarities as well as unique differences between thermocouples and other instrumentation systems are explored, and criteria are developed for the thermocouple environment interface. Several techniques for multipoint applications are discussed, and so is the role of systematic preventive maintenance as an essential system component." (Author)

"Diode Pair Senses Differential Temperature"

D. DeKold

Electronics

July 25, 1974, pages 97-98

"Normally, a germanium diode functioning as a temperature sensor relies on the linear variation of its forward voltage with temperature. But a pair of germanium diodes can be made to serve as a differential-temperature dependent diode property--the logarithmic variation with temperature of the reverse saturation current. The resulting circuit is useful for industrial control applications." (Author)

"Temperature-Sensitive Resistor is Linear"

L. Mattera

Electronics

October 3, 1974, pages 135-136

Difficulties with temperature sensing and compensation have long bothered instrument engineers. This article describes a small, low-cost nickel-film component suitable for a variety of applications in temperature sensing because its value varies linearly from  $-20^{\circ}$  to  $+150^{\circ}$  C.

"Integrated Temperature Transducers"

M. J. Riezeman

Electronics

November 14, 1974, pages 130-132

"The electrical temperature transducer, characterized for many years by slow, evolutionary development, has at last entered the semiconductor age. During all this time, there has been no serious competitor to these sensors--thermocouples, resistance-temperature devices (RTD), and thermistors.

"Despite their newness and limited temperature range of  $-100$  to  $+150^{\circ}$  C at best, the new silicon devices are creating a good deal of interest because of their large and linear outputs - typically 10 millivolts per degree Celsius. The new transducers are cheap and easy to use because of these two attributes, which eliminate the need for signal-conditioning amplifiers, cold-junction compensators, and other accessories." (Author)

"Solid-State Temperature Sensor Outperforms Previous Transducers"

R. A. Ruehle

Electronics

March 20, 1975, pages 127-130

This article describes another solid-state silicone temperature detector which profits from linear heat sensitivity of a sensing transistor's base-emitter voltage. Employing discrete components instead of IC chips, this unit reduces sensor self-heating error. The result is a low-cost package with a stable, accurate output that requires no amplification.

"Too Hot to Touch? To Find Out How Hot, Try Infrared"

R. F. Leftwich

Instruments and Control Systems

October 1974, pages 51-54

Noncontact temperature measurement and control is possible thanks to a basic natural characteristic of all objects. At temperatures above absolute zero everything emits infrared energy caused by molecular thermal agitation. Such infrared thermometers can make noncontact temperature measurements of a particular point.

"Guide to Pressure Transducers"

Celesco Industries, Inc.

Instruments and Control Systems

October 1974, pages 55-56

A varied selection of sensing techniques for a wide range of pressures is presented. The techniques described include mechanical and electrical transductions using diaphragm, Bourdon tube, bellows, piezoelectric, vibrating element, and vacuum sensors.

Differential-Pressure Instruments: The Universal Measurement Tools

V. N. Lawford

Instrumentation Technology

December 1974, pages 30-40

"A very large variety of instruments that measure—and may also control— $\Delta P$  are available for a very broad range of process variables. The author reviews the basics of common and unusual applications which utilize a  $\Delta P$  sensor, placing emphasis on flow and level systems."  
(Author)

"Pressed by Pressure Measurements?"

E. N. Kaufman  
Instruments and Control Systems  
August 1974, pages 53-54

This article describes three different off-the-shelf digital-pressure transducers. Such devices would easily interface with a computerized machinery diagnostic system; however they are large, costly, and somewhat unwieldy.

"Measuring Forces with a Miniature Capacitive Transducer"

G. M. Brown  
Instrumentation Technology  
June 1975, pages 49-52

"Based on a single integrated circuit, this transducer responds to variations in pressure or force by changing its output frequency in direct proportion to the displacement of its capacitive sensor. The author shows that this frequency-modulated device, coupled to either an analog or digital control system, will accurately measure variable-induced displacement of less than five ten-thousandths of an inch, providing adequate sensitivity for force measurements using an elastically deformed member." (Author)

"Pressure Sensor Relies on Frequency"

Editorial Staff  
Electronics  
August 8, 1974, pages 46-48

A new capacitive pressure sensor has been developed for automobile engine emission control and electronic fuel injection systems. The sensor produces a signal frequency varying with pressure. The frequency is then easily digitized for connection to a control element. To reduce costs, hybrid and integrated circuit techniques are utilized. If the variable capacitor was placed in a bridge network, it would be possible to deliver a varying voltage rather than a varying frequency.

"Electromagnetic Flowmetering: Basics, Products, and Applications"

A. S. Webb  
Instrumentation Technology  
March 1974, pages 29-36

"Various electromagnetic flowmeters, sold in the USA and Canada by eight firms are examined in detail. The article also

covers such topics as application tips. Emphasis is on the industrial type of meter, but a short section reviews electromagnetic flowmeters which have unusual configurations and/or applications." (Author)

"Small Turbine Meter Measures Large Flows"

Editorial Staff  
Instrumentation Technology  
August 1973, page 45

The method allows small and easily calibrated flowmeters to be installed in large pipes for flow monitoring. The flowmeter under test measured fluid velocities that were consistently higher than actual average velocities in the pipe; a compensated calibration was necessary. This technique was developed at NASA Lewis Research Center, Cleveland, OH. From NASA Tech Brief B72-10631.

"Microwave Doppler-Effect Flow Monitor"

A. Hamid and S. S. Stuchly  
IEEE Transactions on Industrial Electronics and Control Instrumentation, Volume IECI-22, Number 2  
May 1975, pages 224-228

"This paper contains a discussion of the capabilities and limitations of a modern solid-state microwave doppler radar used for monitoring the flow rates of moving materials. Experimental results of monitoring flow rates of particulate solids are presented. It has been concluded that the average doppler frequency is proportional to the average bulk velocity. When the bulk density and the cross-sectional area of the pipe are known, the system provides contactless means of monitoring the mass flow rate of particulate solids." (Authors)

"Ultrasonic Instruments for Level and Flow"

B. G. Liptak and R. K. Kaminski  
Instrumentation Technology  
September 1974, pages 49-59

"This article surveys the product lines of 17 manufacturers of ultrasonic level and flow instruments, switches as well as transmitters (sic). Three tables list basic application and specification information for about 100 different models. The article also reviews principles of operation and general application concepts." (Authors)

"LVDT's Provide High Resolution Displacement Measurements"

H. Schaevitz  
Electronic Products Magazine  
March 17, 1975, pages 53-61

The LVDT is an electromechanical device that produces an electrical output proportional to the displacement of a separate moveable core. It consists of a primary coil and two secondary coils symmetrically spaced in a cylindrical form. A free-moving rod-shaped magnetic core inside the coil assembly provides a path for the magnetic flux linking the coils.

The LVDT is widely used as a measurement and control sensor wherever displacements of a few microinches to several feet can be measured directly, or where other physical quantities such as force and pressure can be measured directly, or where other physical quantities such as force and pressure can be converted to linear displacement. Its operating characteristics are compared with the most commonly used displacement transducers.

"Ultrafast Proximity Sensing"

M. Wilson  
Electromechanical Design  
March 1975, pages 24-25

Response times of inductively coupled proximity detectors are difficult to define and are usually slower than theoretically possible. A special "linearizing" circuit is presented for state-of-the-art eddy-current type sensors. Such a "linear" oscillator reduces the complexity of the transducer system and improves its response.

"The IC Photo Tachometer"

A. A. Mangieri  
Popular Electronics  
August 1974, pages 54-57

By measuring the revolutions per minute of rotating elements, you can easily detect the effect of worn gear trains or motor brushes and to gauge improvement of performance after repairs. This battery-operated device gives accurate readings up to 50,000 rpm without physical contact.

The Voltensor - A New Control Device and How to Use a Voltensor

S. P. Cuff  
California Electronic Manufacturing Company, Inc., Alamo, CA  
(Papers presented at the Instrument Society of America Control Elements Symposium)

"These papers cover the basic theory, operation, selection, and application of the Voltensor. It is intended to provide groundwork for maximum understanding of the voltensor in theory and practice.

"It must be noted that there is no 'mystique', nor, in fact, any real complexity to the voltsensor, once the basic concepts are grasped. The voltsensor is eminently practical in an infinite variety of applications as an active control or alarm element. Its low cost and great versatility make it an industrial 'tool' in the broadest sense."

(Author)

"Detection and Visualization of Ultrasonic Fields and Vibrations by Means of Liquid Crystals"

Y. Kagawa, T. Hatakeyama, and Y. Tanaka  
Journal of Sound and Vibration, Volume 36, Number 3  
1974, pages 407-415

"Mapping techniques for ultrasonic fields by means of cholesteric and nematic liquid crystals are first examined. It is discovered that with the proper electric field superposed on a nematic liquid crystal detective cell, the sensitivity is increased as much as three times. The techniques to visualize the vibrational modes of a mechanical vibrator by means of a liquid crystal layer formed on the surface are then developed. These techniques are useful for the investigation of hydro-acoustic fields, vibrating bodies and the like as they permit real-time visual observation." (Authors)

"Shock and Vibration Transducers"

A. W. Orlacchio  
Electronic Design 21  
October 11, 1974, pages 68-75

Shock and vibration transducers, usually called accelerometers, provide an accurate method of determining stress levels, load factors, transmissibility coefficients, and fatigue values of a structure being subjected to shock and/or vibration. The different types of accelerometers are tabulated with operating characteristics, primary advantages, and disadvantages. Transducer signal conditioning and connection techniques are included.

"Acceleration/Vibration"

Editorial Staff  
Measurements and Data News  
November-December 1974, pages 77-86  
(Abstracted from the 1975 Measurements and Control Handbook and Buyers Guide)

Acceleration, velocity, and distance are related by time, and these measurements can be categorized as "metrology," a



field that includes all of the following: accelerometers, acceleration generators, displacement meters, velocity meters, vibration meters/switches, spectrum analyzers, balancing equipments, interferometers, surface roughness, proximity detectors/switches, and seismographs. A comprehensive listing of such acceleration/vibration equipments, their manufacturers, and detailed descriptions is presented.

Accelerometers Developed for Vibration Measurement at High Temperature

R. M. Whittier and L. C. Ensor

Endevco Corporation, San Juan Capistrano, CA

Technical Paper TP 254, 1970

(Paper presented at 25th Annual ISA Conference, Philadelphia, PA, October 1970, ISA Paper 606-70)

"This paper reviews the development of several piezoelectric accelerometers designed for measuring vibration at temperatures exceeding 750° F (400° C). The measurement system design considerations, including cable, connector, and signal conditioner characteristics, are examined as they interrelate with the accelerometer. To provide the high temperature transduction element it was necessary to develop the high temperature piezoelectric materials. The critical characteristics of these materials and the resulting accelerometer designs are discussed. One of the accelerometers, with a temperature range to 1400° F (760° C), weighs only 0.6 ounce (18 grams). The methods used to evaluate the vibration, shock, and accuracy capabilities at high temperature are discussed, and the results of tests are presented." (Authors)

An Evaluation of Magnetic Mounting of Accelerometers

LT D. C. Colley, USN

Naval Postgraduate School, Monterey, CA

Department of Mechanical Engineering Master's Thesis  
December 1974, 44 pages

"The performance of magnetic clamps as a means of attaching accelerometers for machinery vibration surveys is investigated. Three conditions that might adversely affect magnetic clamp effectiveness are looked at in detail: (1) the presence of cross-motion, (2) the mounting conditions, and (3) the presence of high levels of acceleration. Results are given for six commercially produced magnetic clamps. Cross-motion and

high-acceleration are found to have little effect on magnetic clamp response to the extent tested. Improper mounting is found to effect response greatly. Procedures are recommended for attachment of clamps and results of tests using these procedures are shown to be reproducible." (Author)

Vibration and Acoustic Measurement Handbook

M. P. Blake and W. S. Mitchell

Spartan Books, New York, NY

1972, 649 pages, International Standard Book Number 0-87671-561-7

This handbook does not attempt to replace existing handbooks; it attempts to fill the information gap between theory and practice. It is aimed at utilizing vibration and acoustic measurement techniques for maintaining the well-being, safety, economy, and general control of the cost of performance of industrial machinery.

Information presented includes some of the fundamentals of acoustic and vibration together with some useful highlights of analytical methods and vibration isolation; examples drawn from the field of machine maintenance, where vibration measuring covers the operation spectrum from safety to economy of operation; and the topics of velocity measuring and severity of levels are given proper consideration. Measurement instrumentation and measuring examples are described, and a chapter devoted to measurement standards and general information for the industrial case is included.

Handbook of Noise Measurement

A. P. G. Peterson and E. E. Gross, Jr.

General Radio Company, Concord, MA

1974, 322 pages, Seventh Edition

Form Number 5301-8111-L

This book is a standard in airborne-noise measurement and analysis. A study of mechanical vibration, as it is related to the sound produced, is included. Important effects of vibration include increased maintenance of machines, appliances, vehicles, and other devices. Descriptions of electronic sound-and-vibration-measuring instruments and systems are given.

The purpose of this handbook is to assist those faced with the necessity of making noise measurements. It attempts to clarify the terminology and definitions used in these measurements, to aid the prospective user in selecting the proper equipment for the measurements required, and to show how these measurements can be interpreted and analyzed to solve typical problems.

Machinery Health Monitoring

Endevco Corporation, San Juan Capistrano, CA

Endevco Publication Number 201

October 1974, 6 pages

"Recent years have witnessed rapidly increasing use of sophisticated instrumentation to monitor and display the condition of industrial machinery. So successful have been these efforts in predicting and preventing equipment failures that a new term has entered the industrial vernacular "Machinery Health Monitoring."

"The actual condition of the machinery replaces prescribed time intervals as the primary basis for preventive maintenance activities. So down time is no longer required for many periodic checks." (Author)

When maintenance is required, the monitoring system will recognize the need; if not, it will assure you of that too. Machinery can remain operational, and the chances of maintenance-induced damage are greatly reduced.

Examples of Application

Bruel and Kjaer Instruments, Inc., Cleveland, OH

B & K Publication 13-147

98 pages

This publication details the major applications of basic vibration instrumentation and advanced, sophisticated vibration measurement/analysis systems. Specific vibration and acoustic measurement techniques for preventive maintenance monitoring of mechanical equipment are presented.

Dynamic Measurements for Rotating Machinery

Hewlett-Packard Company, Palo Alto, CA

HP Publication 02-5952-7000

December 1973, 15 pages

"Signature analysis techniques are being applied daily by people who design, build, test, or use rotating machinery. Now, for the first time, a Fourier Analyzer Signature Analysis System makes those measurements easier, faster, more accurate, and more revealing than ever before. This one system offers complete analysis capability—not only for rotating machinery—but for the total measurement problem." (Author)

Product Improvement Through Dynamic Analysis  
Spectral Dynamics Corporation, San Diego, CA  
Spectral Dynamics Publication CL 5-74  
1974, 13 pages

"Noise and vibration are closely related phenomena, often arising from the same sources. Vibration has long been recognized as a major source of wear and fatigue in critical machinery parts such as bearings and gears, failure of which can quickly shut down a machine or an entire production line or process.

"This brochure describes some of the techniques now available for tracing the sources and analyzing noise and vibration in machinery and structures. No single method fits every case. Results must be weighed against equipment costs and the two compared to the seriousness of the problem. However, there are three closely related steps which must be taken to completely analyze any power-driven structure: (1) Narrow band spectrum analysis, (2) transfer function analysis, and (3) modal analysis." (Author)

Study for Maintenance of Hydraulic Motors  
R. B. Tatge  
General Electric Company, Schenectady, NY  
NASA Report CR-99189  
October 1968, N70-14260, 207 pages

This report describes development of methodology and instrumentation "to detect incipient malfunction or failure of components of functioning hydraulic systems; it is easily applicable to all types of operating machinery. The mechanical vibrations of individual moving components are sensed with piezoelectric accelerometers and measured electronically from outside the working machine. The data yielded are either analyzed directly or stored on tape and subsequently processed and analyzed for indication of defective components that would lead to ultimate failure unless corrective action were taken." From NASA Tech Brief B70-10166, February 1970.

Instrumentation for Predicting Bearing Damage  
B. Weichbrodt and F. J. Bowden  
General Electric Company, Schenectady, NY  
GE Report S-70-1021  
March 1970, AD-869 633, 122 pages

"This report describes the use of Mechanical Signature Analysis techniques for prediction of fatigue damage in large azimuth

antenna bearings without interruption of antenna operation. Bearing areas of specific concern were the inner race, outer race, and rolling elements.

"The hardware used for this prediction consisted of six accelerometers and data processing equipment capable of sensing, recording, and analyzing vibration signals generated during bearing tests.

"Three bearings were tested, with only the second bearing generating enough data for analysis. This testing, carried on at a Rome Air Development Center site, confirmed that Mechanical Signature Analysis can detect impending fatigue failure much earlier than currently used conventional techniques. It is also concluded that Mechanical Signature Analysis can pin point the location of the defect.

"The report describes an electronic system, a Bearing Condition Monitor, which could be used to perform the failure prediction in real time at field antenna sites."  
(Authors)

"Angular-Vibration Analyzer"

K. Arthur and W. Verhoef

Machine Design

April 18, 1974, pages 138-142

"A rotating machine lets you know the minute it's in trouble. Flywheel imbalance, faulty combustion in a multicylinder engine, bearing rough spots, and other rotating eccentricities all set up noise and vibration that are readily detected.

"More important, however, they also produce angular vibration (periodic fluctuation in angular velocity) in rotating shafts, and this vibration can be converted to electrical signals. This means you can measure the amplitude and frequency of angular vibration, determine torsional resonant frequencies, and—as a consequence—can locate and correct the offending machine element." (Authors)

Fundamentals of Time Series Analysis

J. S. Bendat

Time/Data Corp., Palo Alto, CA

April 1974, 32 pages

"This paper discusses fundamental principles for analyzing time series data (also called random data or random processes). Properties of interest are explained for amplitude, time, and frequency characteristics in the data. Requirements are reviewed for data processing procedures, for error analysis of desired measurements, and for determination of system input/output properties." (Author)

The Fast Fourier Transform

E. O. Brigham

Prentice-Hall, Inc., Englewood Cliffs, NJ

1974, 252 pages, International Standard Book Number 0-13-307496-X

The Fourier transform has been a principal analytical tool in signal analysis. The same, however, cannot be said for the discrete Fourier transform. Even with the tremendous computing speeds available with modern computers, discrete Fourier transform found relatively few applications because of the exorbitant amount of computation time required. With the development of the fast Fourier transform (an algorithm that efficiently computes the discrete Fourier transform), many facets of scientific analysis have been revolutionized.

This book provides a concise, meaningful treatment of the fast Fourier transform and its basic applications in signal analysis. Other topics presented include the convolution integral and correlation function for signal waveforms.

"Fast Fourier Transform Primer Provides Physical Picture of FFT"

F. Pfisterer

EDN Magazine

May 20, 1974, pages 47-49

This article, written as a primer on FFT (fast Fourier transform), circumvents the problem of complex mathematical explanations of the subject by developing a simple, physical picture of the FFT. It provides a novel, easily grasped, and intuitively satisfying insight into the process that makes it easier to understand the more mathematical and general developments in the literature.

"The Fast Fourier Transform's Errors Are Predictable, Therefore Manageable"

R. W. Ramirez

Electronics

June 13, 1974, pages 96-102

"One's first brush with the fast Fourier transform (FFT) is often disconcerting because turning the classical Fourier transform into the FFT practically always introduces errors. Known as leakage and aliasing, these errors almost invariably occur when continuous time-domain waveforms are subjected to finite-time-windowing and sampling—both of them operations that are fundamental to the FFT.

"But the engineer who understands why leakage and aliasing occur will fairly soon be able to spot many cases on sight. Also, several methods for combating them become very obvious." (Author)

Continuous Fourier Transform System

R. M. Munoz

NASA Research Center, Moffett Field, CA

NASA Research Center Contract ARC-10466

Ames Research Center Reference TSP 74-10170

A system has been developed for performing a continuous Fourier transform of a time-variable signal from the time domain into the frequency domain or the converse. Because the transform is performed continuously in the analog domain, a relatively complex digital computer is not required, only summing amplifiers and attenuators are used for spectrum analysis, filtering, transfer function synthesis, and communications. From NASA Tech Brief B74-10170, September 1974.

Real Time-Time Compression Spectrum Analysis

Dr. I. M. Langenthal

Honeywell, Inc., Test Instruments Division, Denver, CO

Honeywell Technical Bulletin TB-11

April 1971, 10 pages

"The spectral or frequency domain properties of signals contain valuable information which can be used as an important design or diagnostic and interpretative tool. This technical bulletin describes various techniques for obtaining the spectrum of signals. The more conventional procedures are compared with the time compression technique, an approach which allows on-line, real-time analysis. Section II describes the interplay

among the three most important parameters which enters into the determination of the spectrum using the time compression technique. These parameters are sampling and quantizing, processed signal length and truncation, and memory size required. Section III describes the applications of digital averaging for improving estimates for random data and increasing detection for deterministic signals. The concept of confidence limits, non-redundant averaging and the chi-squared distributions are described."  
(Author)

"Real Time Spectral Analysis - Taking the Mystique Out of This Valuable Maintenance Tool"

J. E. Palm

Spectral Dynamics Corp., San Diego, CA

Proceedings of the Second Turbomachinery Symposium, Gas Turbine Laboratory, Texas A & M University, College Station, TX

Pages 129-141

"A new 'yardstick' for measuring rotating machinery vibration is seen in the real-time spectrum analyzer. This paper presents some actual case history data that was (sic) analyzed using a real-time spectrum analyzer. The object in doing so is to present the reader with a better understanding of the capabilities obtainable through use of this hybrid analyzer for monitoring vibration. Some theory of operation is also presented to describe how this tool works so that its application can be better understood." (Author)

Computer - Aided Vibration Analysis

L. T. Hauck

American Society of Mechanical Engineers Paper 74-DE-1

(Paper presented at Design Engineering Conference, ASME, Chicago, IL, April 1974)

"The advent of the narrowband Real Time Analyzer (RTA) has greatly aided the study of a wide variety of noise and vibration problems. By providing fine frequency resolution and high analysis speed, the RTA can quickly give important information about the status of an operating machine. This paper begins with an introduction to narrowband Real Time Analysis, with emphasis on machinery noise and vibration analysis. The increase in processing speed provided by an RTA can prove to be a mixed blessing. Large amounts of data can be produced very



quickly, and the increase in the bulk of data can result in a data management problem. This paper shows how a minicomputer can be used to manage an RTA. Emphasis is placed on a software approach that makes it possible for any engineer to use the system. By using a mixture of a conversational interpreter language and assembly language subroutines, an excellent balance can be struck between ease of the use, flexibility, and system efficiency. A new method of producing Campbell Diagrams is presented to demonstrate the system concept." (Author)

"Computerized FFT: A Shortcut to Spectral Analysis"

J. Oliverio

Electronic Products Magazine

November 18, 1974, pages 33-41

This article describes an instrument that does a computerized analysis of a signal in the frequency domain using digital techniques and is called a Fourier analyzer. This is because the algorithm used by these digital machines (the fast Fourier transform) is based on mathematical techniques first attributed to Fourier.

The Fourier analyzer is a composite wave analyzer, spectrum analyzer, signal averager-generator-correlator, and general purpose computer. It can be applied to such problems as measurement of mechanical impedance, signature and modal analysis, acoustics, and other machinery performance monitoring and diagnostic cases.

"Fourier Analysis of Stationary Processes"

D. R. Brillinger

Proceedings of the IEEE, Volume 62, Number 12

December 1974, pages 1628-1643

"This paper begins with a description of some of the important procedures of the Fourier analysis of real-valued stationary discrete time series. These procedures include the estimation of the power spectrum, the fitting of finite parameter models, and the identification of linear time invariant systems. Among the results emphasized is the one that the large sample statistical properties of the Fourier transform are simpler than those of the series itself. The procedures are next generated to apply to the cases of vector-valued series, multi-dimensional time series or spatial series, point processes, random measures, and finally to stationary random Schwartz distributions.

It is seen that the relevant Fourier transforms are evaluated by different formulas in these further cases, but that the same constructions are carried out after their evaluation and the same statistical results hold. Such generalizations are of interest because of current work in the fields of picture processing and pulse-code modulation."  
(Author)

Fourier Analyzer Training Manual  
Hewlett-Packard Company, Palo Alto, CA  
HP Application Note 140-0, HP Publication 02-5952-0651  
58 pages

"This manual first describes some typical applications of the Fourier Analyzer, such as analysis of: ship sounds, vibrations in engines and wing structures, brain waves, echoes from underground test explosions in oil research, etc. Then it shows how data is processed by pressing keys on a keyboard, and how individual mathematical operations can be linked together from the keyboard to form programs. A power spectrum program is described, for detecting signals buried in noise. The transfer function and coherence function used in systems analysis is explained. The last section of the manual is an extensive discussion of the mathematical background of the Fourier Analyzer." (Author)

Detecting Sources of Vibration and Noise Using HP Fourier Analyzers  
Hewlett-Packard Company, Palo Alto, CA  
HP Application Note 140-1, HP Publication 02-5952-0635  
15 pages

"The use of spectrum analysis in tracking sources of noise and vibration is limited by the resolution of the spectrum analyzer and the presence of similar frequencies in the various noise sources. If, however, a transducer can be placed on one or more of the sources, then these problems can be overcome by implementing a coherence function program in the Fourier Analyzer. This method also permits the suspected source to be measured independent of such extraneous influences as transducer gain. The techniques described in this note find application by manufacturers of rotating equipment, automotive components, and by engineers involved in ship silencing."  
(Author)

Digital Auto-Power Spectrum Measurements

Hewlett-Packard Company, Palo Alto, CA

HP Application Note 140-4, HP Publication 02-5952-0756

38 pages

"This application note is concerned with a single channel measurement of power using the HP Fourier Analyzer. The measurement is distributed in the frequency domain and is thus a power spectrum or (in some cases) a power spectral density. Several considerations in applying the Fourier Analyzer to the measurement must be exercised and are each discussed. These include classifying the type of data to be analyzed, choosing the proper window, calibrating the displayed spectra, normalizing broadband spectra to density measurements, and others. Statistical ensemble averaging and the energy measurement of transients are also treated." (Author)

"Signal Detection and Extraction by Cepstrum Techniques"

R. C. Kemerait and D. G. Childers

IEEE Transactions on Information Theory

Volume IT-18, Number 6

November 1972, pages 745-759

"A technique for decomposing a composite signal of unknown multiple wavelets overlapping in time is described. The computation algorithm incorporates the power cepstrum and complex techniques. It has been found that the power cepstrum is the most efficient in recognizing wavelet arrival times and amplitudes while the complex cepstrum is invaluable in estimating the form of the basic wavelet and its echoes, even if the latter are distorted.

"Digital data processing problems such as the detection of multiple echoes, various methods of linear filtering the complex cepstrum, the picket-fence phenomenon, minimum-maximum phase situation, and amplitude versus phase-smoothing for the additive-noise case are examined empirically and where possible theoretically, and are discussed. A similar investigation is performed for some of the preceding problems when the echo or echoes are distorted versions of the wavelet, thereby giving some insight into the complex problem of separating a composite signal composed of several additive stochastic processes. The threshold results

are still empirical and the results should be extended to multi-dimensional data.

"Applications are the decomposition or resolution of signals (e.g., echoes) in radar and sonar, vibration, seismology, speech, brain waves, and neuroelectric spike data. Examples of results are presented for decomposition in the absence and presence of noise for specified signals. Results are tendered for the decomposition of pulse-type data appropriate to many systems and for the decomposition of brain waves evoked by visual stimulation." (Authors)

A cepstrum is defined as a power spectral density of a power spectral density and is used to pick fundamental periods out of a signal. A power spectral density is an indication of the energy of a signal which may be associated with a given frequency.

If a signal contains a strong periodic signal other than a sine wave, the spectrum will show amplitude spikes at the fundamental frequency and its harmonics. The corresponding peaks in the cepstrum will show the fundamental periodicity between peaks.

Cepstrum analysis is usually performed digitally.

APPENDIX D

FAILURE PREDICTION TECHNIQUES

"A Reliability Primer"

R. Deushle and J. Goldberg  
Instruments and Control Systems  
February 1974, pages 51-54  
March 1974, pages 67-69

Reliability is a statistical parameter that allows one to evaluate equipment on the basis of failure probabilities. The concept can be applied in a straightforward manner to the specification and design of equipment and systems. Part I defines reliability and statistical tools describing it. Part II describes techniques to estimate and compare quantitative and qualitative reliability.

Reliability Design for Vibroacoustic Environments

D. D. Kana and T. G. Butler, editors  
American Society of Mechanical Engineers, New York, NY  
ASME Publication AMD-Vol 9

187 pages

(Papers presented at Winter Annual Meeting, American Society of Mechanical Engineers, New York, NY, November 1974)

This book is a compendium of papers presented at the ASME Winter Meeting, Vibrations/Applied Mechanics presentation, 1974. Its purpose is to present some fundamentals and current developments in the application of reliability concepts to the prediction of successful functioning hardware in vibration and acoustic environments. Some topics included are fundamentals of mechanical reliability theory and applications to vibroacoustic failures, reliability design criteria for shipping industry, acquisition and analysis of test data to determine reliability parameters, accelerated reliability testing under vibroacoustic environments, and the use of field vibration data in deriving and applying a laboratory vibrations test.

Interactions Among the Various Phenomena Involved in the Design of Dynamic and Rotary Machinery and Their Effects in Reliability

Volume I - Basic Report of Reduced Results and Utilization Thereof  
D. Kececioğlu, L. B. Chester, C. F. Nolf, J. D. Stultz, and A. Vaze

University of Arizona, Tucson, AR  
August 1972, 184 pages, Contract N00014-67-A0209-0002

Since mechanical failures and the factors that cause them are of a distributed, probabilistic nature, it is necessary to include the theories of probability and statistics in design methods for equipment. In any design mechanical product, there is an associated probability of failure. This implies that reliability, another probability, should be the measure of design

adequacy of mechanical equipment. As the design of reliable and optimized components and systems of dynamic and rotary machinery is becoming a matter of increasing concern, methods whereby a specific level of reliability can be designed into a component become quite important. Achieving this goal requires the assembly of the necessary design data in a distributional form.

This is the fifth technical report in a series, beginning in 1968, sponsored by the Office of Naval Research. It describes continued experimental research on material behavior under testing to failure. Test data and interpretations of test results are included with conclusions and recommendations, which identify areas where further research is needed.

"Predict Failures and Overhaul Interval to Minimize Downtime"

L. E. Nino

Hydrocarbon Processing

January 1974, pages 108-110

"Maintenance management can increase equipment availability by mathematically predicting failures. Based on actual shutdown data, a mathematical model can be constructed which will tell you when to repair or replace equipment to minimize downtime. The model can be reduced to a simple line on a nomograph." (Author)

"Predicting Service Life for Zero Wear"

A. Mordkowitz

Machine Design

January 10, 1974, pages 100-103

Predicting service life for sliding components by conventional techniques is difficult; it requires determination of allowable shear stress. The more practical system described in this article substitutes allowable tensile strength for shear strength, compressive loading for shear loading, and uses the "zero-wear" concept to define "life." Derived from laboratory work, zero-work is defined as the wear having an order of magnitude equal to that of the surface finish.

"Failure Prediction in Electronic Systems"

R. A. Kirkman

IEEE Transactions on Aerospace and Electronic Systems

Volume AES-2, Number 6

November 1966, pages 700-707

"If impending failures in aerospace systems can be predicted deterministically during a test or checkout period, action can be taken to replace or repair the defective parts and a mission failure averted. This has the effect of increasing the mission reliability of the system.

"There are several methods of predicting specific failures especially adapted to electronic systems, but also applicable to electromechanical and fluid systems and components. These are classified and discussed in detail, with examples. References are cited for additional detail.

"By way of background, deterministic failure prediction is contrasted with statistical failure prediction. The nature and definition of failure and related concepts are also discussed, together with physical principles upon which the several failure prediction methods are based.

"Used selectively and collectively, these failure prediction methods can form an optimal failure prevention strategy for use in a system test or checkout program."  
(Author)

"Failure Prediction Through the Theory of Stochastic Excursions of Extreme Vibration Amplitudes"

T. S. Sankar and G. D. Xistris

Journal of Engineering for Industry, Transactions of ASME  
February 1972, pages 133-138

(Paper presented at Vibrations Conference, ASME, Toronto, Canada, September 1971, ASME Paper 71-VIBR-60)

"This paper attempts to propose a prediction on the failure of machinery resulting from high vibration amplitudes. Since the monitored record is generally in the form of a randomly fluctuating signal, the principles of stochastic excursions are employed in the investigation. Considering the total record to be made up of piecewise stationary signals with normal distributions, an initial estimation on the state of the machine is obtained by determining the first passage probability of the random excursion about a specified safe level. Further information on the incipient failure of the machine is obtained by evaluating the probability of durations of the excursion above the critical level. A possible maintenance program for vibrating machinery is proposed on the basis of two probabilities, and discussed using a particular industrial application." (Authors)

"Amplitude Excursion Failure of Randomly Excited Mechanical Systems"

T. S. Sankar and K. S. Wong  
Journal of Sound and Vibration, Volume 37, No. 2  
1974, pages 263-272

"The investigation described here is concerned with the amplitude excursion failure probability of linear mechanical systems subjected to wide-band stochastic excitations. The oscillator is idealized as one having two-degrees-of-freedom to represent a large class of mechanical systems. The probabilistic descriptions of both the non-stationary and the stationary responses are derived by using Laplace transform techniques. By employing these results, the probability of the system having within a specified time interval, a motion exceeding a specified critical amplitude is determined. Some numerical results are provided in terms of plots for different values of the physical parameters of the system." (Authors)

"Utilization of a Forced-Choice Technique to Verify Statistical Performance Requirements for Detection Systems"

R. J. Buratti and G. E. Trezona  
Journal of Acoustic Society of America, Volume 57, Number 4  
April 1975, pages 906-912

"An automated forced-choice method of evaluating detection performance is employed instead of the familiar fixed-threshold technique. The latter method utilizes a number of preselected, constant thresholds to estimate both detection and false-alarm probability to estimate only the detection probability. The advantages of the forced-choice technique are a predetermined false-alarm rate, a single parameter test, less required test time, and real-time monitoring of test results by minimizing the amount of data reduction. A comparison of both techniques is presented for two sets of statistics which are representative of those typically encountered in detection systems under test conditions. Because of the uncertainty associated with the variable threshold, the forced-choice results are slightly pessimistic, but are within 0.3 dB of the fixed threshold results. However, the forced-choice technique can easily be made equivalent to the fixed-threshold



procedure by incorporating a correction factor into the test procedure." (Authors)

"State of the Art in Pattern Recognition"

G. Nagy

Proceedings of the IEEE, Volume 56, Number 5

May 1968, pages 836-862

"This paper reviews statistical, adaptive, and heuristic techniques used in laboratory investigations of pattern recognition problems. The discussion includes correlation methods, discriminant analysis, maximum likelihood decisions, minimax techniques, perceptron-like algorithms, feature extraction, preprocessing, clustering, and nonsupervised learning. Two-dimensional distributions are used to illustrate the properties of the various procedures. Several experimental projects, representative of prospective applications, are also described." (Author)

"Patterns in Pattern Recognition: 1968-1974"

L. Kanal

IEEE Transactions on Information Theory, Volume IT-20, Number 6

November 1974, pages 697-722

"This paper selectively surveys contributions to major topics in pattern recognition since 1968. Representative books and surveys on pattern recognition published during this period are listed. Theoretical models for automatic pattern recognition are contrasted with practical design methodology. Research contributions to statistical and structural pattern recognition are selectively discussed, including contributions to error estimation and the experimental design of pattern classifiers. The survey concludes with a representative set of applications of pattern recognition technology." (Author)

"Interactive Pattern Analysis and Classification Systems: A Survey and Commentary"

L. N. Kanal

Proceedings of the IEEE, Volume 60

October 1972, pages 1200-1215

"Starting with the era of learning machines, reasons are presented for the current emergence of graphics-oriented interactive pattern analysis and classification

systems (IPACS) as a general approach to practical pattern-recognition problems. A number of representative systems and their application to a wide variety of patterns are surveyed. Various aspects of alternative hardware and software implementations are commented upon and computational algorithms and mappings relevant to interactive analysis and classification of patterns are discussed."  
(Author)

"Interactive Pattern Recognition - A Designer's Tool"  
E. J. Simmons, Jr.  
Rome Air Development Center, Griffis AFB, NY  
Proceedings of the National Computer Conference  
1973, pages 479-483

"The marriage of interactive processing techniques with the technology of pattern recognition is particularly significant to the designers of equipment requiring the automatic recognition of objects or events. This new tool allows the system designers to develop better recognition logic more quickly than in the past. But, perhaps most importantly, they can develop this logic themselves, so all design alternatives and resulting systems effects can be analyzed in detail. This paper will show how easy it is to use an interactive pattern recognition system to solve a variety of problems." (Author)

"The RADC Interactive Laboratory for Design of Pattern Recognition Systems and Its Application"  
J. C. Faust, H. E. Webb, Jr., and L. A. Gerhardt  
Rome Air Development Center, Griffis AFB, NY  
13 pages  
(Paper presented at Computer Graphics, Pattern Recognition, and Data Structures Conference, Los Angeles, CA, May 1975)

"This paper describes the Interactive Laboratory for Design of Pattern Recognition Systems which exists at the Rome Air Development Center (RADC) of the United States Air Force. A brief history of the research that led to the interactive approach is included, together with the philosophy of the interactive approach. Applications of the laboratory to some real problems are discussed, together with some comments on its use in a course in Pattern Recognition given at RADC. The paper is tutorial in the sense that most of the results have

been previously published in fragments. The main contribution of this paper is a description of a real physical laboratory whose implementation is based on an interactive approach to pattern recognition which has evolved over the years." (Authors)

Pattern Recognition Techniques Applied Diagnostics

E. Cortina, H. L. Engel, and W. K. Scott

Society of Automotive Engineers Paper 700497

(Paper presented at Mid-Year Meeting, SAE, Detroit, MI, May 1970)

12 pages

"The application of Bayes' Procedures to effect statistically optimum diagnostic decisions is described. The thesis is advanced that pattern recognition techniques can be used to reduce processing complexity and thus permit implementation of Bayes' Procedures in practical field portable equipment.

"This thesis is under evaluation in a test program in which journal bearing and wrist pin defects are detected from vibration measurements. Processing of vibration data by a computer programmed Pattern Recognition Technique resulted in design of 'pre-detection' filters which can simplify the equipment required to detect the faults in real time." (Authors)

"Pattern Recognition Signal Processing for Mechanical Diagnostics Signature Analysis"

R. L. Hoffman and D. Fukunaga

IEEE Transactions on Computers

September 1971, pages 1095-1100

"Signature analysis of small, complex, cyclic mechanisms is discussed. An envelope preprocessor for isolating signal events relating to mechanical impacts is developed. A recognition system based on second-order (normal) statistics is used and the use of statistical procedures for signature interpretation is presented. Experimental evidence is presented to support the validity of this approach to mechanical diagnostics signature analysis." (Authors)

"Pattern Recognition Techniques for Predicting Performance"

B. R. Kowalski

Chemical Technology, Volume 4

May 1974, pages 300-304

"A package of computer programs, called RECOG, has been developed that can identify patterns in experimental data that are difficult to recognize by conventional means. These pattern recognition techniques enable one to relate properties of materials or manufactured parts to their function and performance. One can thus predict from analytical data whether or not a material or a part will perform satisfactorily. RECOG has been successfully applied to many chemical problems, including source identification, compound screening, and material production problems. The results of two successful applications to material production problems are discussed here." (Author)

## APPENDIX E

### TESTING TECHNIQUES

#### Evaluation of Wear Testing

American Society for Testing and Materials, Philadelphia, PA

ASTM Special Technical Publication 446

(Papers presented at 71st Annual Meeting, American Society for Testing and Materials, San Francisco, CA, June 1968)

132 pages

This book is a compendium of papers presented at the ASTM symposium on evaluation of wear testing. The purpose of these presentations is to promote the development of test methods and procedures for equipment and to evaluate their relation to service performance of the equipment. The topics included are modes of wear and their controlling factors; wear research in Europe; wear and friction of nonmetallic materials; abrasive wear; abrasive wear of ferrous materials in special operations; and some applications of wear testing technology.

#### "Physics of Failure and Accelerated Testing"

G. E. Best, G. R. Bretts, and H. M. Lampert

Electro-Technology

October 1965, pages 81-92

Experiments and tests conducted to determine the reasons for certain modes of component failures lead to consideration of the structure and composition of materials. Accelerated testing of equipment and components provides useful data.

#### "Accelerated Gear-Life Tests"

E. K. Buckingham

Machine Design

July 25, 1974, pages 87-91

Accelerated life tests cannot replace long-term testing for determining all desired design performance information. However, a combination of material tests and accelerated life tests, with the material tests guiding the life tests, can yield relatively quick, inexpensive predictions of gear-drive life.

#### "Application of Pulse Testing for Determining Dynamic Characteristics of Machine Tools"

I. E. Morse, W. R. Shapton, D. L. Brown, and E. Kuljanic

University of Cincinnati, Cincinnati, OH

(Paper presented at 13th International Machine Tool Design and Research Conference, University of Birmingham, Birmingham, England, September 1972)

"The theoretical relationships between  
the time response of a structure to an input

pulse and the dynamic characteristics of the structure have been known. However, recent improvements in transducers and in data acquisition and computing equipment have occurred which make pulse testing a practical method for determining the dynamic characteristics, frequency response and mode shapes of machine tools.

"This paper presents several pulse test applications and correlations relating pulse test and sinusoidal test results on machine tools and structures. The development of special techniques for pulse testing are also discussed." (Authors)

## APPENDIX F

### FAILURE SIMULATION TECHNIQUES

#### A Survey of Maintenance Models: The Control and Surveillance of Deteriorating Systems

W. P. Pierskalla and J. A. Voelker  
Northwestern University, Evanston, IL  
Technical Report TR-1  
February 1975, AD/A-007 564, 77 pages

"The literature on maintenance models is surveyed. The focus is on work appearing since the 1965 survey, 'Maintenance Policies for Stochastically Failing Equipment: A Survey,' by John McCall and the 1965 book, The Mathematical Theory of Reliability, by Richard Barlow and Frank Proschan. The survey includes models which involve an optimal decision to procure, inspect, repair and/or replace a unit subject to deterioration in service."  
(Authors)

#### Maintenance Models for Stochastically Failing Equipment

J. V. Wagner  
Stanford University, Stanford, CA  
Technical Report Number 153  
May 1973, AD-766 805, 121 pages

"Two maintenance models are developed for machines subject to two distinct modes of failure. In the single machine model, the equipment is inspected at discrete time intervals and classified according to its deterioration, positive states representing deterioration towards one mode of failure and negative states towards the other. Transition among states of deterioration is governed by a Markov chain. At each inspection there is the option of replacing the machine at a cost dependent upon the state of the equipment. If no replacement is made, an operating cost, also state dependent, is charged. Sufficient conditions on the Markov chain and the replacement and operating costs are developed which guarantees the optimal maintenance policy minimizing total discounted and long run average costs is a control limit replacement rule: Replace the machine if and only if its state is higher than a designated positive state or lower than a designated negative state.

Characterization of the optimal policy allows for efficient computation through linear programming. A parametric linear programming analysis indicates how the policy varies with different costs.

"A multicomponent system in which different maintenance procedures can be assigned to individual components is also formulated. Factorization of the system into individual single component systems enables one to formulate optimal control limit maintenance rules for each component." (Author)

Users Manual: Generalized Effectiveness Methodology (GEM)  
Naval Material Command, Washington, D.C.  
Publication NAVMAT P-3920-3  
October 1973

"GEM was developed to permit ease and rapidity of probabilistic analysis of complex systems characterized by on-line repair capability with limited resources, long mission times, and extensive redundancy. These characteristics generally lead to a more complex system model when one recognizes the possibility that a system may be restored to its full capability while a mission is in process. Ignoring this possibility generally results in an unduly pessimistic estimate of system mission reliability. However, the computations required by this more complex system model are prohibitive for systems of any degree of complexity unless machine methods are employed. GEM was developed so that the system models incorporating these important factors can be computerized and exercised with minimal effort on the part of the user.

"In the past problems incorporating these factors were modeled and solved by using Monte Carlo simulation techniques, which can only approximate solutions, and which required long computer running time for long missions. GEM, on the other hand, is an analytical tool which provides the systems Reliability/Maintenance/Availability analyst with the means to analytically model a complex system against equally complex multi-phase mission scenarios and to perform sensitivity analyses quickly and economically under dynamically changing mission revisions,



system design configurations, changes in failure definitions, and trade-off studies."  
(Authors)

"Analyzing Performance Through Maintenance Management"  
A. J. DiPalo  
Naval Engineers Journal  
August 1971, pages 25-32

"The performance of a total system, conventional or otherwise is of vital importance to both commercial and military systems planners. Their prime objective among others is to provide assurance that an adequate level of systems performance will be maintained on random demand, on an efficient, reliable and economic basis under both normal and emergency conditions.

"Since today's systems are generally complex and costly, it is a natural desire on the part of all concerned to maximize the system's availability during the intended useful life period of operation.

"This paper discusses an analytical approach which provides as an output system availability as a measure of performance. It permits one to study the effect(s) that various systems configurations and constraints have on performance without actually building any hardware. This in turn allows the planner alternative choices for consideration in reaching decisions for selecting the best action. It also follows that in the development process defining the model completely is not easy. The reason in part is that one must use logic, probability and value to achieve the desired objectives and as such is completely dependent on the analyst and the degree of sophistication in development." (Author)

Maintenance, Replacement, and Reliability  
A. K. S. Jardine  
A Halsted Press Book, John Wiley & Sons, New York  
1973, 199 pages

This book details the procedures for putting the maintenance of industrial equipment on a systematic and quantitative basis. It accomplishes this by applying the concept of optimization to the solution of mathematical models constructed to represent situations in the maintenance, replacement, and reliability of

of equipment. Economically, the subject is of great importance. The essence of the book is a number of maintenance models presented for evaluation. Such situations include replacement intervals, preventative replacement, frequency of overhaul and repair, optimal design and redundancy, and scheduling of maintenance procedures.

On-Line Diagnosis of Unrestricted Faults

J. F. Meyer and R. J. Sundstrom  
University of Michigan, Ann Arbor, MI  
Report NASA-CR-139375  
1974, N74-29529, 35 pages

"A formal model for the study of on-line diagnosis is introduced and used to investigate the diagnosis of unrestricted faults. Within this model a fault of a system  $S$  is considered to be a transformation of  $S$  into another system  $S'$  at some time  $\tau$ . The resulting faulty system is taken to be the system which looks like  $S$  up to time  $\tau$  and like  $S'$  thereafter. Notions of fault tolerance and error are defined in terms of the resulting system being able to mimic some desired behavior as specified by system  $S$ . A notion of on-line diagnosis is formulated which involves an external detector and a maximum time delay within which every error caused by a fault in a prescribed set must be detected.

"The set of unrestricted faults of a system is defined to be simply the set of all faults of that system. It is shown that if a system is on-line diagnosable for the unrestricted set of faults then the detector is at least as complex, in terms of its state set size, as the specification. Moreover, this is true even if an arbitrarily large delay is allowed in the diagnosis. The use of inverse systems for the diagnosis of unrestricted faults is considered. A partial characterization of those inverses which can be used for unrestricted fault diagnosis is obtained." (Authors)

On-Line Diagnosis of Sequential Systems: II

R. J. Sundstrom and J. F. Meyer  
University of Michigan, Ann Arbor, MI  
Report NASA-CR-139372  
July 1974, N74-29535, 159 pages

"This report describes an investigation of theory and techniques applicable to the on-line diagnosis of sequential systems.

"With decreasing cost of logic and the increasing use of computers in real-time applications where erroneous operation can result in the loss of human life and/or large sums of money the use of on-line diagnosis can be expected to increase greatly in the near future. The importance of this area along with the relative lack of theoretical results is our motivation for initiating this study of on-line diagnosis.

"The purpose of this investigation is to further the currently insufficient store of information on the subject of on-line diagnosis. The formal approach taken in this report leads to a fuller understanding of current on-line diagnosis practices and suggests generalizations of known techniques. It also provides a framework for evaluating the advantages and limitations of the various on-line diagnosis schemes." (Authors)

Methods of Simulating Dimensionless Wear of Machine Parts Subject to Friction

S. S. Slobodyannikov and L. S. Slobodyannikov  
Foreign Technology Division, Wright-Patterson AFB, OH  
Report FTD-HT-23-64-71  
February 1971, AD-727 209, 7 pages

"This article outlines a procedure for calculating the wear of experimental friction couplings; the method is based on certain positions of technical cybernetics and 'black-box' strategy. The indicated procedure makes it possible to predict wear in the absence of information about physical and chemical processes in the contact zone." (Authors) Translated from Russian.

Cybernetic Diagnostics of Mechanical Systems with Vibroacoustic Phenomena

K. M. Ragul'skis, Editor  
NASA, Washington, DC  
Report NASA TT F-14,899  
June 1973, N74-29785, 292 pages

"The 86 articles and abstracts include 23 on measurement and analysis of vibroacoustic phenomena to diagnose condition of gear transmissions of mining machinery, excavators, tractors, and other equipment, bearings, aircraft skin panels, tape, wire and electrostatic recorder feed mechanisms,

textile machinery, automotive engines, aircraft jet engines, stressing data analysis by computer, band filters and reference spectra. Measuring systems and equipment, laboratory studies of vibroacoustics of equipment and structures, laboratory studies of vibroacoustics of equipment and structures, measuring equipment accuracy and damping are discussed. Theoretical studies are presented in detail, or are summarized, including computer programs, algorithms for determination and analysis of processes, systems and phenomena, theoretical calculations of optimum systems, units and measurements and vibration and noise damping." (Authors)  
Translated from Russian.

"Mechanical Impedance Concepts"

K. N. Fieldhouse  
Instruments and Control Systems  
December 1970, pages 75-80

"Mechanical structures can be studied in terms of applied forces and resultant displacements or velocities at the site of force application or at any other location of interest. System transfer functions can be synthesized from measurements of these variables and used as models to describe or predict behavior." (Author)

## APPENDIX G

### SYSTEMS INTEGRATION TECHNIQUES

#### Ship Overhaul and Maintenance Study: Application of Performance Monitoring Techniques to Shipboard Equipment

Harbridge House, Inc., Washington, D.C.

Contract N00014-73-0279

May 1973, AD-910 422L, 38 pages with 2 appendixes

Ship overhaul and maintenance study is an examination of alternative approaches to Navy ship overhaul. It seeks to identify that policy or combination of policies and practices by which overhaul cost, operating cycle, and material readiness are balanced.

This report is an analysis of performance monitoring and its influence on cost and frequency of ship overhaul. The Navy's current performance monitoring programs vary in emphasis that each gives to different aspects of the overhaul. It is sometimes regarded as being principally a preoverhaul or yard availability check to reduce ship overhaul cost. The employed monitoring techniques can be used to avoid unnecessary equipment disassembly during overhaul. It also can be used as a tool to plan when maintenance work and overhauls are necessary. This principle can be extended to built-in systems making performance monitoring an integral part of the ship's overall support plan.

#### An Overview of Current Ship Auxiliary Machinery Monitoring Programs

R. Y. Chapman

Naval Submarine Support Facility, New London, Groton, CN

April 1974, NAVSHIPS Work Request WR-4-5604

This technical note provides an overview and summary of the current ship auxiliary machinery performance monitoring programs. An important evaluation consideration should be the recognition of where the monitoring is accomplished: laboratory, shipyard, or onboard by ship's force.

#### "Test Approach to Machinery Condition Analysis"

M. Welling and S. N. Kutufaris

Naval Engineers Journal, Volume 86

February 1974, pages 65-70

"This paper deals with machinery condition analysis techniques that have been used on selected Navy surface ships; in particular with those of performance and vibration measurement. When properly applied and interpreted by knowledgeable engineers, they can provide surprisingly accurate diagnosis

of defects and deficiencies in operating equipment such as pumps, compressors, turbines and gears. Use of such techniques can lead to extension, and in some cases, elimination of regularly scheduled overhaul periods. Further potential is discussed in regard to development of instrumentation and techniques that are within the capability of ship personnel." (Authors)

"USS KITTY HAWK (CV-63) Ships Force Machinery Condition Analysis Pilot Program"

W. G. Young

Naval Ship Engineering Center, Philadelphia, PA  
Trip Report 6762:WGY/9870/CV-63(FT-4159)/Ser 331  
April 1974, 10 pages

This report details the techniques, successes, and shortcomings of a pilot program for monitoring condition of ship-board machinery by ship's force personnel on CV-63. Machinery repair decisions were based on trend line shape and the relation to the specified limits rather than data with high variance. The ship's force is convinced of the system's effectiveness and is applying a great deal of effort in implementing the program.

"Status of Surface Ship Vibration Analysis Program"

Naval Ship Systems Command, Washington, D.C.  
Letter 0454/JPG/Ser 502  
4 June 1974

This letter with its enclosure, Vibration Monitoring System Implementation Plan and Equipment Specifications, explains the formulation and organization of a Surface Ship Vibration Analysis Program to be implemented in the Fleet. Such a program will be similar to the Ship's Force Machinery Condition Analysis Pilot Program on CV-63; it will be extended to all rotating machinery, both resiliently and nonresiliently mounted, main propulsion equipment, and auxiliary supporting equipment.

Mission Concept Studies: Phase A of Concept Formulation for Central Automated Support System

G. Neumann

Naval Ship Systems Command, Washington, D.C., S46-23, Preliminary Report  
November 1967

This report introduces the requirements for means of determining a ship's operational readiness and its restrictions at any given time. Engineering and maintenance personnel, along with operation personnel, must have status information that they use for each system in their determination of the control or maintenance actions that need to be taken. The report details the concept of a centralized automated support system that would greatly alleviate problems associated with the keeping of engineer-

ing logs and the personnel evaluation and assessment of them. Included are information requirements, subsystems to be monitored, parameters to be monitored, and existent situations for support of electronic, electrical, machinery, and ordnance systems. System configuration and channel performance; failure prediction and fault isolation; and failure reporting, and logistics information are also provided.

Development of Centralized Automatic Test Systems at NELC,  
Volume 1: Proposed System Configurations

Equipments Effectiveness Division

Naval Electronics Laboratory Center, San Diego, CA

Report 1597

November 1968, AD-848 850, 44 pages

"This volume is concerned with major system elements of the overall Centralized Automatic Test System (CATS) development, including computer and mass-memory configuration. Specific recommendations for CATS configurations are made for various applications. As a result of laboratory experimentation, hardware and software development, and test and evaluation results.

"CATS configurations for a small ship (DE) and for a large ship (CVA) are recommended." (Authors)

Development of Centralized Automatic Test Systems at NELC,  
Volume 2: Prime Equipment Sensors and Signal Conditioning

Equipments Effectiveness Division

Naval Electronics Laboratory Center, San Diego, CA

Report 1598

November 1968, AD-865 116, 28 pages

"This volume of the series is concerned with prime equipment sensors and signal conditioning. This report describes development of suitable sensors to enable the CATS Mod 0 to monitor five electronic prime equipments and four mechanical systems. Experience was gained in the application of a variety of passive and active sensors for monitoring both electronic and mechanical shipboard equipment." (Authors)

Development of Centralized Automatic Test Systems at NELC,  
Volume 3: Data Acquisition

Equipments Effectiveness Division

Naval Electronics Laboratory Center, San Diego, CA

Report 1599

February 1969, AD-850 773, 20 pages

"This volume is concerned with data gathering and conversion. The report con-

cludes that CATS data-gathering circuitry ideally should be built into prime equipment, and recommends development of a monolithic large-scale-integration (LSI) metal-oxide-semiconductor (MOS) parameter-to-pulse-width converter and an extended-range LSI MOS multiplier for use in CATS implementation." (Authors)

Development of Centralized Automatic Test Systems at NELC,  
Volume 4: Operational Program  
Equipments Effectiveness Division  
Naval Electronics Laboratory Center, San Diego, CA  
Report 1601  
February 1969, AD-853 867, 34 pages

"This volume is concerned with the operational program. It provides a complete technical disclosure of the eight program branches and a brief description of Mod 0 hardware.

"The Mod 0 CATS is in development, and the program is not final, but a current version exists which is nearing completion, and it is presently debugged and running."  
(Authors)

Development of Centralized Automatic Test Systems at NELC,  
Volume 5: Data Dissemination and Display  
Equipments Effectiveness Division  
Naval Electronics Laboratory Center, San Diego, CA  
Report 1602  
November 1969, 21 pages

"This volume of the series covers development of devices for the dissemination and display of information being collected and processed by CATS: page print-out, digital readout, illuminated indicators, CRT, remote status panel, and auxiliary test unit equipment. The devices have been placed in service in the CATS Mod 0 test installation, and experience with them has led to suggestions for modifications and improvements which are to be included in specifications for the CATS Mod 1 system." (Authors)



Development of Centralized Automatic Test Systems at NELC,  
Volume 6: Technical Evaluation of CATS Mod O  
Performance Monitoring Systems Division  
Naval Electronics Laboratory Center, San Diego, CA  
Report 1603  
September 1970, 82 pages

"This volume of the series covers a laboratory evaluation at NELC and a development assist aboard USS NORTON SOUND (AVM-1).

"The laboratory evaluation covers operator control, data-gathering rates, performance monitoring and fault location prediction, reliability, maintainability, operability, and personnel skills required.

"CATS is shown to have considerable promise in performance monitoring and fault location for both electronic and nonelectronic systems." (Authors)

The Norton Sound, a converted seaplane tender, is classified as a guided missile ship, Norton Sound Class.

Integrated Automatic Test System (IATS) for the Undersea Long-Range Missile System (ULMS): Preliminary Requirements Report (U)  
F. J. Zupan  
Naval Electronics Laboratory Center, San Diego, CA  
Report B4D07C1A-1  
December 1971, 136 pages, unclassified

"This report provides preliminary specification data for a computer-controlled Integrated Automatic Test System (IATS) for the Undersea Long-Range Missile System (ULMS). The IATS will provide on-line performance monitoring, advance fault prediction and corrective fault isolation data for selected system/equipments (electronic, mechanical, hydraulic) aboard the ULMS. The IATS will also interface with other ULMS monitoring systems (such as safety, noise and vibration) to acquire summary type data. IATS will then present related integrated data displays where required.

"The material in this report is preliminary and in some areas general in nature. Selection of the system/equipments to be monitored was not a part of this task. System concepts, philosophy and general requirements have been developed using the

information available and reasonable assumptions. Final IATS specifications will be developed at a later date as another task."  
(Author)

Noise/Vibration Monitoring System Requirements for an ULMS-Type Submarine (U)

L. Strauss  
Naval Undersea Research and Development Center, San Diego, CA  
Report NUC 603-0-122  
November 1971, AD-519 609, 15 pages plus appendixes  
(Text is Confidential)

"(U) This study describes the requirements for a noise-vibration monitoring system for an ULMS-type submarine and an approach toward satisfying these requirements. The 640-Class machinery complement and data has been used for this study since the ULMS machinery complement is not yet defined. A Noise-Vibration Monitor Analyzer (NVMA) program, sponsored by NAVSHIPS 037, is presently underway at NUC. An assessment is made in this study of the capabilities of the NAVSHIPS program relative to satisfying the ULMS requirements. Identification of further areas of effort required for the ULMS program are outlined." (Author)

Final Design for Noise-Vibration Monitor Analyzer (U)

H. L. Smith  
Naval Undersea Research and Development Center, San Diego, CA  
Document 603-022  
May 1972, 79 pages  
(Text is Confidential)

"(U) This document presents the final design for the Noise-Vibration Monitor Analyzer (NVMA), which is an engineering system for evaluating the concept of an automated noise and vibration monitoring system. The design presented herein incorporates proven commercially available components providing high reliability, low maintenance and large flexibility while maintaining a state-of-the-art capability. This design of NVMA is configured to support the monitoring and analysis functions and should not be misconstrued as the detailed design for a production system. It is anticipated that the production units will utilize miniaturization techniques, meet all applicable Military Standards as well as utilize more sensors.

"(U) Included in this design report is a documentation of the NVMA system operational concepts, hardware implementation, and the performance characteristics and specifications of the selected components."  
(Author)

Study Report on Integrated Machinery Automation Concept (IMAC)  
Aerospace Systems Division  
RCA/Government and Commercial Systems, Burlington, MA  
Contract No. N00017-73-C-2404  
May 1973, 37 pages

"An Integrated Machinery Automation Concept (IMAC) was conceived to monitor and control the propulsion, steering, electrical and auxiliaries subsystems. This was based upon the data bus concepts and applicable hardware designs of the Operational Readiness Test System (ORTS) developed as part of the AEGIS program. Work was directed to provide a system concept including functional diagrams, data processed, and modes of operation. A system description, which described the functional attributes of major hardware assemblies, required processor software, reliability, availability and risk assessments, and additional applications of the concept were also prepared." (Authors)

R A Proposal: Shipboard Machinery Performance Monitoring System\*  
Government Communications and Automated Systems Division  
RCA/Government and Commercial Systems, Burlington, MA  
Proposal DSG 74-588-024  
May 1974, 31 pages, one appendix

This proposal submitted to the Machinery Systems Department, Naval Ship Engineering Center, Philadelphia Division, describes an effort to develop requirements, concepts, specifications, a test plan, and costs and schedules for a complete machinery monitoring system for the FFG-7 class ship.

\*"RESTRICTION ON DISCLOSURE OF DATA"

This data furnished herein shall not be duplicated, used or disclosed in whole or in part for any purpose other than to evaluate the proposal provided, that if a contract is awarded to this offeror as a result of or in connection with the submission of such data, the offeree shall have the right to duplicate, use or disclose this data to the extent provided in the contract. This restriction does not limit the offeree's right to use information contained in such data if it is obtained from another source."

The distribution of this proposal is restricted; it contains proprietary information.

Final Report: Propulsion Monitor and Display System Requirements Study

L. J. Veerkamp, Electro-Mechanical Division  
Northrop Corporation, Anaheim, CA

Report No. 69Y168

October 1969, 3 Volumes, Contract No. N00024-69-C-5250

"This report presents the results of a study to determine the feasibility of, and requirements for, a propulsion monitor and display system for the DE 1078 class ships, and to investigate the application of TEAMS (Test Evaluation and Monitoring System) for such purpose. The primary objectives of the monitor and display system are to reduce the visual monitoring burden of the ship's engineering staff, increase monitoring effectiveness, and present to command a measurement of ship's readiness by accurate and timely information on plant performance.

"The report presents the means of defining and justifying the monitor and display requirements for the DE 1078 class power plant through an analysis performed on the man, machine, and the man-machine interface. Since the power plant equipment and manning requirements are defined, the area where improvement can be realized is at the man-machine interface. Since proper operation of the overall power plant cannot always be determined from subsystem or component performance, an approach to check the overall power plant performance and thus determine by a separate means if the major components and subsystems are operating properly, is presented." (Author)

Propulsion Monitor and Display System Configuration, Phase II Study, Final Report

Electro-Mechanical Division  
Northrop Corporation, Anaheim, CA

Report No. 70Y331

12 March 1971, 2 Volumes, Contract N0024-70-C-5459

"This document presents the final report on the study to perform a detailed engineering analysis of the DE 1078 class propulsion plant. The purpose of the study was to define the monitoring requirements for the plant and to formulate a propulsion monitor and display system configuration.

"Two important objectives of the program include

- Improving the ship's operational capability by reducing maintenance downtime and increasing equipment reliability by providing a rapid indication of malfunction/maloperation.

- Providing sufficient monitoring system growth potential by employing a building block technique. A follow-up effort could further aid ship's personnel by providing control of critical functions, such as casualty switching, or even complete automatic control of the engineering plant."  
(Authors)

"Vibration Analysis and Deviation Concept"

C. B. Dickinson  
Naval Engineers Journal  
April 1972, pages 86-92

"The Maritime Administration (MARAD) has for several years been involved in research to find methods of analyzing and reducing the maintenance costs associated with the operation of ships. The Vibration Analysis and Deviation Concept (VIDEC) is an experimental system of process analysis. It is composed of two techniques: vibration analysis of rotating machinery and thermal analysis of the heat cycle of the power plant. Both use the deviation concept in introducing the results of the analysis. VIDEC can be defined as a real-time, computerized implementation of the deviation concept, in the form of heat cycle and vibration analysis. Deviations from a baseline value of the selected parameters are sensed, processed, stored, and displayed for use by the ship's operating personnel in determining the deterioration in machine condition as well as plant performance." (Author)

"The Deviation Concept: A Tool for Preventive Maintenance of Marine Power Plants"

A. R. Kramer, J. Mathieson, S. Pergament, and N. Gleicher  
Marine Technology  
October 1972, pages 405-418

"This paper describes a new computerized maintenance management system aboard ship, using a continuously monitoring refer-

ence comparison technique (deviation concept). Some detailed design goals and expected results are outlined. Appendices contain some details of the machinery lists, instrumentation installation, and analysis of equipment using this concept. Future uses of the system are described." (Authors)

"A Method of Propulsion Plant Performance Evaluation for Marine Applications"

C. B. Dickinson

IEEE Transactions on Industry Applications, Volume IA-10,  
Number 2

March/April 1974

"A performance evaluation system for a steam-propelled merchant ship is described which utilizes a general-purpose computer for data acquisition and analysis. The performance of the steam plant on the ship's maiden voyage is used as the performance baseline and subsequent evaluations are references to this baseline. The diagnostic and prognostic capabilities of the system are presented in a description of the graphical display of the historical and real time data. The operating costs of the vessel are reduced since effective maintenance planning and scheduling can be accomplished resulting in greater ship availability." (Author)

"VIDEC Ship Propulsion System Performance Monitor"

R. P. Wallace, Raytheon Co., Portsmouth, RI

W. L. McCarthy, McCarthy Marine & Ocean Engineering Associates  
(Paper presented at 22nd Meeting of Mechanical Failures Prevention Group, Anaheim, CA, April 1975)

"The vibration deviation concept VIDEC, a computerized performance monitoring and failure prediction system, is presently operating on the SS PRESIDENT JOHNSON. This interim report is an attempt to document the history of an R&D system from its hardware development phase through its software modification, in-plant simulation, shipyard installation, up to and including initial shipboard operation. A brief system description including system concepts is presented. The paper concentrates on the system implementation, installation and initial operation. A discussion of types of data and concepts being evaluated and the methods of evaluation used is presented.

"The paper closes with a discussion of the VIDE~~C~~ system and concept as it relates to other possible shipboard automatic systems and programs. Finally, conclusions and recommendations are presented." (Authors)

Final Report for Machinery Monitoring and Analysis Study Project  
Raytheon Co., Submarine Signal Division, Portsmouth, RI  
Report Number RI449, Contract N00024-74-C-1234  
11 November 1974, 107 pages

"The number of engineering personnel available to the Navy has progressively decreased. This has resulted in the decline of material readiness in the ship's machinery. One approach being taken to offset this deteriorating condition is to determine the practical application of modern machinery condition monitoring and analysis techniques to improve shipboard maintenance practices. The improvements would include alarms when machinery operating thresholds are exceeded, trends-to-failure predictions, and indications of normal conditions thus eliminating the need for scheduled tear-down inspections. The initial approach has been to direct a study to select a limit set of maintenance intensive machines from the DE 1052 class main and auxiliary plants, and to then design a monitoring and analysis system suitable to instrument the selected machines during an evaluation period on a DE 1052 class ship. MATERIAL HISTORY, CASREP, DART Tracking, and MRC data provided by the MSO, Mechanicsburg, Pa., were used to select the following machines:

- SSTG
- Main Feed Pump
- Fire Pump
- LP Air Compressor
- HP Air Compressor
- Main Condenser
- Distilling Plant.

"Research of industry and Navy machinery monitoring programs provided design criteria

for both an automated and an alternative manually-operated monitoring and analysis system for evaluation in a recommended nine-months (sic) period." (Authors)

Distribution of this document may be limited.

"Economical 'Mini-Computer' for Machinery Monitoring Duties"  
Editorial Staff  
Shipbuilding and Shipping Record, Volume 116  
4 December 1970, page 39

Towards the objective of a completely unmanned, automated engine room, a fixed-memory computer was installed in the ore carrier NIHATA MARU. The system will provide continuous-trend monitoring of 75 operational variables including ship's speed, steering movements, meteorological data, hull condition, and machinery performance. The results of measurements made over the period of a year will be analyzed to establish standard values and tolerances for on-line process control of the machinery. The diesel engine room can already be run on a periodically unmanned basis; once the standards and base line operation are established, the goal of a completely unmanned engine-room will be pursued.

"The Computer System for Engine Monitoring and Control Aboard 'Hoega Multina'"  
M. Langbelle  
Shipping World and Shipbuilder, Volume 165  
April 1972, pages 486-490

The system, which is installed in the HÖEGH MULTINA, consists of two main parts, the EO-system and the preventive maintenance system, and is served by two small process computers, PAC and DAC.

PAC performs the monitoring, the process control, and a preliminary evaluation of the main engine's condition. DAC performs further calculations of process parameters and evaluation of data from special instrumentation; it also acts as a standby unit for the PAC computer. There is no conventional automation as backup, and in case of failure, monitoring and control must continue manually.

The main functions of the DAC are turbocharger evaluation, cylinder monitoring, analog data presentation, and reports on engine condition including trend data. Measured values are called by means of a pushbutton panel and presented on digital displays or printed on teletype.

Block diagrams of the system and subsystem for main engine monitoring and component checks are presented. The complete computer hardware system is also described and shown schematically.



"Condition Monitoring of Marine Propulsion Machinery"

R. K. Knudsen  
Veritas, Volume 19  
August 1973, pages 8-10

The principles of various methods of machinery condition monitoring are briefly explained, and some examples are given of how these methods have been applied to the diagnosis of faults in various types of propulsion systems. The requirements of instrumentation systems are discussed in relation to maintainability and cost. The microprocessor technique is suggested as the most effective condition monitoring system presently available for large-bore diesel engines, and the development of similar systems for steam propulsion machinery is in hand. Diagrammatic details of new sensors developed for the computer instrumentation system of the gas carrier HÖEGH MULTINA are included.

"'Thorsholm' - First Ship With DataChief"

Editorial Staff  
Shipbuilding and Marine Engineering International, Volume 96  
August 1973, pages 652-653

The diesel-engined tanker THCRSHOLM is the first merchant ship to be equipped with the Norcontrol DataChief computerized engine room system. This consists of a family of subsystems for automation and maintenance predictions. The subsystems installed are DataSafe, DataPower, AutoChief II, and DataTrend.

DataSafe is a watchkeeping and monitoring system for periodically unmanned engine rooms; its capabilities include checking the engine room state on changeover from manned to unmanned operation. DataPower monitors, controls, and logs the electrical generating system. AutoChief II is a bridge-control system for the main machinery, and embodies engine-protection arrangements.

The DataTrend plant-condition system continuously monitors the state of certain engine components. It monitors the thermal loading of the cylinders and predicts when maintenance work should be done, the computer compares actual with ideal performance. The system predicts by employing linear least-square regression on successive present-condition parameters and incorporates a procedure for checking the influence of changes in external conditions. DataTrend will also simulate the effect of overhauling specific components when there is not enough time to overhaul others and can maintain a watch on combustion, fuel injection, piston ring and valve behavior, liner wear, and even hull fouling.

"Swedish Design of Combined Analog and On/Off Alarm System for Machinery Monitoring"

Editorial Staff  
Motor Ship, Volume 54  
February 1974, page 549

A monitoring system that is simple and easy to maintain is type KL-1 unit manufactured by Netzler and Dahlgren Co. of Gothenburg, Sweden. The KL-1 alarm system installed in the

world's largest dry-cargo vessel, the SVEALAND, can supervise 270 alarm parameters from the main control console. This system is an on/off status monitor and analog parameter-signal monitoring type. The equipment consists of a number of identical cassette modules, each containing a group of alarm channels. A digital panel meter arranged with automatic decimal setting, located in a common central unit, displays the monitored analog parameter values and associated alarm levels. The cassette modules can be flush-mounted or designed as a separate cabinet for connection to other readout display panels or other optional arrangements. A high degree of monitoring system reliability has been achieved.

Definition of Terms for Automatic Electronic Test and Checkout  
Military Standard 1309A  
12 April 1972

"The application of Automatic Electronic Test and Checkout Equipment requires the establishment of a method of communication to ensure that coordinated thinking is applied. Key words and terms more commonly used are defined in this standard."

Policy and Responsibility for Automatic Test, Monitoring and Diagnostic Systems and Equipment; Implementation of  
Chief of Naval Material  
NAVMAT Instruction 3960.4A  
26 December 1973

"This instruction implements the policy established by SECNAVINST 3960.4, establishes CNM guidelines and direction, and assigns responsibilities within the Naval Material Command for the selection, development, acquisition, standardization, application, and logistic support of all types of automatic and semi-automatic test, monitoring and diagnostic systems and equipment, referred to as ATE."

Data Banks for Automatic Test, Monitoring and Diagnostic Systems and Equipment; Utilization of  
Chief of Naval Material  
NAVMAT Instruction 5230.8  
14 November 1974

"This instruction implements the action required by NAVMATINST 3960.4A to ensure the availability of adequate information for properly selecting, acquiring and applying auto-

matic test, monitoring and diagnostic systems and equipment (ATE). The utilization of information available in ATE data banks will facilitate early, cost-effective acquisition decisions, reduce proliferation and promote standardization of ATE within the Naval Material Command."

"A Look at Automatic Testing"

H. T. McAleer  
IEEE Spectrum, Volume 8  
May 1971, pages 63-78

"This survey reviews the current state of automation in the testing of electronic components, networks, and circuits. Elements and characteristics of typical test systems, both hardware-controlled and computer controlled, are described. Paths to be followed and pitfalls to be avoided in achieving automation are discussed in an effort to help the reader toward a better understanding of the subject and its broad applications. 'How to automate successfully,' a major theme in the report, places emphasis on economic justification."  
(Author)

"Automatic Testing: Quality Raiser, Dollar Saver"

M. Eleccion  
IEEE Spectrum, Volume 11  
August 1974, pages 38-43

With increasing systems complexity manufacturers have been turning to automatic test systems to ensure product quality. Some techniques, problems, and pitfalls of automatic testing are included. A chronological listing of automatic test equipment for military systems is presented.

"Automatic Test Systems"

K. To and R. E. Tulloss  
IEEE Spectrum, Volume 11  
September 1974, pages 44-52

The seven basic elements that compose the ideal automatic test system are presented. These elements are (1) a data base of parameter behavior, (2) means of process simulation, (3) method of test generation, (4) a test command language and computer program library, (5) the automatic test equipment, (6) a diagnostic technique, and (7) a scheme for data management. An eighth component would be education for planning, implementing, utilizing, and managing automatic test systems.

"Untangle Automatic Test Equipment"

K. To and R. E. Tulloss  
Electronic Design 24  
November 22, 1974, pages 182-186

The authors identify the basic types of automatic test equipment. Fundamentally, ATE hardware can be put into two classes: fixed program and variable, stored program types with combinations or variations of these programs. The versatility of the variable, stored program technique using diagnostic software routines is emphasized for functional testing.

Automatic Test Equipment: Hardware, Software, and Management

F. Liguori, Editor  
IEEE Press, New York, NY  
Book Number 0-87942-049-9  
1974, 253 pages

This book is a compilation of papers and articles concerning automatic test equipment. The material concentrates on seven topics. They are (1) planning, preparing and staffing for ATE, (2) test system concepts and design, (3) test design philosophy and techniques, (4) test languages and program preparation, (5) software tools and techniques, (6) configuration control and management, and (7) a bibliography of related literature on ATE. The emphasis is on military systems' applications, but information for commercial systems' applications is included.

The Automatic Support Systems Symposium for Advanced Maintainability Record

Aerospace and Electronic Systems Group  
Institute of Electrical and Electronics Engineers, New York, NY  
Publication 70C52-AES  
1970

This book is the record of the Automatic Support Systems Symposium presented at St. Louis, MO, October 1970. Significant topics of interest include on-line testing for jet engines and sensor development, military ATE programs, and techniques for data management and dynamic fault detection for automatic support systems.

The Automatic Support Systems Conference '72 Record

Aerospace and Electronic Systems Group  
Institute of Electrical and Electronics Engineers, New York, NY  
Publication 72CHO 699-9 AES  
1972

This book is the record of the Automatic Support Systems Symposium for Advanced Maintainability presented at Philadelphia, PA, November 1972. Relevant papers include an explanation of an RCA built-in test system for Army vehicle readiness, fault isolation in linear systems, a simple infrared testing technique,

data management for ATE, NAVMAT's ATE management office, an ATE data bank, and an ATE support software system.

The Automatic Support Systems Conference '73 Record  
Aerospace and Electronic Systems Society  
Institute of Electrical and Electronics Engineers, New York, NY  
Publication 73 CHO 804-5 AES  
1973

This book is the record of the Automatic Support Systems Symposium for Advanced Maintainability presented at Arlington, TX, November 1973. Important papers included are application of infrared signatures for analysis of digital circuit modules, a design of an adaptable automatic test system, new techniques in ATE for maintenance testing/monitoring, the documentation impact on ATE, and technical management techniques for large-scale automatic test systems.

The Automatic Support Systems Conference '74 Record  
Aerospace and Electronic Systems Society  
Institute of Electrical and Electronics Engineers, New York, NY  
Publication 74CHO 891-2 AES  
1974

This book is a record of the Automatic Support Systems Symposium for Advanced Maintainability presented at San Diego, CA, October 1974. Significant papers of interest are the Navy's Systems Test Equipment Program as a solution to ATE problems; a practical technique to estimate MTBF, MTR, and availability of complex, maintained systems; the status of automatic test equipment standards; advances in system software languages, computer maintainability concepts; system self-repair utilizing multimicroprocessors; advanced built-in test equipment concepts; employing microprocessors for test controller design; secondary effect sensing techniques for ATE and diagnostic systems; using automatic support systems for energy resource management; the automation of the Navy's standard measurement technique for ship and depot applications; and a historical evaluation of ATE.

Test Points, Test Point Selection and Interface Requirements for Equipments Monitored by Shipboard On-Line Automatic Test Equipments  
Military Standard 1326 (Navy)  
15 January 1968/1 April 1969

"This standard establishes the requirements for providing test points in prime equipments for monitoring by on-line Automatic Test Equipment (ATE). It provides criteria for guidance in optimum test point selection. It defines interface and data requirements, a system of test point data

generation, and procedures for submission of data disclosing the selections of these test points."

"An Automated Ship Maintenance System"

G. L. Steckman

Naval Engineers Journal

April 1973, pages 23-32

"Any shipboard computer system meets its system objectives only when it is totally operational. When it is down due to system failure it is a useless collection of electronic components. In present and future ship computer systems, maintainability is not only desirable, it is mandatory. Also system maintainability must keep pace with the increased sophistication and complexity of the systems themselves.

"To meet this maintainability requirement, system designers must consider system maintenance at the time of system design and development. In the philosophy of an automated maintenance system such as the one discussed in this paper, the system design and development process is geared to making all operating system information, which could be used in system maintainability, available in an orderly meaningful manner. This process means designing the system software to monitor system status and performance data, to use this data along with preventive maintenance scheduling and fault prediction analysis in performing total system evaluation. This evaluation process then results in the definition of recommended preventive testing or the required fault detection and isolation testing. During the latter stages of fault isolation testing and continuing through fault correction, the system is also responsible for making the available reconfiguration recommendations for the failure being corrected.

"Following the correction of a system failure the system is automatically reconfigured to the normal operating system. Data appropriate to the system failure is categorized and recorded to be used in future fault prediction and preventive maintenance scheduling.

"All of this occurs in real-time and on-line, in conjunction with the normal operation of a system program. This capability is provided for during the software design period. While not totally automatic or totally comprehensive, it provides maintenance personnel with the information required to determine what is happening within the system. This data combined with other features mentioned greatly reduces the essential and critical tasks of the maintenance personnel. Finally the entire process results in the required expansion of critical system availability."  
(Author)

"Operational Readiness Monitoring System Program Plan"  
J. G. Kammerer  
Naval Electronics Laboratory Center, San Diego, CA  
Code 4050 Technical Memo ORMS-M-5-75  
10 March 1975

"Operational Readiness Monitoring System (ORMS) is defined as a system for automatically acquiring, processing, and presenting operational readiness data to afloat command authority. Current emphasis on minimum maintenance manning for new ships requires some degree of automation. CRMS is a means for: (1) reporting status rapidly so that command is aware of the 'health and condition' of the ship; (2) identification of failed or degraded units; (3) decreasing PMS check man hours; and (4) reducing ship turn-around time.

"Inherent benefits include positive contributions to improved combat effectiveness and maximum operational availability. Presentation of such command-assist information in real time will directly support the command control decision-making process and is invaluable in meeting critical response times so necessary for mission accomplishment." (Author)

"A Bayesian Analysis of Avionic Subsystem Built-in Test"  
E. C. Harmon  
IEEE Transactions on Aerospace and Electronic Systems  
Volume AES-7, Number 5  
September 1971, pages 982-987

"A major development in test philosophy of aircraft being built today and those being designed for the immediate future is the incorporation of on-board, computer-controlled

'built-in' testing (BIT) into the airplane as part of the avionic subsystem.

"A requirement being imposed by today's specifications is a possibility of 0.95 or better that the BIT function will detect a failure. The discussion presented in this paper will show that a single specification of BIT capability is insufficient to completely define the requirements for BIT. The proof of this conclusion is offered in the form of an analysis of the conditional probabilities involved in the occurrence and reporting of subsystem failures.

"As a result of this analysis it is imperative that the customer be cognizant of the significance of BIT requirements levied on the contractor and that the designer be allowed more latitude in his BIT requirements so that an optimum product will be obtained." (Author)

Fault Detection and Self-Test Systems: A State-of-the-Art Review for Trident Steering and Diving Control Systems Development

L. J. Puckett and C. L. Patterson, Jr.  
Naval Ship Research and Development Center, Annapolis, MD  
Report 27-382  
May 1973, 66 pages

"The state-of-the-art in fault detection systems was investigated to provide guidance for incorporating fault detection and self-test features in the Trident Steering and Diving Control systems. This report summarizes the results of that investigation. Appendixes are included to provide background information on current fault detection concepts, characteristics, techniques, and systems." (Authors)

"Information Requirements for Systems Understanding"

H. Chestnut  
IEEE Transactions on Systems Science and Cybernetics  
Volume SSC-6, Number 1  
January 1970, pages 3-12

"Some significant ways are discussed for describing or identifying systems and systems concepts so that less information is needed to understand them and this information can be communicated more quickly. The three major categories, structure, names of distinguishing qualities, and magnitude, prob-



ability and time, identify the similarities and differences between various systems. Emphasis is put on the possibility that parts of these various systems may be sufficiently similar for detailed and authentic work on one system to be of value for another system. With the advent of large multi-processing computers, such characteristics may result in more efficient use of hardware and software." (Author)

"Electronic Components for Low-Cost Automation"

K. S. Mortimore  
Automation, Volume 9  
February 1973, pages 27-30

Low-cost automation is a technique which essentially comprises the use of smaller, simpler systems utilizing relatively cheap and readily available elements to minimize or even eliminate human effort in certain operations and, in some instances, to make human decisions for control and other purposes. Constructed usually on modular principles, the technique enables the benefits of reduced labor to be achieved with a comparatively modest outlay.

"Microcircuits: The Brain and the Brawn"

D. J. Hoertt  
IEEE Transactions on Industrial Electronics and Control Instrumentation, Volume IECI-22, Number 2  
May 1975, pages 159-163  
(Paper presented at Semiconductor Electronics Devices and Applications Short-Course Conference, IEEE, Cleveland, OH, May 1974)

"For years the semiconductor industry has been building more and more circuits faster and faster. To do the processing job, the computer industry has used these tools to develop bigger and faster computers. The limitations of input and output as well as cost have prevented the small user from taking a computer approach to solving a wide range of commercial and industrial problems. This paper will discuss three new developments in microcircuits which enable the small user to approach these problems in a computer-like fashion. These circuits are the microprocessor, the pressure transducer, and the temperature sensor." (Author)

"Using Integrated Circuits in Distributed Decision"

S. J. Bailey  
Control Engineering  
October 1974, pages 74-77

It is obvious that one man cannot hope to supervise a complex operation unless he has the ability to delegate authority to others. Neither can a computer system control the operations of a plant complex without "delegating" local authority to exercise close supervision over subtle changes in plant response. The concept of distributed decision, applied carefully to process control, can improve throughput economics and quality by reducing signal traffic in the central control area. Proper design of remote decision circuits, taking advantage of integrated circuit hardware now available, will alter conventional plant machinery control.

"Event-Sequence Detector"

Editorial Staff  
Instrumentation Technology  
April 1974, page 49

A disclosure of a NASA patent application, this short article details a circuit that was developed to detect the sequence of a series of failures which occur virtually simultaneously.

"Monitor Circuit Stores Sequence of Alarms"

P. Alfke  
Fairchild Journal of Semiconductor Progress, Volume 3, Number 1  
January/February 1975, pages 18-19

This article shows a practical way to determine the sequence of alarms when several circuits are monitored by a central unit. This system can pinpoint the origin of an alarm or spot the source of a system breakdown, thus saving valuable time and money.

"The Navy Standard Hardware Program"

J. A. Merz  
Naval Engineers Journal  
October 1974, pages 79-91

"The Standard Hardware Program represents the start of an endeavor to standardize the modular building blocks of all Navy solid-state electronic systems. When fully expanded, this vital program will lower the cost and increase the availability of electronic systems for operating forces.

"The administrative, electrical and mechanical principles of the program are explained. It is shown that forecasting and controlling system costs can be simplified

because: (1) the characteristics of the standard modules are known quantities; (2) the designs have been tested; (3) vendors have been qualified; and (4) production costs are known and stable.

"The impact on maintenance and training is discussed as a function of using modules that are inexpensive enough so that they can be economically discarded upon failure. Statistics derived from Fleet operation are shown to illustrate much better than average reliability for the standard modules."  
(Author)

Requirements for Employing Standard Hardware Program Modules  
Military Standard 1378A (Navy)  
14 March 1973

"This standard provides the equipment contractor with specific direction for optimum implementation of Standard Hardware Program (SHP) modules and reduction of system life cycle costs. This standard also provides guidance on the procedures and information on submitting a Design Approval Request for recommending new modules for addition to the list of standard modules."

Design Requirements for Standard Hardware Program Electronic Modules  
Military Standard 1389 (Navy)  
14 March 1973

"The purpose of this standard is to guide contractors and suppliers with respect to the requirements to be considered during the design of new functional modules for use in the Standard Hardware Program (SHP). Modules design in accordance with the requirements of this standard must also meet the requirements of MIL-M-28787."

"Using Computers to Automate Instrument Systems"  
D. G. Dykes  
Instruments and Control Systems  
March 1973, pages 63-64

Automated test equipment has advantages in applications such as functional and life testing of components or measuring response to complex stimuli where considerable amounts of data are amassed and human error may adversely affect results. To overcome such problems, inexpensive, off-the-shelf minicomputers have been employed offering considerable operational capability

with ease of expansion. Several applications of such instrumentation systems are presented.

"Minicomputer Applications in the Seventies"

R. K. Jurgen  
IEEE Spectrum  
August 1970, pages 37-52

Small, programmable digital computers are taking over many of the tasks that previously have been handled by hard-wired logic systems or large, expensive computers. The strength of the minicomputer is in the fact that it is one of the cheapest forms of digital logic available. Several monitoring system applications for "minis" are included.

"The Future with Computer Control and/or Monitoring"

R. H. Eisengrein  
IEEE Transactions on Industrial Electronics and Control Instrumentation, Volume IECI-21, Number 3  
August 1974, pages 111-115

"Evaluating the true worth of computers as applied to assembly machines is a valid quest. Assuming computers have a place in the world of assembly machines, several questions naturally arise and should be pondered: In what areas are they applicable and why?; What is the real worth of computers to assembly machining systems?; What are some of the major conclusions to remember in their application?

"All of the above questions are discussed and case histories cited to provide some answers.

"With assembly machines becoming more complex, end users need all the help they can get in understanding what machine performance really is and how it can be improved. Computer monitoring is a tool which can aid considerably in this task." (Author)

"Technology Update - Computers"

W. B. Riley  
Electronics  
October 17, 1974, pages 70-77

The microprocessor, the culmination of two fast growing technologies: computers and solid state, is bringing automation to new applications and is also being used to further boost the performance of minicomputers. Computer networks are putting pressure on the developers of mass-storage systems, and a major attempt has begun to systematize numerous, varied software approaches.

"Computer Diagnosis of the VW"

R. K. Kaminski  
Instrumentation Technology  
September 1972, pages 60-62

Since mid-1971 all Volkswagens have been equipped for a unique VW computer diagnosis, more than 60 separate checks to determine the condition of a car. Each of these VW's contain sensors and wiring which are connected to a socket in the engine compartment. At a dealer's service center, an umbilical connection cable will tie the VW to a special purpose computer and the approximately 21-minute check-out begins. System hardware and test procedures are explained in the article.

"Minicomputer Controls Temperature-Sampling System"

J. G. Hurt and H. G. Riekers  
Electronics  
November 22, 1973, pages 120-125

This article describes a computerized data collection system that is used to perform a detailed thermal analysis on military equipment. The system gathers analog data from 300 thermistors at sampling rates that vary with rates of change of the individual temperatures and then converts the data into binary numbers for processing and storage in the minicomputer. The system determines mechanical stresses for prototype systems from thermal gradients during temperature cycling.

"Computer Diagnostics Now!"

B. Feinberg  
Manufacturing and Engineering Management, Volume 72, Number 43  
May 1974, page 43

A remote computerized diagnostic system is being used to maintain and repair numerical control machining systems. This new system, similar to the NASA Skylab diagnostic system, substantially improves the dependability and profitability of the complex machines, since 95% of N/C downtime is expended in troubleshooting and pinpointing malfunctions.

"The Transient Monitor - A Minicomputer Application for the Nuclear Power Industry"

J. M. Lovallo  
IEEE Transactions on Industrial Electronics and Control Instrumentation, Volume IECI-22, Number 1  
February 1975, pages 8-10

"The pre-operational testing period at Duke Power Company's Oconee Nuclear Station established a need for a specialized data acquisition system. This system is required to acquire and preserve data for some time period before a transient condition is detected and then provide comprehensive

display facilities for an operator or plant engineer. Such a system has been designed and three units fabricated by the Industrial Systems Section of the Lynchburg Research Center. They are currently undergoing testing at the Duke Power Company Oconee Nuclear Station." (Author)

"Minis Versus Micros: Getting the Right Machine for the Job"  
J. Birkner  
Electronic Products Magazine  
March 17, 1975, pages 45-51

For a specific application, users must decide whether a minicomputer or a microprocessor can best do the job. The question of minicomputers versus microprocessors is broken down into areas covering what each is, what each can cost the user to install, and how costs can be judged against the performance of each.

The Microprocessor Handbook  
Texas Instruments Learning Center  
Texas Instruments Inc., Dallas, TX  
Publication LCBl76J-R, Second Edition  
1975, 225 pages

This handbook is a compilation of video tape, television lectures by TI detailing the foundations and fundamentals of microprocessors in book form. Topics include digital computer system architecture, chip fabrication technologies, potential applications and limitations of microprocessors, chip architecture, designing with microprocessors, a detailed communications application of microprocessors, and appendixes with a review of digital subsystems and a glossary of microprocessor-related terms.

"Primer on Microprocessors" (in two parts)  
Editorial Staff  
Electronic Products Magazine  
January 20, 1975, pages 23-32  
February 17, 1975, pages 37-45

Part 1 of this article describes the basic elements of a microprocessor, tells how a microprocessor functions, and introduces the concept of instructions. It also concludes that microprocessors are computers in IC form, and that the terms "microprocessor" and "computer" can be used synonymously.

Part 2 deals with how to tell the microprocessor what to do. This can be implemented using hardware or software, but defining the solution is the most important and difficult part.

**"Networked Minis and Micros - Configurations, Applications, and Standards"**

T. N. Pyke, Jr.

National Bureau of Standards, Washington, D.C.

(Paper presented at Mini Micro Computer Symposium, U. S. Naval Academy, Annapolis, MD, April 1975)

"Both minis and micros have found their way into extensive use as a part of computer networks. Minicomputers have a head start, but microcomputers will fast catch up in numbers, especially as a part of terminals connected to networks. Mini/micro network configurations can be divided into categories, local and distributed. Most research-oriented and operational networks can be placed directly into one of these categories. Successful development and operation of these networks employing minis and micros requires (sic) a variety of standards, both internally and externally." (Author)

**"Join Micros into Intelligent Networks"**

H. A. Raphael

Electronic Design 5

March 1, 1975, pages 52-57

"Distributed-intelligence systems can be built with the new generation of micro-computers. The computational and control capabilities allow each micro in the network to perform a dedicated task. The overall network can provide hardware and software redundancy at an attractive price, compared with a single large processor. Common-memory software and hardware techniques provide one of the newest ways to handle the necessary intercommunication between sub-systems." (Author)

**"Air Force Wants Standard Microcomputers for Its Aircraft"**

Editorial Staff

Electronics

April 17, 1975, pages 31-32

Since microprocessors are gradually replacing other kinds of logic in military hardware, the U.S. Air Force is exploring a scheme to use them as the main computing resource on its aircraft. It is looking at a standard network of distributed microcomputers for handling avionics and monitoring functions, all interconnected by a large serial data bus.

### "Mini/Microcomputers for Naval Applications"

H. F. Wong

Naval Electronics Laboratory Center, San Diego, CA  
(Paper presented at the Mini Micro Computer Symposium, U. S.  
Naval Academy, Annapolis, MD, April 1975)

This paper presents applications of minicomputers and microcomputers in Navy information systems. Currently, microcomputers do not have total minicomputer replacement capability but with continued progress in LSI technology areas, microcomputers will eventually replace currently available minicomputers. It is also projected that minicomputers will continue to increase their performance capabilities by incorporating improved LSI technology, and they will replace or consolidate with present-day maxicomputers. Both microcomputers and minicomputers are needed for information processing, and design engineers must be aware of the relative merits of each for systems applications. Finally, the electronic modular building block approach will provide the realistic, reliable, economic means for systems design and development.

### "Navy Opportunities for Microcomputers"

W. J. Dejka

NAVSEA Journal

January 1975, pages 26-30

"The Navy will soon see a new component in its shipboard systems that will have a significant impact on system performance, design, and system availability. This is the microcomputer, a small computer developed out of a few integrated circuits. It is indicative of the advance of the large-scale integrated circuit (LSI) microelectronic technology. The microcomputer dissipates little heat and requires little power since it has only a few parts. It is programmable, and will reduce design time, errors, changes, and other design problems. These small computers can be used in many ship applications such as propulsion control, damage control, performance monitoring, and tactical data systems." (Author)

### "Microprocessor Application Onboard Ships"

P. Fredrikson, L. Tønning, and O. Andersen

IEEE Transaction on Industrial Electronics and Control Instrumentation

Volume IECI-22, Number 3

August 1975, pages 337-342

(Paper presented at Annual Meeting, IEEE Industrial Electronics and Control Instrumentation Group, Philadelphia, PA, March 1975)

"Following several research projects with computers onboard ships, the R & D



department in Det Norske Veritas has assisted in development of four different types of microprocessor units for installation on-board ships. These are: condition monitoring unit for diesel engines, condition monitoring unit for mechanical conditions in steam power plants, condition monitoring unit for thermodynamic conditions in steam power plants, and condition monitoring unit for dynamic hull loads. The applications will be presented with a description of history, function, type of sensors, complexity of hardware/software and experience obtained." (Authors)

"System Integration and Testing with Microprocessors: I. Hardware Aspects"

J. Leatherman and P. Burger

IEEE Transactions on Industrial Electronics and Control Instrumentation

Volume IECI-22, Number 3

August 1975, pages 360-363

(Paper presented at Annual Meeting, IEEE Industrial Electronics and Control Instrumentation Group, Philadelphia, PA, March 1975)

"In the development of a microprocessor-based system, component and system checkout becomes a real problem. The microprocessor might be in one integrated circuit package while the random access and read only memories occupy several different circuit packages. The data bits encoded into processor instructions, the data stored in random access memories, and the data from input/output devices all time share the same hardware circuitry. Under these conditions it is nearly impossible to locate a fault or a series of faults using conventional engineering aides, such as oscilloscopes, meters, digital probes, etc. Our solution to the hardware checkout problem is to use a minicomputer. From the hardware point of view it is a great advantage to start with a known, proven hardware component such as a well-built minicomputer should be. The hardware system integration between the minicomputer and the microprocessor can be made on a variety of system levels."  
(Authors)

"System Integration and Testing with Microprocessors: II. Software Aspects"

P. Burger and J. Leatherman

IEEE Transactions on Industrial Electronics and Control Instrumentation

Volume IECI-22, Number 3

August 1975, pages 364-367

(Paper presented at Annual Meeting, IEEE Industrial Electronics and Control Instrumentation Group, Philadelphia, PA, March 1975)

"The programming and machine language of microprocessors are compared to those of mini-computers. It is shown that microprocessor software usually lacks advanced programming aides. The lack of these programming aides hinder effective program development of systems that employ microprocessors. The conventional method of microprocessor program development on some large host computer or time sharing facility is examined. The drawbacks of using microprocessor simulators on large computers are demonstrated. The main drawbacks are expensive operation and inflexibility." (Authors)

"A Microprocessor Applied to Supervisory Control"

H. J. Binck and J. H. Zouck

Instrumentation Technology

January 1975, pages 45-52

"This article explains how a micro-processor was used in the aerospace industry for fuel control during ramjet testing in a wind tunnel. This 'microprocessor' approach can be replaced directly to certain control systems in the process industries." (Authors)

"Microcomputers in Instrumentation and Control"

W. G. Rudd

Instruments and Control Systems

April 1974, pages 63-66

In many applications, especially in communications and process control, minicomputers are too powerful and expensive to make their use attractive. It is these applications where the low cost and modularity of microcomputers will serve, not to replace minicomputers but to add a new capability in the use of intelligent machines in automation. Some examples of distributed control are presented.

"Diverse Industry Users Clamber Aboard the Microprocessor Bandwagon"

L. Altman, Editor  
Electronics  
July 11, 1974, pages 81-108

This special report details the prolific applications of microprocessors. Some of the topics covered include industrial automatic control applications, data-handling flexibility, increased computer peripheral capability, automated instrument systems, and hardware/software design.

"Microprocessors Await the Call"

A. Santoni  
Electronics  
March 20, 1975, pages 76-80

A microprocessor-design can simplify an instrument's operation, improve its accuracy, and add novel self-test and self-calibration features. However, the chips are too expensive to be worth designing into equipment costing less than \$200.

"Microprocessors Add New Twist to Torque Monitoring"

Editorial Staff  
Electronics  
June 13, 1974, pages 42-44

Several General Motors assembly plants have installed fastener torque certification systems. These microprocessor-based systems monitor, control, and provide hard-copy documentation for the 30 to 50 critical fasteners installed on each vehicle. A simple diagnostic routine is included to detect faults in the fasteners such as stripped or crossed threads. Remote microprocessor terminals are linked to a host mini-computer to obtain factory-wide information.

"Focus on Data Acquisition Equipment"

D. Bursky  
Electronic Design 12  
June 7, 1974, pages 70-84

An overview of the maze of information gathering electronics is presented. The focus begins by looking at amplifiers and other specialized components and closes with coverage of complete data acquisition systems. Important points for such systems that are considered are system accuracy, overall system throughput, noise immunity, temperature stability, computer programming, and real system cost.

"Building an Analog Peripheral Inside a Minicomputer Chassis"

F. Molinari and A. Fishman  
Electronics  
August 22, 1974, pages 104-107

A general-purpose, compact, expandable data acquisition subsystem is presented. Such a system placed inside a minicomputer

enables the total package to implement a wide variety of applications; including wide dynamic range measurements, extending flexibility in channel addressing, and expanding the number of channels, as well as providing various through put measurement rates. The diverse needs of different applications-oriented acquisition hardware can be fulfilled with a 'standard' device that performs the basic data conversion function and allows the user to configure his specific need without customizing the high-precision circuitry portion.

"Microprocessors Expand Industry Applications of Data Acquisition"

A. J. Weissberger

Electronics

September 5, 1974, pages 107-110

"Industrial applications of computerized data-acquisition systems have grown less rapidly than many people expected, despite great advances in computer and measuring-instrument technology. Minicomputer-controlled systems that might be perfectly acceptable in physics laboratories require just too much in the way of space and dollars, and their maintenance also is often too demanding in such applications as operating traffic lights, keeping tabs on pipelines, or testing automobile engines.

"For applications like these, however, a microcomputer controlled data-acquisition system is almost ideal. It is smaller, cheaper, and more reliable than alternative, functionally equivalent systems." (Author)

"Microcomputers for Data Acquisition"

C. W. Rose and J. D. Schoeffler

Instrumentation Technology

September 1974, pages 65-69

"Sensor-based data acquisition systems can take advantage of small, inexpensive microcomputers in a variety of ways not heretofore economical, and so can computer-oriented instrumentation systems. The authors characterize those instrument and data applications specially suited to microprocessor capabilities, explore the communications problems of a microcomputer based data system, and offer a line-sharing network of microcomputers as a solution." (Authors)

"Distributed Microcomputer Data Acquisition"  
E. Y. Linn, J. D. Schoeffler, and C. W. Rose  
Instrumentation Technology  
January 1975, pages 55-61

"Microcomputers are small, low cost devices which offer a powerful but economic approach to the design of computer-oriented systems. In this article, the specific problem addressed by the authors is the design and implementation of a distributed data acquisition system of microcomputers, I/O devices and a single minicomputer. Such pertinent questions as data transmission rates, I/O access speed, network software needs, and characteristics of microcomputers in a distributed network environment are discussed." (Authors)

"Prospects Brighten for Data Acquisition"  
S. Harris  
Electronics  
April 3, 1975, pages 83-87

The integration of transducer and data converter functions at the sensor sites promises to make systems practical in areas now out of reach. These raw analog data are gathered at the transducer source and converted directly into digital form. Then, microprocessor-based "satellite" controllers shuttle the data under direction of a larger coordinating computer.

"Fiber Optics Technology and Systems in the Navy"  
D. Williams  
Naval Engineers, Journal, Volume 87, Number 2  
April 1975, pages 165-173  
(Paper presented at ASNE Day 1975, American Society of Naval Engineers, Washington, D.C., May 1975)

"Fiber optics technology has become a promising candidate to replace metallic wire conductors in many Navy applications. The stimulus behind this is the technical achievements in the reduction of signal attenuation of fiber optics from over 1000 dB/km to the recently achieved attenuation factor of under 4 dB/km. The Naval Electronics Laboratory, San Diego, is pursuing a technology effort aimed at developing a general set of fiber optics components. These would be the cables in various loss factors; light sources in electro-optic modules for bulk-head mounting to interface with several logic and linear circuit standards; and photo detector modules. The state-of-the-

art in the technology and design considerations of interest to naval engineers when dealing in fiber optics will be described along with the rationale and justification for using optics in place of metallic wires." (Author)

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