

Automated Helicopter Vibration Diagnostics for the US Army and National Guard

Paul Grabill, Intelligent Automation Corporation, San Diego, CA
Paul.Grabill@iac-online.com
Dr. John Berry, US Army AMCOM-AMRDEC, Redstone Arsenal, AL
John.berry@redstone.army.mil
CW5 Lem Grant, South Carolina Army National Guard, Columbia, SC
GrantLE@SC-ARNG.ngb.army.mil
Jesse Porter, US Army AMCOM-RTTC, Redstone Arsenal, AL
Jesse.Porter@rttc.army.mil

The US Army and South Carolina Army National Guard have developed an automated vibration monitoring and fault diagnostic tool as part of the Vibration Management Enhancement Program (VMEP). This paper outlines the VMEP system rationale, design and the vibration diagnostic algorithms used to find faults in the helicopter rotors, engines, and drive train. The concepts that differentiate VMEP from traditional Health and Usage Monitoring Systems (HUMS) implementations are described. Specifics of the system implemented in the Apache and Black Hawk helicopters found in the National Guard are shown. The software architecture used in the on-board component, the ground-based component, and the development station is presented. The data collection effort during the initial field trials is described and examples of vibration test data and algorithm processing results are presented. We believe that the system presented here represents a way of meeting many of the integrated vibration diagnostics goals for Army Aviation.

Historical Perspective

In Vietnam we used a tracking flag and the seat of our pants to track, balance and reduce vibrations on our Huey helicopters. In the early 1970s technology arrived in the form the Chadwick-Helmuth, Vibrex. We could now measure vibrations. In the 1980's, with 54 helicopters to maintain, the South Carolina Guard began using the "Vibrex" to measure the vibration level of rotating components on the Huey. The measurements resulted in several time saving diagnoses. Over the past 15 years, numerous examples of emanate failures that were detected from vibrations, have occurred. A dream of predicting problems before they occurred, or scheduling "unscheduled maintenance" was born and we named it VMEP.

VMEP Requirements/Objective

The VMEP system was intended primarily as an aid to the Army aviation maintainer. The goal is to reduce unscheduled maintenance and the total

number of maintenance test flights required to complete maintenance activities. In addition the system should have a minimal impact on operational crews. Army aircrews should not endure additional workload from an embedded maintenance system. The intent of this system is to capture, during operational flight activities, the vibration environment of the major components of the helicopter. The vibration data is analyzed by the embedded system to produce a set of specific machinery health indicators. These indicators are stored for post flight use by the aircraft maintainers. Maintenance actions are correlated to these health indicators and clearly communicated so that actions can be scheduled. Completion of these maintenance actions prior to the requirement for unscheduled maintenance both increases the productivity of the overall aviation operation, but precludes very expensive collateral damage resulting from component failure.

During the initial fielding phase of the VMEP, a statistically significant set of indicators will be collected and used to establish nominal operating limits for measurements that do not have previously established limits. Only when these limits have been technically demonstrated to have clear operating bounds will this system be used to provide aircrew warnings of impending system trouble that requires crew action. The

*Presented at the American Helicopter Society
57th Annual Forum, Washington, DC, May 9-11,
2001.*

*Copyright ©2001 by the American Helicopter
Society International, Inc. All rights reserved*

crew will not be notified during flight when maintainer exceedances have been identified. This technical demonstration will include operating experience from a range of specific aircraft and operating environments. The establishment of limits will also incorporate, when available, specific fault experience (preferably through seeded fault tests).

Comparison with HUMS

It is convenient to compare the functions included with the VMEP with those functions that are often associated with Health and Usage Monitoring systems (HUMS). The primary intent of HUMS (as applied to systems operating, for example, in the North Sea) has been for increased system safety and reliability. The VMEP has been developed at the insistence of Army helicopter maintainers with a background of using vibrations as indicators of aircraft health and fault diagnosis. Analysis of flight time spent for maintenance activities points to a striking percentage of time spent on basic rotor smoothing activities. Of all of the potential benefits of HUMS functionality for the Army, rotor smoothing demonstrates the largest single benefit to aviation costs by shifting flight hours that have been used for maintenance flight time to operational usage. The benefit from other HUMS functions such as parts life tracking and/or structural usage and monitoring (SUMS) has less impact on the Army helicopter fleet due to low airframe usage rates. An additional goal of the VMEP program is to capture detailed usage data for comparison with maintenance costs. Cost to benefit analysis for the implementation of specific HUMS functions depends on data from operational experience. Future analysis of this captured data may well verify many of the predicted benefits of additional HUMS functions. Only basic vibration related HUMS functions have been implemented in the VMEP.

VMEP Functions

Rotor Smoothing – Although normally referred to as Rotor Track and Balance, this function minimizes the fundamental harmonic of main and tail rotor vibration through one-time-track and continuous monitoring of vibration. Suggestions for adjustments that will minimize vibration will be available after each flight where flight measurements are made. Adjustment options for weight, trim tabs and/or pitch link length are provided.

Drive Train Diagnostics –

Accelerometer measurements for all drive train components are provided. The components that can be monitored include, transmission, high-speed inputs, auxiliary drives, tail-rotor drive shaft hanger bearings, intermediate gearbox, and tail-rotor gearbox. Other critical components may be monitored through the addition of sensors on available spare channels. Classical machinery monitoring algorithms are used for isolation of specific drive train faults. Examples of these algorithms are given in reference [1] and further described below.

Vibration Surveys – The system can make general vibration survey measurements from the suite of transducers, or from transducers attached to the spare channels. This function is available for diagnosis of abnormal vibrations. The aircrew can ask the system to record spectral information at any time for post-flight analysis. This mode can also be used for special “one time” measurements as directed.

VMEP System Design

The impact on the aircraft is to be minimal, that is very low weight and volume. A minimal crew interface provides control of the data acquisition functions needed for on-going rotor smoothing (track and balance). The overall supportability concept for this system is to provide an architecture that the Army has unrestricted access to, using Commercial Off-The-Shelf (COTS) hardware component assemblies and COTS software development tools. The government retains unlimited rights to the source code for the software elements of the system, reducing the cost of planned and unplanned future system modifications and migration to additional helicopter configurations.

On-board System

The VMEP on-board equipment includes the accelerometers, tachometers, cables, and various sensors that are connected to the Vibration Management Unit (VMU). The goal for the on-board system is to be fully integrated and qualified with each Army airframe. As an interim measure, the VMU (the major on-board component) is a stand-alone system that does not depend on or adversely interact with any other system on the aircraft. Figure 1 shows the major components of the VMEP system on the AH-64A aircraft. Table 1 lists the sensors for the AH-64A and Table 2 lists the sensors for the UH-60A/L.

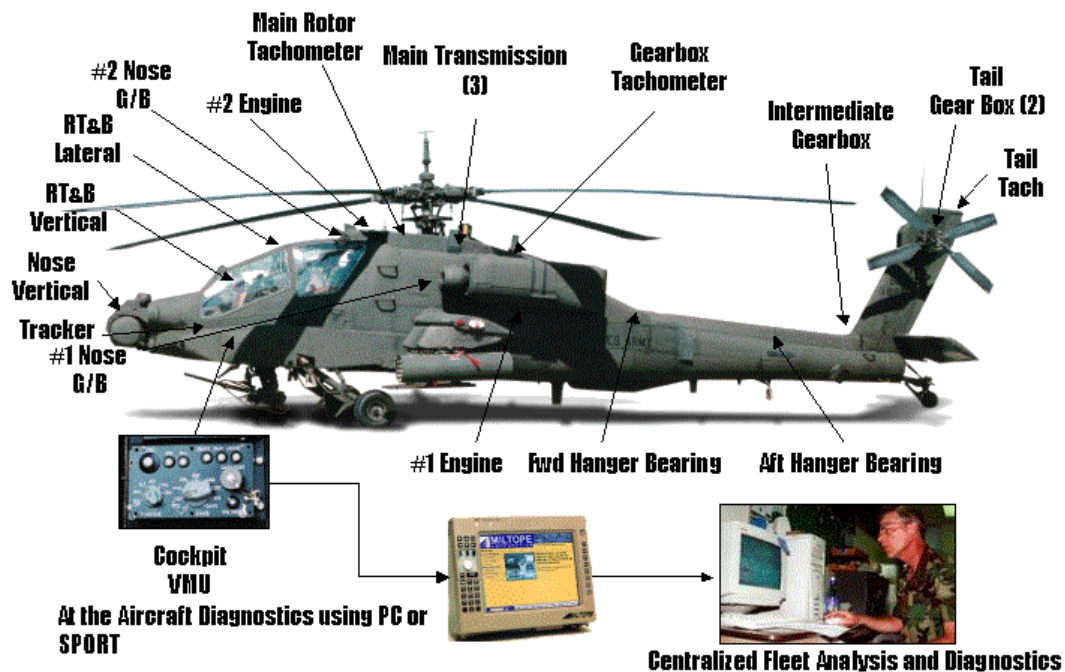


Figure 1 - VMEP Configuration for AH-64A

Table 1 – AH-64A Sensor List

Number	Name	Sensor Type	Location
TR1	TRK	Blade Tracker	Main Rotor Blade Tracker
TAC1	NRTB	Tachometer	Main Rotor Tachometer
TAC2	NT	Tachometer	Tail Rotor Tachometer
TAC3	NR	Tachometer	Gearbox High Speed Tachometer
ACC1	Cockpit Vert	Accelerometer	Cockpit Vertical (RT&B Vertical)
ACC2	Cockpit Lat	Accelerometer	Cockpit Lateral (RT&B Lateral)
ACC3	Nose Vert	Accelerometer	Nose Vertical
ACC4	TR GBX Vert	Accelerometer	Tail Rotor Gearbox- Vertical
ACC5	TR GBX Lat	Accelerometer	Tail Rotor Gearbox- Lateral
ACC6	INT GBX	Accelerometer	Intermediate Gearbox - Vertical
ACC7	ENG 1	Accelerometer	Engine #1 (left) – Vertical
ACC8	ENG 2	Accelerometer	Engine #2 (right) – Vertical
ACC9	Nose GBX 1	Accelerometer	Nose Gearbox #1 (left) – F/A
ACC10	Nose GBX 2	Accelerometer	Nose Gearbox #2 (right) – F/A
ACC11	H BRG FWD	Accelerometer	Forward Hanger Bearing – Lateral
ACC12	H BRG AFT	Accelerometer	Aft Hanger Bearing - Lateral
ACC13	Input Left	Accelerometer	Main Transmission Input #1 - Vertical
ACC14	Input Right	Accelerometer	Main Transmission Input #2 - Vertical
ACC15	Main GBX	Accelerometer	Main Transmission Accessories - Vertical
ACC16	TR Swash	Accelerometer	Tail Rotor Swashplate – Lateral
ACC17	MR Swash	Accelerometer	Main rotor Swashplate – Vertical
ACC18	APU Clutch	Accelerometer	Auxiliary Power Unit Clutch - Radial

Table 2 – UH-60A/L Sensor List

Number	Name	Sensor Type	Location
TR1	TRK	Blade Tracker	Main Rotor Blade Tracker
TAC1	N-RTB	Tachometer	Main Rotor Tachometer
TAC2	NT	Tachometer	Tail Rotor Tachometer
TAC3	NR	Tachometer	Gearbox High Speed Tachometer
TAC4	N-ENG	Tachometer	Temp Optical Tachometer for Eng Bal
ACC1	A	Accelerometer	Cockpit Copilot Side Vertical
ACC2	B	Accelerometer	Cockpit Pilot Side Vertical
ACC3	PHV	Accelerometer	Pilot Heel Vertical
ACC4	TAIL GBX	Accelerometer	Tail Rotor Gearbox
ACC5	INT GBX	Accelerometer	Intermediate Gearbox - Vertical
ACC6	ABS	Accelerometer	Absorber Frame - Vertical
ACC7	ACC GBX 1	Accelerometer	Accessory Gearbox #1 (left) - Vertical
ACC8	ACC GBX 2	Accelerometer	Accessory Gearbox #2 (left) - Vertical
ACC9	INPT GBX 1	Accelerometer	Input Gearbox #1 (left) – Vertical
ACC10	INPT GBX 2	Accelerometer	Input Gearbox #2 (right) – Vertical
ACC11	ENG 1	Accelerometer	Engine #1 (left) – Vertical
ACC12	ENG 2	Accelerometer	Engine #2 (right) – Vertical
ACC13	MAIN TRAN	Accelerometer	Main Transmission
ACC14	OIL CLR 1	Accelerometer	Oil Cooler - F/A
ACC15	OIL CLR 2	Accelerometer	Oil Cooler – Hanger Bearing
ACC16	HB FWD	Accelerometer	Hanger Bearing #1 (Fwd) - Vertical
ACC17	HB MID	Accelerometer	Hanger Bearing #2 (Mid) - Vertical
ACC18	HB AFT	Accelerometer	Hanger Bearing #3 (Aft) - Vertical

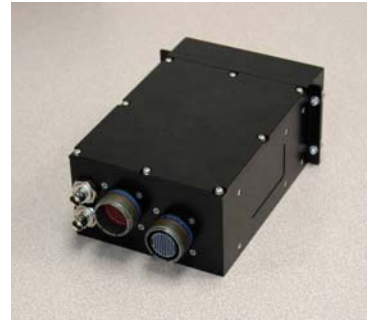
The VMEP system uses two styles of accelerometers. One sensor is a standard “spark-plug” style accelerometer that is used primarily for rotor smoothing and machinery monitoring where the larger sensor can fit. The other sensor is an integrated bracket-sensor that can fit on most bolted flanges found on gearboxes and bearing mounts and does not require bulky, specialized mounting brackets. Figure 2 shows a bracket-sensor mounted on the UH-60 intermediate gearbox.



Figure 2 - VMEP Bracket-sensor on UH60 Gearbox

VMEP also utilizes a Government Furnished Equipment (GFE) optical rotor blade-tracking sensor that measures helicopter blade height and lead-lag position. The system also senses standard 1/rev main and tail rotor tachometers as well as multi-pulse high-speed gearbox tachometers.

The Vibration Management Unit (VMU) is a lightweight acquisition and processing unit based on the PC-104 industry standard bus. Figure 3 shows a picture of the VMU with technical specifications. Open architecture hardware and software standards provide a low cost, easily upgradeable core system that can meet or exceed a wide variety of on-board diagnostic system needs including: rotor track and balance, drive train vibration monitoring, turbine engine diagnostics, and gearbox monitoring. The box weighs 4 lbs 5 oz and meets the Mil-Spec requirements for on-board systems. The VMU front panel has two knobs, one button, and five LEDs on the front panel. The pilot/copilot interact with the VMU by selecting a data collection “MODE” and aircraft “STATE” and pressing the data collection “DO” button. An indication is provided to the operator via a cockpit display on the status of the data



Technical Specification Overview

Temperature Range: -40C to +55C
Input Power: 6-40VDC, MIL-STD-704A
Power: <18 W
Dimensions: 3" x 5" x 9" w.o. mounting ears
Weight: 4lbs 5oz
Mounting: Dzus Rail
Interconnection: MIL-STD 38999 connectors
Environmental Qualification: MIL-STD-810C
EMI/RFI Qualification: MIL-STD-461B

Processor: Pentium compatible 233MHz
SDRAM: 128Mbyte
DiskOnChip: 72Mbyte
Compatibility: PC/AT compatibility, AVA
Com. Channels: two RS232/422/485, 1553 option
Vibration Channels: 24 (6 simultaneous)
Tachometer Channels: 8 (2 simultaneous)
Blade Tracker Channels: 1 channel
General Purpose Analog : 8
Low Signal Level Analog: 8

Figure 3 - Vibration Management Unit Technical Specifications

acquisition process. This manual operation insures high quality rotor smoothing data acquisitions. The VMU also automatically acquires data continuously during the flight for vibration exceedance checks.

The VMU utilizes WindRiver's industry standard VxWorks real-time operating system for the embedded software that collects, processes, stores and transfers data from all installed sensors. VxWorks was selected as the operating system for the VMU because of the wide variety of available development tools, market dominance, performance and robustness. The on-board non-volatile memory can store over 50 flights of data.

Figure 4 provides a diagram of the VMU software that has been developed for the VMEP program. The measurement executive controls all monitoring and processing activities. The measurement executive measures and processes data according to setup files that are stored in the on-board flash file memory system. The position of the front panel switches is monitored continuously to allow the pilot or co-pilot to enter the flight condition or desired measurement

manually. When a new flight condition is sensed the measurement executive parses the setup file finding the required measurements and diagnostic processing for the selected flight condition. The measurement executive sends setup commands to the Input Reader and one or more of the Diagnostic Processing Units (DPU). Inter-task communication functions of VxWorks are utilized for setup and data communication between the various on-board modules.

Setup files allow measurements and diagnostic processing configuration without the need to upload new object code. DPUs can be configured for new components by changing setup parameters. Measurement and diagnostic chaining allows an extensive survey to be conducted on a single flight or operating condition.

The input reader function shown in the block diagram provides high speed processing of vibration samples generated by the PC-104-VIB card. The basic measurement types are supported: Asynchronous Time Domain (ATD), Synchronous Time Domain (STD), Asynchronous Frequency Domain (AFD) and

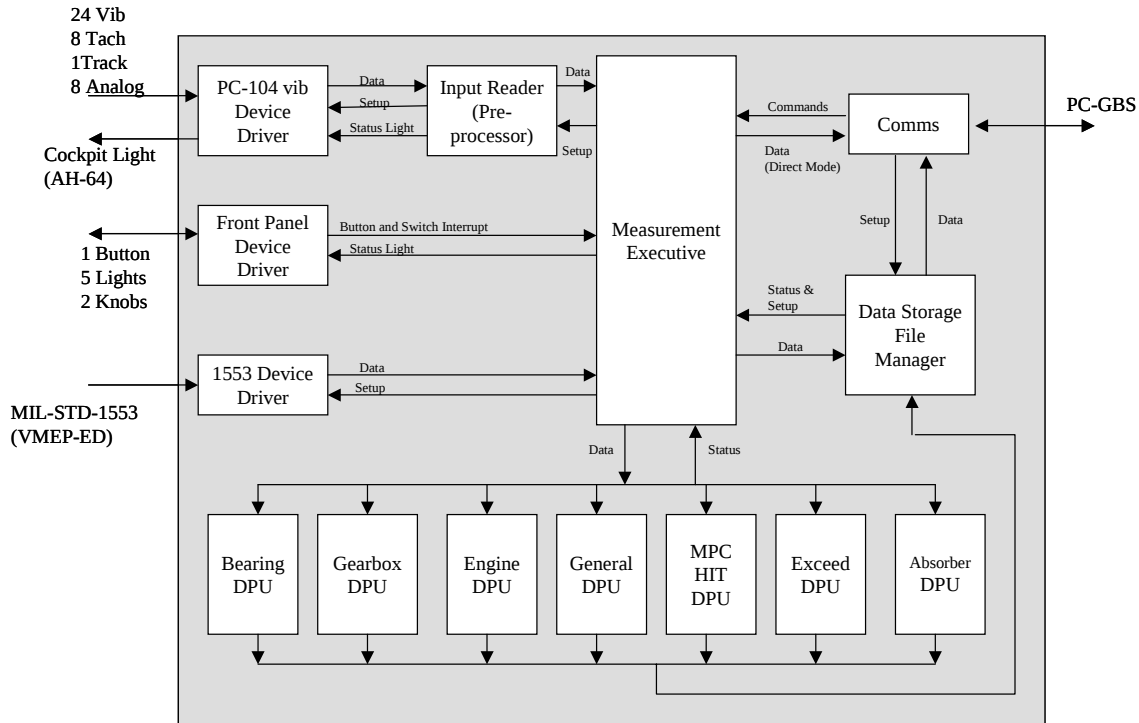


Figure 4 - VMU Software Architecture

Synchronous Order Domain (SOD). Data from the input reader is communicated to the Diagnostic Processing Units (DPUs) through a high-speed shared memory mechanism provided by VxWorks. The DPUs operate on one or more of the measurement types to create Condition Indicators (CIs). CIs are used within a DPU to diagnose a machine fault. A CI produces a single number that represents some aspect of a machine fault condition. Many different CIs and DPUs for diagnosing various types of mechanical equipment failures have been developed. These include DPUs for bearings, gearboxes, shafts, turbine engines and helicopter rotor systems.

After flight, the data acquired on the aircraft is downloaded over a serial link to a laptop PC at the aircraft for immediate, at-aircraft rotor smoothing adjustments and mechanical diagnostics. Then this data can be transferred to a centralized site for distributed diagnostics and long-term trend analysis.

PC-Ground Based Station (PC-GBS)

The PC-Ground Based Station (PC-GBS) uses a Windows® based software program that receives measured data from the on-board system, stores

this data into a database and performs analysis of the data producing easy to understand corrective actions for maintenance personnel.

The PC-GBS is also designed to operate effectively on any PC computer with a Pentium 133 MHz or faster processor. The PC-GBS transfers the aircraft data from the VMU for at-aircraft maintenance and diagnostics. The data transfer process takes less than 3 minutes per flight, and is recoverable if the transfer process is interrupted. One PC-GBS is capable of storing at least 1000 flights and can transfer archived aircraft data to a centralized location. The main user interface indicates the current status of the aircraft with easy to understand graphics or summary tables. Figure 5 shows a few of the screens from the PC-GBS. Minimum training is required by the user to operate the software and perform the basic functions without any prior expertise in rotor track and balance and vibration analysis.

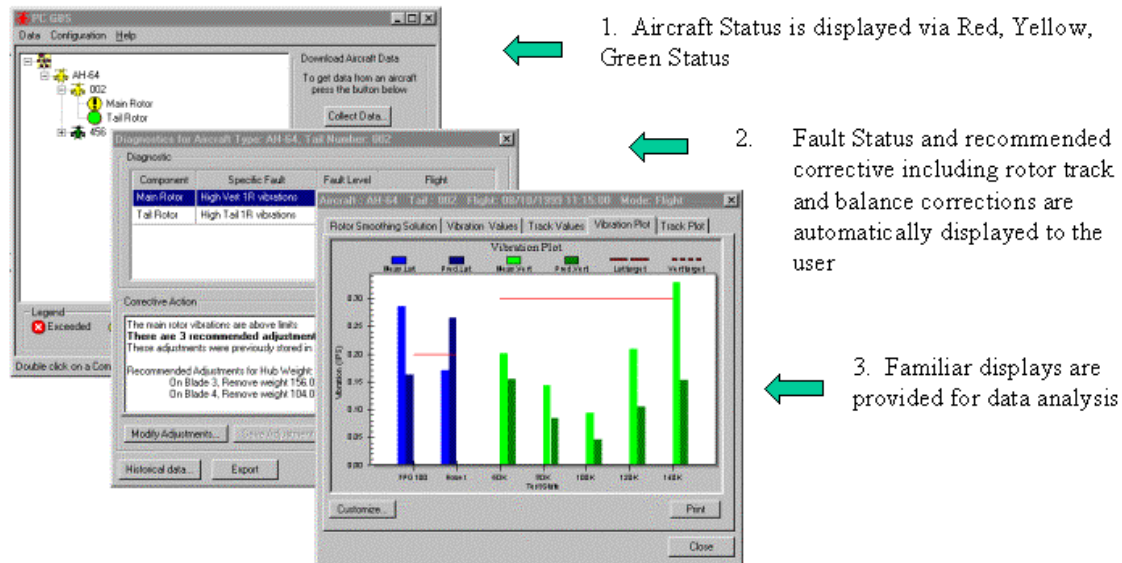


Figure 5 - PC-GBS Screens

The PC-GBS uses a neural network based rotor smoothing algorithm to calculate the maintenance actions required to optimize the rotor 1/rev vibration levels and rotor track [2]. The system presents an optimal solution to the user that lowers aircraft vibration based on a cost function that minimizes the number of adjustments required to lower the vibration. The system includes displays to allow the user to interactively edit the solution and view the predicted vibration response.

Diagnostic algorithms on the PC-GBS are used to automatically analyze acquired vibration data to provide a comprehensive indication of the health of the aircraft machinery such as engine, drive-shafts, gearboxes, bearings, pumps, and generators.

Vibration Diagnostics Using Simulink

The VMEP program supported the development of an intelligent mechanical diagnostic system (*i-mds*) for machinery diagnostic and prognostic systems. The *i-mds* development environment allows rapid prototyping of combinations of many different diagnostic techniques in parallel. *i-mds* includes a development environment that allows the software to be configured for different mechanical components such as turbine engines, helicopter gearboxes or any complex rotating or reciprocating machine. *i-mds* includes a graphical user interface that provides simple visualization of the processing flow and results.

Generic and multipurpose algorithms such as the Fast Fourier Transform (FFT) and digital filters as well as specialized algorithms for machinery fault detection such as a gear-tooth fault feature extractor are included. New diagnostic systems can be easily configured to include new or proprietary diagnostic algorithms into the processing flow.

The *i-mds* is built on a foundation of MATLAB. The *i-mds* library of diagnostic algorithms are supported by both MATLAB M-file scripts and C code compiled to run in the Simulink environment. The algorithms are developed and tested in Simulink before being compiled for use on the on-board system or PC-GBS. The *i-mds* model-based tools involve the use of Condition Indicator (CI) algorithms. The model-based tools use *a priori* knowledge of the mechanical system as a basis for the fault diagnosis. This *a priori* knowledge includes information about rotational speed, mechanical construction (such as gear ratios and inner and outer race data on bearings), and information on structural vibration or acoustic resonance of the system to be diagnosed. A condition indicator uses some form of measured data as input and produces a single real number as output. This single number can be thresholded, trended, fused or otherwise analyzed to provide an indication of the location and type of fault condition. There is a large body of literature on mechanical signature analysis, [1,3-7] which is used to develop the knowledge base for the diagnostic toolbox.

The software tools in *i-mds* are a combination of MATLAB and compiled C tools that can be divided into six main categories. Figure 6 shows the *i-mds* toolbox in the Simulink environment.

Bearing CI – Diagnostic algorithms designed to detect the onset of rolling-element bearing faults. These techniques use a combination of time and frequency domain processes. Many of these algorithms use signal demodulation or the Hilbert transform to enhance the bearing fault signature. A Cepstrum analysis tool is included which has been found effective in detecting bearing defects very early in the fault progression.

Engine CI – Diagnostic algorithms designed to detect the faults associated with gas turbine engines. These techniques are designed to find gas turbine faults such as rotor unbalance, rubs, accessory faults, and augmentor faults (fixed-wing applications).

Gear CI – Model-based feature extractors that are founded on the *a priori* knowledge of gear faults to include meshing faults, spalling, pitting, and heavy wear. The algorithms have been developed [1] to extract the gear fault data from averaged time domain data. Many of the algorithms have been developed at NASA and have been proven over the last 10 years.

General CI – Algorithms that extract information from frequency spectra. These algorithms include spectral peak detectors that can be programmed to select the peak or energy in a band based on frequency ranges or RPM. Many of the basic faults in drive shafts such as unbalance and misalignment can be detected with these algorithms.

Measurement CI – Algorithms that are designed as pre-processors for vibration measurements. These algorithms include the basics such as filtering, averaging, and re-sampling.

Neural Network – Tools that allow the fusing and evaluation of non-model based tools. The neural network is trained with good and known fault conditions so that it can recognize normal, novelty and faults. The training allows the neural network to use one or many CIs to determine the machinery fault condition. The data fusion characteristics of the neural network allows for higher probability of detection of mechanical faults with lower false alarms.

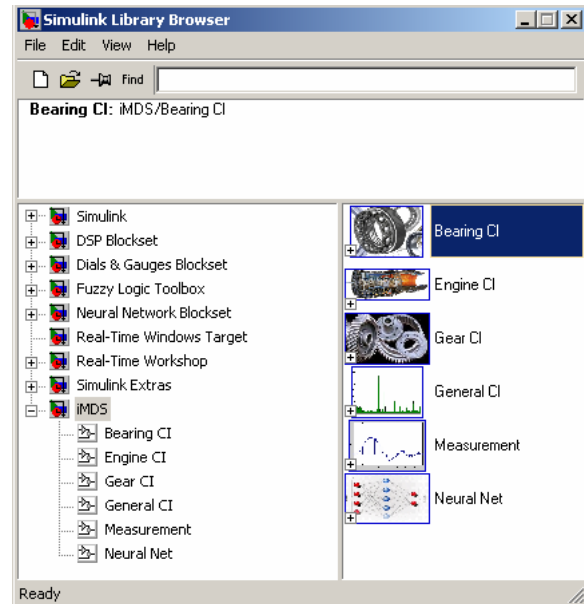


Figure 6 – Machinery Diagnostics Software Toolbox

AH-64A Vibration Data Collection and Results

Before the VMU was installed on the first AH-64A aircraft, a detailed vibration survey was performed on the aircraft at South Carolina Army National Guard (SCARNG). The objectives of the test were to acquire and record raw time-domain vibration data from the AH-64A engines and drive train. The testing included a modal vibration survey of the mounted accelerometer locations as well as ground runs. This data was used to develop and to refine the VMEP machinery diagnostic software toolbox.

Test Setup

The test used the following instrumentation:

1. (1) Eight channel dynamic signal tape recorder – RTTC provided Metrum tape recorder.
2. (5) VMEP accelerometers with built-in bracket - Dytran 3077A – 10mv/g.
3. (2) VMEP “spark plug” style accelerometers – Dytran 3061A – 25mv/g.
4. (7) VMEP accelerometer cables.
5. (1) High-speed tachometer cable.
6. (1) Eight-channel accelerometer power supply – Dytran 4120 ICP signal conditioner.
7. (1) Modal test impact hammer – PCB – 10 mv/lbf.

The recording configuration was as follows:

Channel	Location
1	Tail Gearbox
2	Intermediate Gearbox (IGB)
3	Hanger Bearing
4	Main Transmission – Accessories
5	Main Transmission – Input
6	Nose Gearbox
7	T701 Accessory Gearbox
8	Tachometer / Hammer

Test Procedure

The first test recorded the modal vibration response of each of the mounted accelerometers. Each sensor location was excited with a light tap from an instrumented modal test impact hammer. The signals from the hammer and the accelerometers were recorded on the tape recorder. The second test required a ground run of the aircraft. The vibration data from the seven accelerometers and one tachometer were recorded while the aircraft was operating in the following states:

1. 100% Nr, 30% Torque (Light on Wheels)
2. 100% Nr, Flat Pitch Ground (FPG)
3. 70% Nr, Flat Pitch Ground (FPG)
4. Shutdown

Test Results

Modal Impact Testing

The impact testing of the aircraft using the hard tip on the instrumented hammer involved recording four or more “good” (no double hits or over-ranging) measurements for each location. The impact location was on the gearbox or bearing structure as near as possible to the accelerometer. The data was recorded on a Metrum tape recorder as well as digitized on a Laptop PC for each impact.

The data collected on the PC was post-processed with the following procedure:

- Time domain signal evaluation for impact errors or amplitude clipping
- Frequency domain signal evaluation of both hammer and vibration signal
- Frequency Response Function (FRF) Calculations
- Coherence calculations
- Signal averaging

The results from the modal test showed that most accelerometer locations had significant resonant frequencies well within the measurement bandwidth of the VMU. Conventional wisdom regarding accelerometer bandwidth for a “flat” frequency response up to 30 KHz may need further study. Accelerometer brackets typically induce resonant frequencies that are well below the 30 KHz. To minimize this bulky bracket effect, the VMEP program designed the bracket-sensor, which is shown in Figure 2.

The first 3 resonant frequencies from each sensor tested are listed in Table 3. An interesting result was found on the Intermediate Gearbox test. This sensor is a spark plug style sensor that is mounted directly into a machined boss on the gearbox housing. There is no bracket to resonate, yet the first natural frequency was relatively low at 2986 Hz.

The modal vibration test data is important when analyzing the operational data for vibration fault analysis. Structural modes can affect the results when using pre-processing algorithms such as time synchronous averaging [1]. The structural resonance information is also useful when determining which bandwidth to demodulate for a bearing fault algorithm.

Table 3 – Resonant Frequencies (Hz)

Channel	Location	Mode 1	Mode 2	Mode 3
1	Tail Gearbox	2018	2534	3663 *
2	Intermediate Gearbox (IGB)	2986 *		
3	Hanger Bearing	921 *	2850	4800
4	Main Transmission – Accessories	1546	2109 *	2688
5	Main Transmission – Input	1820 *	2208	4311
6	Nose Gearbox	2220	2850 *	4009
7	T701 Accessory Gearbox	1773	2754	4561 *

- = Most Significant Mode

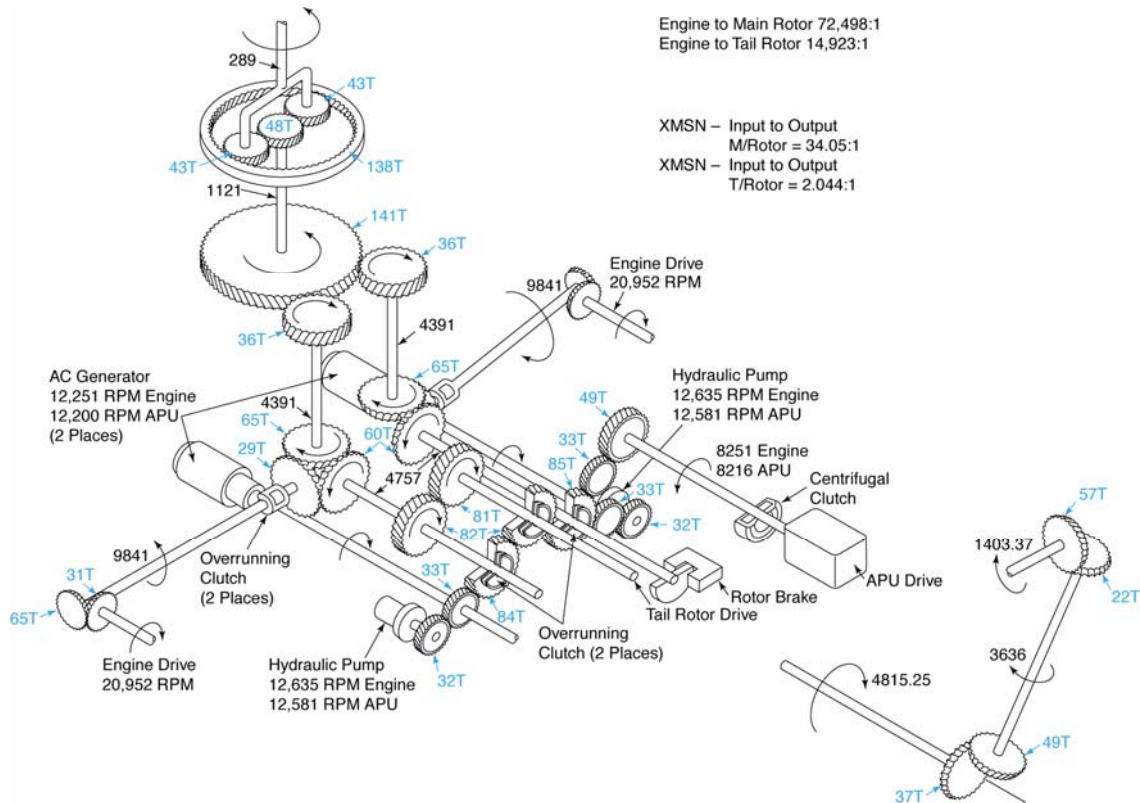


Figure 7 – AH-64A Mechanical Drive Schematic

Ground Runs

The ground run data was processed into frequency spectra to identify major vibratory components. This is the first step in developing diagnostic algorithms for a specific mechanical device. The major vibration sources identified include gear-clashing tones, bearing frequencies, shaft frequencies and structural natural resonances. Figure 7 shows the physical geometry of the AH-64A drive-train which is used to calculate the spectral frequencies.

Figure 8 shows a typical spectral response from the tail gearbox for this test. The main tones are a response of the 57 tooth gear meshing with the 22 tooth gear. The spectral data was processed with the following signal processing parameters:

- Sample rate – 60 kHz
- Anti-alias filter – 22 kHz
- 2048 point FFT
- Hanning window
- 50 averages (linear)

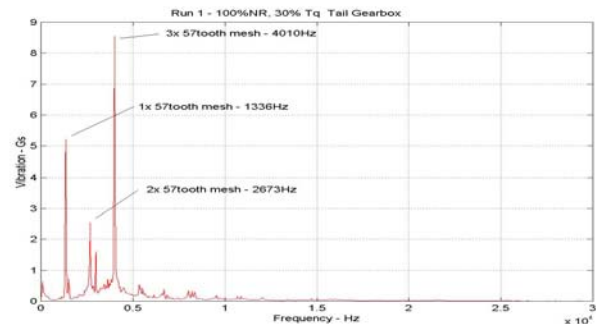


Figure 8 – Tail Gearbox Sensor Spectral Response

Algorithm Development

The AH-64A data was used to develop the *i-mds* diagnostic algorithms. Figure 9-10 show the *i-mds* script for developing gear fault algorithms. Data from the AH-64A ground runs are routed to sensor processing blocks shown in Figure 10. The pre-processing algorithms for each gear have input tools that let the user specify the number of pulses per revolution on the

tachometer, the gear ratio and the number of gear revolutions per block to average. Figure 10 shows the connection between the re-sampled and averaged data with the gear CI algorithms.

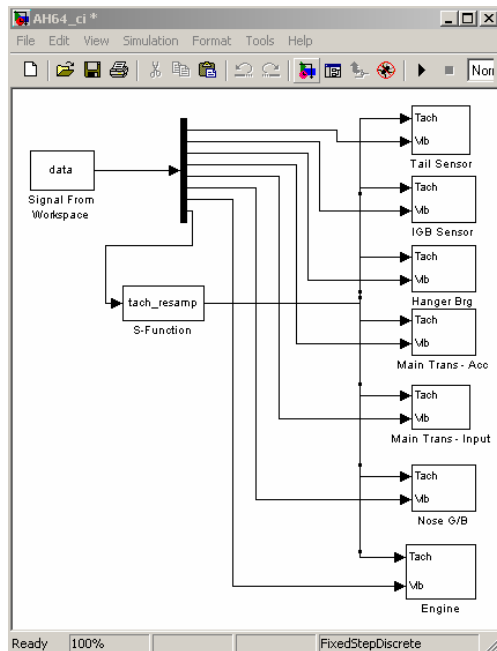


Figure 9 - imds Gear CI Development

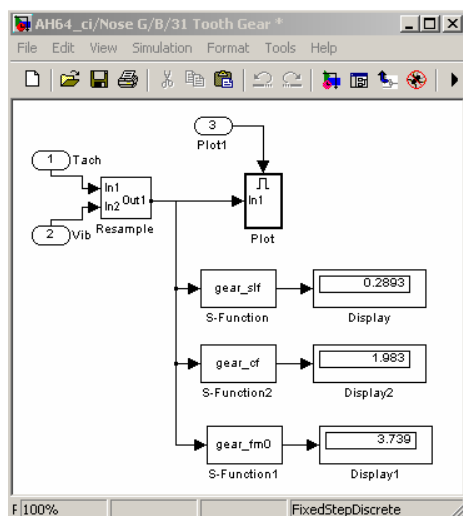


Figure 10 - imds Gear CI Results

Figure 11 shows the plots of the gear re-sampling and averaging algorithms. The raw vibration data is processed so that gear synchronous vibration is enhanced for each gear

in the aircraft. The top plot in Figure 11 shows the time domain waveform from the vibration signal acquired on the nose gearbox. The raw data was re-sampled and averaged into blocks of data so that the 31 tooth gear was reinforced. All other vibration not synchronous with this gear was eliminated. The bottom plot in this figure shows the order spectra corresponding to the averaged data. The CI algorithms shown in Figure 10 process this waveform and order spectra to extract gear fault signatures.

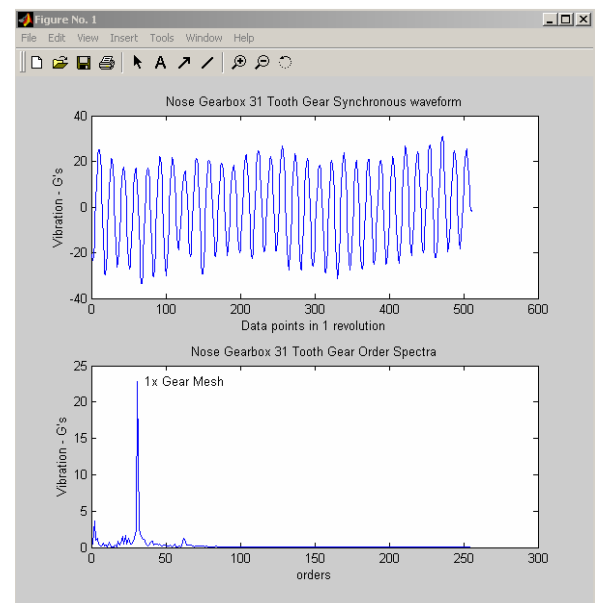


Figure 11 - Gear Vibration Waveform and Order Spectra

Development Status

From the hand full of aircraft that are currently implementing this system, and gathering data today, we expect to complete fielding to all of the South Carolina Army National Guard Apache and Black Hawks by the end of this year. Data collected from these aircraft will form the statistical basis for development of maintenance thresholds. Plans include fielding additional National Guard units as well as implementation of a web-based data collection, configuration management, and user assistance site.

The VMEP system for vibration monitoring and rotor smoothing will provide the basic platform for aircraft mechanical diagnostics. Near term plans for the VMEP include the addition of a COTS 1553 data bus monitor. This will enable the VMEP system to perform on-board engine

health checks and monitor analog parameters for exceedances. The aircraft parameter data will enable future automatic data acquisition using regime detection algorithms.

Concluding Remarks

This paper has shown the development of a system for vibration diagnostics that has been implemented. The goals of low-cost and low-weight have been demonstrated. The use of commercial off-the-shelf hardware and software has reduced the cost and complexity of this implementation. The infusion of emerging technology for vibration diagnostics has been simplified through the use of a software toolbox environment.

We now have an on-board system with data obtained on every flight. We can monitor both the main rotor and the tail rotor and evaluate their performance. We are measuring the vibration level of almost every rotating component and anticipate validation of prognostics in the near future. The dream is alive and will continue to grow with every new development in technology. The South Carolina Army National Guard is proud to be a participant in this innovative application in technology.

References

1. Zakrajsek, J., "An Investigation Of Gear Mesh Failure Prediction Techniques," NASA Technical Memorandum 102340, AVSCOM Technical Memorandum 89-C-005, Nov 1989.
2. Wroblewski, D., Branhof, B., Cook, T., "Neural Networks for Smoothing of Helicopter Rotors.," AHS International 57th Annual Forum, Washington D.C. , May 2000.
3. Braun, S., "Mechanical Signature Analysis Theory and Applications", Academic Press INC. ISBN 0-12-127255-9 1986
4. McFadden, P.D. and Smith J.D., "Vibration Monitoring of Rolling Element Bearing by the High Frequency Resonance Technique," Tribology International, Vol. 17,1, February 1984
5. Szczepanik, J., "Time Synchronous Averaging of Ball Mill Vibration," Mechanical Systems and Signal Processing, Vol. 3, Number 1, pg. 99, January 1989
6. McFadden, P., "Analysis of the Vibration of the Input Bevel Pinion in RAN Wessex Helicopter Main Rotor Gearbox WAK143 Prior to Failure," Department of Defense, Defense Science and Technology Organization, Aeronautical Research Laboratories, Aero Propulsion Report 169, AR-004-049.
7. Childers, D., Skinner, D., Kemerait, R., "The Cepstrum: A Guide to Processing" Proceedings of the IEEE, Vol. 65, No. 10, October 1977