A USN Development Strategy and Demonstration Results for Propulsion and Mechanical Systems Diagnostics, Prognostics and Health Management

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1. INTRODUCTION

The Helicopter Integrated Diagnostic System (HIDS) program developed and tested a prototype automated system to diagnose aircraft health and track life usage of parts [Ref. 1-4]. HIDS was conceived to fulfill the Navy requirement, as identified in a Mission Needs Statement from the Joint Atlantic and Pacific Fleet Commanders, for a reliable state-of-the-art diagnostic capability onboard rotary wing aircraft. Such a system is expected to enhance safety, increase aircraft availability, improve maintenance efficiency, and significantly reduce life cycle cost through its ability to accurately track parts life and predict impending failure of both structural and dynamic drive system components. Resulting system information can be used to direct on-condition maintenance actions, shorten troubleshooting time, and/or alert the pilot to conditions affecting flight safety.

A vendor selection competition was conducted and Technology Integration (later procured by BF Goodrich Aerospace) was selected to provide two systems for this non-production technology integration demonstration. The program approach was two fold, first to integrate available low risk monitoring technologies into a single comprehensive onboard system for flight evaluation and "showcase" demonstration at Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, MD. Second, to use the unique drive train (SH-60 setup of T700 engines, main transmission, gearboxes, and shafting driven at full power) test cell facility at NAWCAD, Trenton, NJ to document and evaluate the systems capability to detect component faults through very intensive seeded fault testing. This seeded fault testing focused mostly on but was not limited to gearbox vibration diagnostics because gearbox vibration monitoring was the least understood and hardest to validate of the helicopter monitoring functions. The SH-60 HIDS provides engine monitoring (a new set of algorithms so that, though not part of this program, it would...
be relatively easy to integrate airframe structural life monitoring capabilities. The test cell HIDS configuration also included advanced oil debris monitoring and engine electrostatic exhaust debris capabilities.

The diagnostic portion of HIDS targeted the detection and classification of mechanical component faults in the engine and drive train primarily because these systems are responsible for the majority of Navy helicopter Class A mishaps (loss of aircraft and/or personnel). The key capabilities of HIDS included:

- Condition monitoring of gears, bearings and shafts by vibration analysis
- Automation of existing shaft balancing procedures
- Automatic engine health checks (continually provides pilot with engine power available conditions)
- Parts life usage tracking
- Automated on-board Rotor Track and Balance
- User friendly ground station

Operational flight testing of HIDS began at Naval Air Station (NAS) Patuxent River in early 1995 on the SH-60 platform. For safety reasons, faulty parts are being tested and characterized with a second system at the NAWCAD HTTF. Together, the ground test facility and the SH-60 flight test aircraft provide a unique aircraft mechanical systems diagnostic laboratory to test current and emerging techniques and technologies, including several Small Business Innovative Research (SBIR) diagnostic technology efforts. The HIDS program served as the Navy’s cornerstone effort to develop, evaluate, and demonstrate helicopter integrated diagnostic capabilities and provided high quality technical data and support to the H-53 Integrated Mechanical Diagnostic Health and Usage Monitoring System (IMD HUMS) and V-22 Vibration Structural Life and Engine Diagnostics (VSLED) programs.

2. DATA COLLECTION AND ANALYSIS

The data acquisition system developed by BF Goodrich records digitized vibration and tachometer data for up to 32 channels in parallel. Gear, shaft, bearing and data quality analyses are performed and displayed using the MATLAB computation and visualization environment. Each test cell run lasts roughly one hour with six acquisitions being taken at input torque ranging from 25 to 110 percent.

All vibration data was analyzed automatically using the BF Goodrich AutoHUMS and TrendHUMS diagnostic routines. AutoHUMS saves all of the diagnostic algorithm results into an indicator database that can be trended over time with TrendHUMS. The diagnostic system reports numerous health indicators from gear, shaft and bearing analyses. The bearing algorithms include indicators based on raw and enveloped vibration data. The system also performs a real time data quality check on all raw data.

3. SEEDED FAULTS AND DIAGNOSTICS – CASE EXAMPLES

Numerous seeded fault tests were conducted as part of the HIDS program, specifically targeted to address the major reliability and safety areas, and have been fully described [1]. Significant fault propagation tests were successfully conducted where a small EDM notch was used as a stress riser in the root of the tooth. Cracks were grown from the notch until root-bending fatigue occurred in the tooth. A complete data set, from crack initiation to failure, was acquired for these tests. The fault propagation tests are prominent because they provide an understanding of failure progression dynamics, and eliminate the discrete step characteristics of other seeded fault tests.

**Planetary Gear Algorithm**

An algorithm developed by the Aeronautical and Maritime Research Laboratory of the Defence Science and Technology Organisation (DSTO), Australia, for the improved detection of planet gear faults in epicyclic gearboxes was evaluated by NAWCAD using HIDS program data through the medium of The Technical Cooperation Program (TTCP).

The DSTO planet separation algorithm uses a unique windowing/synchronous-averaging technique to discriminate between the vibration signatures of individual planet gears [5-7]. Simply put, the technique measures the vibration at a fixed point on the ring gear, applies a window function to “separate” the signals from the planet gears as they pass the measuring point, and then synchronously averages the separated signals. The technique requires no additional instrumentation over that needed for regular synchronous averaging. The separation achieved with the algorithm is excellent and does not suffer from the windowing discontinuity problems present in other planetary separation algorithms. However, it has been found that the level of separation achievable is dependent on the level of planet-pass modulation evident at the accelerometer location, and that a stronger modulation results in a more effective separation.

The DSTO planet separation algorithm was evaluated using vibration data obtained from a seeded-fault test in an SH-60 main transmission in which ½ of one tooth was removed from one of the five planet gears. This was a severe planet fault. Data were available from port and starboard ring gear accelerometers at three different torque conditions. Unfortunately, the vibration data were contaminated with a large noise signal from a generator electrical fault that overwhelmed the vibration signal (see Figure 1). This lessened the effectiveness of the algorithm. Regular and separated planet averages were computed from the data. As the fault was known to be impulsive, the averages were compared by applying the residual signal kurtosis analysis technique to both types of averages. This technique
consisted of computing the kurtosis (normalized 4th statistical moment) of the residual signal obtained after the mesh and other regular frequency components were removed from each average.

The results of the comparison are presented in Table I where the row denoted by “Comp. Planet” presents the composite planet results using regular synchronous averaging. Note that because there was no absolute planet index reference, the planets were numbered from that which produced the highest peak in the planet-pass modulation at the accelerometer position. This produced some discrepancy in the planet numbering at the various torque settings because torque has a strong affect on vibration. However, it is easy to see that the DSTO planet-separation algorithm produced residual kurtosis figures at least twice as high as that of the regular synchronous averaging technique despite the low signal to noise problem. For comparison purposes, Figure 2 shows the regular and separated synchronous averages for the port accelerometer at 200 ftlb where the separated average is for Planet 4. The fault impulse is clearly more evident in the separated average.

<table>
<thead>
<tr>
<th>Residual K</th>
<th>Port Ring Accelerometer</th>
<th>Starboard Ring Accelerometer</th>
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<tbody>
<tr>
<td></td>
<td>200 ftlb</td>
<td>300 ftlb</td>
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<tr>
<td>Comp. Planet</td>
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<td>Planet 1</td>
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<td>Planet 5</td>
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Table I. Residual kurtosis values (mesh & additional frequencies removed).

Figure 1 - Vibration signal showing noise contamination (395 Hz component).

Figure 2 - Regular and separated planet averages (port accelerometer, 200 ftlb).
The HTTF officially commenced testing during the summer of 1999 after being transferred to Pax River from Trenton, NJ. The test article was a Coast Guard HH-60J main transmission input module emanating high vibrations at half of the gear mesh frequency. The Navy has encountered a few incidents of half-mesh input modules, where every other tooth of a semi-hunting mesh is highly loaded. Since both the pinion and gear have even numbers of teeth, wear occurs at a much faster rate. Moreover, aircraft with these half-mesh input modules have a history of rejecting engines because of power turbine shaft wear and resultant cockpit torque indication errors. The Coast Guard rejected one engine on the subject aircraft because of the torque indication problem. The cause of half-mesh anomaly is believed to be gear profile errors introduced in the machining process.

The objectives of the test were to exercise the input module in a highly controlled and instrumented environment: a) develop a reliable method for the Coast Guard to identify half mesh modules using their field vibration equipment, b) determine if Navy tests could be conducted at lower torque than the current 75% requirement, making the test compatible with shipboard operations, c) test a novel fix, indexing the pinion by one tooth thereby changing mating teeth in mesh, and d) return the asset to service if within acceptable vibration limits.

All of the objectives of the test were successfully accomplished, with the exception that the material condition of the test article precluded a return to service. Prior to initial test run, inspection of the mating gears via the input module inspection port revealed wear patterns and spalling, confirming high loading of every other tooth in the gear mesh (see Figure 3). The degree of spalling was unexpected, requiring the asset to be overhauled. However, the pinion was still indexed to determine whether vibrations at the half-mesh frequency could be brought to within acceptable limits. As exhibited in Figure 4, the vibration
was reduced well below the Navy limit of 0.15 IPS, and would have allowed the asset to be returned to service. Reliable limits were developed for Coast Guard field vibration equipment by comparing measurements from several vibration monitoring systems. The chart also shows that a low 40% torque, such as required for single-engine flat-pitch operation, provides similar detection capability as for higher torques. With the real time monitoring capabilities of IMD HUMS about to enter the fleet, detection of aircraft system faults such as this half-mesh anomaly are automated and performed every flight, lowering operational costs and increasing safety.

4. DIAGNOSTICS VS. PROGNOSTICS

Diagnostics has traditionally been defined as the ability to detect and sometimes isolate a faulted component and/or failure condition. As a working definition for this paper: prognostics is the capability to provide early detection and isolation 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 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.

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 diagnostics.

The prognostics problem can be thought of as being broken down into two related but distinct technical discipline areas: first, the sensors and technologies needed to find and "see" the early incipient fault prior to actual component failure, and second, the technologies and techniques needed to accurately predict useful remaining life at any current point in time.

The prediction of accurate useful life remaining is further broken down into major enabling areas. Statistical techniques can be used to establish the degree of confidence in any life remaining prediction. Related statistical techniques are also used for boundary life remaining predictions. Modeling techniques can be employed to develop a degree of understanding of individual component and/or sub-element failure progression characteristics. Validating these models would require the generation of enough examples of actual failure events to characterize specific fault to failure progression rates. Various components and different failure modes of the same component element may have very different fault to failure progression rates.

A significant degree of component failure prediction and prognostics was demonstrated during the seeded fault tests by applying many of the same algorithms and techniques used for vibration based mechanical diagnostics. Often the extrapolation of vibration frequency data, statistical parameters and/or trending of diagnostic indices 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 similar types of "faults" so that the failure progression rate is well understood.

The experience database knowledge and the understanding of various types of failure progressions will both enable the intelligent setting of alarm thresholds for diagnostics and provide the initial basis for the prediction of useful life remaining predictions. 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 real or calculated parameters 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 (driven by either sensor or algorithm indices) 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. The recently introduced concept of applying a "Reasoner" to various levels of the diagnostic/prognostic decision process should also greatly improve accuracy.
5. PROGNOSTIC DATA DEVELOPMENT

Many factors are required to enable accurate prognosis of materiel condition. One factor that is of paramount importance, and that was addressed under the HIDS program, is reliable, repeatable, high-quality failure progression data. Comprehensive seeded fault testing accomplished during the HIDS program generated some of this data, which provides insight into failure modes and the characteristics that accompany component failure, without jeopardizing safety. Common practice when fielding health-monitoring systems has been to collect failure data on an opportunistic basis from fielded systems. The drawbacks to this approach are obvious. Safety is only increased incrementally based on data from actual mishaps, and fault data takes many years to accumulate, and is of a limited scope due to limitations of on-board systems. Tests conducted in HTTF are conceived and conducted to short-circuit this cycle, thereby enabling increased safety with reduced false alarm calls earlier than would otherwise be achieved. The up-front investment to conduct testing will be saved many times over by increasing system effectiveness, thereby preventing mishaps.

6. A STRATEGY FOR PREDICTIVE PROGNOSTICS

Most recently a strategy is being evolved to more fully develop and demonstrate the predictive aspects of prognostics. This is a very difficult quest and currently this strategy is still being generated with many of the necessary steps only defined as potential (moving) targets. This strategy will become more definitive over the next year; but the present notional thinking and approach is presented below.

Predictive prognostics is an extremely difficult and challenging area for a number of reasons, including the following. There are usually many ways a specific component type can fail, and each failure mode may require an unique analysis. Failures are often very difficult to accurately model and models can ignore “real world” effects. There is a great lack of empirical data from actual controlled failure propagation tests on which to base prognostic calculations; and these tests are very difficult and expensive to perform. It is impossible to precisely determine the future loads that a damaged component will experience.

For the development of predictive prognostics to be an achievable and manageable proposition, it needs to be broken down into “bite-sized” portions. Since this endeavor will involve many technical disciplines and intensive testing, significant collaboration between various diverse organizations will have to be implemented wherever possible to improve outcomes and reduce costs. A basic strategy to develop predictive prognostics would include the following steps. Decide which drive-train elements (in a generic sense) are best suited to prognostics. Develop fault to failure progression characteristic and useful life remaining models for these targeted elements. Perform as many experimental seeded-fault tests as affordable to verify and validate these models. Modify the useful life remaining model predictions to account for the “real world” considerations.

Some initial thoughts for a predictive prognostics development and demonstration program based on the SH-60 and the HTTF might proceed as follows. First, attempt to identify those SH-60 drive-train components which might have understandable fault to failure progression characteristics. Though an analytical study, we could at the very least, identify and eliminate for consideration those components which have no chance of having understandable failure progression characteristics. Second, do seeded faults tests in the HTTF for those few SH-60 components that have been identified as having very high failure rates and also fall in the group of components that might have understandable fault to failure progression characteristics. Do enough seeded fault examples so that we have a defined database for understanding the fault to failure progression rates of these few components. Third, develop and/or procure component specific models on fault to failure progression models (maybe a unique analysis). Failures are often very difficult to accurately model and models can ignore “real world” effects. There is a great lack of empirical data from actual controlled failure propagation tests on which to base prognostic calculations; and these tests are very difficult and expensive to perform. It is impossible to precisely determine the future loads that a damaged component will experience.

Fourth, implement this modeling software in the early SH-60 COSSI IMD fleet aircraft. It is imperative to have a defined database for understanding the fault to failure progression rates of these few components. Third, develop and/or procure component specific models on fault to failure progression models (maybe a unique analysis). Failures are often very difficult to accurately model and models can ignore “real world” effects. There is a great lack of empirical data from actual controlled failure propagation tests on which to base prognostic calculations; and these tests are very difficult and expensive to perform. It is impossible to precisely determine the future loads that a damaged component will experience.

Fifth, if and when we get fault or failure event indications; pull the components and continue to run them in the HTTF to full failure and/or do destructive tests to validate life remaining predictions.

The HTTF is a unique asset for doing some for this type of work. The SH-60 COSSI IMD program is the perfect aircraft platform to implement a fleet demonstration like this and would be an easy transition vehicle.

7. DIAGNOSTIC/PROGNOSTIC CASE EXAMPLE – MAIN BEVEL INPUT PINION INTEGRAL INNER RACE

The SH-60 main transmission module input pinion (P/N 70351-38104-102) is a complex part consisting of the female spline for the qulf shaft, 21 tooth spiral bevel pinion and integral roller bearing inner raceway, Figure 5. Roller bearing SB 2205 reacts the radial load from the spiral bevel pinion and has 30 rolling elements with a roller diameter of 0.630 inches and a pitch diameter of 7.476 inches. This fault is particularly challenging since it is located deep inside the gearbox, suggesting it would be difficult to detect.
The starboard main sensor condition indicator toggles into alarm when the fault is implanted and reverts back to okay when the fault is removed. The port main sensor 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 confirmation of the starboard condition indicator.

Statistical parameters, such as enveloped kurtosis, were the main indicators 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.

The statistical parameters used are sensor specific indicators as opposed to component specific. That is, they do not discriminate between bearings. One can however, determine the location of the fault to be on the starboard side as levels of the starboard main sensor are greater than that of the port main.

The purpose of bearing diagnostics as implemented in the HIDS program is to identify faults in the early stages of development. The fleet rejected bearing fault under test was in an advanced stage, with the spall covering approximately 1/3 the circumference of the part. Since most of the bearing health indicators are designed to detect localized faults, they did not respond to this distributed fault.

A useful approach implemented by the HIDS program is the simultaneous acquisition and analysis of a component signature by two different sensors. This is a data quality and analysis confidence measure aimed at improved diagnostics and reduced false alerts. Prior to the subject test, sensor starboard main was considered the primary sensor and starboard input the secondary. The starboard input sensor was not sensitive to this fault. Analysis to locate a sensitive secondary sensor identified the port main accelerometer as providing excellent results. While the port main and starboard input are a similar distance from the fault, the port main is on the same housing as the fault and has a better sensor orientation for this particular shaft. These efforts show the utility of redundant sensor analysis. It also exhibits the value of the parallel acquisition and storage of raw vibration data for all channels for re-processing purposes. One can then identify which accelerometer sensors and orientations are most appropriate for specific faults thereby optimizing a final, productionized version of the diagnostic system.

Prognostics could effectively be applied to the failure of this component. As the most common dynamic component cause for gearbox removal in the H-60 community, the failure mode is well recognized. The SB 2205 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. Specific indications from the inner race defect indicator will be observed. As the fault becomes progressively larger, the statistical indicators are among the dominant indicators that identify the degraded condition. By carefully tracking the progression of this fault via magnitude of response and migration across indicators, maintenance and mission planning can be conducted in an effective manner, and unscheduled downtime can be effectively reduced.

Prognostics can enable effective management of fleet assets based on the current tempo of operations. If the availability of a particular asset is not critical and a component with a well understood failure mode, such as SB 2205, is identified as degrading over time, maintenance can be scheduled in a timely manner so as to minimize secondary damage, thereby reducing repair complexity and cost. This particular component of the main transmission is readily accessible by pulling the input module. Given early detection capability, it is feasible to change the way maintenance is performed by repairing the gearbox on the aircraft, thereby precluding pulling and replacing the main rotor head and main transmission and performing the ensuing rotor track and balance evolutions. However, if aircraft availability is of paramount importance, the failure progression can be closely monitored to ensure aircraft safety while keeping a critical asset in service until such time as maintenance can be performed.

Further development and validation of advanced model-based analysis, data fusion, and other techniques is needed to reduce and/or eliminate false alarms and to completely implement a fully comprehensive prognostic capability.
8. HELICOPTER TRANSMISSION TEST FACILITY

HTTF DESCRIPTION

The test cell uses aircraft engines to provide power to all of the aircraft drive systems except the rotors. Power is absorbed through 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 increases the main rotor speed by a factor of 32. This gearbox 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. This capability provides for helicopter system level testing, uniquely enabling the detection and isolation of dynamic interface problems. Operational simulations include engine transients, topping, start up and cool down, clutch engagements, dual engine operation, over running clutch operation, one engine inoperative, rotor brake operation, and full accessories loading.

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. 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.

9. HTTF ACCOMPLISHMENTS

HTTF has served as an indispensable fleet support asset, and has made significant contributions to a number of key US Navy rotary wing platforms. These contributions are summarized below by platform.

H-60
- HIDS Extensive Seeded Fault Testing
- Qualified Improved Durability Gearbox
- Improved Durability Gearbox Sump cracking
- T-700 Flameout Testing
- T-700 Alternate Fuel Testing
- Second Source Qualification Testing
- ECP-319 High Speed Shaft
- Developed Detection Methods for Fleet Transmission Problems
- 700 Hour Simulated Mission Endurance Test
- USCG Half Mesh Detection Procedure

H-3
- Upgraded Main Transmission Qualification
- VH-3 Clutch Qualification
- Engine Flameout/Clutch Spoutout Investigation
- Emergency Lube Flow Verification
- Disconnect Coupling Failure Test
- Torque Tube Gimbal Mount Modification
- Qualified Second Source Components
- Redesign of A-Frame Oil Cooler Support
- VH-3 Over-running Clutch Anomaly

H-1
- Bevel Gear Failure Investigation
- Upgraded Transmission Qualification
- 400 Hour Simulated Mission Endurance Test

10. HTTF STATUS

The HTTF, which was originally located at NAWCAD Trenton, NJ, last operated on July 31, 1997, and was shut down as a result of the Base Realignment and Closure (BRAC) action of 1993, which closed Trenton in 1998. The cell, which was configured to accommodate an H-60 aircraft drive system, was dis-assembled, and subsequently shipped along with other Trenton test cells and equipment, for incorporation into the Propulsion System Evaluation Facility (PSEF) at NAWCAD, Patuxent River, MD.

The Helicopter Transmission Test Facility has been reassembled to the Trenton H-60 configuration and officially commenced testing during the summer of 1999. Testing will continue, using seeded faults in an H-60 main, intermediate, and tail transmissions; as well as engine, shafting, hanger bearings, and accessories. This work will support the fleet wide introduction of the IMD HUMS into the H-60 and H-53 aircraft. Additional 'piggy-back' testing of various sensor technologies in support of the H-53, H-60, H-1, V-22, JSF, and other programs, as well as qualification testing for CIP and alternate source parts is also planned.
11. HTTF PLANNED TECHNOLOGY EVALUATIONS

Several new technologies have been procured to enhance our capabilities to evaluate diagnostic and prognostic algorithms and methodologies. Some of these technologies are being developed under Small Business Innovative Research (SBIR) programs to evaluate potentially beneficial and promising techniques. These new technologies will be used as advanced test cell instrumentation. They will also be evaluated on their own merit.

Oil System

Innovative Dynamics, Inc. is developing a real time oil debris monitoring system for use in the gearbox lubricating system flow path. The system is a combination of sensors allowing for the detection of multiple size particles, varying from 5 to 2000 mm in size. Algorithms used in the system discern air bubbles from wear particles and trend the amount of debris generation along with the particulate size. The concept has been proven in a water lab and computer oil-flow simulation model. IDI's oil debris monitoring system will be tested in the HTTF for further validation and verification before being flight-tested for incorporation in the SH-60R.

Vibration Sensing and Analysis

Hood Technology Inc. is currently working on a system to detect low cycle fatigue in gas turbine engines. The system uses multiple sensors to monitor rotor tip clearance as well as blade passage. A tachometer is used to monitor disk location and rotational velocity. Each blade is tracked to monitor for the onset of elastic and plastic deformation. Hub cracks are associated with a change of arrival time of the blades, while asymmetric lengthening of the blades is an indication of plastic deformation leading toward disk burst. The system is currently being tested in the US Navy Patuxent River spin pit facility and working toward military and commercial certification.

Neural Network and Data Fusion

Orincon classical and neural network diagnostic algorithms operating in the RIPPENO (Real-time Interactive Programming and Processing Environment) software package will be evaluated in near-real-time mode using the SH-60 drive system configuration in the HTTF with various seeded faults. The software package is a graphical based environment that allows you to quickly and easily create information processing systems which can be encoded into a variety of computer platforms. In addition, Orincon data fusion techniques will be demonstrated with the objective of maximizing fault detection ability while reducing incidence of false alarms.

Multivariate Analysis

Hotelling's T2 Multivariate Analysis is based upon the underlying correlation of the individual indicators used to build the composite T2 indicator. The greater the change in correlation in the presence of a fault, the more robust the component condition call. The effectiveness of the condition call is dramatically increased when used with statistical methods to select the indicators used. The indicator has been shown to change by orders of magnitude in the presence of a fault, over current multiple indicator hard-threshold based methods. Hotelling's T2 Analysis shows promise with a more robust classification of faults and a large reduction in false alarm calls. Future work in this area will be to explore alternative methods which better estimate in-control parameters, further decreasing false alarm rates while preserving the responsiveness of the T2 analysis to faults.

12. HTTF FUTURE EFFORTS

Currently the US Navy has a library of fault tests run in the HTTF. The library’s database consists of artificially induced and naturally occurring faults. Continued seeded fault testing is planned to expand the library’s database, as well as advance current diagnostic/prognostic techniques and evaluate new technologies. The database already contains some fault propagation data examples, from fault initiation to near failure conditions. Testing will be planned to expand the database of component fault progression examples. To evaluate the sensitivity of diagnostic and prognostics techniques to fault progression; components with varying degrees of degradation will be tested. Following a successful diagnosis of a most severe case, a fault propagation test is completed. These tests will also be used in an attempt to characterize failure progression rates.

The planetary drive system is the next major component group to be tested. The planned fault run is to insert a sun gear with 1/3 of a tooth removed. If diagnosed correctly, a failure progression test using an EDM notch for crack initiation will follow.

In order to obtain naturally occurring faults the Navy is working closely with Storage, Analysis, Failure Evaluation and Reclamation (SAFR), an organization that tracks and collects faults found in fleet aircraft. The Navy has a list with SAFR to collect drivetrain components prone to operational or premature failure. These components will be tested in the HTTF in order to gain knowledge of the fault’s signature so a fleet occurring catastrophic failure can be avoided.

13. CONCLUSIONS

Fault propagation tests provide an understanding of failure progression dynamics, and eliminate the discrete step characteristics of other seeded fault tests. Reliable, repeatable, high-quality failure progression data obtained from these tests is of paramount importance, enabling
increased safety with reduced false alarm calls earlier than could otherwise be achieved.

Prognostics can enable effective management of fleet assets based on the current tempo of operations. If the availability of a particular asset is not critical and a component with a well understood failure mode is identified as degrading over time, maintenance can be scheduled in a timely manner so as to minimize secondary damage, thereby reducing repair complexity and cost. However, if aircraft availability is of paramount importance, the failure progression can be closely monitored to ensure aircraft safety while keeping a critical asset in service until such time as maintenance can be performed.

The HTTF has served as an indispensable fleet support asset, and has made significant contributions to a number of key US Navy rotary wing platforms.

Further development and validation of advanced model-based analysis, data fusion, and other techniques is needed to reduce and/or eliminate false alarms and to completely implement a fully comprehensive prognostic capability.

REFERENCES


