The IMD HUMS as a Tool for Rotorcraft Health Management and Diagnostics

Robert Hess
(802) 877 4710
rhess@aisvt.bfg.com

Alan Duke
(802) 877-4619
aduke@aisvt.bfg.com

David Kogut
(802) 877-4269
dkogut@aisvt.bfg.com

BFGoodrich Aerospace
Fuel and Utility Systems
Vergennes, VT 05491

Abstract – The current generation BFGoodrich Integrated Mechanical Diagnostics Health and Usage Monitoring System (IMD HUMS) is the result of many years of development on earlier programs. The resulting system provides an extensive set of functions to support rotorcraft health and diagnostics processing. These functions support rotor track and balance operations, gearbox and drivetrain mechanical diagnostics, operational and structural usage, exceedance detection and processing and engine power assurance checks. The system is comprised of both onboard, flightworthy LRUs which perform the requisite realtime data acquisition, analysis, display and storage, supplemented with networked ground-based workstations which provide maintainer configuration and maintenance management functions along with specialized diagnostics tools. The system is being fielded on a number of helicopter platforms. These programs demonstrate the capabilities of the IMD HUMS as a tool for rotorcraft health management and diagnostics.

TABLE OF CONTENTS

1. HISTORY

BFGoodrich Aerospace has been very involved in rotorcraft health management and diagnostic system development over the past decade. Its first generation health and usage diagnostic systems were used to prove the advanced processing capabilities being demonstrated in the current generation of Integrated Mechanical Diagnostics Health and Usage Monitoring System (IMD HUMS). Two programs in particular provided the groundwork for the BFG IMD HUMS – The H-60 HIDS and the H-53 EOA.

H-60 HIDS - The H-60 Helicopter Integrated Diagnostics System (HIDS) program was initiated in 1993 by the U.S. Navy NAVAIRWARCENACDIV to advance multiple helicopter HUMS technologies[1]. This program performed flight and ground-testing testing to demonstrate:

- Acquisition of mechanical diagnostics data to support development and evaluation of diagnostic algorithms.
- Automation of data acquisition, analysis, and communications in a flightworthy system.
- Integration of engine monitoring, gearbox / drivetrain vibration diagnostics, in-flight rotor track and balance, parts life usage tracking, automated flight regime recognition and power assurance checks.

H-53 EOA - BFGoodrich was awarded a contract in April 1996 to install an Integrated Mechanical Diagnostics System (IMDS) on two CH-53E helicopters. The goal of the program was to conduct an early operational assessment (EOA) of BFGoodrich IMDS technology for possible fleet insertion via the CH-53 Lead the Fleet Program.

The EOA IMDS system was based on the H-60 HIDS system and consisted of the following components:

- KT-1 (Main Processing Unit) - Measures aircraft parameters and controls other system components
- KT-3 (Vibration Processing Unit) - Measures and processes vibration and indexing data
- CDU (Control Display Unit) - Displays IMDS information on board and allows aircrew control of system functions.
- DTU (Data Transfer Unit) - Stores data from KT-1 to a PCMCIA memory card
- CSMU (Crash Survivable Memory Unit)
- COTS Flight Data Recorder
- RMSU (Removable Mass Storage Unit) - Hard Disk that records KT-3 vibration data
- GBS (Ground Based System) - Workstation for analysis of IMDS data

The first system was installed at NAVAIRWARCEN. Once the flight clearance was issued, the baseline system was flown. Aircraft parameter data was successfully collected and displayed on the GBS.

About this time, BFGoodrich moved its IMD HUMS product line forward and reengineered the IMDS system as an open architecture, dual-use (military/civil) product. The importance of the EOA program shifted from it original goal to one of risk reduction for new generation IMD development.

A complete IMDS system was installed and flight test began in 1998. During the flight test period, the team accomplished the following:

- Acquired Rotor Track and Balance (RTB) influence coefficient data for vibration and blade track (Main rotor and tail rotor)
- Performed RTB trials to validate BFGoodrich RTB capability
- Acquired baseline mechanical diagnostics data including vibration data at traditional locations
- Acquired regime data under known regimes to validate BFGoodrich regime recognition algorithms
- Acquired engine and other aircraft parameters for further analysis

2. IMD HUMS

Background – In 1997 BFGoodrich started the development of its current generation health and mechanical diagnostics system. The IMD HUMS development was performed under the auspices of the DoD Commercial Operations & Support Savings Initiative (COSSI). COSSI programs are used to streamline the contracting process in weapons systems acquisition. They emphasize the use of commercial practices to create dual use (military / commercial) products. COSSI programs provide a phased plan for technology introduction. In Phase I, BFGoodrich developed a system to demonstrate both technical and cost benefit / cost avoidance aspects of the system. These include, but are not limited to:

- Decreasing maintenance man-hours per flight
- Reducing scheduled component removals
- Improving Aircraft Safety
- Identifying failing components prior to catastrophic failure
- Providing aircrews with detailed secondary indication capability
- Providing support teams with better information for making in field component life extension calls
- Increasing availability
- Increasing reliability
- Enabling rapid determination of aircraft status
- Identifying maintenance and logistics actions

Following a successful Phase I demonstration, COSSI programs enter the Phase II fleet-wide production deliveries. The current IMD HUMS programs with the Navy are completing their Phase I efforts and are transitioning into COSSI Phase II efforts. COSSI efforts for the Army and Marines are in Phase I development and are expected to enter Phase II efforts following successful cost benefits analyses.

3. IMD HUMS FUNCTIONALITY

Typical Functions – The IMD HUMS has been designed to support a variety of health and maintenance related functions. These include:

- Engine Performance Assessment – The IMD HUMS automates traditional engine health checks (HIT check, max power checks, etc.) in accordance with established engine power assurance procedures. Other measures of engine health (temperatures, pressures, chip detection, etc.) are also monitored.
- Rotor Track and Balance (RTB) – Both trackerless and tracker-based RTB operations are supported. Both prompted and automatic data acquisitions can be used to calculate track and balance solutions, on-board or at the maintenance facility.
- Absorber Tuning – Vibration information collected from cabin-mounted accelerometer packages is used to support the tuning of vibration absorbers.
- Mechanical Diagnostics – Vibration information acquired from the drivetrain is analyzed by the IMD HUMS in-flight to ascertain drivetrain health.
- Exceedance Monitoring – Monitoring, annunciation and recording of flight manual-based limit exceedances or other types of limit exceedances (drivetrain vibration levels, health indicators, etc.).
- Usage Monitoring – The IMD HUMS monitors operational usage parameters (engine operating hours, flight hours, etc.) as well as calculating structural usage measures derived from usage-spectra-based regime recognition.

IMD HUMS Elements – The IMD HUMS achieves its functionality using a number of elements:

- Data Repository - A common shared memory area allowing differing processing elements to share information.
- Event Monitoring – Periodic or instantaneous detection of limit exceedances or flight-related events (takeoff, landing, etc.).
- Automated Procedure Processing – Background data acquisition and processing / recording of rotor and drivetrain vibrations as well as operational and structural usage monitoring.
- Prompted Procedure Processing – User driven data acquisition and processing / recording of rotor and drivetrain vibrations and engine power assurance checks.
- Data Logging – Periodic and event-driven logging of acquired data and analysis results.
- Display Interface – A generic display interface capability can be configured to support a BFG-supplied crew display, or the system can be configured to operate with an existing aircraft display, such as a multi-function display (MFD).
- I/O – Management of data acquisition and communication with other aircraft subsystems.
- Vibration Processing Management – Control and acquisition of vibration data.
- Debrief – Post-flight debrief of the aircrew and its related electronic logbook operations.
- Maintenance Action Generation – Recommendation of specific maintenance operations with events observed in-flight.
- Trending – All archival data can be trended on the ground to support fault detection.
- Diagnostics – Diagnostics can be generated on the ground to support maintenance operations. Traditional customer maintenance rules can be implemented as well as advanced disgnostic techniques.
- CM/MM – The IMD HUMS can utilize an existing customer configuration management / maintenance management system to support serialized parts tracking and parts usage.
- Open Architecture - The open design of both the hardware and software of the BFG IMD HUMS allows it to be reconfigured for new aircraft applications, as well as allowing new BFG or third-party hardware and software technology to be inserted [2][3].

IMD HUMS Processing – Owing to the modular design of the IMD HUMS, each of the major processing elements described above can be configured to provide the health management and diagnostic functions. Top-level dataflow diagrams for these functions for a typical program are presented in Figures 1a thru 1e.

4. IMD HUMS ELEMENTS

The IMD HUMS is composed of two major elements. On-board acquisition and processing is managed by the On-Board System (OBS), while ground-based maintainer operations are performed in the Ground Station (GS) element.

On-Board System - The OBS is responsible for collecting, processing, analyzing, and storing data obtained from sensors located throughout the aircraft. The principal element of the OBS is the Main Processing Unit (MPU). The MPU analyzes the input data for exceedances and events, calculates various flight regimes, performs various diagnostic algorithms, normalizes trend data, and stores the data to an onboard data cartridge. The MPU is a VME-based system housed in a ½ ATR enclosure (see Figure 2).

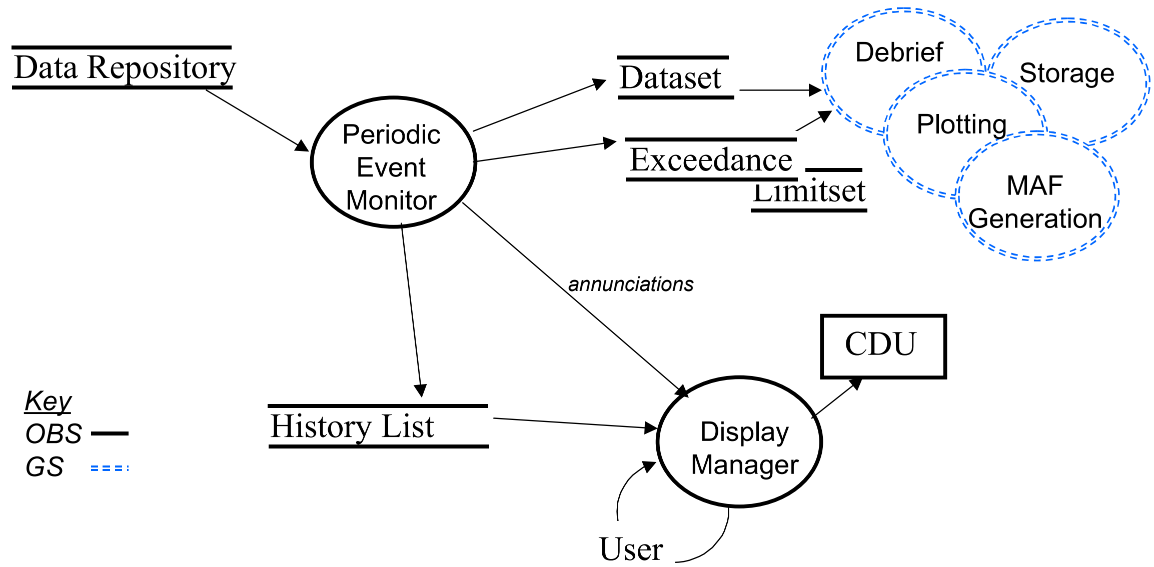


Figure 1a. Organization of IMD HUMS Elements to Perform Exceedance Processing

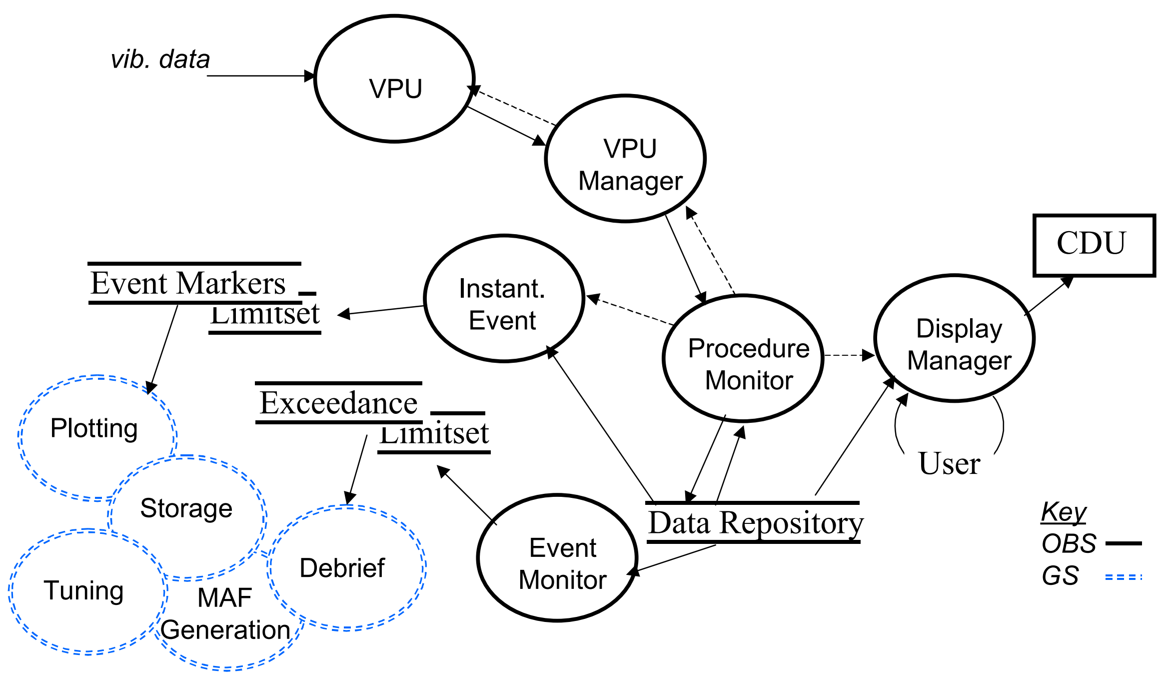


Figure 1b. Organization of IMD HUMS Elements to Perform Rotor Track and Balance Processing

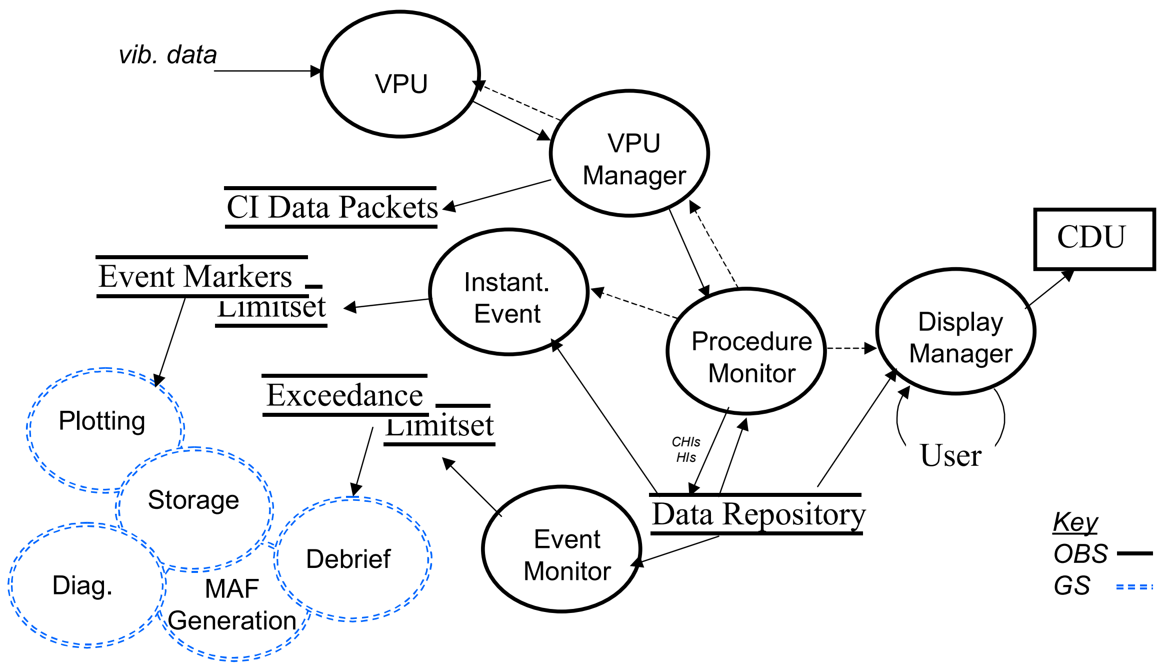


Figure 1c. Organization of IMD HUMS Elements to Perform Mechanical Diagnostics Processing

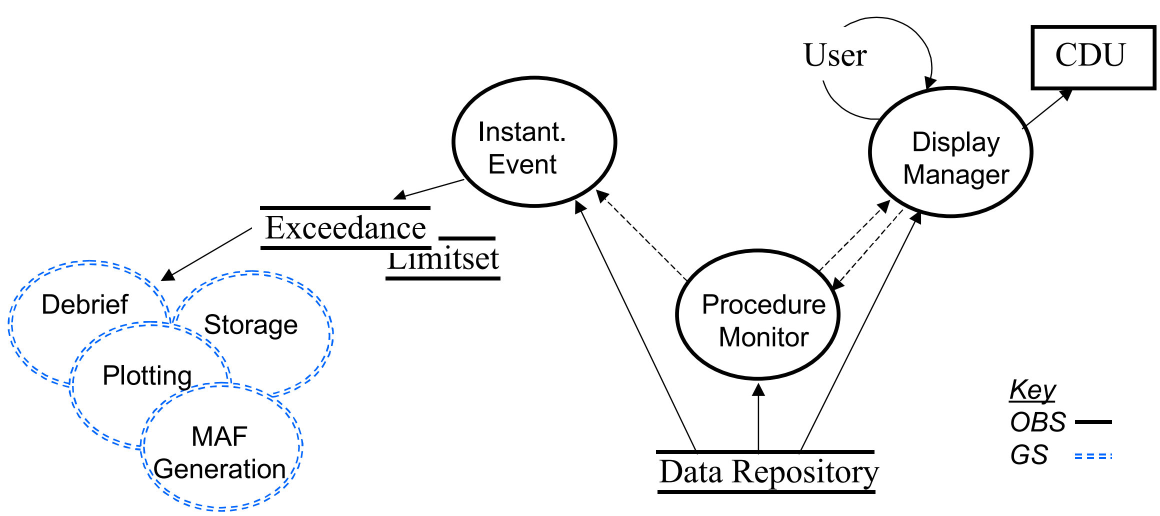


Figure 1d. Organization of IMD HUMS Elements to Perform Engine Power Assurance Processing

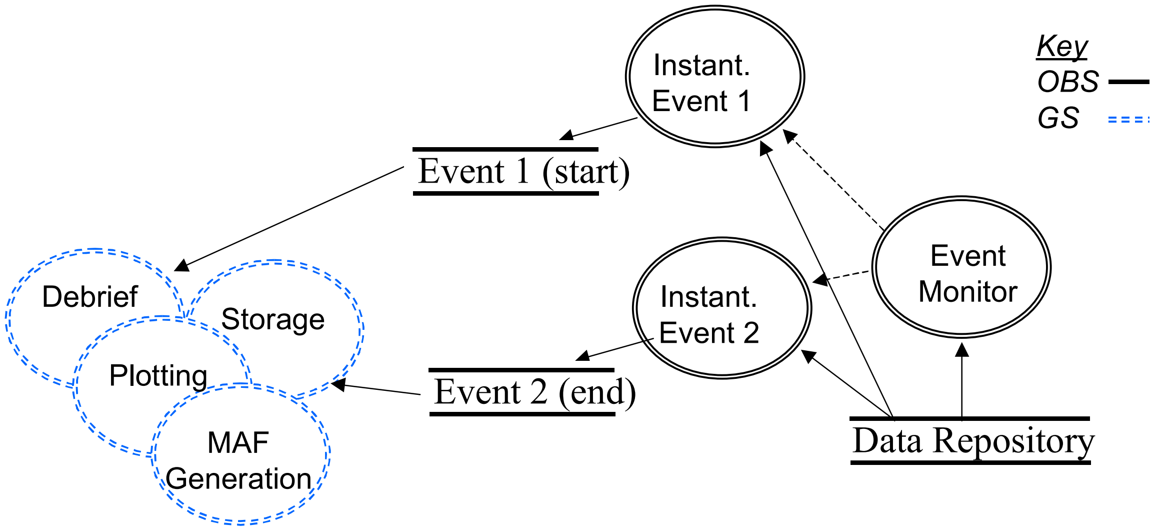


Figure 1e. Organization of IMD HUMS Elements to Perform Operational Usage Processing

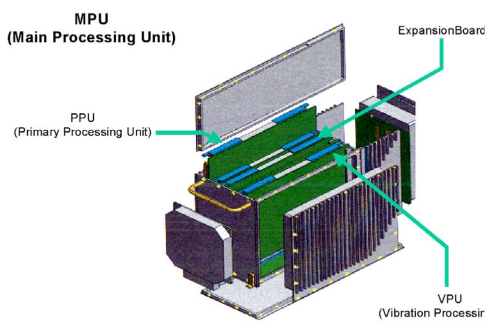


Figure 2. IMD HUMS MPU

Two specific processors are utilized in the MPU. The primary processing unit (PPU) performs select data acquisition, processing, and communication with external interfaces. The PPU is supplemented with the vibration processing unit (VPU), which performs high-speed data acquisition and processing of vibration (accelerometer) data. The MPU supports a number of bus and signal interfaces (see Table 1).

A user interface is provided via an on-board Control Display Unit (CDU) or other display devices connected through a data bus. This interface allows the operator to view aircraft operating data in real-time and provides password protected maintenance information. Exceedance alerts and aircraft status data to the aircrew is also provided. In addition, this interface also provides the aircrew with the appropriate prompts for sequencing through the diagnostic operations. The acquired flight data is stored on the IMD HUMS Data Transfer Unit (DTU), a PCMCIA flash memory card device.
IMD Sensors – The existing aircraft sensors are augmented with a set of accelerometer and index sensors used to collect vibration data associated with the rotor system and drivetrain. These sensors are permanently installed on the aircraft to allow continuous monitoring and data collection of vibration data. Accelerometers are mounted on the input and output of each major drivetrain assembly as well as throughout the cabin area.

Remote Data Concentrator - For those aircraft that do not support modern avionics bus communications, a remote data concentrator (RDC) is used to collect the required aircraft signals. The RDC has been specifically designed to collect a wide variety of signal types found on aircraft (see Table 2). The MPU can support data collection with up to three RDCs.

Table 1. MPU Interfaces

Interface Type	Number
MIL-STD 1553 (type A or B)	1 redundant bus
ARINC 429 Tx	4
ARINC 429 Rx	14
RS-422	4
RS-232	2
RS-485	2
ARINC 717	1
Frequency / Tach	12
Index	8
Accelerometer	46

Table 2. RDC Interfaces

Signal Type		Available
Discrete Input		48
Synchros		4
AC Signal		16
DC Signal		32
ARINC-429	Inputs	1
	Outputs	1

Ground Station - The GS is the primary user interface with the HUMS system. It is responsible for logging and maintaining all flight and maintenance data, generating aircraft maintenance-due lists based on flight data, performing aircraft configuration and parts tracking, generating engineering and management reports, and archiving data.

The GS is hosted on a networked server / workstation environment. The minimum Server hardware requirements are:

Hardware

- Dual 400MHz Pentium II Processors w/512K Cache.
- 24-X CD-ROM Drive,
- 512Mbytes of installed RAM.
- Six 9.0Gbyte Hard Drives
- Network interface

Software

- WindowsNT Server 4.0, Build 1381, Service Pack 4.
- WindowsNT Server Resource Kit.
- Oracle RDBMS 8.0.5.0.0.

The minimum client workstation hardware requirements are:

Hardware

- 266 MHz Pentium II processor
- 256 Mbytes of installed RAM
- PCMCIA Card Reader
- Network interface
- 20X CD ROM Drive
- 9 Gbyte Hard Drive

Software

- WindowsNT Workstation 4.0, Build 1381, Service Pack 4.
- Microsoft Data Access Components Version 2.0 Service Pack 2.
- Oracle Client 8.0.5.0.0.

GBS functions include:

- DTU Initialization and Download
- Parts and Maintenance Configuration Tracking
- Usage Calculations/Updates
- Condition Indicator Extraction
- Drivetrain, Rotor and Cabin Absorber Diagnostics
- Data Graphing, trending, and Reporting
- System/User Administration
- Interfacing to external Applications (Interactive Electronic Tech Manuals, Customer Configuration / Maintenance Management Systems)

5. CURRENT PROGRAMS

Navy CH-53E – The first program to use the newest generation IMD HUMS was the Navy CH-53E Super Stallion. A complete suite of HUMS functionality is supported by the IMD HUMS. This includes:

- Exceedance Processing
- Rotor Track and Balance Monitoring
- Rotor Monitoring
- Swashplate Monitoring
- Tail Rotor Drive Shaft Monitoring
- Aircraft Absorber Tuning
- Engine Monitoring, including Engine Power Monitoring, Engine Life Usage Monitoring, Engine Over Temperature Monitoring
- Powertrain Monitoring, including Traditional Vibration Analysis Operations as

well as Advanced Mechanical Diagnostics Monitoring

- Oil Debris Monitoring
- Drive Shaft Monitoring
- Free Wheeling Unit (FWU) Monitor
- Operational Usage Monitoring
- Structural Usage Monitoring

The CH-53E IMD HUMS uses the BFG MPU and DTU device. As the CH-53 is not a heavily bussed aircraft, two RDCs are used to collect the requisite discrete signals, angular rates, attitude angles, body-axis accelerations, fuel quantities, pressures, and temperatures. The MPU is configured as a MIL STD 1553 Remote Terminal. As such, it collects a variety of flight parameters. Crew display is accommodated using the CH-53E CDNU. 32 accelerometers / index sensors were distributed throughout the drivetrain to collect vibration data. A total of 6 engine accelerometers and 3 cabin accelerometer packages were also installed to collect engine and cabin accelerations. The locations of the IMD HUMS LRUs are presented in Figure 3.

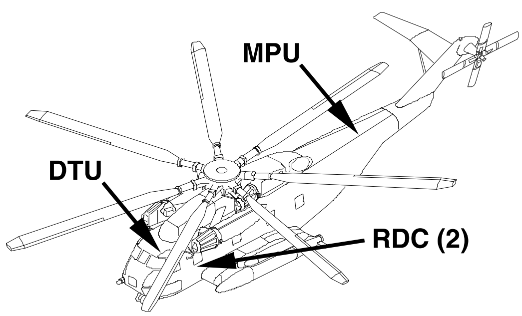


Figure 3. Location of IMD HUMS LRUs on the CH-53E

The Navy CH-53E IMD HUMS completed a 97 hour Development Test (DT) program in 2000. This test emphasized functional evaluation and demonstration of IMD HUMS. Of specific interest were fault insertion tests of the rotor system. Tests were performed to assess the system's ability to identify the proper maintenance actions required to correct out-of-balance conditions on the main and tail rotors, and out-of-track conditions on the main rotor. A series of flights were flown with pre-selected main and tail rotor track and balance adjustments. The values of these pre-selected adjustments were based on solutions provided by the Sikorsky Blade Track and Balance (SBTB) software. By knowing the baseline value of the aircraft's track and balance condition, simulated changes to pitch change rods, trim tabs, and rotor hub weights can be made in the SBTB software until a predicted fault value matches the desired fault value (typically 5% lower than the flight clearance limit). In the case of the tail rotor, only hub weights were adjusted and a series of vibration polar plots were be used to determine predicted vibration levels. The adjustments that resulted in the desired fault value were then made to the aircraft. Once the changes to the rotor system were made, the aircraft was flown (ground turns only for tail rotor adjustments) and the IMD HUMS provided an adjustment that returned the rotor system to within MIMS limits within two test flights. This testing was repeated for both sets of algorithms (with and without main rotor tracker) used by the IMD HUMS.

The CH-53E IMD HUMS has successfully transitioned from developmental test into its operational test (OT) phase. Operation test will occur between Q2 and Q3 2001. An additional 3 CH-53E will be fitted with the IMD HUMS for the OT program. An initial low-rate production contract for additional IMD HUMS was awarded in October 2000. Installations of the initial production system will start after the OT installations are complete.

Navy SH-60B – Concurrent with the development of the CH-53E IMD HUMS was the development of the Navy SH-60B Seahawk IMD HUMS. Developmental testing of the SH-60B IMD HUMS started in February 2000. As with the CH-53E platform, the testing emphasized functional evaluation and demonstration of IMD HUMS (engine checks, usage, RTB, exceedance detection, and mechanical diagnostics). Of most interest were the flights used to assess the system's ability to execute diagnostics currently performed in the U.S. Naval Aviation Vibration Analysis Program (NAVAP)[4]. The VATS currently performs these procedures throughout the H-60 and H-53 fleet. The IMD HUMS was designed to improve upon the current methods utilized by the VATS by constantly monitoring the vibration levels of certain aircraft components to reduce maintenance hours spent doing time-based maintenance. In addition to evaluating the capability of the IMD HUMS to perform output shaft balancing and vibration absorber tuning operations, the IMD system's ability to detect mis-shimming of the SH-60B's Thomas couplings was also evaluated (both for tail rotor drive shaft (TRDS) and the input to the intermediate gearbox (IGB)).

The SH-60B IMD HUMS utilized the same basic elements as that of the CH-53E, but configured specific to SH-60B interfaces and operations. As with all IMD HUMS applications, the BFG MPU and DTU were installed on the SH-60B. The SH-60B required only a single RDC (owing to the need to collect data from 2 engines on the SH-60B versus 3 engines on the CH-53E). 22 accelerometers / index sensors were distributed throughout the drivetrain to collect vibration data. A total of 4 engine accelerometers and 3 cabin accelerometer packages were also installed. The SH-60B IMD HUMS was configured to act as a MIL STD 1553 Bus Monitor to collect requisite flight parameters. Unlike the CH-53E, crew display functions were handled with a dedicated display provided by the BFG Avionics CDU. The locations of the BFG IMD HUMS on the SH-60B are illustrated in Figure 4.

The DT phase of the SH-60B IMD HUMS is expected to be complete by Q1 2001. The OT testing for the SH-60B IMD HUMS will occur between Q3 and Q4 2001. An additional 2 SH-60B aircraft and 1 SH-60F aircraft will be fitted with the IMD HUMS for the OT program.

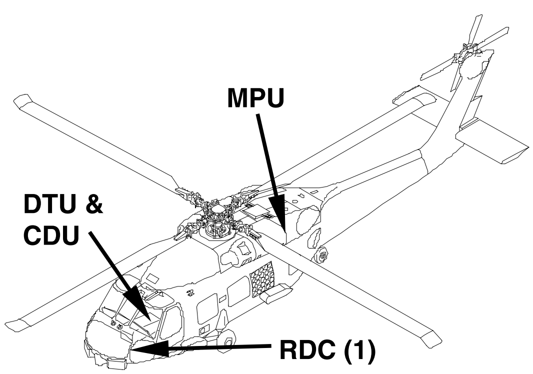


Figure 4. Location of the IMD HUMS LRUs on the SH-60B

Army UH-60A and HH-60L – In 1999, BFG was awarded a contract to reapply the SH-60B IMD HUMS product to the Army UH-60A and HH-60L Blackhawk aircraft. The IMD HUMS LRU complement used on the Army Blackhawk is similar to that used on the SH-60B. There are two main differences in the Army and Navy applications:

- Differing avionics components, engine-variants, and transmissions.
- Differing business-rules of each service.

One of the key points of the IMD HUMS to be evaluated is the interchangeability of the system components regardless of the model rotorcraft on which they are installed. This interchangeability / interoperability will be demonstrated across the UH-60A and HH-60L platforms, with further supporting analysis from the Navy IMD HUMS programs. The sensors and the LRU's are identical, although each IMD HUMS installation generally consists of different numbers of the sensors. This is also true of the basic software. The only differences between software loaded into specific helicopter models are the platform-specific configuration tables. Therefore, if the services use the IMD-HUMS, the government's cost of ownership will be reduced because of the interchangeability of components.

The first flight for the UH-60A IMD HUMS is planned for late-March 2001. Flight testing for the UH-60A IMD HUMS is to be completed by Q3 2001. Operational checks of the HH-60L IMD HUMS will start May 2001. Unlike the Navy programs, there will not be any dedicated OT program for the Army IMD HUMS. The Army anticipates leveraging the OT results from the Navy SH-60B tests in support of its evaluation of the operational performance of the IMD HUMS.

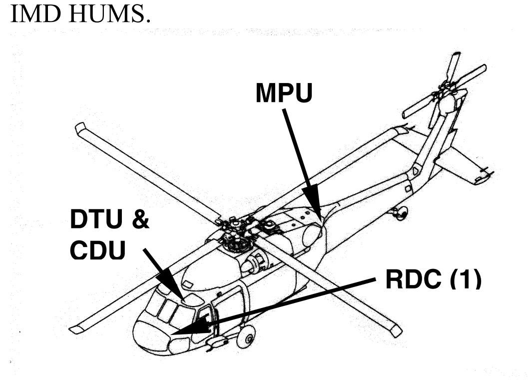


Figure 5. Location of the IMD HUMS on the Army UH-60A

Marines AH-1Z and UH-1Y - 1999 also saw the introduction of the IMD HUMS to the AH-1Z Cobra and UH-1Y Huey platforms. This introduction is occurring concurrent with the introduction of the H-1 avionics upgrade program. The H-1 IMD HUMS represents the first introduction of the IMD on a fully bussed aircraft. An RDC is not utilized all aircraft data is available via the existing H-1 MIL-STD-1553 databus. Owing to the commonality in the avionics design by the Bell / Litton team, the IMD system for both the AH-1Z and UH-1Y are nearly identical, except for some minor parameters differences.

The current IMD HUMS program on the H-1 platforms will demonstrate the ability of the system to operate autonomously. Sets of accelerometers and index sensors are mounted on the drivetrain and in the cabin to collect vibration signals. In the initial program phase, the IMD HUMS will not interface with any of the displays in the H-1 cockpits. Rather, all operations will be implemented as automatic procedures, not requiring any pilot interaction. As with the other systems, the resulting data will be collected and written to the DTU memory card for processing on the ground. An important aspect of the H-1 program is to collect vibration data to support the development of mechanical diagnostics limits and health indicators.

The first flight of the H-1 IMD HUMS will occur August 2001. Flight-testing is to be finished by July 2002. Following a successful evaluation of the IMD HUMS, it is hoped that the system will be fully integrated with the aircraft cockpit displays, allowing the system to also perform prompted procedures, such as on-demand engine power assurance checks.

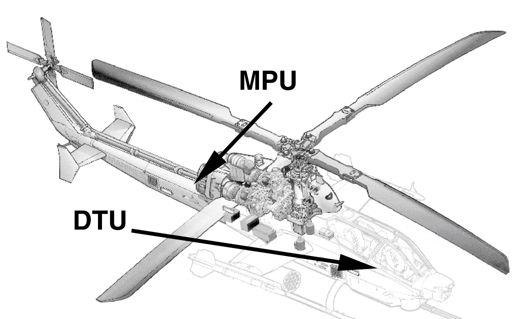


Figure 6. Location of the IMD HUMS on the Marines AH-1Z

Sikorsky S-92 – The first commercial application of the IMD HUMS has been to the Sikorsky S-92. As with the H-1 application, the S-92 IMD HUMS will operate on a fully bussed aircraft. Again, the MPU and IMD sensors will be installed. Unlike the H-1 program, the IMD HUMS will interface with the S-92 multi-function display (MFD), providing both automated and prompted operations. Though the S-92 IMD HUMS provides the same types of functionality as that on the military platforms, it has some significant differences in its implementation. As the Full Authority Digital Engine Controller (FADEC) in the S-92 engines provides a comprehensive set of engine performance assessments, such functionality is not configured into the S-92 IMD HUMS. The biggest difference between the S-92 HUMS and the military IMD HUMS applications driven by commercial certification. Whereas the military HUMS programs are certified to military air-worthiness standard, the S-92 is to be certified to FAA certification standards. This drives additional testing and documentation. The need for commercial certification also drives some differences in the application. The GS has been developed to DO-178B Level B standards, but is tested to DO-178B Level D. As such, critical processing related to application of structural usage measures to serialized parts has been moved from the GS in the OBS, which is tested to DO-178B Level B standards.

Flight testing of the S-92 IMD HUMS will occur between March 2001 and September 2001. This will be followed by final FAA certification testing which is to be completed by March 2002.

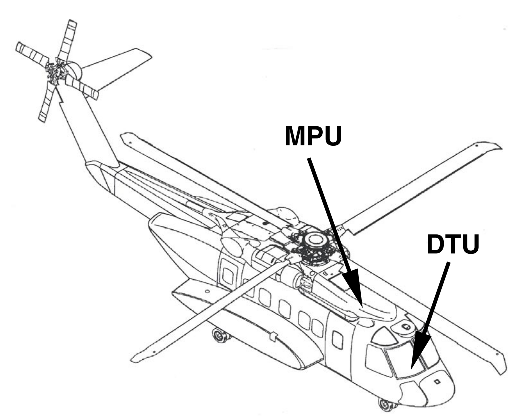


Figure 7. Location of the IMD HUMS on the Sikorsky S-92

6. EXAMPLES

Rotor Track and Balance – The ability of the IMD HUMS to automatically recognize and collect rotor track and balance (RTB) data during normal flight provides one of the most beneficial cost savings /avoidance mechanisms of the entire IMD HUMS system. The system has demonstrated both tracker-based RTB and trackerless[5] rotor tuning functions on both the H-53 and H-60 platforms.

Data from fault tests were used to evaluate RTB and rotor tuning operations. Tests were performed with a variety of fault inputs. These include:

- Weight faults
- Single / Multiple PCR faults
- PCR and tab faults
- Complex faults (weights, PCR and tab changes)

The generic requirement for the IMD HUMS to correct the rotor fault within two attempts. In general, this means that the IMD HUMS will be able to provide an RTB solution from data automatically collected onboard the aircraft and arrive at a solution with at most a single check flight. This eliminates the need to fly specialized RTB data collection flights.

The RTB solution computed from the IMD HUMS is the solution that optimally minimizes the mean square error across all flight conditions. One aspect of the IMD HUMS that differentiates it from conventional RTB tools is its ability to generate RTB solutions using higher shaft order information. This approach allows the IMD HUMS to achieve excellent RTB and rotor tuning solutions within a single attempt.

Table 3 presents a series of rotor system faults and the IMD computed solutions. A variety of test conditions are presented, for both tracker-based and trackerless operations. In general, the IMD HUMS was able to correct the inserted faults. It is interesting to note that the optimal solution recommended by the IMD HUMS, though within the same order / magnitude of the inserted faulted, may also include adjustments to PCR / trim tabs / weights which were not initially entered. This is due to the fact that system always attempts to provide a solution that is globally optimal. In all cases, the IMD HUMS system was able to reduce vibrations to within 0.3 ips limits (inserted faults drove the single axis vibration levels up between 0.309 ips and 0.698 ips).

Table 3. IMD HUMS Rotor Track and Balance Solutions

TEST	FAULT	IMD HUMS SOLUTION
PCR / TAB Fault (w/ Tracker)		
PCR	Black Up 7	Red Up 2 Blue Up 5 Black Down 5
TAB	Blue Down 8	Blue Up 6
WEIGHT	-	Red Remove 12 Black Remove 5
Double Tab Fault (w/ Tracker)		
PCR	-	Yellow Down 3 Black Down 4
TAB	Red Down 14 Blue Down 15	Red Up 7 Blue Up 11
WEIGHT	-	-
Complex Fault (w/ Tracker)		
PCR	Blue Down 10 Yellow Up 12 Black Up 4	Blue Up 6 Yellow Down 10 Black Down 9
TAB	Blue Up 7 Yellow Down 12	Red Down 9 Blue Down 17
WEIGHT	Yellow Rem. 30	Blue Remove 5 Yellow Add 5
Double PCR Fault (w/o Tracker)		
PCR	Yellow Up 5 Black Down 10	Red Up 5 Yellow Down 6 Black Up 10
TAB	-	Blue Down 3 Yellow Up 11
WEIGHT	-	Blue Add 13 Yellow Rem. 18
Weight Fault (w/o Tracker)		
PCR	-	Red Up 1 Blue Up 2 Yellow Up 3
TAB	-	Red Down 6 Blue Down 7
WEIGHT	Red Add 20 Blue Add 45	Red Remove 26 Blue Remove 47

The polar plots in Figures 8a and 8b illustrate actual vibration level reductions across flight regimes realized by the IMD HUMS. Again, a series of faults were inserted into the rotor system. Vibration levels were measured before and after the IMD HUMS solution was implemented. In all cases, the IMD HUMS was able to successfully reduce the vibration levels to within specified limits.

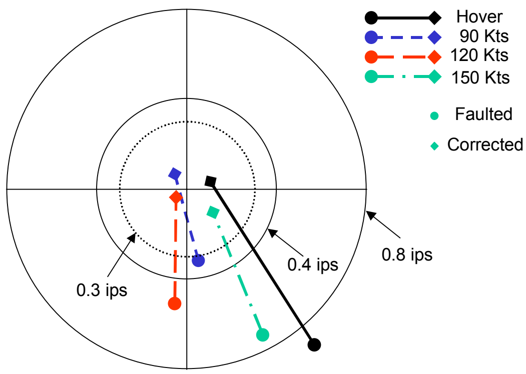


Figure 8a - Comparison of faulted and IMD-corrected rotor lateral vibration levels.

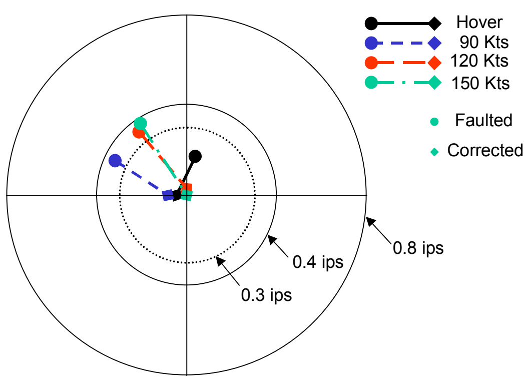


Figure 8b - Comparison of faulted and IMD-corrected rotor vertical vibration levels.

Mechanical Diagnostics - Onboard monitoring of aircraft drivetrain vibrations requires analysis of both faulted and unfaulted drivetrain data. This collection and analysis has been initiated on the CH-53E, SH-60B, UH-60A and H-1 programs.

Figure 9a illustrates a normal (unfaulted) enveloped RMS histogram from a CH-53E swashplate bearing. Its distribution, being Gaussian, is indicative of a non-faulted condition. This contrasts with the enveloped RMS histogram from a faulted H-1 main gearbox (Figure 9b), which does not display a Gaussian RMS distribution. Figure 9c shows the enveloped RMS level of the gearbox. The test consisted of endurance runs, low lube conditions and complete loss of lubrication conditions.

The detection of faults is clearly identifiable by taking measurements of these vibration signatures. Starting with the low lubrication runs, the overall level of Enveloped RMS (15k – 20k Hz) has increased. Starting with data point 31, beginning of eminent failure (not complete destruction), the indicator value (as well as the rate of change) has increased dramatically. The failure case is obviously detectable, but the first indication of a problem starts with the low lubrication case. Such knowledge is being incorporated into the IMD HUMS to support the development of advanced mechanical diagnostics of rotorcraft drivetrains.

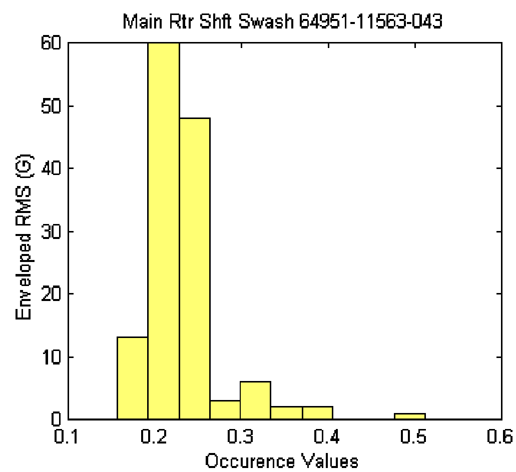


Figure 9a - Enveloped RMS histogram from an unfaulted CH-53E swashplate bearing.

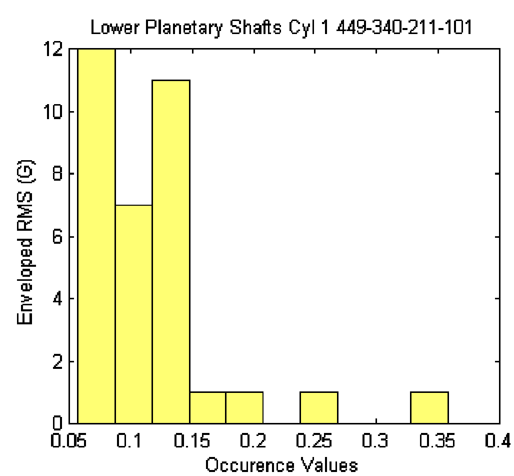


Figure 9b - Enveloped RMS histogram from an H-1 main gearbox allowed to run without lubrication

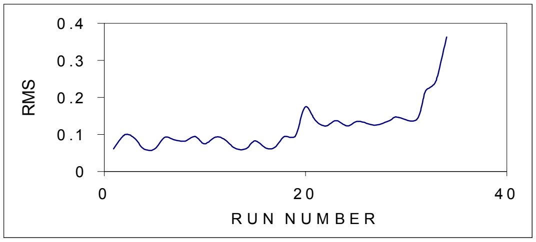


Figure 9c - Enveloped RMS levels from the faulted H-1 main gearbox versus run number

Engine Power Assurance - Another aspect of the IMD HUMS is its ability to extend engine power assurance testing. The processing power of the MPU and the variety of signals made available to the IMD HUMS allows the IMD HUMS to automate many traditional power assurance checks. In addition, the system can also support determination of many power indices. An example of the ability to automate engine performance checks is presented in Figures 10a thru 10c. This example illustrates the ability of the IMD HUMS to automate four-point engine checks [6] supported on the CH-53E. The four-point check consists of collecting and recording various engine parameters at a series of engine temperature conditions. This information is traditionally recorded into the aircraft logbook for later analysis by the aircraft maintainer. The IMD HUMS automates the process by guiding the operator through the test procedure, automatically collecting and recording the requisite data, and performing the data analysis onboard. With the system, the results of the four-point check can be displayed to the operator. Generation of any engine-related maintenance actions associated with the testing is also automated within the IMD HUMS groundstation.

Groundstation Operations - The ability of the IMD HUMS to support maintainer operations is primarily managed within the IMD HUMS groundstation. A wide variety of data is downloaded to the IMD HUMS groundstation. This includes:

- Exceedances
- Events
- Operation Usage
- Structural Usage
- Operational Regimes
- Onboard System Faults
- Signal Data
- Computed Data
- Condition & Health Indicators
- Rotor Track and Balance Data
- Absorber Tuning Data
- Shaft Balancing Data

Figure 10a - Main CH-53E IMD HUMS Display

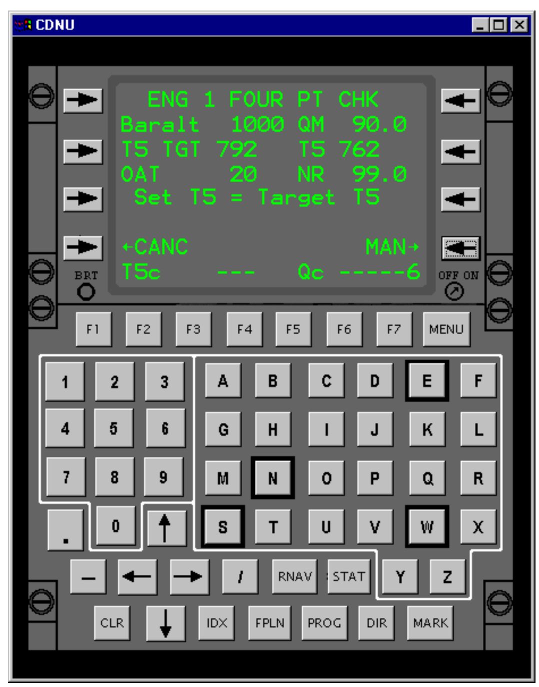


Figure 10b - CH-53E IMD HUMS four-point check procedure screen.

Figure 10c - CH-53E IMD HUMS four-point results display.

The groundstation automates the transfer of this information from the PCMCIA datacard. During this download operation, the data is analyzed and is used to support pilot debrief operations (see Figure 11a). The maintainer can get an immediate view of the status of the aircraft and whether something occurred which requires attention. Normally, the maintainer would not be exposed to detailed flight information. However, the groundstation user interface has been designed to support more detailed analyses. The maintainer and engineering analysts can drill down through the data to get more detailed information, such as those provided in time histories (see Figure 11b) or as trend plots. Not only does the groundstation support status and overview operations, it provides diagnostic capabilities to compute RTB solutions (Figure 11c) and analyze mechanical systems problems (such as the vibration analysis screen presented in Figure 11d).

The groundstation also supports administrative operations (card initialization, data archiving, report generation) and configuration management (parts tracking) and maintenance management tasks.

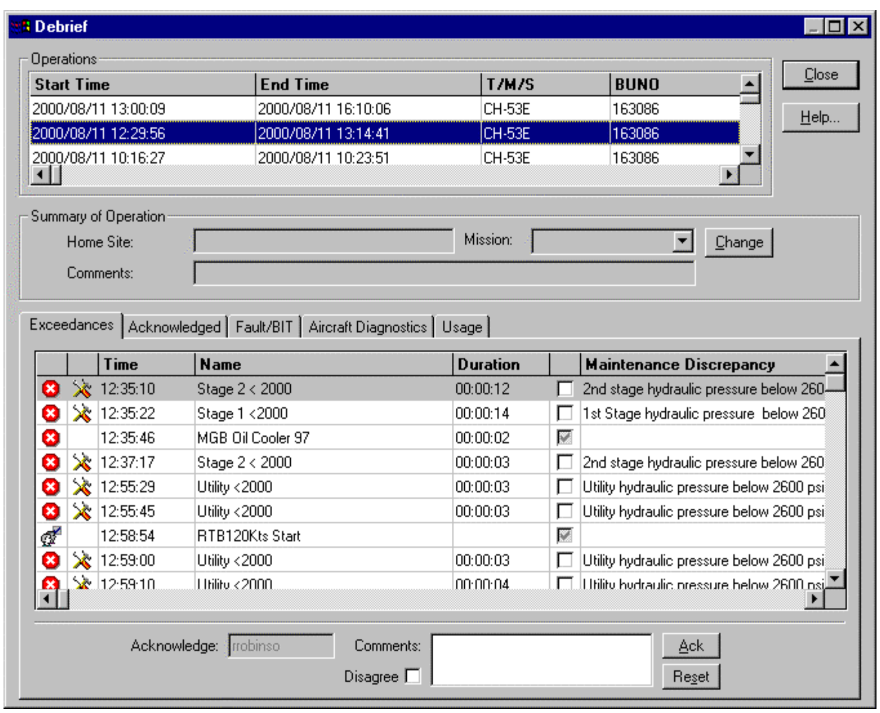


Figure 11a - IMD HUMS groundstation flight briefing screen.

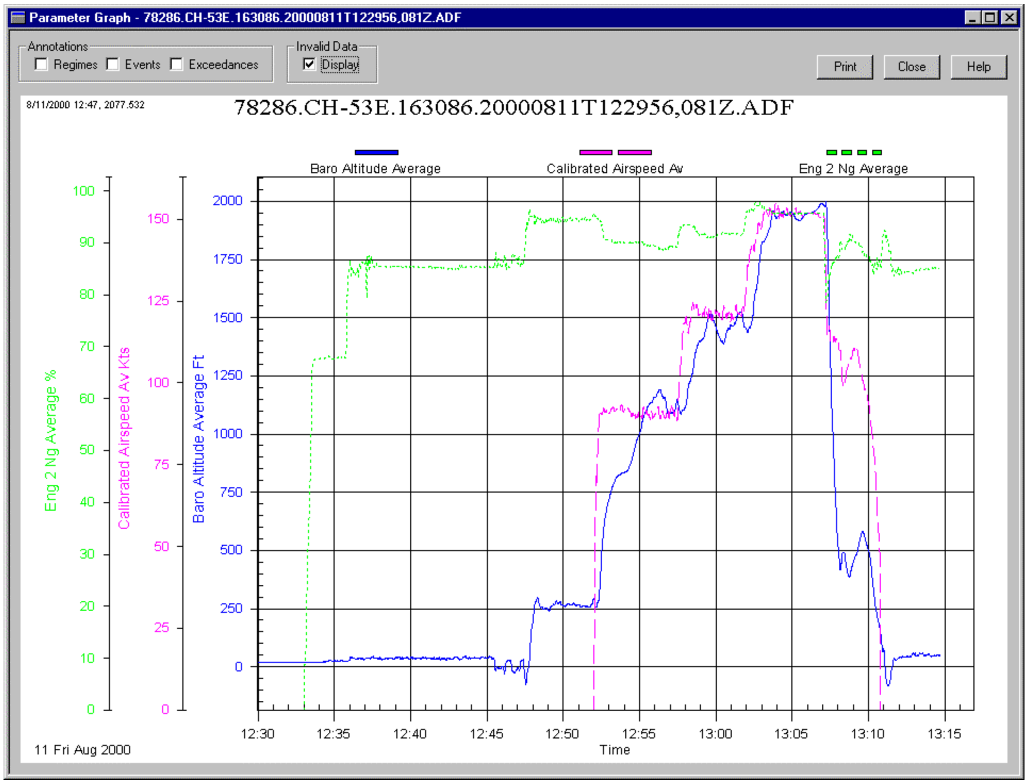


Figure 11b - Sample time history plotting screen on the IMD HUMS groundstation

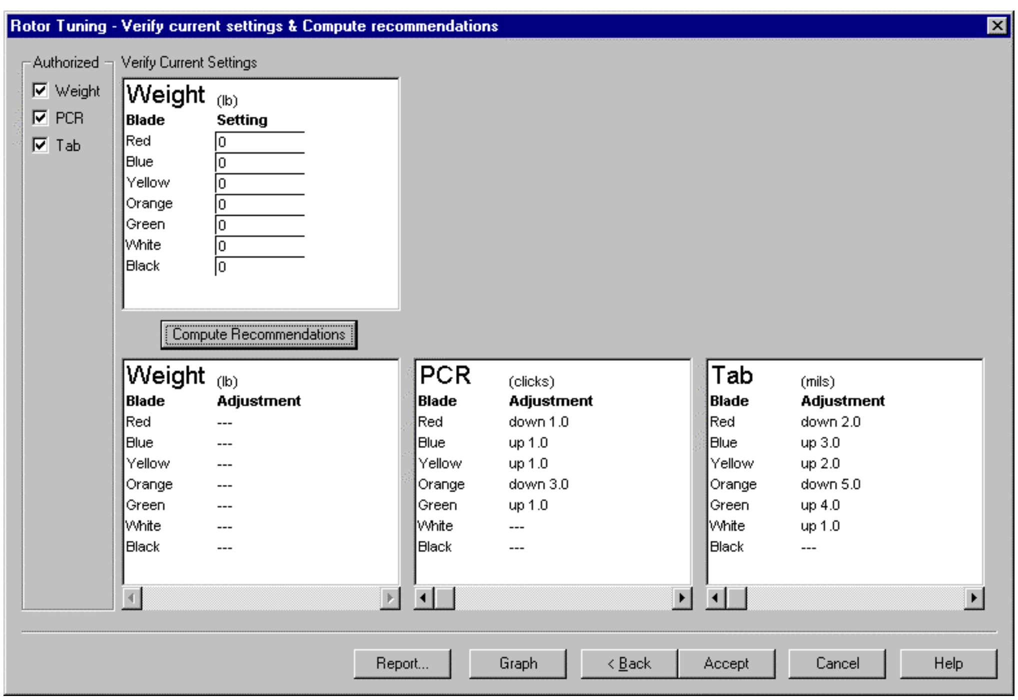


Figure 11c - Sample RTB solution screen on the IMD HUMS groundstation

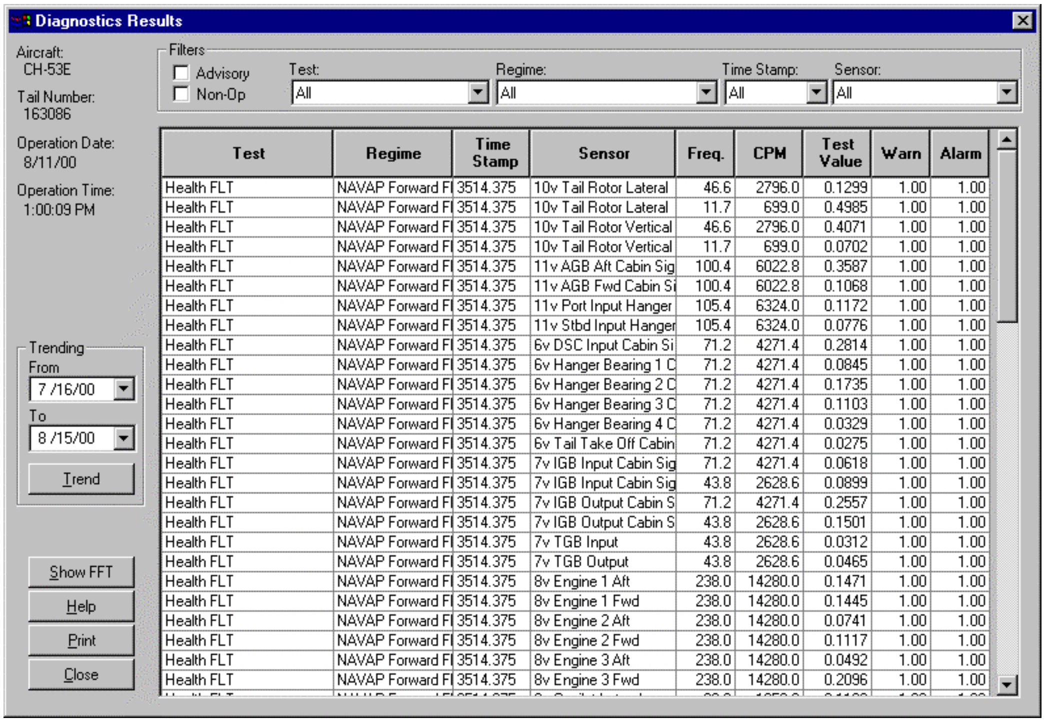


Figure 11d - Representative diagnostics results screen on the IMD HUMS groundstation

7. LESSONS LEARNED

System Architecture - It is important to always maintain constant focus on the overall goal of lowering the platform user's maintenance cost while improving operational readiness and safety. Lower operational cost benefits the user in obvious ways and keeps the manufacturer competitive. Each participant "wins".

Strive to distinguish between what the system is required to do and how the system is to accomplish the goal. What the system does is correlate data from diverse sources (Original Equipment Manufacturer (OEM) sensors, pilot input, aircraft "state" parameters, HUMS-specific accelerometers and sensors, aircraft configuration data, maintenance histories, etc.) in order to allow platform maintainers and designers to optimize operational costs given various constraints. The "how" part is accomplished by efficiently acquiring and manipulating that diverse data for use in advanced algorithms (functions). Indeed, the results of many of the calculations serve only as input for subsequent calculations or "higher-level" functions.

Develop and execute the data acquisition and reduction functions as efficiently as possible. This will provide the best chance of delivering the HUMS to the customer(s) who developed the original requirements. HUMS applications are sometimes so complex that turnover in the personnel who are developing the system (customer and HUMS provider alike) hinders progress.

Providing the HUMS only signals the start of maintenance practice optimization. The ease with which the HUMS provides the data needed by the maintainers and operators to optimize their processes is only an enabler – not an end goal.

Usage Monitoring - Automated Usage Monitoring frees the pilot from administrative cockpit tasks and promises more accurate recording of the time spent in damaging regimes. Accurate reporting of the distribution and duration of regimes flown is important in order to determine the amount of "life" time to decrement from life-limited parts.

Reprocessing regime data with more accurate regime definitions offers the potential to reclaim spent life while maintaining high flight safety standards and extending the time period between maintenance actions for life-limited parts subject to low frequency vibration. This is because high usage factors are usually assigned to all regimes within the flight sequence that are denoted as "unrecognized".

The transition from a fleet of non-HUMS equipped aircraft to fleet-wide implementation will require the aircraft operators to determine the life already decremented from a component based on previous operations. This will become the starting point from which subsequent life will be decremented from the component as determined by the HUMS. Advanced condition assessment techniques (direct physical observation) coupled with HUMS-derived component degradation data will permit spent life to be accurately determined through physical inspection. Test cell data or laboratory determinations will validate degradation rates.

Insight gained from tracking the actual usage of individual helicopters will permit maintainers and operators alike to schedule the aircraft for maintenance activities and certain missions based on the known condition of the helicopter's components.

Mechanical Diagnostics - The key to enabling advanced mechanical diagnostic and prognostic functions is a data analysis and reduction system that is automated to the greatest degree attainable. This is true even for modestly sized fleets (small fixed-base operators). The automated system must permit an analyst to introduce new algorithms and thresholds (warning or alarm). It must also provide the ability to reprocess historical data using those new algorithms and thresholds. Short of this, the analysts will be overwhelmed by the amount of data to be processed and will not even be able to establish a baseline set of diagnostic and prognostic functions to improve upon.

The aircraft operator and equipment manufacturer must work closely to set the warning and alarm thresholds such that the operator can maintain the desired safety of flight within the maintenance expense constraint. The historical condition indicator (CI) and health indicator (HI) data provided by the diagnostic and prognostic functions, associated with the observed physical condition of flight critical components (as documented during maintenance actions) are the critical pieces of data needed to advance to condition-based and subsequently, just-in-time maintenance.

The transition to condition based maintenance can be enabled by using data acquired by destructive component testing. This is because faulted parts are usually (conservatively) removed from an aircraft before a statistically significant amount of data can or will be acquired. Data-intensive destructive testing correlated with scientific observation of the component's deteriorating condition will provide the additional insight needed to enable on-board prognostic functions with confidence. Destructive testing of "spent" components in a test cell environment is a viable source of data to validate prognostic algorithms. This data will enable the tradeoff studies that will relate component condition with safety of flight and required maintenance. A reasonable number of tests-to-failure are needed to guarantee statistically significant results or to permit the training of neural network algorithms to recognize developing trends.

Rotor Track and Balance - A resident (full time) rotor balancing system is currently considered to be the function that has the greatest potential for reducing helicopter operating cost. The ability to acquire rotor tuning related vibration data at any time (within the bounds of pre-defined flight events) precludes the need for mounting special balancing equipment and balance-specific flights. However, the cost savings can easily be diluted in many ways. First, by pursuing the best overall balance attainable (over-maintaining the rotor hub). Second, by frequently changing the location at which you want to achieve low vibration levels. Third by frequently changing the regime in which you want to experience the least vibration. Fourth, by allowing maintainers (with different preferences for how to achieve proper balance) to chose the manner in which they will balance the rotor. Thus, the ability to attain low vibration levels (proper balance) can lead to increased maintenance effort unless the system operators (owners maintainers and HUMS-provider) determine how best to act upon the information provided by the rotor tuning function.

Intelligence vs. Information - The BFG IMD HUMS design resulted from many years of work in the area of helicopter health and usage analysis, test and development. One area where the design was optimized to concentrate information down into useable intelligence was in VPU processing. The VPU software was designed to collect raw vibration data and to perform spectral analysis. The resulting spectral data (representing a small amount of information compared to the raw time history data) is easily transferred to the PPU via the dedicated RS-422 line. However, as new concepts data processing occur, the design might need to accommodate the transfer of the full 32 MB VPU acquisition memory across the 115 Kbaud RS-422 link through the VME bus to a third party board in the MPU. An obvious way mediate the thruput problem would be to change the speed of the RS-422 link between the PPU and VPU. However, this proves impractical as both PPU and VPU hardware designs are very mature and not amenable to redesign. Fortunately, BFG has allowed the additional processing to be inserted into the VPU to support new processing needs.

Another area where the need to deal with information was contrary to the need to deal with intelligence is in data logging. A simple view of the IMD HUMS is one of a basic data acquisition system, like a flight data recorder. Data is collected periodically by the HUMS, tagged, and periodically output for later consumption. In reality, the HUMS does not perform processing in this manner. Though data is periodically collected, storage of information to the memory card is more aperiodic. Select signals are only written when they change (such as an exceedance indication), different data are recorded at different rates, and the same data may be output at different rates based on event-processing logic. This is most apparent in the area of structural usage regime monitoring, whereby the HUMS may only log time in flight regime buckets instead of logging all relevant aircraft state information. All this is done so as to minimize the amount of data written to the memory card resulting in minimizing card change operations and GS processing. The requirements to store as much information to the card drives increased GS processing. This leads to the maintainer waiting for the GS to process data.

Data Management - Time spent to correlate and make available data from diverse sources will reward the customer and HUMS developer alike. Incidentally, this speaks (again) to the need to automate data access and the data reduction processes. Access to a wider variety of data allows the analyst to develop solutions based on interpreting already-available information (sometimes precluding the need for any additional sensors). Likewise, using indicators that otherwise do not have a direct relationship with one another gives the analyst confidence that the combined indications truly represent a developing condition.

Initial solutions to customer requirements will typically have to be “brute-forced” before an elegant solution becomes available. Access to disparate data allows the analyst to experiment using various data correlation techniques to determine the most effective indicator combination. In the same manner, knowing the critical indicators (and those that are normally unrelated) allows the analyst to build in safeties against false warnings and alarms. The elegant indicator set and algorithms usually become apparent only after many false starts and extensive reprocessing of the same data.

8. CONCLUSIONS

Achieved Product Objectives - BFGoodrich's objective to develop a dual-use HUMS product has been demonstrated on the Army, Navy, Marine and commercial programs. Common hardware platform and functionally modularized flight software, coupled with a modular groundstation, allows the system to be applied to new systems without the need for additional non-recurring hardware and software development. Customer-specific business rules and maintenance practices and platform-specific interface differences are managed through program-specific configuration data.

Customer Information and Maintenance Needs - As BFG works with each customer, new needs for information processing and reporting are encountered. Each customer has parts management and maintenance management information needs that the system must accommodate. This has been achieved by defining crisp interfaces between IMD HUMS data processing needs and CM / MM functions unique to each customer. Though the intended end-user of the system is the airframe maintainer, the need for the customer's engineering organization to be exposed to information has emerged as a requirement of the product.

Ability to Achieve RTB Objectives - Automating RTB operations (tracker-based and trackerless) has been successfully demonstrated for the CH-53E and SH-60B platforms. The BFG RTB algorithms are able to provide excellent results, with solutions generally achieved in a single attempt.

*Advanced Health Process Maturatio*n - The IMD HUMS has successfully demonstrated the capability to perform regime detection and acquire drivetrain vibration data. Unlike RTB operations, realizing the full advantage of the IMD HUMS will require analysis of flight and vibration data so as to mature structural usage and advanced mechanical diagnostics capabilities.

Success Related to Early Programs - BFG's success is meeting its product objectives and introducing the IMD HUMS is directly related to the experience achieved on its earlier HUMS programs. Early efforts by the COSSI team members (BFG, Government, airframers, and subcontractors) has greatly accelerated BFG's understanding of the end-customer needs. This has directly led to the development of a full-capability HUMS system to support rotorcraft health and diagnostics activities.

9. References

[1] Hess, A., Hardman, J., Neubert, C., "SH-60 Helicopter Integrated Diagnostics System (HIDS) Program Experience and Results of Seeded Fault Testing", presented at the American Helicopter Society 54th Annual Forum, May 1998.

[2] Hess, R., Chaffee, M., Page, R., Roseberry, K., "Realizing an Expandable Open HUMS Architecture", presented at the American Helicopter Society 56th Annual Forum, May 2000.

[3] *HUMS Open Systems Specification*, BFGoodrich Aerospace, E-3424, August 30, 1999.

[4] *Organization Maintenance Vibration Manual, Navy Models SH-60B, SH-60F, HH-60H*, Naval Air Systems Command, A1-H60CA-VIB-000.

[5] Ventres, S., Hayden, R., "Rotor Tuning Using Vibration Data Only", presented at the American Helicopter Society 56th Annual Forum, May 2000.

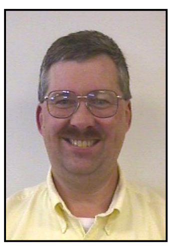
[6] *NATOPS Flight Manual, CH-53E Helicopter*, Naval Air Systems Command, A1-H53BE-NFM-000.

Bob Hess

Bob Hess is the Systems Engineering Manager for the IMD HUMS program. He has been at BFGoodrich for eight years, supporting system simulation, design and test. He has been at directly involved with system development and test of the IMD HUMS over the last three years. He holds a M.S. in Aeronautical Engineering and a B.S. Mechanical Engineering.

Dave Kogut

Dave Kogut is the Applications Engineering Manager for the IMD HUMS. He is responsible for diagnostics application development for the IMD HUMS product line. Since joining BFG in 1998, he has worked in development and integration of the CH-53E and SH-60B systems. He holds a B.S. Mechanical Engineering from Rensselaer Polytechnic Institute.



Al Duke

Al Duke is the Technical Director for BFGoodrich's Health and Usage Monitoring Systems business unit. During his 18 year career with BFG, Mr. Duke has worked in the areas of electronic packaging, vibration analysis and systems engineering. He has led HUMS engineering development teams for the past 5 years beginning with the US Navy HIDS program and, most recently, the IMD HUMS.