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IMPROVING MILITARY HELICOPTER SUPPORTABILITY WITH THE INTEGRATED MECHANICAL DIAGNOSTICS (IMD) HEALTH & USAGE MONITORING SYSTEM (HUMS)

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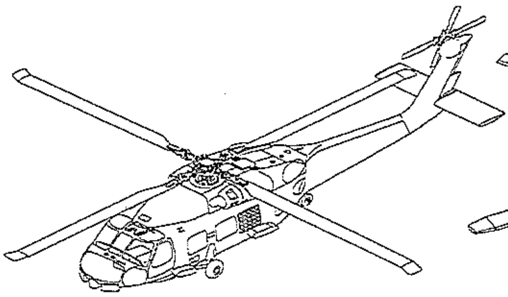

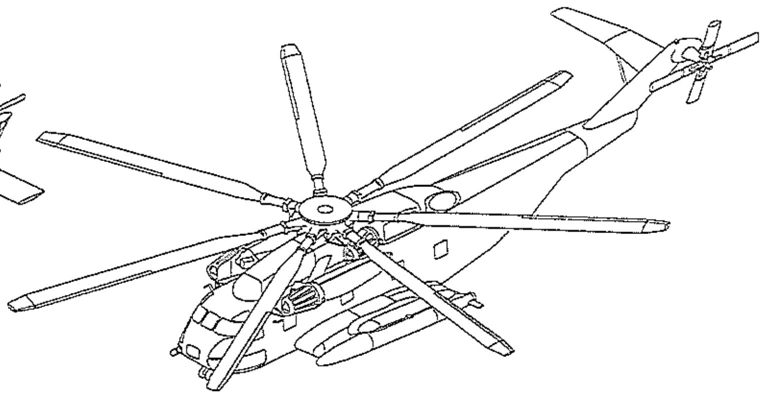

Abstract

Compared with fixed-wing aircraft, helicopters have a far greater number of dynamic components in the rotor system and drive train. Many components are life limited, and most require significant troubleshooting and maintenance. Current diagnostic techniques depend heavily on manual fault detection and isolation. Thus, maintenance is labor intensive and dependent on experienced personnel. The diagnostic process is inexact, leading to a sequential "remove and replace" approach based on incomplete or inaccurate data. This may result in maintenance-induced damage or retirement of components with remaining useful life. The IMD HUMS system combines several significant diagnostic capabilities into an even more capable integrated system. A team led by BFGoodrich Aerospace and the program offices of the H-53 and Executive helicopters (PMA-261), and the SH-60 Multi-mission Helicopters (PMA-299) was selected in a 1997 competition run by DARPA to implement the BFGoodrich IMD-HUMS system on the H-60 and CH-53E under the OSD Commercial Operations and Support Savings Initiative (COSSI). The scope of the program includes outfitting each aircraft model with a production-ready on-board system, deploying ground station software within the fleet environment, and linking the entire information system to various Government functional organizations, the

aircraft OEM, and the IMD-HUMS supplier. The system performs automated monitoring, status evaluation, diagnostics, and reporting on the aircraft. Some of the features of the in-flight system include continuous monitoring of engines, flight regimes, and critical mechanical systems; automated rotor track and balance calculations. The ground system performs usage and structural life consumption calculations, maintenance required forecasting and reporting, and links to the logistics system.

The program adopted several important systems engineering and .acquisition reform tenets, including performance-based specifications, an open systems architecture, requirements management/engineering, and joint leadership of integrated program teams. These reforms will ultimately result in an early delivery of a more capable product, at lower cost, which is more easily migrated to other helicopter platforms. The system represents a revolutionary change in the Navy's aviation maintenance philosophy, providing the enabling technologies for condition-based maintenance and the resultant labor and cost savings that come from such an approach.

1. Introduction: The United States Navy and United States Marine Corps, in partnership with BFGoodrich Aerospace, have embarked upon an ambitious program to improve operational readiness and flight safety while slashing maintenance-related costs. As of this writing (July 1999), the IMD HUMS program has completed integration testing of the first fully functional production-ready system on two aircraft types, the SH-60B multi-mission helicopter and the CH-53E heavy lift helicopter. Flight test and full system technical evaluation has commenced on the CH-53E with SH-60B testing scheduled to commence in 4-6 weeks. The system has evolved under Joint Dual-Use Program Office's (JDUPO) Commercial Operations and Support Savings Initiative (COSSI) and is now referred to as IMD-HUMS. This paper presents the system's current state of evolution and outlines how the system will continue to evolve as we progress toward fleet-wide deployment. This paper will describe the components and processes that make up the fully functional and integrated system. It will also outline the near term implementation plan to prepare for eventual transition from initial installation to fleet-wide deployment.

2. System Description: The IMD HUMS consists of an airborne system and a ground based system, both implemented with an open systems architecture approach. The architecture enables efficient data and information exchange between the two systems and among other ground base stations. Figure 1 summarizes the functional capabilities of the system. Note that the system is modular and scaleable; ie, the functionality summarized in Figure 1 can be implemented fully or partially, and the system can be scaled from the smallest single engine helicopter to the largest 3-engine helicopters such as the CH-53E. The airborne system acquires and processes data related to four specific areas; current performance and limit exceedances, mechanical diagnostics, rotor track and balance, and service life utilization. The data used by the system is obtained primarily from state sensors that are part of the basic aircraft (including busses), and specially mounted accelerometers and shaft position sensors. Information of immediate benefit to the flight crew is automatically (and can be selectively) displayed in the cockpit. However, the majority of the raw data and processed information is exported to the ground based station after landing. The ground based station is used to conduct preliminary analyses to aid local maintainers. In the Navy implementation, ground station software resides on the Navy's maintenance management and logistics support work stations hardware and passes pertinent trending , prognostic, and planning data to an up-line database The software is designed with flexible, configurable, published interfaces to allow other functionality to be readily integrated. The NT-based operating system uses an ODBC-compatible Oracle™ database. These features enable the effective transition of several Navy diagnostics and maintenance programs to the current highly integrated and flexible system.

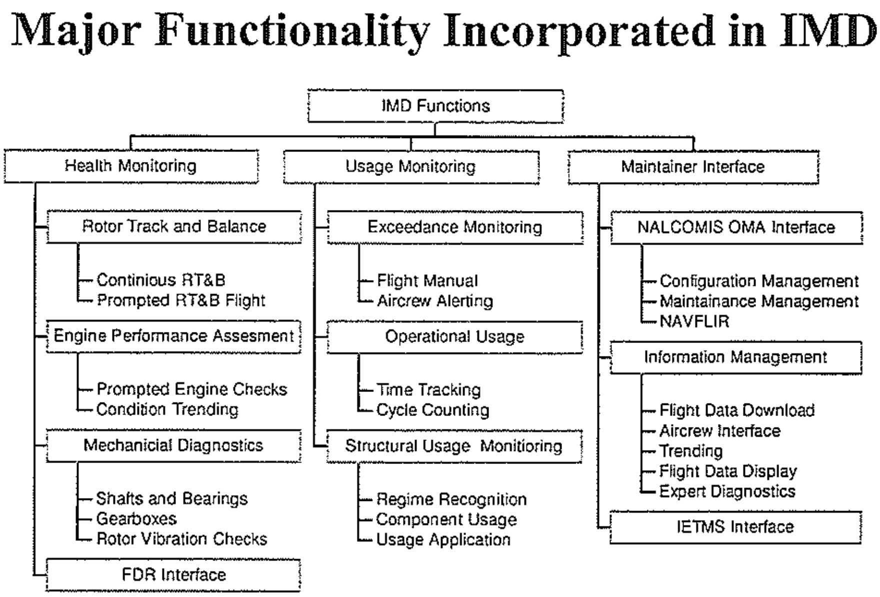

Figure. 1 System Functionality

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

The Main Processor Unit (MPU) is composed of a Primary Processor Unit (PPU) and a Vibration Processor Unit (VPU). See Figure 2. The PPU serves as the system controller by managing information both in and out. It receives information from the Remote Data Concentrator (RDC) and the VPU. The RDC provides information derived from the state sensors and processors that make up the original manufacturer's equipment suite. The VPU provides selected raw data signals as well as processed signals. During flight, the MPU acquires data at 10 hertz, and stores most data at 1 hz, unless there is an exceedance or other noteworthy event. In the case of an exceedance, the MPU will acquire and record raw signals from the VPU for the exceedance duration plus and minus 15 seconds. The CDU provides an interface that allows the operator to view this data in real-time. Based on the information requested, the MPU sends information to the CDU. Both raw and processed flight data is transferred to the Ground Base System via the DTU. The DTU uses a PCMCIA flash memory card as a medium for temporary flight data storage. It is easily removable from the aircraft for data transfer to the ground station. The card serves a dual function as it is also used to upload the data needed to configure the on-board system.

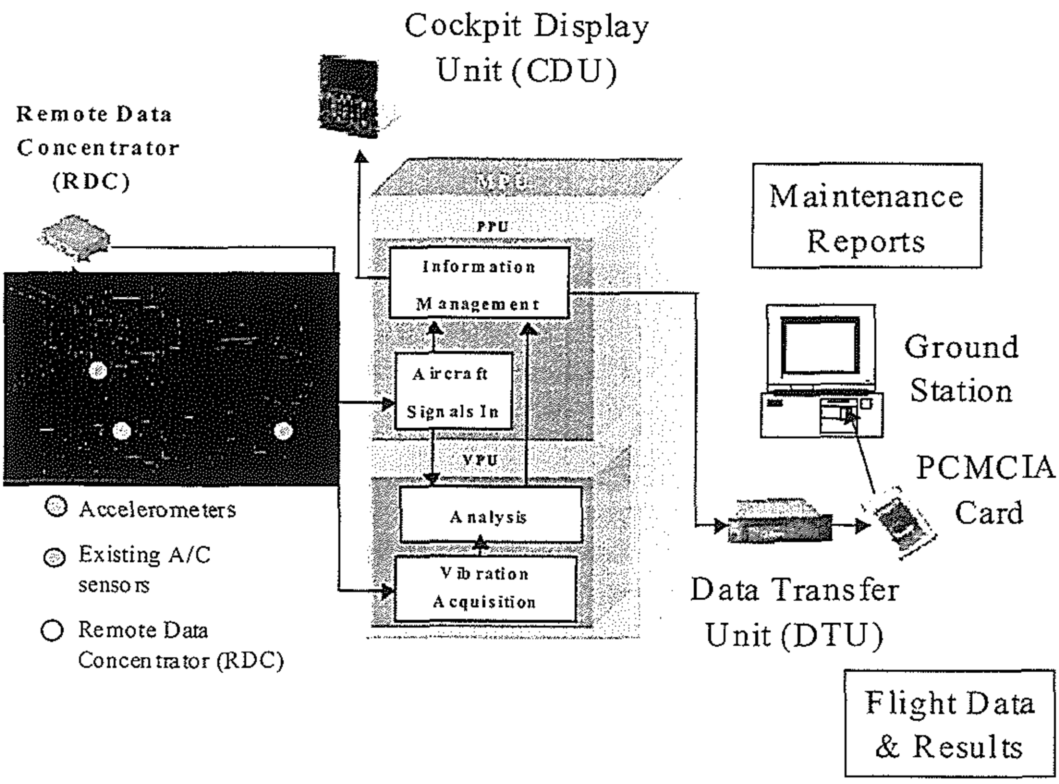

Figure 2. General Configuration of the Airborne System Primary Components

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

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

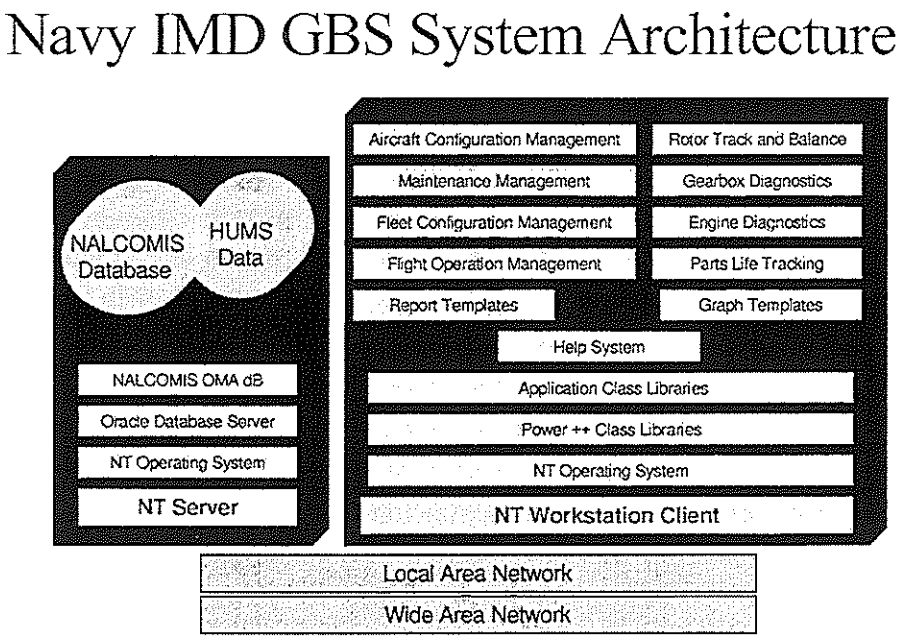

Figure 3. Ground Station Software Integrated With NALCOMIS

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

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

Usage Monitoring. One primary IMD dual use program objective is to introduce and institutionalize a family of automated structural usage data acquisition and processing algorithms. Given this capability, parts life determination is individualized and now based upon the actual helicopter usage. The usage monitoring subsystem determines the percentage of flight time the helicopter has spent in each flight mode (regime) as well as the specific regime sequence. The regime data is then used to calculate component damage accrual rates as well as a projected removal from service date to maintain the required reliability level.

A regime is the basic building block of an aircraft usage monitoring system. Some examples of regimes are takeoff, hovering, level flight, various turns and landing. Time histories of flight parameters are analyzed to determine the instantaneous phase of flight. Subsets of regimes can exist within the confines of a basic regime and are determined using parameters such as normal acceleration, angle of bank, and power levels. For a given flight, the time spent within each regime is measured and tabulated as part of a usage spectrum. It is unlikely that an aircraft will be flown into every regime on a single flight. However, over a period of time, the aircraft can be expected to fly into every basic regime with the distribution of regimes depending on the missions flown. The continuing summation of multi-flight experience defines the mission-specific and composite usage spectra for the aircraft and its components.

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

In addition to providing an accurate determination of parts usage, the algorithms introduce improved data collection accuracy via automation. Usage data are collected for each flight of each aircraft - a process that produces a massive amount of usage information. Automated analysis converts this data into manageable information that is then archived and automatically distributed to enhance the logistics decision-making process. This automated data collection enables individualized parts life determination, addressing the actual usage of each aircraft in the fleet. Inappropriate parts life penalties will be eliminated for those aircraft that are not flown severely. In addition, safety is improved in the unlikely event that usage on a particular aircraft is more severe than anticipated. Additionally, all fleet aircraft in the model will be treated to the same effective margins of safety by the improved system of algorithms. The intent of this approach is to retain the high confidence levels (6-9's, or "one-in-a-million" probability of catastrophic failure) historically embodied in the original safety regulations. Please contact Dr. Harrison Chin (hchin@aisma.bfg.com) or Mr. Gene Barndt (barndtgl@navair.navy.mil) for technical details related to the usage monitoring functions.

Note: The "equivalent safety" imperative mentioned above dictates a need for affordable human oversight using automated and semi-automated procedures. IMD HUMS provides this oversight capability without the need for operator input or action. The oversight required will diminish as confidence in the system improves, but it will always be present. The system objective is a process that allows engineering management the opportunity to randomly inspect the data as a quality assurance function or to inspect on exception.

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

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

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

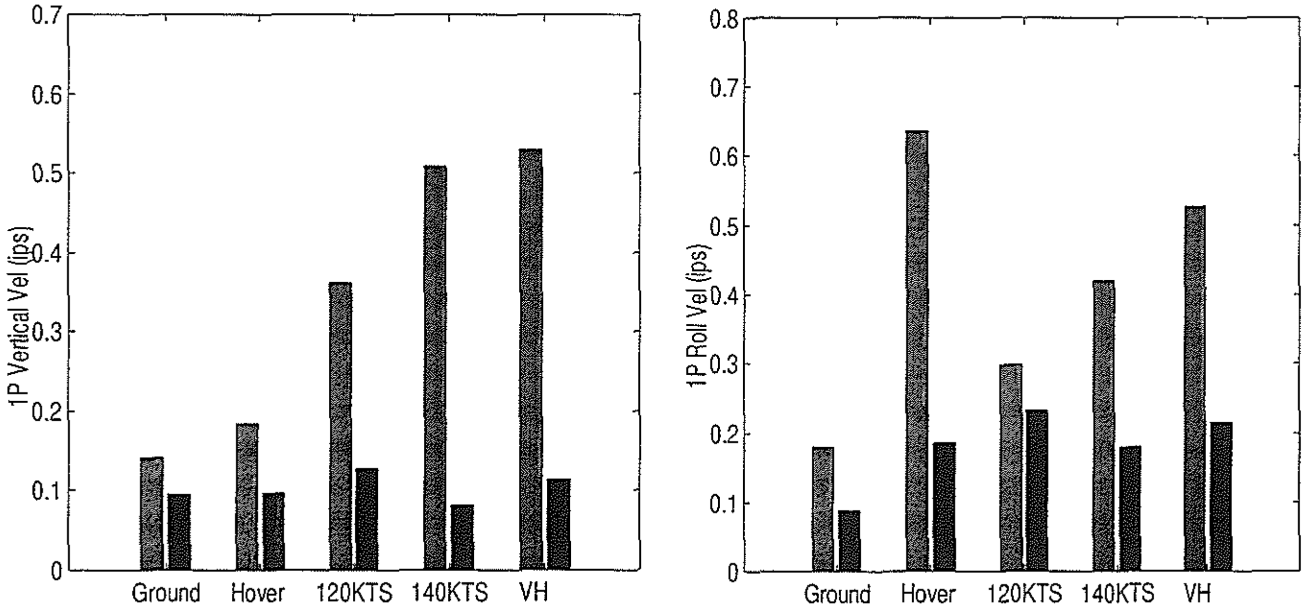

Figure 4. One Pass Optimization of 6 Degrees-of-Freedom Balance (H-60 vertical and roll data)

<u>Mechanical Diagnostics.</u> The diagnostics function provides both comprehensive integrated component- by -component mechanical diagnostics, as well as traditional NAVAIR 01-1A-24 procedures for the CH-53E, and A1-H60CA-VIB-000 procedures for the SH-60 models. The IMD diagnostics focus on individual gears, bearings and shafts. The function includes advanced diagnostics software that is both modular and upgradeable. The IMD HUMS system was designed to provide mechanical diagnostics capabilities far in excess of those offered by the Navy's NAVAIR 01-1A-24 Vibration and Analysis Test System (VATS) or equivalents, while still providing equivalent functionality in the aforementioned areas. Figure 5 shows the extent of the components covered by the IMD HUMS system for the SH-60 in comparison to those covered by the VATS. IMD HUMS data acquisition is fully automated and occurs without aircrew intervention, unless specifically requested. The system will autonomously provide Flight Safety Advisories in the event that signals associated with critical components exceed

preset thresholds. In fact, the system is designed for DO178 Level B certification in accordance with the United States Federal Aviation Administration procedures.

IMD HUMS's expert diagnostics depend highly upon advanced signal processing as well as the ability to determine component condition based on the signals and indicators obtained from a variety of diverse sources. Relying on a single sensor to indicate a component's wellness may give spurious indications due to sensitivity, the efficiency with which the sensor receives the intended signal, robustness of the analysis algorithm(s), etc. To preclude this, the results obtained by analyzing signals obtained from multiple sensors are combined to provide a single indicator that is both distinct and robust.

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

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

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

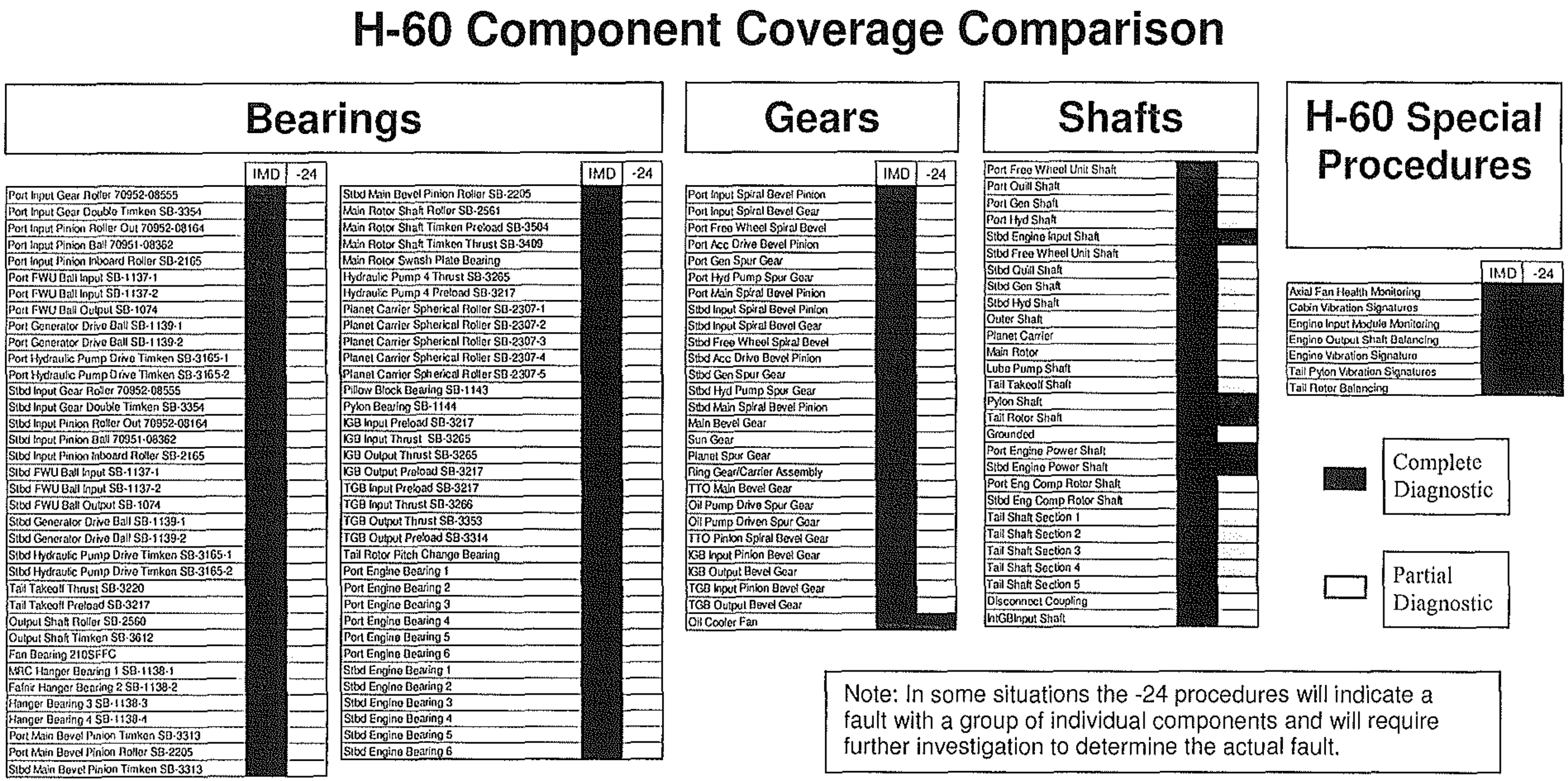

Figure 5. Component Coverage Comparison Between H-60 and NAVAIR 01-1A-24

6. Deployment Schedule and System Characterization: As of this writing (July 1999), two aircraft (one aircraft of each type) are fitted with the IMD HUMS system and flight trials have commenced on the CH-53E at NAS Patuxent River MD. Five additional aircraft of each type will be fitted in late 1999 and early 2000. These aircraft will be deployed in fleet training squadrons and serve as data sources for accelerated system characterization and service suitability evaluations. Navy, Marine and BFGoodrich engineers and maintenance specialists will jointly analyze data obtained from operational service. It will be used to hone the system sensitivities and allow the customer to confidently set cautionary thresholds and exceedance levels. The data will subsequently be used to determine the effectiveness of developmental algorithms by comparing their performance to the results obtained by using current techniques.

Together with Optimized NALCOMIS OMA, IMD HUMS enables the Navy and Marine Corps to start the transition to true condition-based aviation maintenance. This new capability to capture actual usage and condition, coupled with total visibility into the current component configuration for each aircraft, makes possible the process re-engineering that leads to extensive operations and support cost savings.

7. Conclusion: The IMD HUMS has become reality under an aggressive schedule due to the close cooperation between user and provider. The Integrated Product Team concept which united US Navy, US Marine Corps, and BFGoodrich team members has produced a system which will fulfill the promise of improved operational readiness and flight safety with reduced maintenance-related costs. Once the integrated team has successfully completed both technical and operational evaluations, a full rate production decision will allow the outfitting of all Navy H-53E, and H-60 aircraft. This program will also serve as a prototype for additional savings to be realized by installing like systems on a much wider variety of complex aircraft and ground vehicles. As of this writing, BFGoodrich has been awarded two additional COSSI programs through OSD to leverage the IMD HUMS program and prototype the system on U.S. Marine Corps UH-1Ys and AH-1Zs, and the Army's UH-60Gs.

References

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