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The US Navy's Helicopter Integrated Diagnostics System (HIDS) Program: Power Drive Train Crack Detection Diagnostics and Prognostics, Life Usage Monitoring, and Damage Tolerance; Techniques, Methodologies, and Experiences

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

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

This paper will describe the HIDS program background, development, system capabilities, and accomplishments; but will also focus on the most recent demonstrated drive train crack detection diagnostic techniques; aircraft component life usage monitoring philosophies and capabilities; and damage tolerance methodologies. Data and results from both the seeded fault "iron bird" test cell rig and flight test aircraft will be presented. Experience, results, and lessons learned will be emphasized. HIDS initiated functions and capabilities being applied to the commercial off-the-shelf (COTS) SH-60 Integrated Mechanical Diagnostics System (IMDS) production program will be described. Conclusions and lessons learned that can be applied to future Helicopter Usage Monitoring Systems (HUMS) and/or Integrated Mechanical Diagnostic (IMD) systems will also be discussed.

Introduction

Background

The U. S. Navy and U. S. Marine Corps rotary wing operators have long had a requirement to improve readiness through more effective maintenance, eliminate losses of aircraft and personnel, and dramatically reduce maintenance related costs. The requirements to extend the service life of aircraft and the limitations on manpower have increased the urgency of effecting these types of improvements. A major cause of the Class A mishaps (loss of aircraft and/or personnel) in Navy helicopters are caused by

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engine and drive train failures. The need to accurately identify and diagnose developing faults in mechanical systems is central to the ability to reduce mechanically induced failures and prevent excessive maintenance. The Navy has successfully developed and deployed engine monitoring systems in fixed wing aircraft, notably on the A-7E and subsequent fighter/attack aircraft. These Engine Monitoring Systems (EMS) have positively impacted flight safety, aircraft availability, and maintenance effectiveness. The Navy also successfully demonstrated a promising automatic mechanical fault diagnostic capability on its gearbox overhaul test stands in Pensacola, Florida.

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

While diagnostic capabilities to detect a specific impending component failure are relatively straightforward, prognostic capabilities are less mature and can provide a much larger benefit payoff. Any system considered for fleet-wide implementation should have both capabilities to maximize effectiveness. Any program to demonstrate and validate diagnostic capabilities must also address some degree of prognostics. This program attempts to do both.

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

A significant disadvantage of first generation commercial systems in 1992 was the lack of raw data acquired to validate and optimize the full, Integrated Mechanical Diagnostic (IMD) functionality. As a result, these systems exhibited false alarms and missed calls and did not routinely collect the supporting raw data that would enable improvement of the diagnostic accuracy. Raw data acquisition is necessary in any development effort, in order to reliably indicate mechanical and rotor system faults, avoid false alarms, and develop structural and mechanical system usage routines. These are some of the keys to preparing a production IMD system for deployment.

Present Work

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

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

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

2. *Ground Testing:* Conduct fault detection validation testing in the unique NAWCAD full scale Helicopter Transmission Test Facility (HTTF) which currently consists of the entire SH-60 power drive system (engines, transmission and tail drive system). Evaluate and validate the TII/BFG system and associated algorithms to detect seeded faults while building a base of raw data for evaluating other fault detection methods. In addition, the program is evaluating other advanced technologies in parallel with the TII system. The information generated from this testing will form a body of knowledge from which

specifications can be written to procure effective production versions of the integrated diagnostic system.

One purpose of this paper is to describe the overall program, diagnostic system, NAWCAD HTTF, seeded fault testing, flight testing and major accomplishments to date. A second purpose is to discuss both diagnostic and potential prognostic capabilities demonstrated during this development experience. Thirdly, possible impacts of HIDS type systems on damage tolerance concerns for aging aircraft will be briefly discussed. Finally, several lessons learned that that can be applied to future production HUMS and IMDS programs will be identified.

Description

This section will describe the systems and facilities used in support of the HIDS program. The test articles are the diagnostic and prognostic technologies. The SH-60 test facilities were used to exercise various diagnostic and prognostic technologies and evaluate their relative performance.

HIDS Diagnostic System

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

Structural Usage Monitor: The TII/BFG system performs aircraft usage monitoring, engine condition monitoring, drive shaft and gearbox condition monitoring, chip detector monitoring and rotor track and balance. Data is stored to a PCMCIA card providing the usage spectrum of the aircraft, engine performance information, flight regimes for trending gearbox vibration information and an actual record of the mission. This data is available for post-processing, enabling recalculation of regime recognition and structural usage parameters.

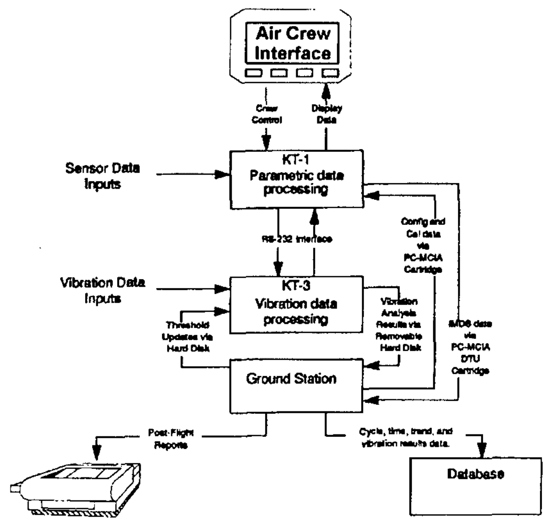

Fig. 1. Diagnostic System Architecture.

Engine Performance: The HIDS Cockpit Display Unit (CDU) depicted in Figure 2 interfaces with the pilot to execute and display results of automated NATOPS T700 engine health checks and the engine Power Performance Index (PPI). The PPI is a fourth order best fit curve representing an engine degraded 7.5% from the specification line, and can provide a warning to the pilot when an engine has degraded due to salt ingestion, sand erosion or other foreign object damage (FOD).

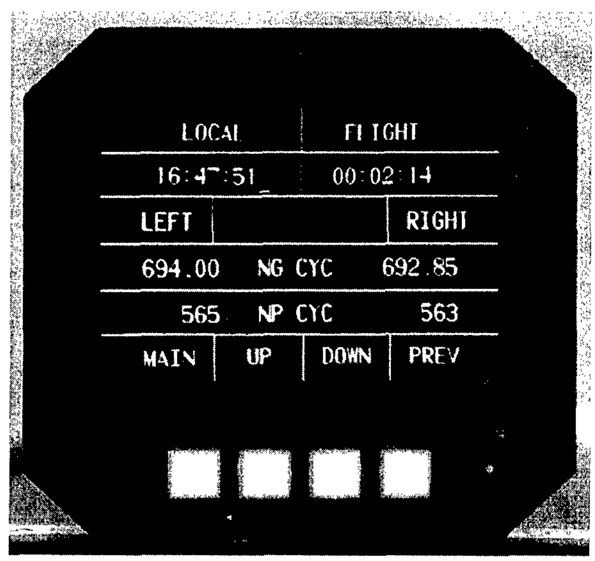

Fig. 2. Central Display Unit.

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

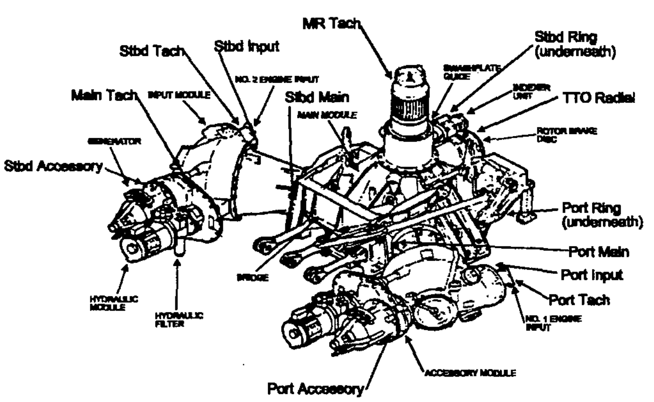

Fig. 3. Accelerometer Locations on Input and Main Modules.

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

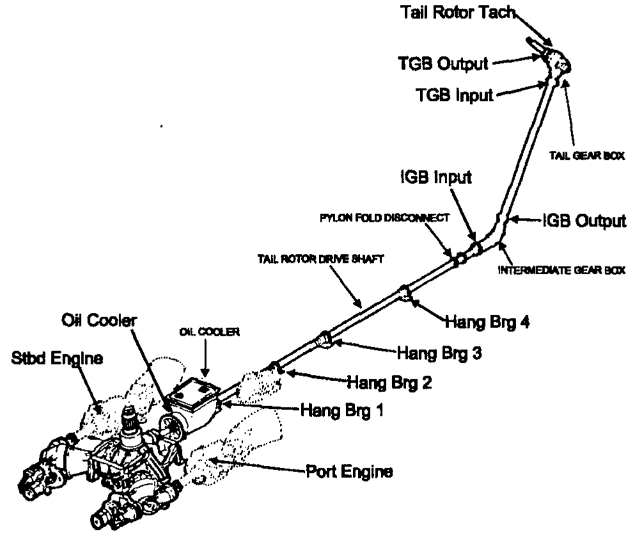

Fig. 4. Accelerometer Locations on the Tail Drive System.

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

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

Vibration Based Prognostics: Though it is often difficult to separate diagnostic and prognostic performance in a seeded fault program such as this, one of the by-products of this testing was the demonstration of the potential and performance of prognostics.

As a working definition for this paper: prognostics is the capability to provide early detection of the precursor and/or incipient fault condition to a component or sub-element failure condition; and to have the technology and means to manage and predict the progression of this fault condition to component failure. The early detected, "incipient" fault condition, is monitored, "tracked", and safely managed from a "small" fault as it progresses to a "larger" fault, until it warrants some maintenance action and/or replacement. Through this early detection and monitoring management of incipient fault progression, the health of the component is known at any point in time and the future failure event can be safely predicted in time to prevent it.

Applying many of the same algorithms and techniques used for vibration based mechanical diagnostics, a significant degree of component failure prediction and prognostics was demonstrated during these tests. Often the extrapolation of vibration frequency data, statistical parameters and/or diagnostic indices trends is the technique used to enable failure prediction. It is of course key to have sensors, algorithms, and diagnostics indicators (or indices) that are sensitive and accurate enough to "see" the precursor or incipient "small" component fault. It is equally important to have a reliable experience database of examples of similar types of "faults" so that the failure progression rate is understood. Using this experience database knowledge and the understanding of various types of failure progressions will enable the intelligent settings of alarm thresholds. It is envisioned that in most cases, the alarm thresholds for safety-of-flight (cockpit warning) will be significantly higher than for maintenance. Establishing these alarm thresholds is a very necessary step in implementing future failure event prediction and enabling prognostics. Without having the benefit of an extensive experience database of actual component failures with fault progression data and/or a comprehensive "seeded fault" trials as the SH-60 HIDS program, establishing these alarm thresholds approaches the realm of "magic".

There are other important elements needed in the "diagnostic tool kit" or "bag of tricks" before prognostics can be successfully implemented. One of these can be called "Model Based" diagnostics or prognostics. Another can be grouped as a series of approaches and techniques to handle data scatter and manage false alarms. Model based techniques require a detailed and accurate understanding of the underlying physics of the system to model how a specific component, system, or machine, operates in normal and degraded conditions. Using measured parameters, real or calculated, against this accurate model, enables the determination of relative "health" of the component monitored at any point in time. Some of the approaches applied to deal with inherent data scatter and to manage false alarms include: fuzzy logic and neural network techniques; data fusion; and multiple indications (either sensor or algorithm indices driven) required prior to alarm. At times, and with varying degrees of application and success, all of these approaches and techniques were tried during this program.

Rotor Track and Balance: The ROTABS system promises to negate the need for on-board trackers and utilizes higher order mathematics and a significantly larger data set to resolve the adjustments required to keep the rotor system in track and balance. ROTABS does not collect or use track data to compute rotor adjustments. On other aircraft types, the system has demonstrated the ability to maintain track limits while simultaneously optimizing vibration in 6-degrees-of-freedom at 1/rev and selected harmonics thereof. Results obtained during HIDS testing have been presented in detail (Ref. 3).

A continuous monitoring of the in-flight rotor track and balance condition will alert the maintainers of out-of-limit conditions that, among other things, will result in high vibration stress conditions. By keeping the rotor system in a "better" track and balance condition, overall vibration levels on all aircraft structural components and subsystems will be reduced. This could significantly increase the life of many of these aircraft structural components and subsystems. In particular, avionics systems could see a large improvement in life. This capability alone would positively impact several damage tolerance issues on aging aircraft.

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

Description of the Test Cell

The NAWCAD HTTF has been described in detail (Ref. 4). The facility was originally located in Trenton, NJ and has now been transferred to the new Propulsion Systems Evaluation Facility (PSEF) at NAWCADPAX. The test cell uses aircraft engines to provide power to all of the aircraft drive systems except the rotors. Power is absorbed through both the main rotor mast and tail rotor shaft by water brake dynamometers. The main rotor shaft is loaded in bending, tension and torque to simulate flight conditions. There is a speed increasing gearbox between the main rotor mast and the water brake, which raises the main rotor speed by a factor of 32. This currently allows water brakes to extract up to 8,000 shaft horsepower (SHP) and will soon be upgraded to handle up to 18,500 SHP. The complete aircraft lubrication system is used with the oil cooler, oil cooler blower and blower drive shaft part of the system assembly. The tail drive system is installed and power is extracted from the tail at operating speed. The tail water brake can extract up to 700 SHP.

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

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

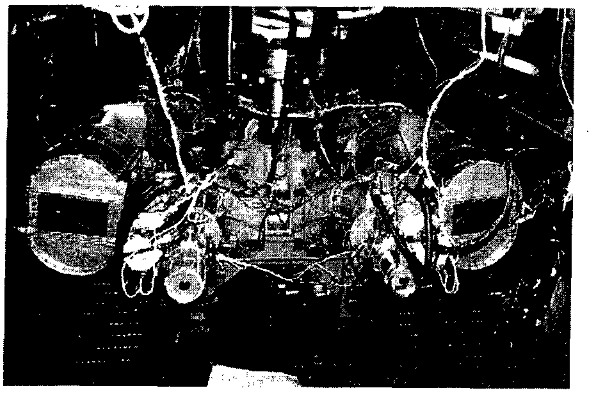

Fig. 5. Main Transmission Assembly including Accessories.

Aircraft Installation

The HIDS installation is the first health and usage monitor with advanced gearbox diagnostics to be placed on-board a US military helicopter. The system has a menu driven cockpit display (see Figure 2) for pilot information/interface. The usage monitor is built on an open architecture, 1/2 ATR short box, which has unused slots for future integration of selected vibration monitoring functions. Downloads from the aircraft are accomplished via the data transfer unit (DTU), a Type II PCMCIA card. The vibration analysis system is housed in a vibration isolated chassis with removable hard drive and full VME chassis. This system is necessary for the development program to acquire all of the raw data that generates an airborne warning or alarm for either confirmation of the fault, or development of additional algorithms that identify a data problem that resulted in a false alarm. A significant benefit of this system is the comprehensive database, which is a powerful resource for diagnostic development. This same system was used to support data collection for the first phase of the IMD program.

Evaluation

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

Test Objectives

To insure a comprehensive test effort, the planning for this test program included support from individuals and organizations involved with the design of the H-60 aircraft and diagnostic systems. The team developed and documented the program plan (Ref. 4). All seeded fault test planning was discussed with Sikorsky drive system engineering prior to execution. Team discussions led to the objectives and test sequence previously described in detail (Ref. 3). A subset of these is summarized below.

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

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

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

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

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

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

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

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

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

10. Evaluate as many currently available propulsion and power drive system diagnostic technologies as possible in the HTTF and assess their relative effectiveness.

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

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

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

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

Vibration Monitoring Test Plans

Testing of the diagnostic system was divided between two Navy activities that could exercise as much of the entire diagnostic system as possible. The NAWCAD HTTF and operational SH-60 aircraft both operated the entire propulsion and power drive system during testing. Test plans were designed to maximize the return on investment when the system is evaluated in a single type of test vehicle.

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

The NAWCAD HTTF personnel began acquiring seeded fault assets at the program inception. These parts had been removed from the overhaul process for discrepancies and were set aside for test rather than scrapped. This provided tremendous cost savings by avoiding purchase of good parts for artificially seeded fault specimens, while supplying naturally created faults for test. Sikorsky Aircraft parts from prior bench qualification tests are also available for test. These parts are "bench test only" assets since they experienced over-torque conditions during test. The program has over two full sets of Not For Flight Asset (NFFA) gearboxes. The spares can be implanted with faults while another gearbox is tested.

The testing initially concentrated on the tail drive system to verify the TII/BFG diagnostic system operation and performance. Subsequent testing has been performed on all drive system components, including artificially implanted and naturally occurring faults. The test conditions have consisted of sequentially varying power settings throughout the normal range of operation. It is essential to understand the sensitivity of the diagnostic algorithms as a function of changing aircraft power. Ambient temperature variation effects are included in the analysis. The first data set from each run is taken before the oil warms up at low torque to obtain a database that can be compared to flat pitch maintenance ground turns for troubleshooting.

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

System Installation

The HIDS system is capable of accommodating multiple configurations. The HTTF and aircraft Bureau Number (BUNO) 162326 installations are the same for a majority of the inputs. The aircraft has many additional parameters that are not present in the test cell, such as flight parameters including altitude, airspeed, pitch, roll and heading. Also, the aircraft system measures fuel quantity while the test cell system measures fuel flow. Aircraft 162326 was made available for instrumentation in the spring of 1994 and the entire system was installed by 1 August 1994. The initial installation was completed with a majority of parameters in good operation and a system that functioned and passed installation acceptance tests. Several modifications have been incorporated since the commissioning. Performing checkout of system functionality at the HTTF tested the aircraft system changes, and many of the aircraft discrepancies were found to be in areas where the aircraft was different from the HTTF. The interface documentation was updated and validated accordingly. In March of 1997, the next generation HIDS system was installed on PAX aircraft 804 for continued analysis and development. When the IMD schedule was accelerated, the HIDS system supported the effort on the SH-60 platform, while an improved variant was utilized for the CH-53E.

Vibration Data Analysis

The HIDS program has correlated the seeded fault test data acquired in the HTTF to NAWCAD flight data. The diagnostic system user interface and its ability to detect faulty components in a full drive system were evaluated using the HTTF data. The operational characteristics, rotor track and balance and user interface were evaluated on the NAWCAD-PAX aircraft.

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

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

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

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

Damage Tolerance Concerns

The actual operational lives for aircraft and their subsystem components are now commonly being extended well past their original design lives. This trend has been increasing in recent years because of reduced defense budgets and growing operational demands. Services are having to operate longer, in some cases much longer, with the aircraft and systems they already own. Thus, a pressing problem becomes how to best manage damage tolerance issues in a fleet of ever aging aircraft.

One of the most important damage tolerance issues is the accurate accounting for life usage accumulation on components with design life limits. Gas turbine engines, gearboxes, helicopter rotor assemblies, and other stressed airframe parts are all subject to finite design limits on life limited components. The data acquisition and life usage monitoring capabilities of HIDS type systems provide an excellent means to track damage accumulation and effectively manage parts life consumption on aging aircraft.

Another important damage tolerance issue is the problem of dealing with secondary damage. Diagnostic capabilities provided by HIDS type systems will identify the small faults and component failures early, before they become significant contributors to more severe secondary damage.

Accomplishments

Accomplishments Summary

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

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

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

The data library consists of over 2000 sets of 32 channel simultaneous acquisitions of raw time series data with tachometers and accelerometers recorded together, providing a rich database to enhance diagnostic techniques. Multivariate techniques are being investigated to exploit the additional information inherent in the relationships between indicators and to increase the robustness of health evaluation calls.

Compliance with Objectives (Examples)

1. Evaluate the ability of the diagnostic system to identify localized faults in an entire drive system. The HIDS system has demonstrated the ability to identify localized faults on a number of H-60 drive system components. The engine high speed shaft/input module interface (see Figure 7) has been a problem area, where the difficult to inspect Thomas Coupling disc pack has suffered several failures. The Figure 8 engine high speed shaft (with cracked Thomas Couplings) was removed from the fleet and tested at Trenton. Figure 9 illustrates baseline test data with good driveshafts, and the degraded component installed at the starboard engine location for one acquisition at run number 31. The HIDS system detects the fault and isolates it to the starboard side. This provides a rationale for providing a cockpit alert for critical, rapidly degrading components. The

HIDS system also detected a fleet removed input module suspected of being an every-other-tooth gearmesh candidate. These gearboxes were emanating a strong tone at one-half the normal gearmesh frequency, and it was believed this tone was contributing to premature removals of the mating T700 engines due to torque reference shaft wear. Figure 10 exhibits a gear health indicator (algorithm) of such a component tested at Trenton which shows baseline and fault (run numbers 149 through 170) data.

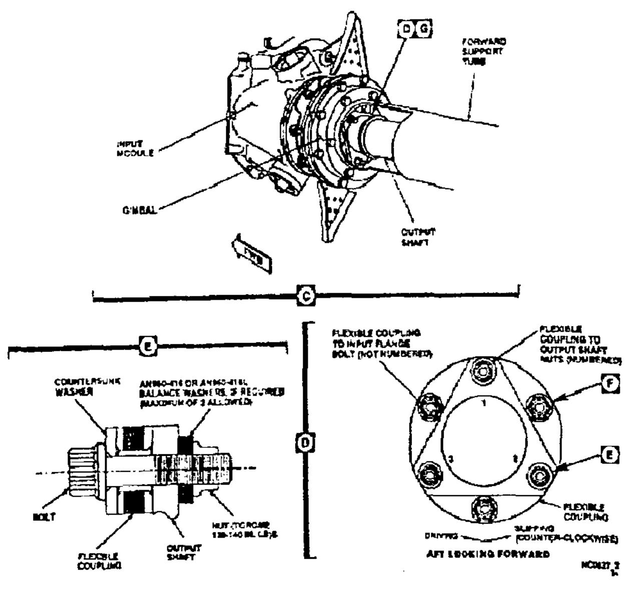

Fig. 7. High Speed Shaft Interface.

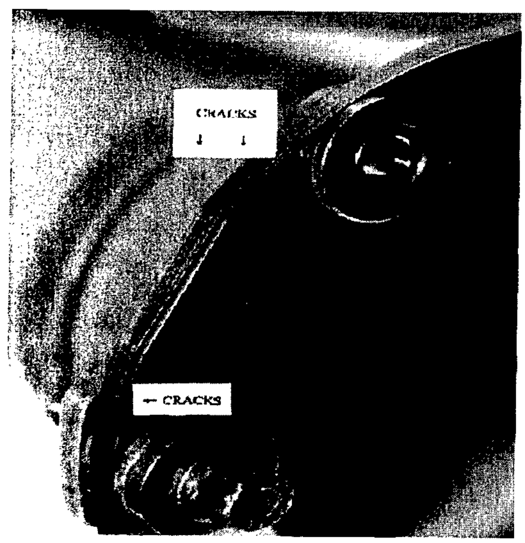

Fig. 8. Cracked Thomas Coupling.

2. Evaluate the diagnostic algorithms for cracked gear fault identification and sensitivity. A critical part of the HIDS program is to demonstrate the detection of catastrophic gear faults. The most serious of which are root bending fatigue failures. Depending upon gear design, this type of crack can either propagate through the gear tooth causing tooth loss, or through the web causing catastrophic gear failure and possible loss of aircraft.

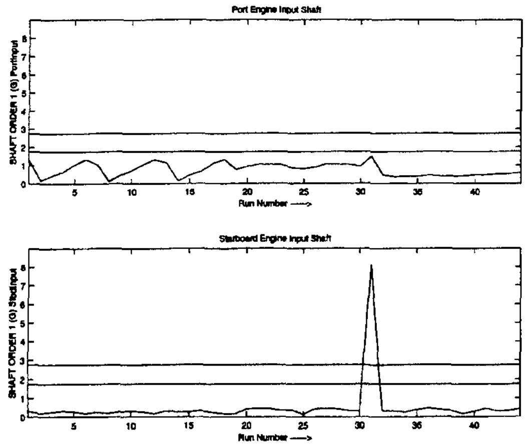

Fig. 9. Degraded Shaft at Position 31.

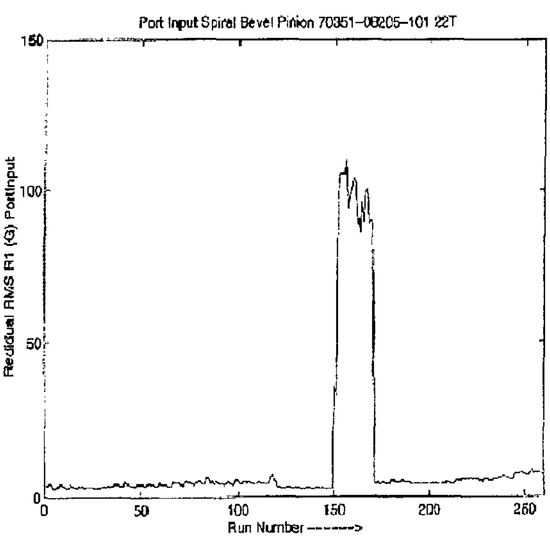

Fig. 10. Response for Half Gearmesh Anomaly.

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

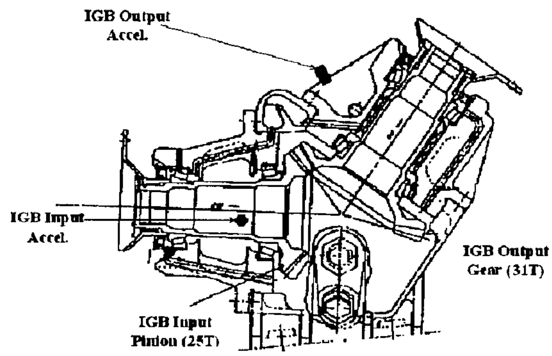

Fig. 11. SH-60 Intermediate Gearbox Cutaway.

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

A review of the diagnostic results shows the TII/BFG model based algorithms successfully detect the presence of the gear tooth fault. Figures 13, 14 and 15 respectively exhibit "Component Condition" and the early and late responding health indicators from which it was derived. After indicating a healthy gear for roughly 267 minutes (most acquisitions were acquired 15 minutes apart), the indicator levels raised steadily for the next 139 minutes, thereafter exhibiting sharp changes in level until test termination at 548 minutes (Ref. 5 discusses indicator results of another pinion tooth fault). Test results illustrated an EDM notched tooth behaves much like adjacent teeth until the part is fatigued and a crack develops. The crack effectively weakens the tooth in bending, causing the faulted tooth to share load unequally with adjacent teeth. Depending upon the crack path, other dynamic anomalies are manifested. Also, synchronous averaging techniques employed in model based diagnostics can "filter out" non-synchronous vibration providing a health determination of a specific component.

Fig. 12. Cracked Intermediate Gerabox Pinion.

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

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

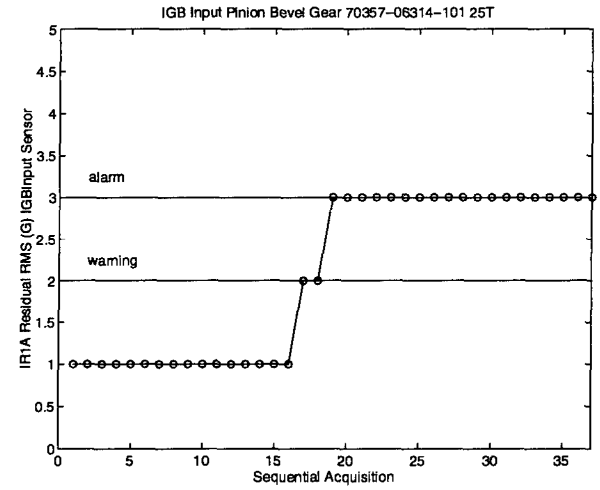

Fig. 13. IGB Pinion Component Condition.

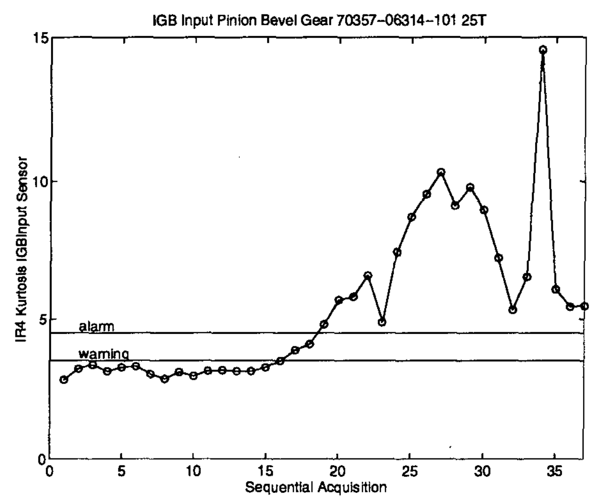

Fig. 14. Early Responding Health Indicator.

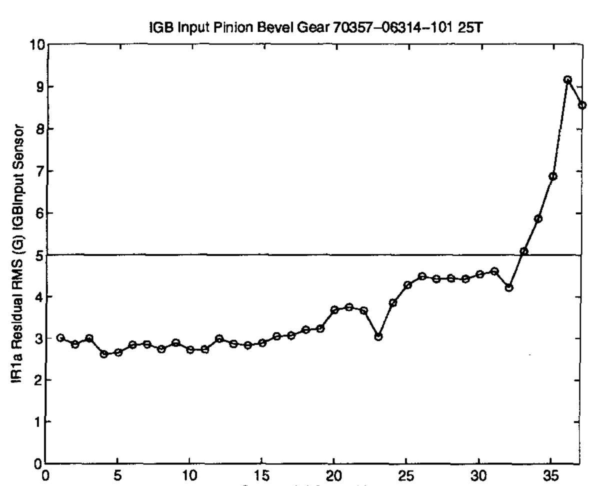

Fig. 15. Late Responding Health Indicator.

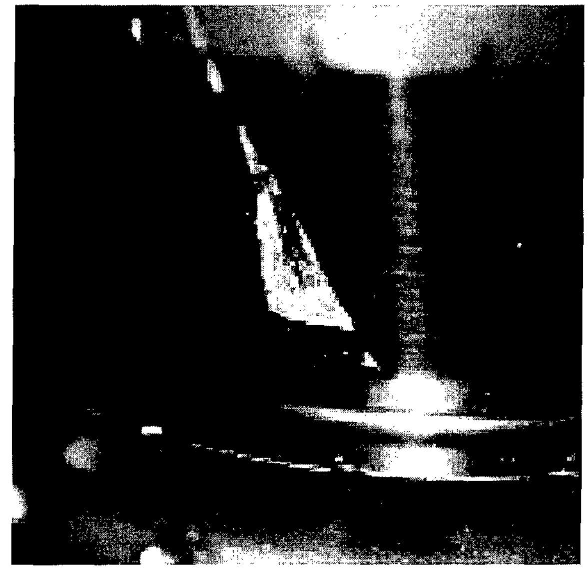

Fig. 16. Main Transmission Input Pinion Crack.

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

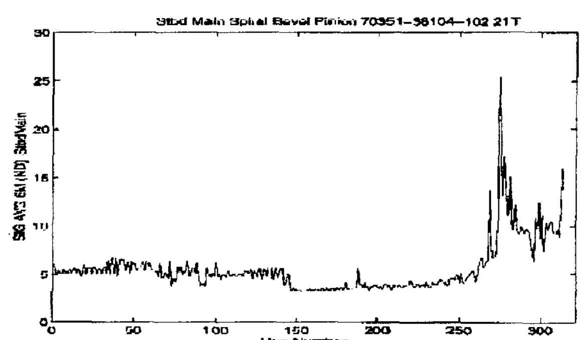

Fig. 17. Response to Main Module Pinion Fault.

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

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

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

4. Evaluate diagnostic system sensitivity to defects and faults in tail drive shafts and bearings. Hanger bearing assemblies are used to support the helicopter tail drive shaft. The main components of the assembly consist of a grease-packed sealed ball bearing that is pressed into a viscous damper bladder and supported by a housing that mounts to an airframe interface. The bearing is expected to be lightly loaded since it doesn't support any significant radial or axial loads, though those imposed from imbalance and misalignment occur in-service. Figure 18 shows the hanger bearing assembly and associated accelerometer installed at the number 2 location in the tail drive system. Since the viscous damper is in the vibration transmission path, there was concern it would inhibit the transmission of high frequency tones from the bearing to the vibration sensor.

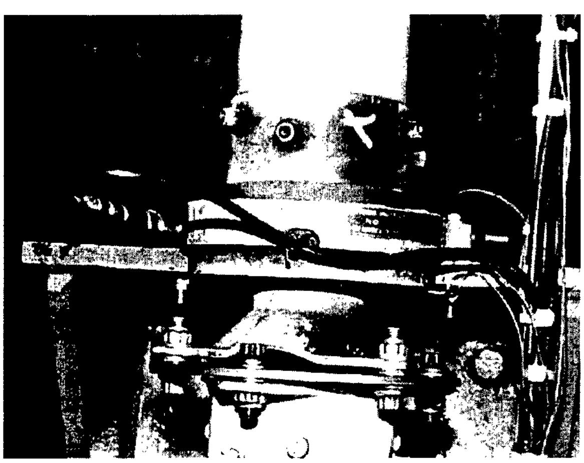

Fig. 18. Hanger Bearing Assembly.

A fleet removed hanger bearing with a very light click was installed in the HTTF. There was considerable opinion that the click was due to dirt in the bearing. 12.7 drive system operating hours were accumulated and 129 data points were acquired. Figure 19 shows a representative envelope spectral plot for the fleet rejected hanger bearing. A fault clearly exhibits itself by the strong tones at frequencies specific to the inner and outer race defect frequencies and also at shaft speed. By comparison, fault-free hanger bearings did not generate bearing defect frequencies. The Figure 20 indicator is derived from the information contained in the spectral plot, and presents data from four different bearings which were installed in the #2 hanger bearing location. Data from the fleet rejected bearing is easily identifiable between run numbers 199 through 325. Note that the viscous damper attenuation concern did not materialize.

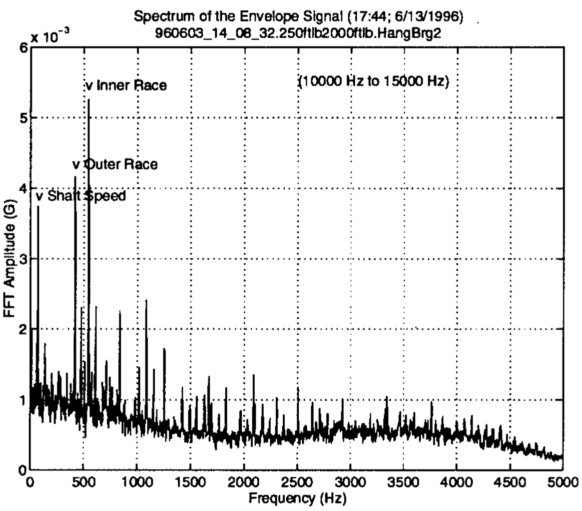

Fig. 19. Rejected Hanger Bearing Spectral Plot.

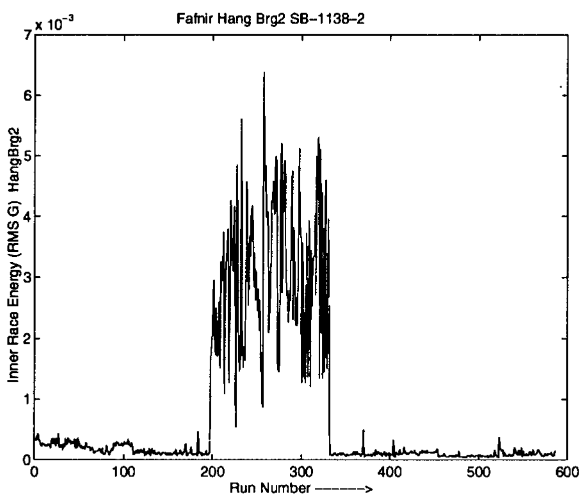

Fig. 20. Hanger Bearing Inner Race Energy.

Posttest inspection of the bearing revealed that the inner ring was fractured as shown in Figure 21. Also, the bearing was found to have about 1.5 grams of grease remaining, which is within the range normally found in bearings operating to their 3,000 hour overhaul life. Hanger bearings with inner race fractures have been known to eventually purge all the grease through the fracture leading to overheating, seizure, and loss-of-aircraft.

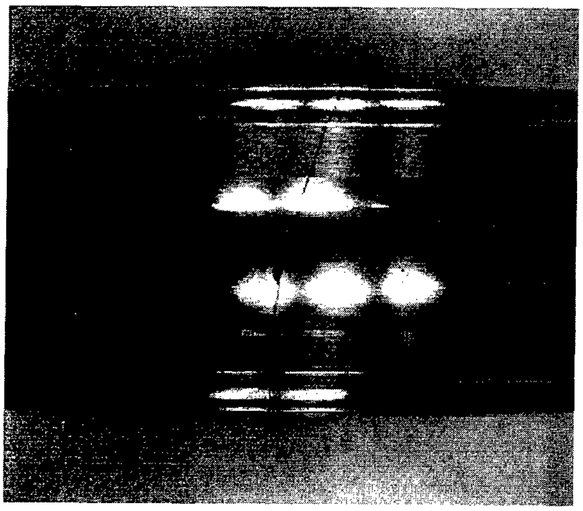

Fig. 21. Post-Test Condition of Hanger Bearing.

5. Evaluate the diagnostic systems sensitivity to bearing defects in gearboxes. The spalled integral raceway bearing (P/N SB 2205) is the most common dynamic component cause for gearbox removal in the H-60 community. This fault is particularly challenging as it is located deep inside the main transmission, (see Figure 22) suggesting it would be difficult to detect. Figure 3 illustrates the SH-60 main transmission system and respective vibration accelerometer locations. The Figure 23 fleet rejected component was installed in the HTTF starboard location. Bearing condition for the starboard and port main accelerometer locations are presented in Figures 24 and 25 respectively. The starboard main condition indicator toggles into the alarm position when the fault is implanted at acquisition number 254 and reverts back to the okay position when the fault is removed at acquisition number 300. The port main indicator is also sensitive to this fault because the sensor is located on the same structural housing member, and is rotated about 90 degrees around the housing from the starboard main sensor. The port indicator serves as a confirmation of the starboard condition. Enveloped kurtosis is the main indicator used to evaluate bearing condition for this fault. One of the keys to obtaining meaningful results with this technique is to envelope an appropriate frequency range. The frequency range used in this analysis was determined analytically as well as experientially. Figures 26 and 27 respectively exhibit the Kurtosis values of the primary (stbd main) and secondary (port main) sensors for the bearing SB-2205 fault.

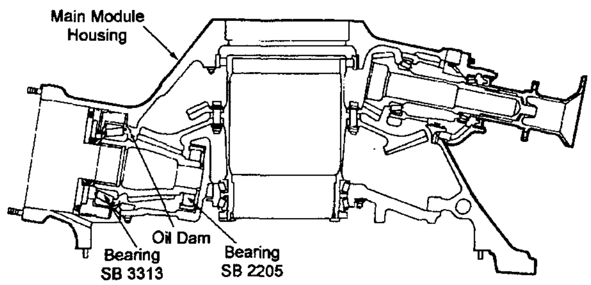

Fig. 22. Locations of SB-2205 and SB-3313 Bearings in the Main Module.

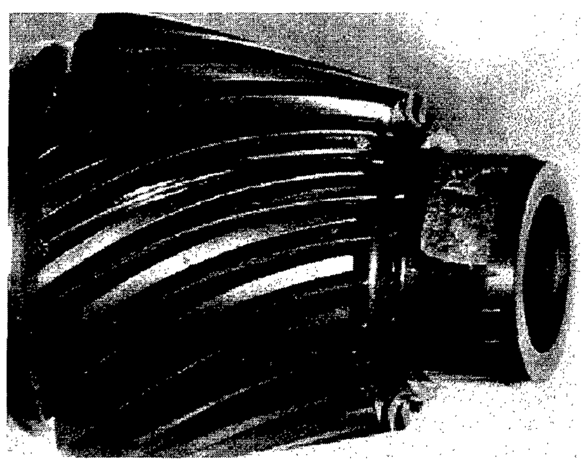

Fig. 23. Main Module Input Pinion with Spalled Integral Raceway Bearing SB 2205.

Fig. 24. SB 2205 Condition Call from Starboard Sensor.

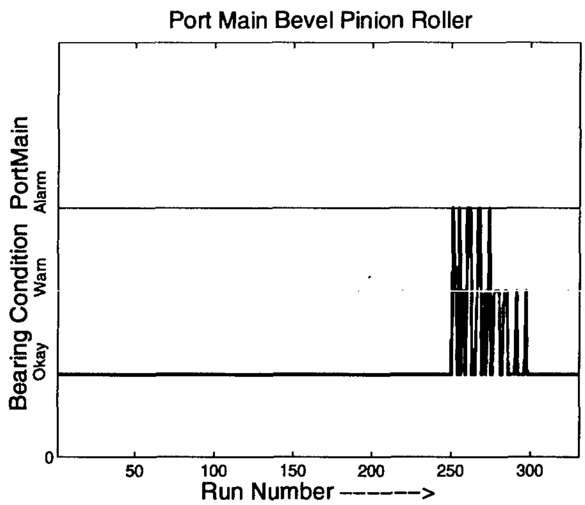

Fig. 25. SB 2205 Condition Call from Port Sensor.

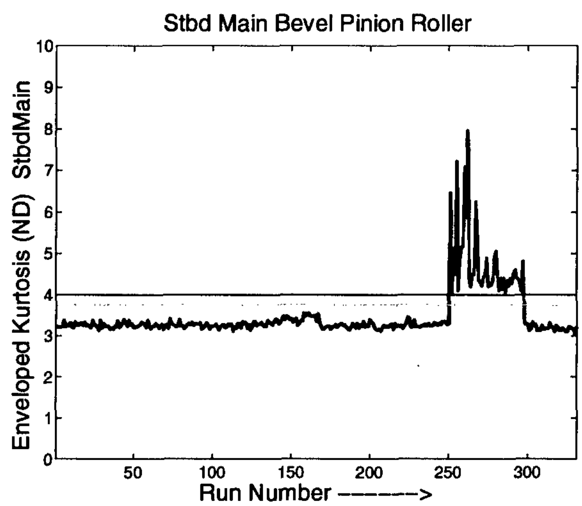

Fig. 26. SB 2205 Starboard Main Kurtosis Trend.

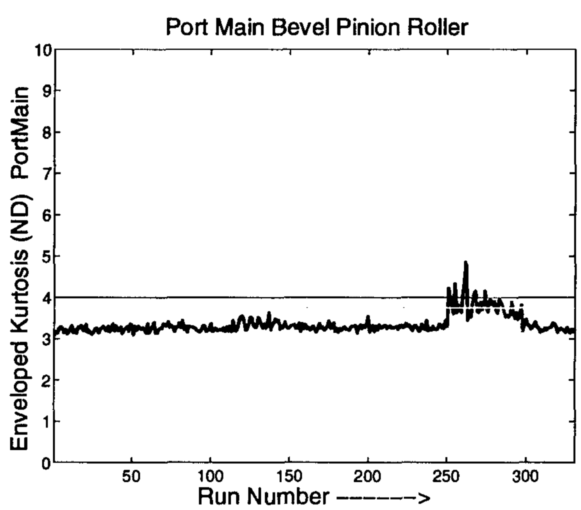

Fig. 27. SB 2205 Port Main Kurtosis Trend.

Prognostics could effectively be applied to the failure of this component. The SB2205 fault progresses in a repeatable manner from a small, localized spall into a larger one that will eventually encompass a good portion of the inner race diameter. At this point, the chip detector will provide an indication of a failure somewhere in the gearbox with no indication of fault location or severity. On the other hand, the model based bearing indicators identify the presence of the fault early in this process. As the fault becomes progressively larger, the statistical indicators in Figures 28 and 29 are among the dominant indicators that identify the degraded condition. By carefully tracking the progression of this fault, maintenance and mission planning can be conducted in an effective manner, and unscheduled downtime can be effectively reduced.

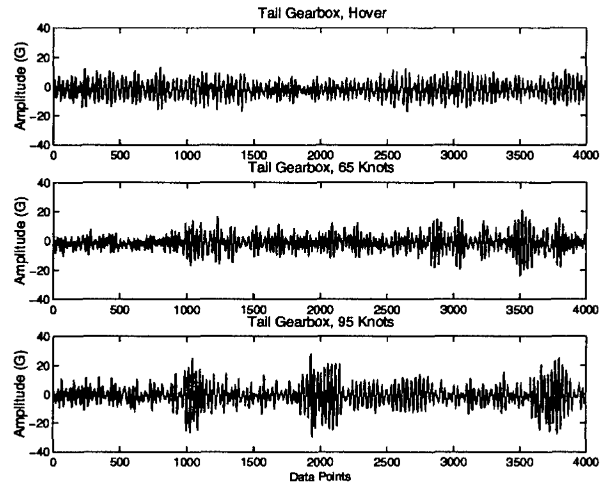

Fig. 28. Dissimilarity of Tail Gearbox Time Series Data for Various Flight Regimes.

6. Evaluate variability of data across flight regimes (including torque and weight variations). Figure 28 exhibits time domain tail gearbox vibration data at different flight regimes. There is considerable difference in the signal between forward flight and hover. This introduced considerable scatter in the algorithm indicators. It was determined a large main rotor 4/rev component (rotor wash) is interacting with the tail pylon in forward flight, which is causing this data instability. This and other flight regime nuances are being investigated.

7. Evaluate sensor placement sensitivity for the various defects. The objective is to minimize the total number of sensors required to identify faults large enough to require maintenance action and to increase robustness by verifying use of secondary sensors. The test of bearing SB 2205 provided an interesting study for sensor placement. At the time of

test, the stbd main was the primary sensor for the stbd SB-2205 bearing, and the stbd input sensor was the secondary. Test results however showed otherwise. Figure 29 shows that the enveloped kurtosis of the stbd input sensor does not respond to the fault, whereas the port main sensor does (see Figure 27). Based on results from this test, the port main sensor was then mapped as the secondary sensor for the stbd SB 2205 bearing.

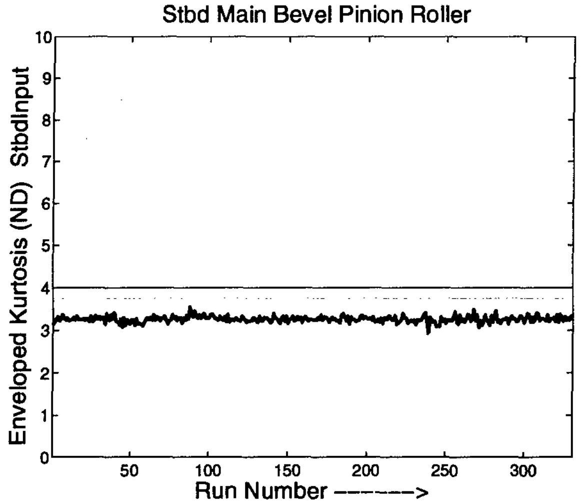

Fig. 29. SB 2205 Starboard Input Kurtosis Trend.

8. Evaluate the potential for detecting misalignment, bad pattern and improper shimming during assembly that may be the cause of premature damage in mechanical systems. Misalignment and imbalance testing have been performed on a number of drive system components. Specifically, the engine high speed shaft/input module assembly has been investigated under these conditions and findings were documented (Ref. 6). Other similar tests (some naturally occurring) were recorded. Gearbox gear pattern shim surveys were also performed. Test results are pending data review.

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

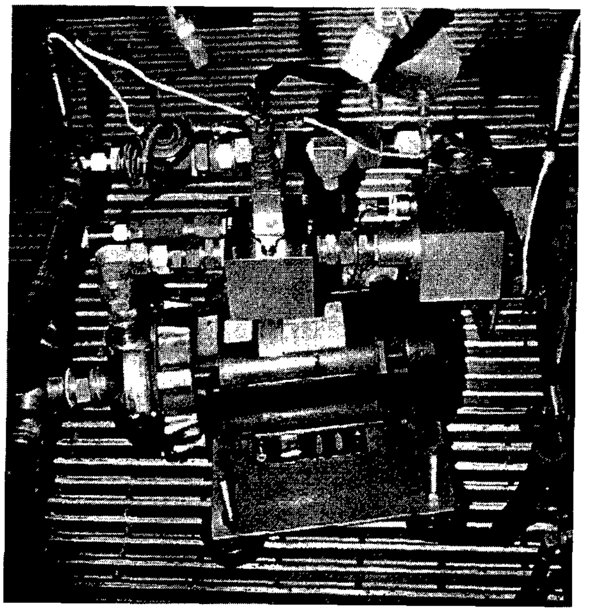

Fig. 30. Test Rig for Oil Monitoring Evaluation.

10. Evaluate as many currently available propulsion and power drive system diagnostic technologies as possible in test cell 8W and assess their relative effectiveness. Engineering evaluation testing of Stress Wave Analysis, Electrostatic Engine Exhaust Monitoring, Inductive Oil Debris Monitoring, Quantitative Oil Debris Monitoring, Optical Oil Debris Monitoring, and Acoustic Emission have been done in parallel with HIDS testing evaluation at Trenton. Two of these efforts are US Army SBIR efforts. As a means to evaluate the IDM and QDM MKII oil debris monitoring systems simultaneously, a modified main transmission lubrication scavenge apparatus was provided by Vickers Tedeco (See Figure 30). The system attaches to the main transmission module at the normal chip detector location and a positive displacement pump adds sufficient head to pump the oil through an external plumbing arrangement. Sump oil enters the pump, IDM, QDM MKII, and finally the production main module chip detector and returns to the transmission. A fine mesh screen is included to capture particles that are not captured by the QDM MKII and main module magnetic detectors. The Figure 23 main transmission input pinion with a spalled integral bearing raceway was used as a tool to generate debris for the evaluation. This test (Ref. 7) found the fault generated particles much smaller (5-20 microns) than what a typical bearing fault (>100 microns) is known to produce. This evaluation provided sensitivity and performance information.

11. Evaluate the data collected on-board the aircraft with the test cell data to validate the pertinence of test cell proven algorithms for use on-board an aircraft. As part of the HIDS program, drive system vibration data was acquired on 22 and 23 May and 30 August 1995 from SH-60 BUNO 164176 at NAWC-ADPAX. Data was also collected on two other SH-60 aircraft using the same data acquisition system. The data was acquired primarily to support a next generation diagnostic effort based on neural network technology and designated the Air Vehicle Diagnostic System (AVDS) program. The intent was to acquire raw vibration data on fault-free aircraft to use as a means for baselining the neural network process. For aircraft BUNO 164176 a total of 46 separate acquisitions were taken at several different flight conditions including ground turns, hover in-ground effect, hover out-of-ground effect, straight and level and descent. Torque ranged from 28-100%. Approximately one month after the May data had been acquired from BUNO 164176, HIDS project personnel were informed that the aircraft had a history of setting off the main transmission chip detector light. The chip detector events prompted an analysis of vibration data collected from BUNO 164176 using HIDS diagnostic algorithms. The same analysis was also conducted on one of the other aircraft, namely BUNO 162326, to provide a baseline for comparison to aircraft BUNO 164176. Representative envelope spectral plots of baseline and faulted aircraft data are shown in Figures 31 and 32 respectively. The fault clearly exhibits itself by the strong tones at frequencies specific to the main bevel pinion tapered roller bearing (SB 3313) both in the test cell and the aircraft. The Roller Energy indicator for the aircraft data is displayed in Figure 33.

The analysis clearly indicated a fault in the rolling elements of the starboard main bevel input pinion tapered roller bearing, P/N SB 3313 (see Figure 22 schematic for location) and represented a safety-of - flight concern. Further confirmation of fault location was provided by chip elemental analysis, conducted by Sikorsky Aircraft, which determined that the chips were CBS 600 steel indicating that this bearing was one of several possible sources of the chips. Based on the analysis, the HIDS team strongly recommended that flight operations on aircraft BUNO 164176 cease and the main gearbox could be removed and sent to the HTTF for continued testing. The data collected in the test cell environment was compared to flight test data (see Figure 34 for test cell data). Moreover, the urgency to remove the gearbox from service was a result of the HIDS team assessment that the presence of the oil dam (P/N 70351-38124-101), adjacent to the bearing was a barrier to chip migration. This (1) prevented the chip detector from indicating the true severity of the failure development and (2) created a reservoir of chips which may act to increase the failure progression rate. Action was taken to comply with the recommendation. Subsequent teardown and inspection confirmed that 13 of the 23 rollers in the bearing were severely spalled as shown in Figure 35. Inspection revealed a large amount of debris harbored by the oil dam, confirming the HIDS team suspicion that the oil dam acted as a chip reservoir.

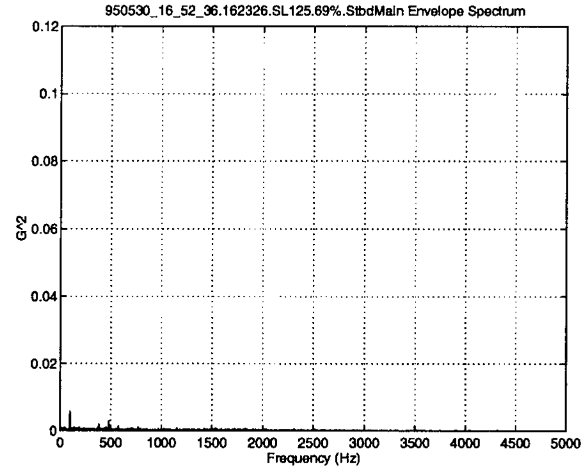

Fig. 31. Baseline Spectrum for Bearing SB 3313.

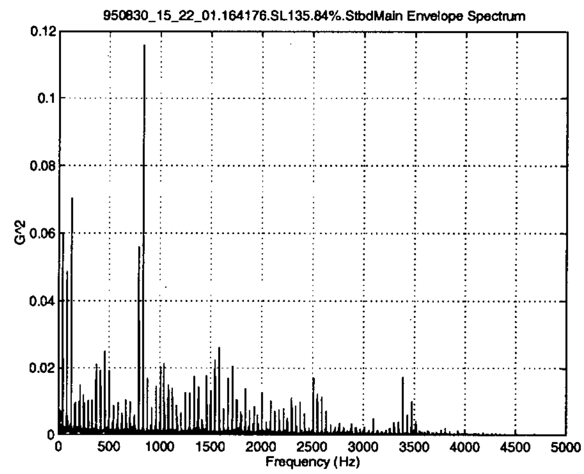

Fig. 32. Fault Spectrum for Bearing SB 3313.

12. Categorize diagnostic results with respect to aircraft flight regime to define optimized system acquisition and processing requirements. Review of Figures 33 and 34 reveals a great deal of scatter in the value of the faulted bearing indicator. This is due to the differences in flight regime and torque. A fault must be loaded to excite a discrete frequency, and a determination of what regimes produce satisfactory results is needed.

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

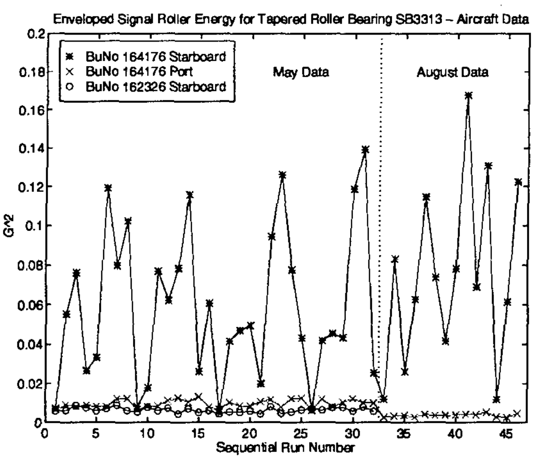

Fig. 33. Enveloped Signal Roller Energy for Bearing SB 3313, Aircraft Data.

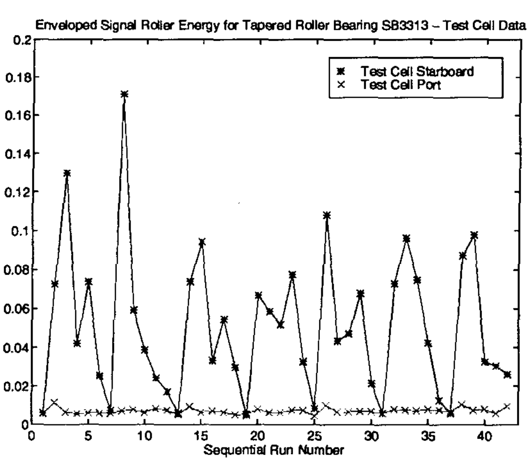

Fig. 34. Enveloped Signal Roller Energy for Bearing SB 3313, Test Cell Data.

14. Demonstrate methods that reduce false alarms and improve component condition assessments. Numerous indicators have been developed to quantify health of the drive train components. Rather than use each of these indicators in isolation, utilizing data fusion can derive additional benefit. Previous multiple sensor data fusion techniques have had great success in fault detection and classification. An automated data fusion technique currently under investigation is Hotelling's T^2 Multivariate Analysis. This technique combines multiple indicators into one composite indicator. The composite indicator has been shown to increase the robustness of condition calls since the indicator changes by orders of magnitude in the presence of a fault. In addition, false alarm calls are reduced by establishing tighter control limits that take advantage of the underlying correlation among the indicators.

In order to select the indicators that produce a more robust response, a goodness of fit test is being employed to ensure that the assumption of normality is not being violated on baseline data. All indicators not falling within the multivariate normal distribution are dropped from consideration. A correlation study is performed to further select indicators with favorable relationships. The indicators showing the strongest change in correlation between fault and baseline data are used in the T^2 analysis.

The advanced statistical quality control technique has been applied to the HTTF crack propagation data and compared to current component condition call indicators. A preliminary study produced good results and will be reported under a future NAWCAD report. This technique has provided a more robust classification of the fault with a large reduction in false alarm calls. Alternative methods exist which yield a more robust estimate of the in-control parameters, which would further decrease false alarm rates while preserving the responsiveness of the T^2 analysis to faults.

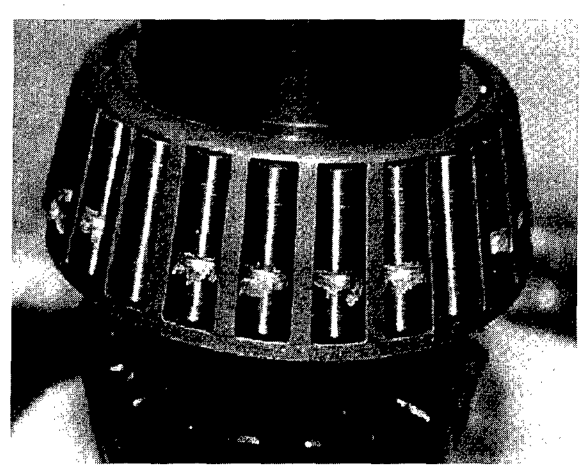

Fig. 35. SB 3313 Removed from PAX Aircraft.

Structural Usage Monitoring

Objectives

One primary HIDS program objectives was to introduce a family of structural usage data acquisition and processing algorithms. Given this capability, parts life determination is now individualized and based upon the actual helicopter usage. The usage monitoring subsystem determines the percentage of flight time the helicopter has spent in each flight mode (regime) as well as the specific regime sequence. The regime data is then used to calculate the rate that various structural components are being used up and when they need to be removed from service to maintain the required reliability rate. This capability is particularly important for aging aircraft because it enables life usage history tracking for an aircraft and its parts.

Methodologies

HIDS aircraft usage was quantified using a basic building block, or regime. Regimes are generally defined by a particular operational phase, such as takeoff, hovering, level flight, various turns and landing. Time histories of flight parameters are analyzed to determine the instantaneous phase of flight. Normal acceleration (Nz), power and yaw rate are parameters that define subsets of regimes. The time spent within each regime (or subset), during a given flight is measured and tabulated as part of a usage spectrum. Although it is almost impossible for an aircraft to be flown into every regime on a single flight, the aircraft can be expected to fly into all basic regimes over time. The continuing summation of this multi-flight experience defines the usage spectrum for the aircraft and its components.

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

In addition to providing an accurate determination of parts usage, the algorithms introduce improved data collection accuracy via automation. Usage data are collected for each flight of each aircraft - a process that produces a massive amount of usage information. Automated analysis converts this data into manageable information that is then archived. It is automatically distributed and archived to enhance the logistics decision-making process. This automated data collection enables individualized parts life determination, addressing the actual usage of each aircraft in the fleet. Additionally, all fleet aircraft in the model are now treated to the same effective margins of safety by the improved system of algorithms. This approach retains the high confidence levels (6-9's reliability) historically embodied in the original safety regulations. By the same token, it is designed to reduce inappropriate and unwanted parts life penalties.

Applications

Since its introduction in 1995, the HIDS structural usage monitoring capability has been extended to other joint BFG/Navy/USCG/USMC programs. These include USCG HUMS, the CH-53E Early Operational Aircraft (EOA) program, and the Integrated Mechanical Diagnostics (IMD) Cost and Operational Support Savings Initiative (COSSI) program, as well as to the commercial S-92/S-76 HUMS program. It is expected to provide a significant reduction in maintenance cost and improved flight safety in each of these applications.

Operational Description

The HIDS system includes all of the hardware and software to acquire data in flight. It provides on-aircraft warnings and maintenance advisories as well. The airborne portion includes interfaces to existing sensors, added production representative sensors, interfaces for all added production representative sensors as well as signal conditioning and data acquisition capability for all sensors. It executes the algorithms required to complete all of the in-flight functions and data transfer functions to the ground station. The HIDS system also includes a separate ground station that performs post-flight analysis, data report processing, maintenance diagnostics, and data archiving. The ground station hardware and software are designed to be operable in the current U.S. Navy, Coast Guard and Marine Corps maintenance environment. It provides maintenance data output products that can be readily integrated with the Navy's maintenance concept and daily operation.

Various signals are collected during the HIDS program by the on-board system. The system is comprised of two processors, a KT-1 (low frequency parameter capture, 1 Hz) and KT-3 (higher frequency parameter capture, 10Hz). The KT-1 captures aircraft state parameter data and the KT-3, high frequency vibration and optical tracker data. The KT-1 software commands the on-board system to constantly capture aircraft state parameter data at 10 Hz. When the condition is nominal, the parameter data is averaged into 1 Hz data before storing on the PCMCIA flash memory card in the Data Transfer Unit (DTU). For each exceedance, the higher rate data of a set of selected parameters is recorded for the 15 seconds before and after the exceedance. This information is stored in conjunction with the 1 Hz data record. The pilot or an aircrew member could manually initiate higher rate data recording by pushing a button on the CDU. The parameter data is downloaded to the HIDS ground station after each flight. Regimes are then "recognized" in sequence by analyzing the downloaded data. The sequence is then tabulated to produce a usage spectrum. Figures 36 and 37 show an example of the HIDS ground station flight profile outputs of flight profile (i.e., regime sequence report) and flight spectrum, respectively, for a single flight. The parameter data and regimes can be cross-checked with the ground station regime data viewer, as shown in figure 38. This capability provides users the ability to verify the data as well as the regime definitions and algorithms. Parts life tracking is performed with the cumulative flight spectrum that represents the usage history of all tracked parts installed on a given aircraft. Calculated total damage and retirement time for a given part-failure mode are presented in the usage report shown in figure 39. Other mechanical conditions also contribute to a part's fatigue damage. For example, a properly balanced and smoothed helicopter that produces little or no vibration could prolong the structural usage of some aircraft parts. One of the HIDS (and other Navy program) goals is to establish a link between these areas so that structural usage, rotor track and balance, engine performance, and drive train diagnostics can be fully integrated and jointly performed on aging aircraft.

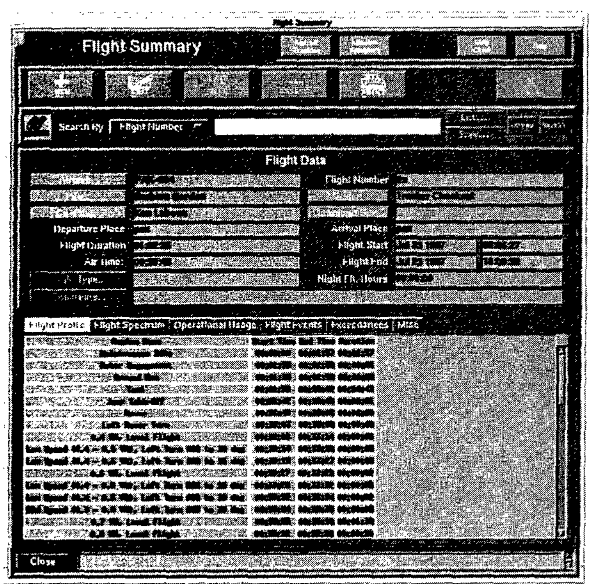

Fig.36. Regime Sequence Report for a single flight.

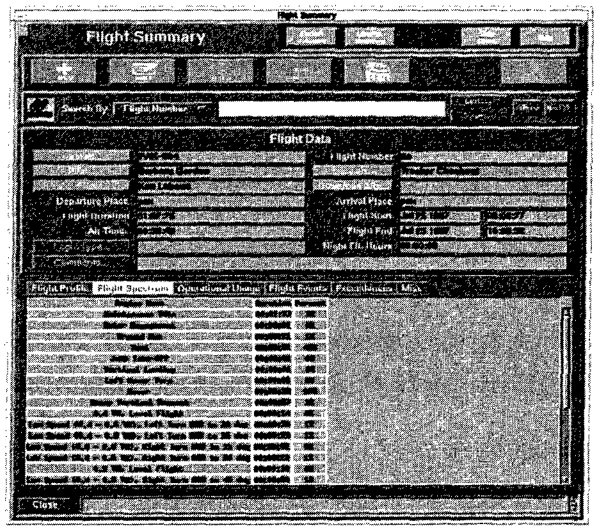

Fig.37.Regime Spectrum Report based on a single flight.

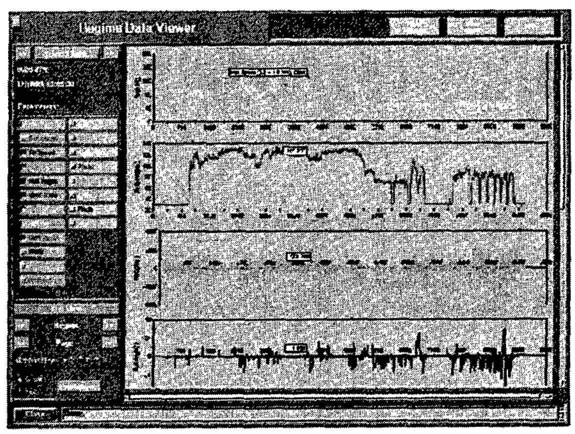

Fig.38. Regime data viewer for regime validation.

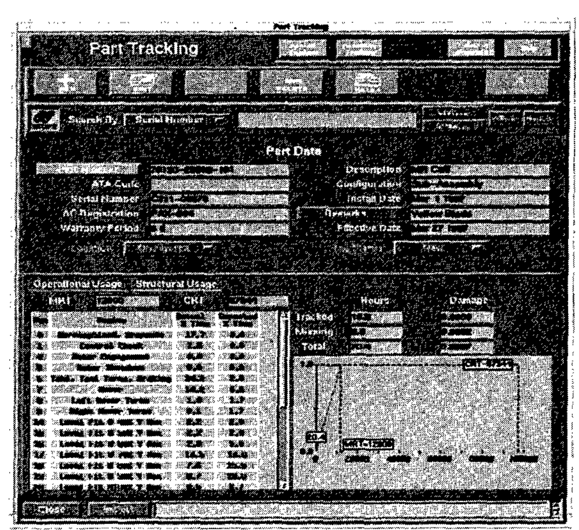

Fig.39. Parts life tracking based on actual aircraft usage.

Conclusions and Recommendations

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

2. Raw digital time series data files are a valuable asset for evaluating the performance of diagnostic and prognostic algorithms, and are necessary to identify system problems that result in false alarms. The data allows for development of additional system analysis and test capabilities to negate potential false alarms, and provides for system maintenance direction.

3. Technology to monitor and diagnose aircraft systems exists today, but reliable vibration diagnostics and prognostics requires the capability to record raw data for baseline development of various aircraft and component types to establish production system algorithms and thresholds.

4. Testing will continue in the HTTF to expand the database and refine the correlation of defect size to algorithm output level for alarm threshold settings on the SH-60 and H-53E. Continue refinement of vibration diagnostic algorithms and QA/QC routines and implement into aircraft system. Expanded testing to include the following:

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

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

(c). Continued testing of additional planetary system seeded faults.

5. NAWCADPAX needs to continue flying to continue evaluation of functional capabilities while developing recommendations and requirements for a fleet system.

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

(b) Expand diagnostic system database for regime recognition and structural usage monitoring algorithms for the SH-60.

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

7. Both the potential and actual application of various diagnostic and prognostic techniques were successfully demonstrated during this program.

8. Further development and validation of advanced model based analysis, data fusion, and additional techniques for reducing and/or eliminating false alarms is needed to completely implement a fully comprehensive prognostic capability.

9. For engines, gearbox and drive trains, rotor head assemblies, and other structural components; diagnostic and life usage monitoring capabilities are invaluable for managing damage tolerance concerns on aging helicopter fleets.

10. There is a great benefit and need to conduct significant "seeded fault" tests in order to establish an experience base for realistic alarm threshold setting and to understand fault progression rates. An adequate understanding of various component fault progression rates taken to failure is needed to fully enable prognostics.

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