Rotor Smoothing and Vibration Monitoring Results for the US Army VMEP

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Abstract— Automated systems to perform aircraft diagnostics and prognostics are of current interest. Development of those systems requires large amounts of data (collection, monitoring, manipulation) to capture and characterize fault events, and to ensure data is captured early-on in a fault progression to support prognostic system development. Continuous data collection is also required to capture relatively rare, potentially catastrophic events. Data collected can then be analyzed to assist in the development of automated systems and for continuous updating of algorithms to improve detection, classification, and prognostic performance. A test-bed is being developed in collaboration with the US Air Force and Army to perform data collection, and develop diagnostic and prognostic processing techniques using Army helicopter vibration and engine performance data as part of the Army's Vibration Management Enhancement Program (VMEP). The field system and the testbed being developed for collection and processing of VMEP data are described here.

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1. INTRODUCTION

The US Army and South Carolina Army National Guard (SCARNG) are currently employing the Vibration Management Enhancement Program (VMEP) for helicopter rotor smoothing and vibration monitoring. VMEP is an automated vibration monitoring and fault diagnostic tool that is composed of three primary components. The first component is a permanently installed on-board system that measures and processes vibration and parameter information. The second component is the PC-GBS a ground-based Windows ™ software system that displays recommended maintenance actions at the aircraft, aircraft status to the maintenance manager, and measurement details to the engineer. The third component is a system of web-based tools that provides data archiving, software configuration management, management reports, and an advanced engineering development testbed.

The VMEP objective is to develop a low cost and effective maintenance tool for rotor smoothing (track and balance) and vibration monitoring. It is believed that a significant cost savings can be realized with a system that will reduce vibration and related maintenance test flights. Further cost savings are expected from maintenance actions taken from early diagnosis of faults prior to significant, in-flight failures. The VMEP system has been operational on 18 AH-64A and 8 UH-60L aircraft since September 2001. The VMEP system is also in operation on 1 UH-60L and 1 AH-64D at Ft Rucker. A significant amount of vibration data has been collected on the airframe, rotors, engines, drive shafts, gearboxes, and accessories. This data is used by the aircraft maintainers for corrective actions and is transmitted via the Internet to a centralized data archive and analysis system.

This paper will summarize the data collected and will present the results of using VMEP to perform rotor smoothing and vibration fault diagnostics. Case studies of fault detection events will be presented. The Web based data analysis and data fusion tools will be described with examples of how the system is used to set vibration limits and find novelties. Identification of novelties is a precursor to future diagnostic and prognostic development when they can be associated with specific system faults and corrective actions.

2. OVERVIEW OF THE VIBRATION MANAGEMENT ENHANCEMENT PROGRAM

The primary function of the VMEP system is to provide a built-in capability to perform routine vibration maintenance functions (such as rotor smoothing and mandatory vibration checks) during routine operational flights. In addition, the system monitors the status or health of the dynamic drive system components and will record engine related exceedances. A capability for flight regime recognition and related structural usage monitoring

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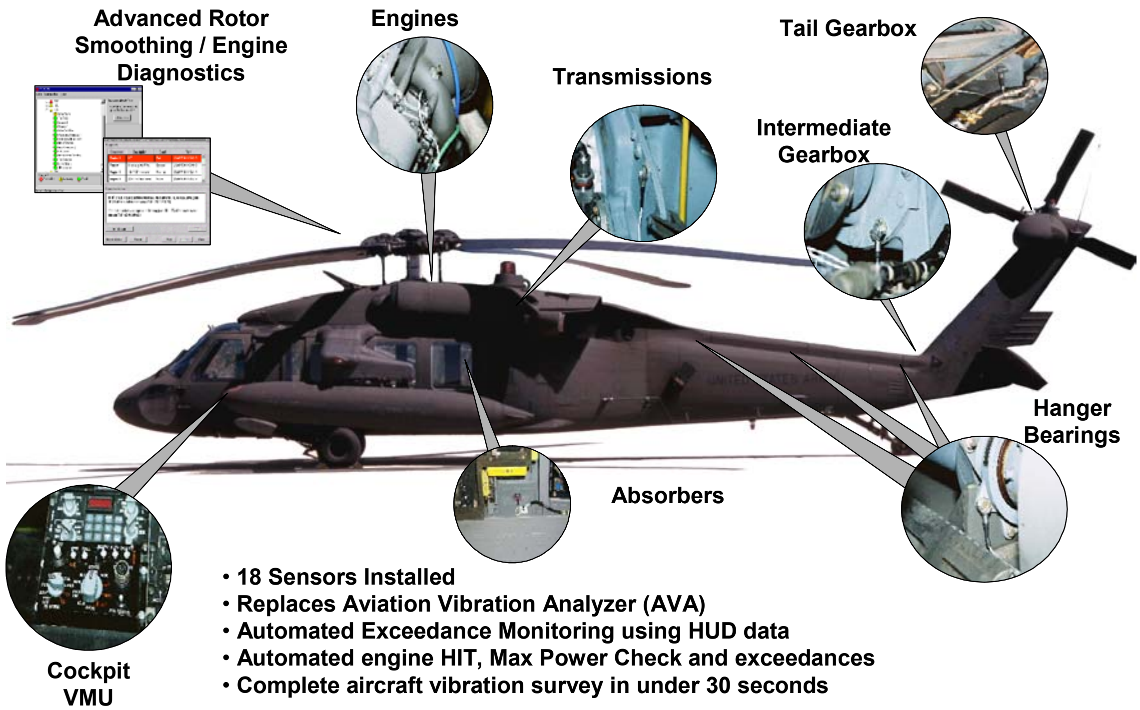

Figure 1 The VMEP on-board system

is currently being added. The availability of advanced signal processing for machinery fault diagnostics allows much of the processing of vibration signatures and other monitoring operations to be completed during in-flight operation of the aircraft. The VMEP is intended to detect faults with sufficient lead-time so that the ground-maintainer can schedule corrective actions well before the fault becomes an in-flight failure.

Overall system description

The VMEP system consists of the three main components described below. Specific details of the overall VMEP system can be found in [1,2].

On-board system

The on-board system, shown in Figure 1, consists of a Vibration Management Unit (VMU), a wiring harness, and sensors. The VMU front panel provides the aircrew a simple method of selecting acquisitions at specific flight conditions and receiving system status information. The sensors include tachometers and accelerometers distributed throughout the helicopter's drive train.

The data acquisition process on board the VMU is configurable. The system can be configured for engineering data acquisition or for day-to-day data collection. An engineering setup may include collecting data in a raw format like a digital tape recorder. This allows for the most flexibility in post processing. In normal day-to-day operation the VMEP is setup to pre-process the data and only store condensed Condition Indicators (CIs) in small compact data files.

If a new problem is found in a mechanical component, a small change in the setup file can be made to allow the VMEP to collect raw or intermediate results for detailed engineering analysis.

The data that is collected and processed in the VMU is stored for data transfer to the PC-GBS. The current VMU has 96 Mbytes of non-volatile memory for program and data storage. A typical flight contains fewer than 200 Kbytes of data allowing 450 typical flights to be stored before the data needs to be downloaded. Typically data is downloaded on a routine bases (daily, weekly, 10hrs/14 day) at the operators discretion. The typical download process only takes one minute. The size of the data files can be changed if engineering desires more raw data with the pre-processed Condition Indicators.

Ground based station

The ground-based software runs on a PC based Windows platform. The system is referred to as the PC Ground-Based System (PC-GBS). The operator downloads the processed data from the VMU after data has been captured in flight via a serial cable. The PC-GBS interprets the processed data and presents the user a status of the aircraft and its monitored components as shown in Figure 2.

Where sufficient data is known about a specific fault indicator, the instructions are provided for corrective action. This software also allows the trending of data across time for a specific tail number or across the fleet for comparison with other aircraft.

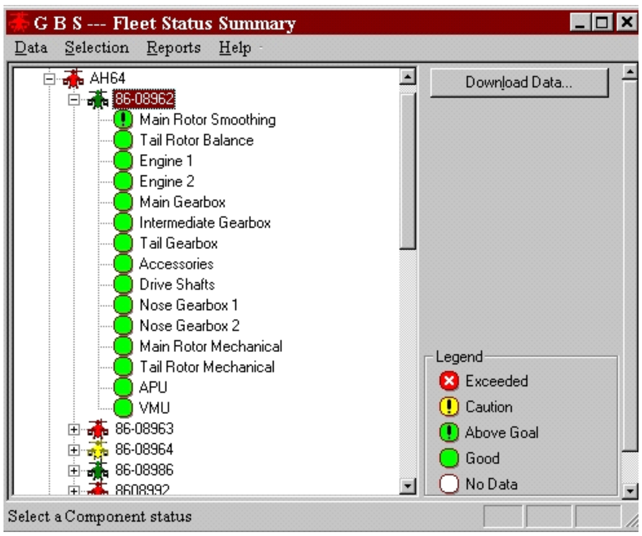

Figure 2 VMEP PC-Ground Based Station – Aircraft Status

The on-board system and PC-GBS are a continuous data collection system. This data is automatically downloaded to the web component of VMEP whenever the PC-GBS is attached to the web system.

3. ROTOR SMOOTHING RESULTS

Introduction

The VMEP system is permanently installed so rotor smoothing can be conducted anytime that the PC-GBS recommends a correction. Data is collected during all flights and is downloaded to the PC-GBS. This enables the users to keep the aircraft smooth between major maintenance events. The decision to make adjustments is up to the maintenance personnel and based on how far out of tolerance the vibration is. On the PC-GBS component status is shown by the color of the component's icon as shown in Figure 3.

Rotor smoothing typically applies to main rotors (for all aircraft), tail rotors (for all aircraft except CH-47) and some drive shafts (UH-60 high speed shaft).

Main Rotor

The goal of main rotor smoothing is to keep the in-plane (lateral) and out-of-plane (vertical) 1P vibrations of the main rotor at a minimum. The main rotor 1P vibration is typically measured from an in-plane and an out-of-plane accelerometer. Adjustments to the main rotor to reduce these vibrations are recommended by the PC-GBS. The default solution is determined by the following:

The rotor smoothing solution always tries to select the least amount of adjustments to get the best reduction in vibration. The reason that this is done is to minimize the chance for an error when making corrections, which experience has shown that 20% of adjustments are done incorrectly.

If data was collected with a blade tracker installed the track data is used to select the best solution which also optimizes the track.

Main rotor smoothing Maintenance Test Flights (MTF) are required whenever a component of the main rotor system has been adjusted or changed (pitch link, rotor blade, etc.). During MTF the main rotor vibration is typically reduced below the goal, which is indicated by a solid green icon on the PC-GBS.

Figure 3 - Aircraft component status

Main Rotor adjustment tweaks

One of the goals of VMEP is to allow rotor smoothing tweaks between major maintenance. Before the introduction of VMEP, once an aircraft was released from MTF the aircraft would be flown until it was written up for high 1P vibrations. Typically aircraft would fly with high main rotor vibrations for a long period of time. Once the aircraft was turned over to maintenance, test equipment must be installed and a dedicated MTF is required to smooth the main rotor. Now that VMEP is installed vibration can be reduced before an MTF is required due to high vibrations. After the aircraft is release from MTF the main rotor component on the PC-GBS will stay green for some time. When the main rotor vibration is above the goal, which is indicated by a green icon with an exclamation point in it, the PC-GBS will recommend a solution that will reduce the vibration. This adjustment is called a tweak between major maintenance. The objective is to allow these adjustments without a MTF required. These tweaks would keep the aircraft smooth between major maintenance and will save MTF's for rotor smoothing. These adjustments are only allowed if the main rotor status is above goal. If the main rotor status is yellow (caution) or red (exceedence) a dedicated MTF for rotor smoothing would be required. A MTF is required for this because the adjustments that would be required to reduce the vibration could produce excessive vibration if they were done incorrectly.

Tail Rotor

The goal of tail rotor smoothing is to keep the 1P in-plane vibration at a minimum. This is accomplished by adding or subtracting weights to balance the tail rotor. The tail rotor 1P vibration is measured from an accelerometer that is in-plane with the tail rotor. Adjustments to the tail rotor to reduce the in-plane vibration is recommended by the PC-GBS. Tail rotor vibration is monitored on all flights.

A dedicated rotor smoothing MTF is required whenever a component of the tail rotor system has been adjusted or changed (pitch link, rotor blade, etc.). During MTF the tail rotor vibration is reduced below the goal, which is indicated by a solid green icon on the PC-GBS.

The goal to reduce vibration between major maintenance on the tail rotor is achieved by allowing adjustment tweaks as described in the Main Rotor section above.

Engine High Speed Shaft (HSS) Balance (UH-60 only)

The engine HSS on the UH-60 requires balancing. Due to the criticality of keeping the HSS vibrations low, a hard limit is used that the shaft must be below. If this shaft requires balancing the PC-GBS will direct the user to collect the data to balance the shaft. Once the data is collected the PC-GBS will recommend the addition or subtraction of washers to reduce the vibration below the limit.

Rotor Smoothing Algorithms

A general, neural network based algorithm has been developed and applied to the problem of helicopter rotor smoothing. This approach provides non-parametric mappings between the spaces of rotor adjustment and vibration measurements, which are derived directly from empirical data, and permits to relax the usually used linearity assumption. Additionally, the rotor smoothing solutions are optimized to minimize the number of required adjustment moves. [3]

Tools for Rotor Smoothing

The PC-GBS has polar charts that display the rotor smoothing vibrations and also indicates where the vibration should move to, based on the current set of adjustments as shown in Figure 8 for the main rotor smoothing example. These polar charts can also be utilized to determine the health of the rotor. The PC-GBS will direct the operator to view the polar chart if the solution is not reducing the vibration to a satisfactory level (check the health of the rotor).

The PC-GBS has trending polar charts that are used to plot the vibration from one flight to the next to determine the affects that the adjustments had on the vibration as shown in Figure 10 for the tail balance example. The PC-GBS will recommend a review of this display if the vibration did not move in the correct direction (the wrong move was made).

Whenever the PC-GBS recommends a solution there are hot links that are associated with each type of adjustment. When the link is selected it takes the user to the procedure on how to perform this adjustment. Figure 4 shows an example of the instructions for an AH-64 tail rotor.

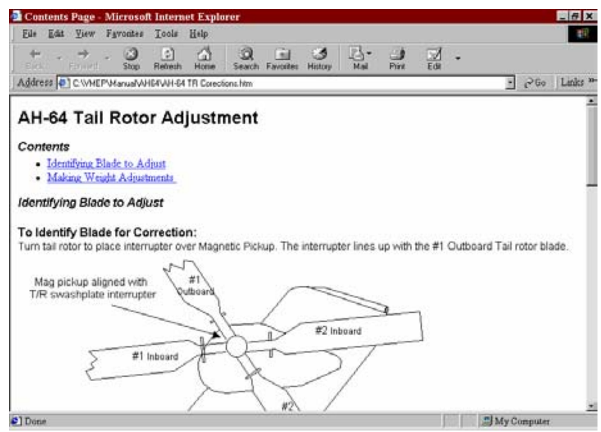

Figure 4 – Instructions for Rotor Smoothing Adjustments

The PC-GBS has a data quality indicator for each test state that rotor smoothing data was collected. This gives an indication of the stability of the vibration measurement (amplitude and phase) for the duration of the synchronous average. If the data quality indicator is low for a test state there is an option in the PC-GBS to not include this test state in the solution. By using the data quality indicator and the polar chart display it can be determined if a test state should be excluded from the rotor smoothing solution. The Data Quality indicator is shown in Figure 6.

Main Rotor Smoothing Example

To illustrate the rotor smoothing process the following example from a recently smoothed AH-64A aircraft tail number 86-09013 at South Carolina Army National Guard (SCARNG) is shown.

First vibration data from the rotor smoothing flight is downloaded to the PC-GBS where the maintainer is presented with the status of the Main Rotor Smoothing component. If the status is anything other than solid green (meaning vibration levels are above goal), the user will select the component to view the corrective actions as shown in Figure 5. For this example the user selected the flight from 5 February 2003 at 14:07:17 where the aircraft was in Exceedance due to high main rotor vibrations. In the corrective action area, the default solution is presented. This is the adjustment that was made to the aircraft.

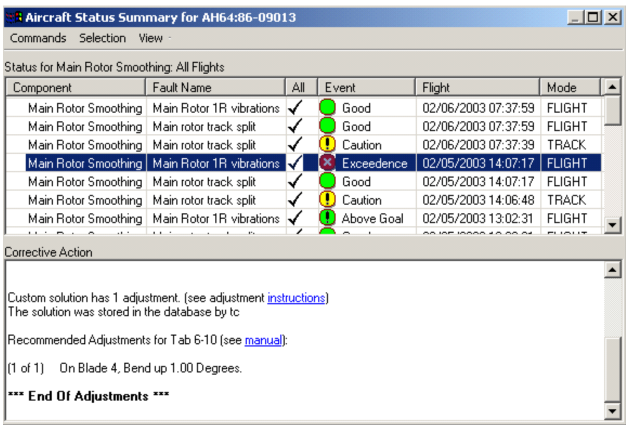

Figure 5 – Aircraft Status Summary

To view more details and to make changes to the adjustments the user can select the flight and is presented with the dialog shown in Figure 6. Here the measured vibrations and predicted vibrations are shown based on the current rotor smoothing solution. For this example the predicted in flight vibrations were below goal, which reinforced the application of the default solution.

If the user desires to change the rotor smoothing solution because an adjustment can not be made (weights or tabs are at a maximum) the Rotor Smoothing Solution Tab can be selected and is shown in Figure 7. There are many options to customize the solution such as resolve to limit and limiting adjustments. The users can also manually enter an adjustment and view the predictions. These features are normally used for difficult to smooth aircraft as the default solution shown in Figure 7 is sufficient. For this aircraft the solution was not modified because the tab move could be made.

To view the measured vibrations and predictions based on the current solution the user selects the Vibration Plot as shown in Figure 8. A polar chart shows vibration levels as a distance from the center of the chart (the center being zero vibration). The phase of the polar chart is the spatial relationship between vibration and a location on the rotor. The objective of the algorithm is to move all of the vibration points to the center of the polar chart. The vibration limits are shown as dashed circles and serve as a target. This plot is useful for troubleshooting difficult to smooth aircraft. Sometimes the points are spread around the polar plot and an optimum solution for all vibration points is difficult to achieve. In this example aircraft the points were grouped and the solution drove the vibration towards center as shown in Figure 8.

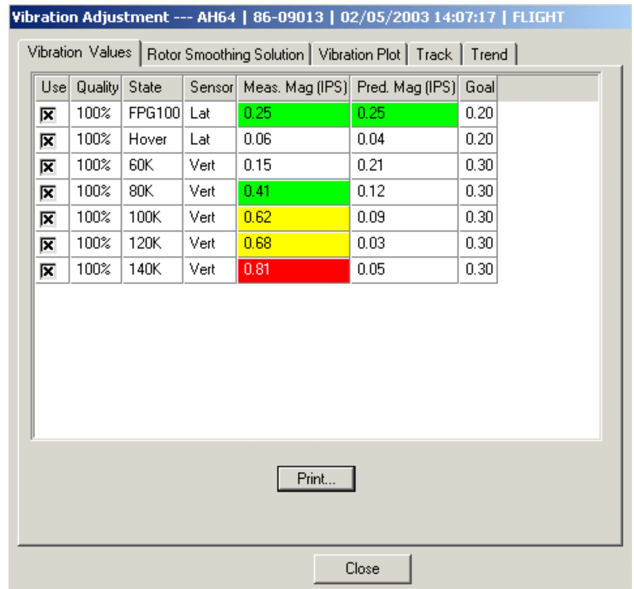

Figure 6 – Rotor Smoothing Vibration Values

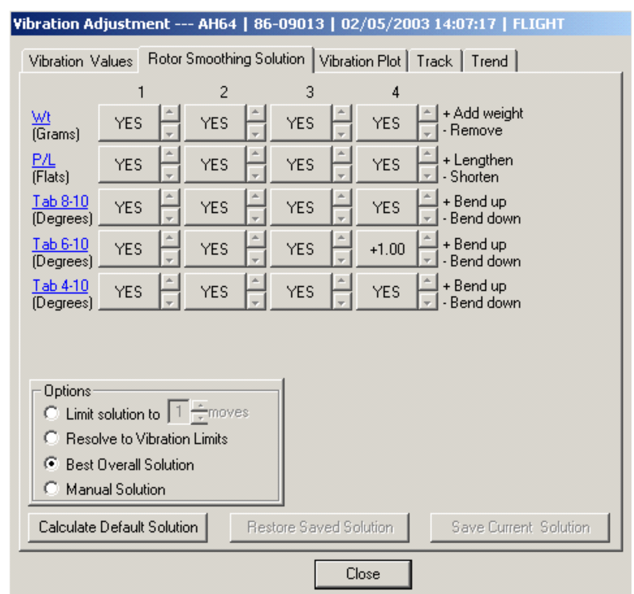

Figure 7 – Rotor Smoothing Adjustments

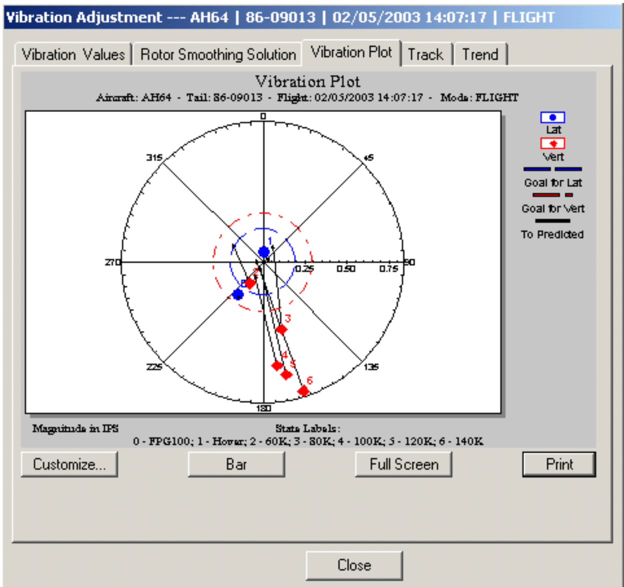

Figure 8 – Rotor Smoothing Polar Plot

A tracker was installed during data collection on this aircraft therefore a Track tab is available on the vibration adjustment screen. To view the track data the user selects the track tab as shown in Figure 9. The user can view the effects of the current adjustments on track by comparing the measured track (top display) to the predicted track (bottom display). Other track data is available for display such as lead-lag. For this aircraft the recommended adjustment to blade 4 (red) moved the blade up thus improving track while reducing vibration.

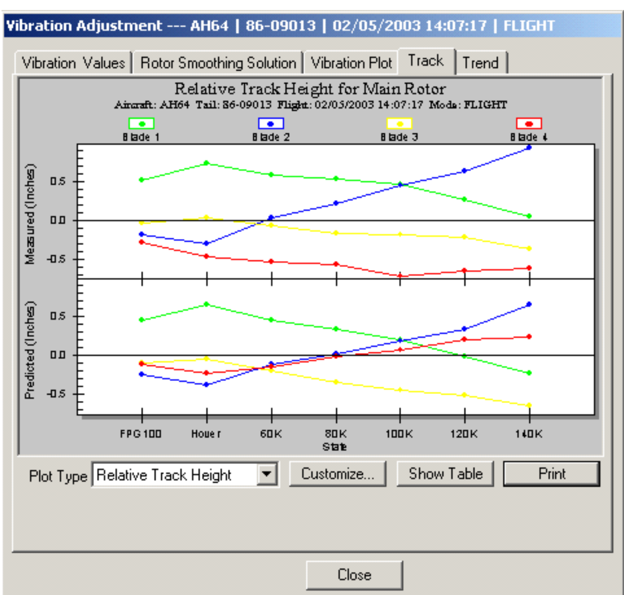

Figure 9 – Rotor Smoothing Track Display

The default correction was applied to the aircraft. Blade 4 tab sections 6-10 were bent up 1 degree. The next flight had all vibrations below goal. Table 1 shows the measured and predicted vibrations from the first flight with the measured vibrations from the second flight.

Table 1

State	Sensor	Flight 1 IPS	Predicted IPS	Flight 2 IPS
FPG100	Lat	.25	.25	.17
Hover	Lat	.06	.04	.03
60K	Vert	.15	.21	.21
80K	Vert	.41	.12	.13
100K	Vert	.62	.09	.19
120K	Vert	.68	.03	.18
140K	Vert	.81	.05	.17

Tail Rotor Smoothing Example

To illustrate the tail rotor smoothing process the following example from a recently smoothed UH-60L aircraft tail number 92-26415 at South Carolina Army National Guard (SCARNG) is shown.

First vibration data from the tail rotor ground run is downloaded to the PC-GBS where the maintainer is presented with the status of the Tail Rotor Balance component. For this example the tail rotor started out on 6/14/2002 with below goal vibrations of 0.20 IPS. The vibrations increased over time to a maximum level of 0.23 IPS at which time the maintainers decided to make an adjustment. The default solution of –29 grams from the target quadrant was applied to the aircraft on 8/13/2002. The results from this adjustment are shown in Table 2.

Table 2

State	Sensor	Run 1 IPS	Predicted IPS	Run 2 IPS
FPG100	Tail	.23	.00	.02

The vibrations from tail rotors increase over time. A current Army procedure has tail rotor balance checks every 100 hours. By having VMEP installed the vibrations can be kept at a minimum. A trend chart which shows the progression of vibration levels over time is illustrated in Figure 10. The points A, B and C show the progression over time with out any adjustments being made. The reduction in vibration from the default adjustment is shown as the points go to the center from C to D. After the adjustment was made, the vibrations will continue to increase as shown in the points from D to E to F.

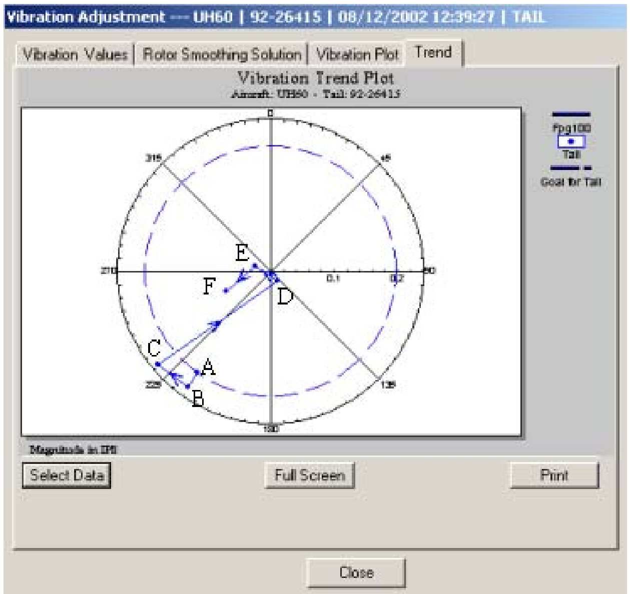

Figure 10 – Polar Trend

4. FAULT DETECTION EVENTS

Loose Gearbox Mount

AH-64A aircraft tail number 86-09002 was operational at SCARNG. A VMEP data download on 15 August, 2001 showed caution level vibrations from the Tail Swashplate accelerometer. The CI plot and the corresponding fault summary display is shown in Figure 11.

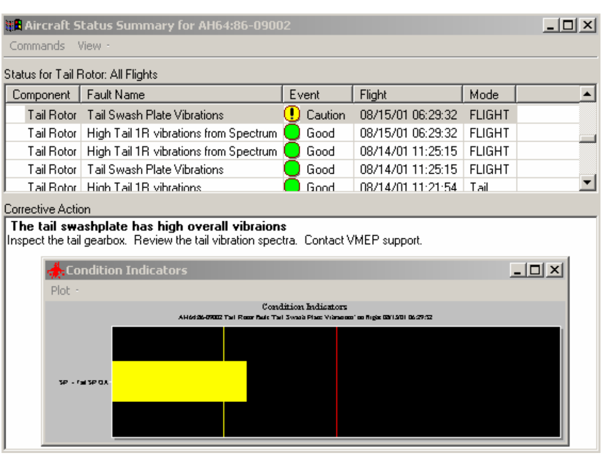

Figure 11 - Loose Gearbox Mount CI display

A visual inspection of the tail gearbox revealed that the mount link shown in Figure 12 was loose with a considerable amount of end-play in the turnbuckles. The mount was re-torqued to within specifications, and the resulting vibrations were reduced from 14.07 Gs to 2.23 Gs.

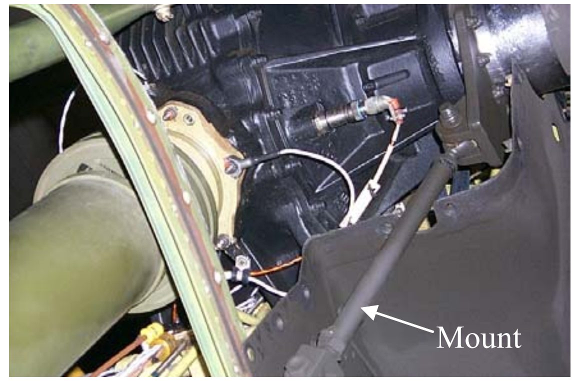

Figure 12 - AH-64 Tail Gearbox Mount

Driveshaft Vibrations

AH-64A Aircraft 86-08992 from SCARNG had a good "green" aircraft status when it went into phase maintenance in October 2001. When the aircraft came out in March of 2002, the VMEP system noted above caution level "yellow" indicators for the tail rotor drive shaft component. The aft hanger bearing drive shaft 1R component increased from around 1.0 IPS to 2.5 IPS as shown in Figure 13. The aft hanger bearing was changed with no effect on vibrations. The aft hanger bearing accelerometer was checked and found to be OK. The drive shaft was then removed, inspected and re-installed swapping directions end-for-end. The resulting vibrations were reduced to below caution levels.

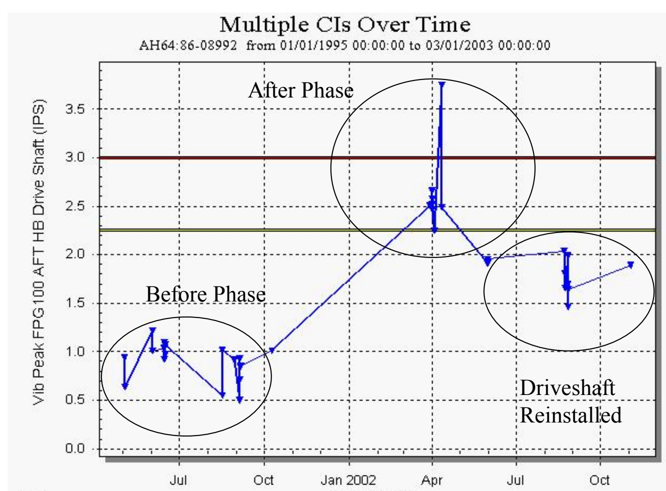

Figure 13 - AH-64 Driveshaft Vibrations

The helicopter maintainers in South Carolina realize the significance of fault detection. This information is used during the 10hour /14 day PMS to better inspect their aircraft. When the VMU data is downloaded, the crew chief is interested in trended vibration data. He wants to know what areas of his aircraft show increased vibration levels. He then more carefully looks at this area to try and locate a problem. On several occasions the crew chief has been successful in either correcting or replacing a small item thus savings a larger more expensive item.

The Army National Guard maintainers in South Carolina believe that this fault detection will not only prevent major in-flight catastrophic failures but will provide the supporting documentation to safely extend the flight time between inspections.

5. VMEP Web Server

Connectivity

The VMEP system includes an internet utility to collect, analyze, and make available data from the PC-GBS located at the unit/aircraft. The successful development of algorithms for helicopter condition health monitoring requires real data that represent specific conditions. These conditions are: nominal operation; operation with known faults; and, most importantly for prognostics, operation leading up to the time that a fault can be detected. Typically, data is saved only when a fault is detected; too late to be useful for prognostics development.

Figure 14 shows the hardware and connectivity of the system used to perform data collection. The VMU

collects vibration and 1553 (VMEP plus configuration) data. Maintenance personnel download the data, via serial port, to a PC-GBS, which is typically a ruggidized laptop computer.

Data is then transferred to the VMEP Server automatically when the PC-GBS and server are connected. Agent based software detects if new files exist on the PC-GBS that do not exist on the server. If not, that data is automatically sent.

Users that do not have the PC-GBS can also have access to data and results using a standard web browser interface.

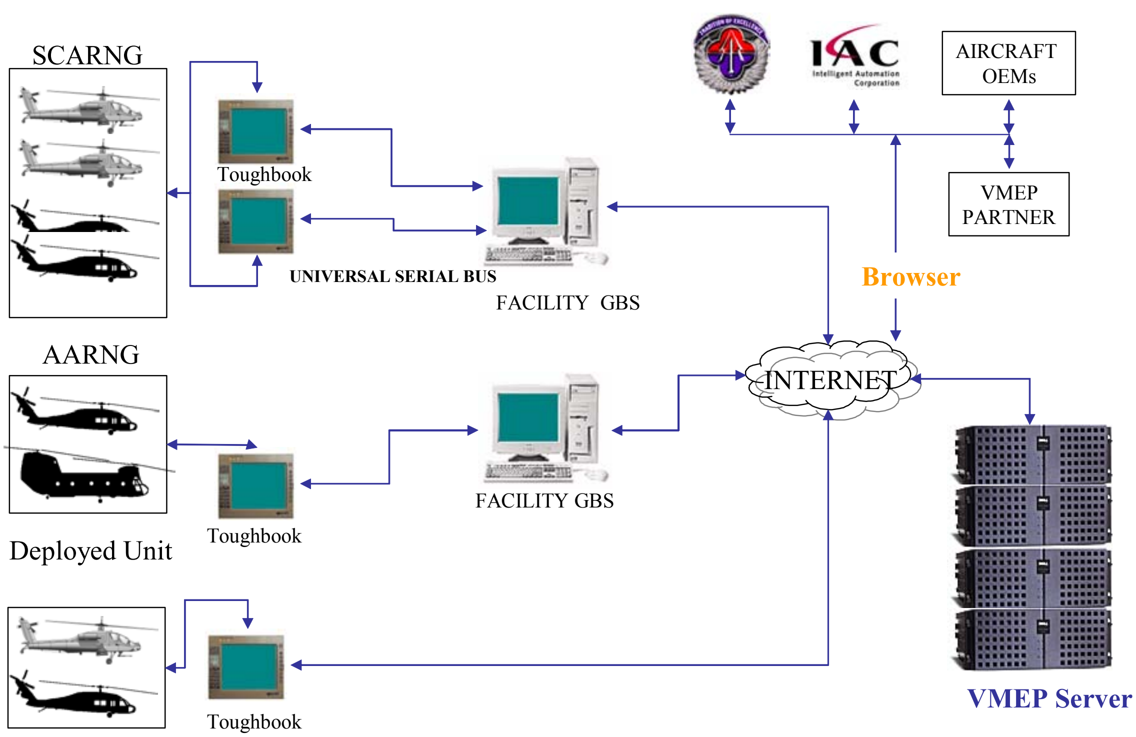

Figure 14 VMEP system connectivity

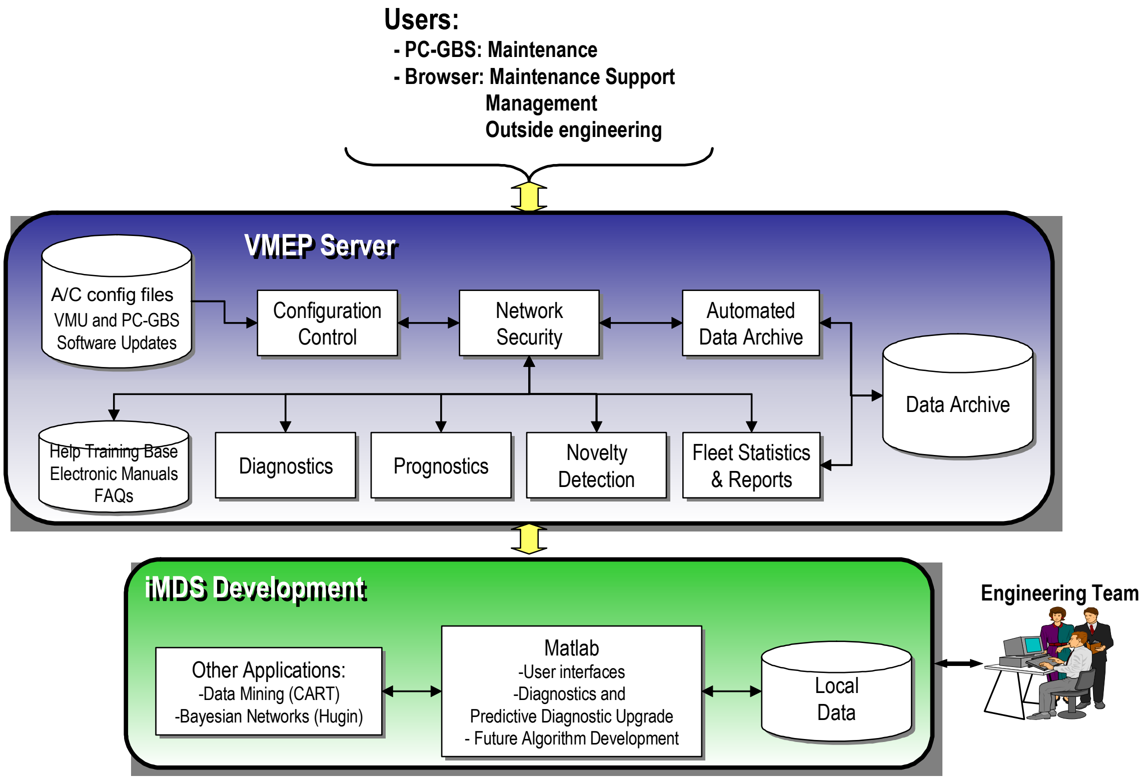

Figure 15 VMEP Server functional overview

Functional flow of VMEP Server

Figure 15 shows an overview of the functional flow of the

VMEP Server system. There are two major components to that system as indicated in the figure. The first is the *VMEP Server* itself. As described above, the VMEP Server is the central data repository for collection and organization of all aircraft collected data. This processing is handled by the Automated Data Archive in the Server.

Network Security is performed using a secure internet connection and password protection to access the system. The user / password are context sensitive so that user's will only be able to access those components of the web system for which they are authorized.

Aircraft Configuration and Software Updates for the PC-GBS and VMU are stored on the VMEP Server and automatically transferred during WEB connection using Configuration Control. The updates are first transferred to the PC-GBS and then onto individual aircraft on-board systems as opportunities arise (i.e. when maintenance personnel interface a PC-GBS to a specific tail number VMU). Configuration control will inform maintenance if too much time has passed between the time an upgrade is posted and it has not been transferred to a specific tail number. All the maintainer needs to do is attach a PC-GBS with the updates to the on-board system that does not have the updates.

A most useful portion of the Server for maintenance is the Fleet Statistics & Reports section. Here, fleet data, statistics, trending, and summary reports are available. These reports are available down to individual tail number and component level.

Electronic 'Help' is available in the form of electronic user's manuals, power point training presentations, and FAQs.

Advanced engineering contains a variety of modules to analyze the incoming data. These include Diagnostics, Prognostics, and Novelty Detection.

Diagnostics and prognostics algorithms are designed to respond to known fault conditions. A novel event is an unknown off-nominal condition. That is, the novel event is not nominal nor is it classified in any of the known fault conditions. *It's something completely new.*

Novelty detection is an important component in the operation of the Server. All incoming data is screened to detect, set aside, and flag for engineering analysis anomaly events. Engineers will not have to continuously examine "normal" events. Rather only "interesting" events need be examined. It is these sorts of events that are on the edges of the data distributions between normal and fault that are of the most interest for developing prognostic algorithms.

The second component of the Server is the *intelligent Machinery Diagnostics System* (iMDS*)* development system. The iMDS Development system is a "behind the scenes" set of tools used by diagnostic engineers. It contains tools for performing advanced engineering analysis on data stored on the Server and elsewhere. The toolkit allows engineers to prototype algorithms that can later be incorporated into upgrades for the PC-GBS and on-board systems.

iMDS Development is standalone from the other VMEP Server system components; however, it has the ability to download and process data from the iMDS Server. Details of the iMDS Development system can be found in [2,7].

6. VMEP SERVER OPERATION - EXAMPLES

Figure 16 shows the opening screen the user sees when entering the VMEP Server via the browser interface. There are 5 major links from the home page.

Fleet Analysis is designed for the maintainer and maintainer support personnel. It contains graphical summaries of fleet status as well as details of individual aircraft, aircraft component, and individual condition indicator (CI) status. Configuration control of VMEP software releases is also included.

Advanced Engineering is designed for engineers. It allows for visualization of data sets, selection and labeling of 'normal' and 'fault' representative data sets, setting of individual component CI detection thresholds, and development of models for diagnostics, prognostics, and anomaly detection.

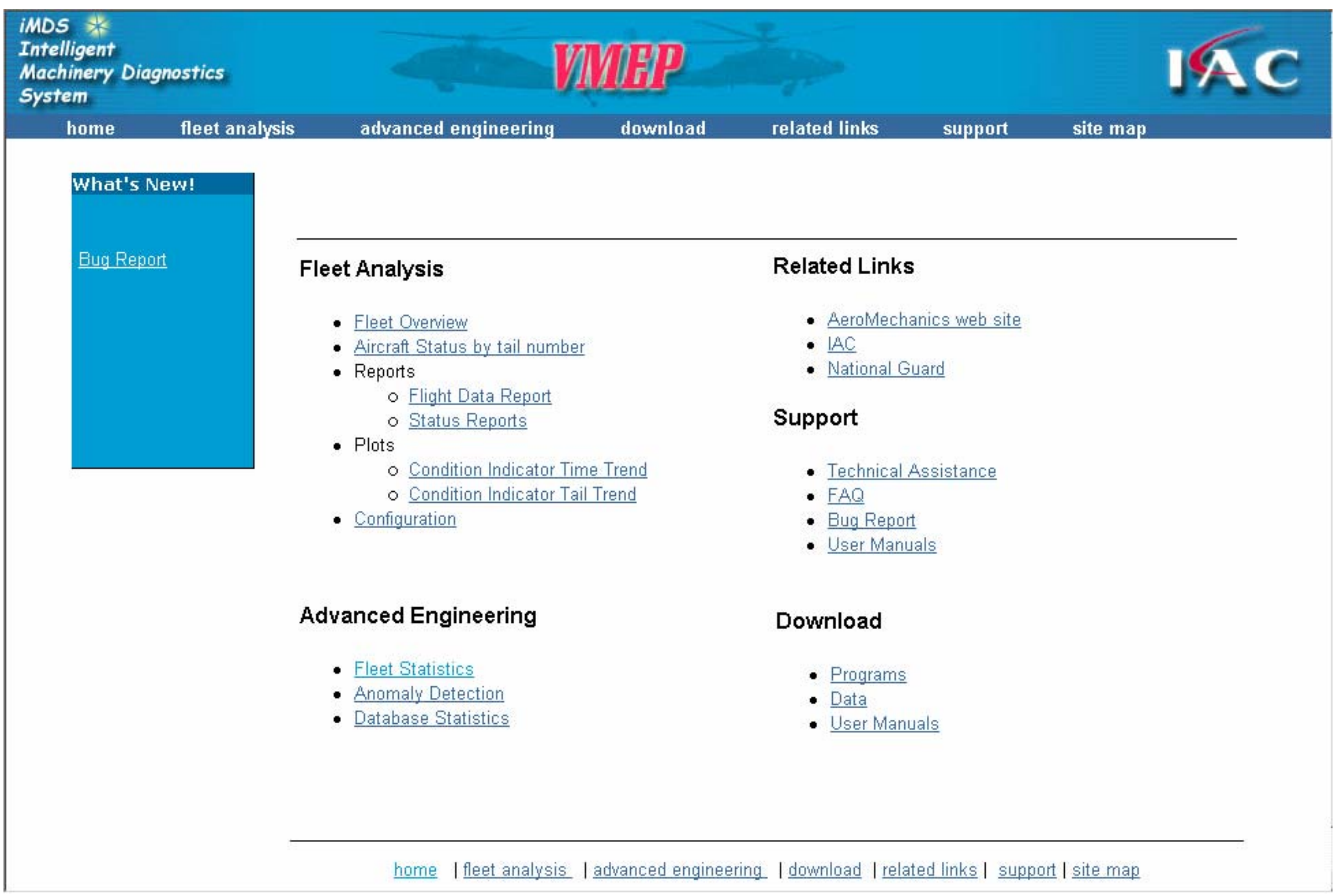

Figure 16 VMEP Server Browser Interface

Download contains the latest releases of both the PC-GBS and on-board system software as well as archived data and the latest VMEP related user manuals.

Support contains links to FAQ's, a bug reporting mechanism, and aircraft (non-VMEP) related user's manuals.

Related Links contain links to other websites that may be of interest to the user.

Fleet Analysis

Whenever possible, visualization of data processing results and summaries have been used in the Server. The browser interface uses all the standard pull down menus, 'back' button, and hyperlinks familiar to users. *'Fleet Analysis'* is the main summary page used by maintenance and fleet maintenance support personnel. Figure 17 shows a sample screen that is available from *Fleet Overview*.

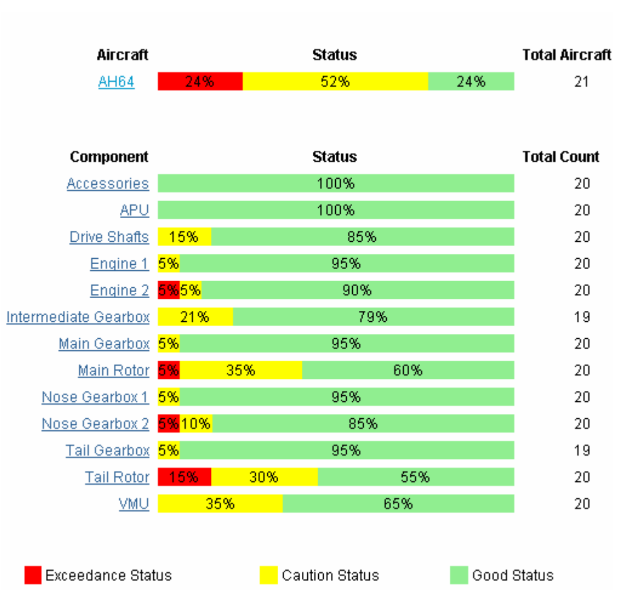

Figure 17 Fleet Overview example

The figure shows at the top a summary status for all AH64 aircraft at a unit; of the 21 aircraft being monitored 24% have at least one component that has a red (in exceedance) status, 52% are Yellow (or caution) status, and 24% are Green (good) status. The numbers / percentages shown here are for demonstration purposes only. Note this is not a complete data set, rather selected tails / times to give a good demonstration.

Details on which are the troublesome components can be found in the bottom portion of the display. Here we see that the Tail Rotor is the most troublesome with 15% of the aircraft having tail rotor vibrations in exceedance of the specified levels. Additional details can be found by clicking on the Tail Rotor hypertext to bring up all of the CIs computed for the tail rotor. A similar bar graph summary display is presented. The CI level information further isolates problematic areas.

The Fleet Analysis window also allow maintenance and maintenance support to quickly see what the readiness of all / or specific type aircraft at a unit or across the fleet is. The most troublesome components and the faults associated with them can quickly be identified.

Figure 18 shows an example of the detail available when *Aircraft Status by Tail Number* is selected. A tree structure similar to a Windows Explorer tree is brought up. That tree can be expanded / collapsed to supply the user with the detailed required.

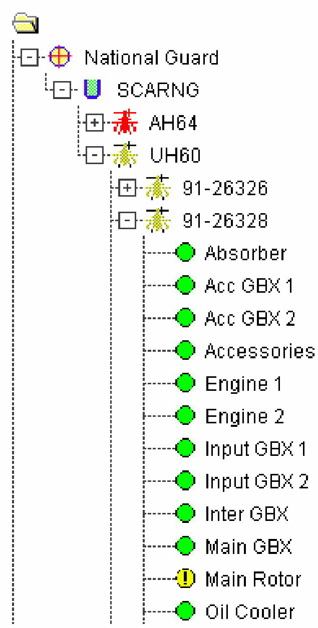

Figure 18 Aircraft Status example

Red, yellow, and green colors are again used in the icons to indicate the current status of all the aircraft at a given point in the tree. Green means everything is within tolerance. Red means that some component is out of tolerance. Yellow indicates that the component is in a 'warning' band and requires close monitoring. For example, in Figure 18 at least one of the AH64s has a red status while at least one of the UH60 has yellow status. The tree has been expanded to show that for a particular UH60 tail number, the component that leads to the caution status is due to the Main Rotor.

Advanced Engineering

Advanced Engineering is intended for the more sophisticated engineering user. Currently, Advanced Engineering includes:

- Database statistics
- Fleet statistics and
- Anomaly detection.

Figure 19 shows an example of the output obtained when the user selects *Database Statistics* from the *Advanced Engineering* window. The example shows all the data that has been stored for all AH64 aircraft to date. As shown, a total of 857 data sets has been collected which contain 8750 CIs that have been found from that data. This is really not nearly enough if we want to use real data to specify a 10^{-5} false alarm threshold.

Aircraft type: AH64

Mode	Number of Data Sets	Number of CIs
BIT	2532	2532
FLIGHT	518	23545
GNDBAL	157	142
MONITOR	1583	11023
SURVEY	136	47
TAIL	166	155
TRACK	178	168
Totals	5270	37612

Figure 19 Database statistics for AH-64

Fleet Statistics brings up a display that compares single component – single CI for a particular tail number to all aircraft within the fleet. Similar to the Aircraft Status summary tree, Fleet Statistics summary for all the CIs can be obtained through a similar tree.

On Figure 20, the left side shows the Fleet Statistics summary / selection tree expanded to highlight specific tail number 86-08996. For that tail, the current condition is Red (there is a component in exceedance that is not shown). The individual components indicate that Engine 2 vibrations are in the Yellow / caution limit and that the CI labeled *SP2 FPG100 #2 Eng GG* gives rise to the caution.

The right hand side of Figure 20 shows a *box plot* summary of the selected tail / component / condition indicator compared to that CI found for <u>all</u> AH64 aircraft.

A box plot summarizes the CI data. It indicates the median, upper and lower *quartile*, upper and lower *adjacent values*, and *outlier* individual points. The boxplot in Figure 20 is broken down as follows. The large dot in the plot shows the median (middle point value) of the data. The 'box' is drawn so that 50% of the data will reside inside the box. 25% of the data is to the left of the box and 25% is to the right of the box. The dotted lines are called *fences* or *gates*. The gates are sort of a poor man's single CI anomaly detector; if the data is well behaved all the points should fall between the gates. Outlier points are plotted as individual circles outside the gates.

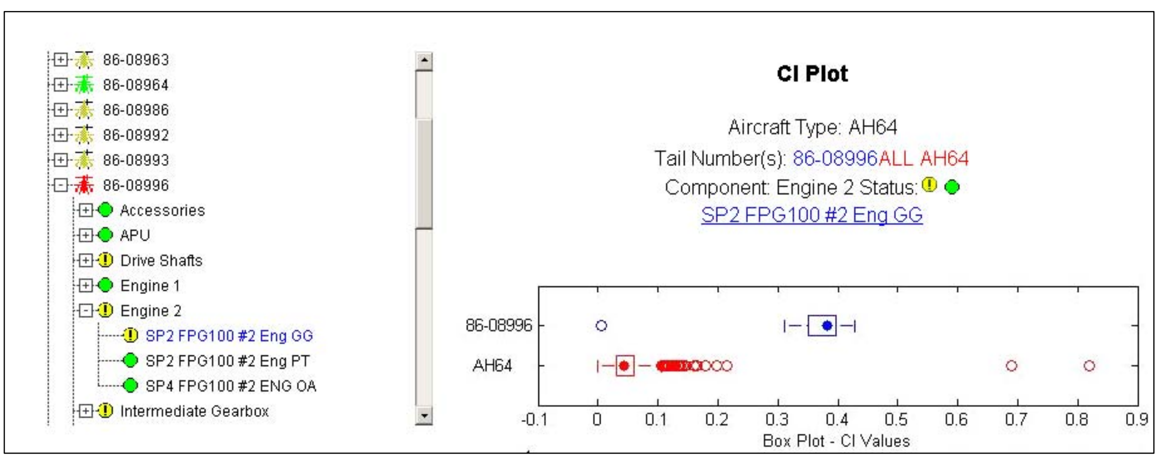

Figure 20 Advanced Engineering Fleet Statistics example

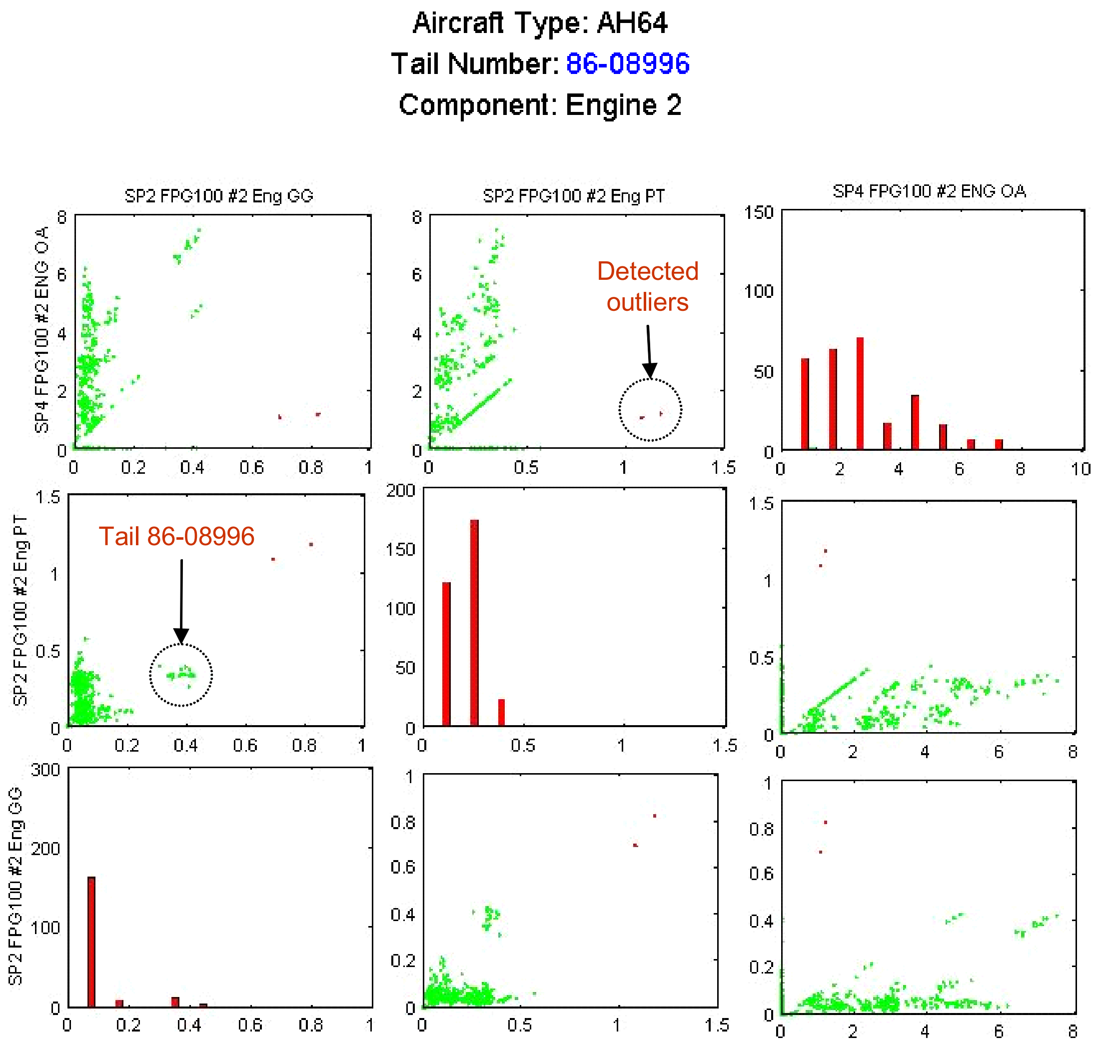

Figure 21 Anomaly Detection example

In Figure 20 we see that the points associated with the selected tail number are self consistent. For the most part (with the exception of a 0 value) they all lie with in the blue box plus gates. However it is easily seen in the display that as a group, they are very different from the same CI calculated from all the other aircraft in the database.

Anomaly Detection

Up to this point, each of the CIs has been handled as single variables. Fusing information from several CIs will take advantage of the relationships of CIs in order to improve component level processing.

There are a variety of anomaly detectors (ADs) that can be used for the problem [4]. On the Server we use a neural net solution to the problem [5]. The basic neural net anomaly detector uses radial basis function (RBF) neural nets to form a statistical model of "nominal" data. As new data enters into the system, it is compared to the RBF neural net model. If data falls within the boundaries defined by that model, then it is flagged as "nominal". If is does not, then it is flagged as an "anomaly". In the web site several different anomaly detectors are implemented using not only the RBF neural network, but *Support Vector Machines* and *Fuzzy Logic*. The user can call up the different detectors from a pull down window.

Notice that there is an implicit Gaussian assumption in the AD as implemented using the RBF neural network. In order to visualize distribution of the multi-CI data we have created sets of 2-dimensional plots (one for each pair of CIs) to see how the CIs are related and to determine if the model fit is appropriate. Figure 21 shows an example of that plot for the Engine #2 on the AH64 aircraft.

The Engine #2 component has 3 CIs associated with it. Thus there is the 3 x 3 array of plots shown in Figure 21. The plots correspond to pairs of CI values for the off diagonal plots. The plots along the main diagonal are histograms for the corresponding CI. Note that the scales on the plots are different depending on what is being plotted. The CI values plotted are labeled at the top and sides.

The CI that was flagged in the single CI case corresponded to tail number 86-08996. Those points stand out as a cluster in two dimensions in the figure. For anomaly detection purposes, those points were labeled as "good" along with all the other green points shown in the plot. A neural net model was built using those green points. Two outliers, identified as the red points, were found by the anomaly detector.

Single CI Detection Threshold Setting

Initial settings for single CIs on the Server have either been set based on the original manufacturers specifications or by engineering judgment as to what is acceptable or not. Since a substantial amount of data for Army aircraft has been collected, the website has included an automated statistics based setting for the various thresholds of single CIs. The automated setting of thresholds is based on ordered statistics of the data.

Figure 22 shows an example of that page for the AH64 Drive shafts for single CI threshold setting. There are four CIs associated with that component but only two are shown in the figure (the user would scroll down on the website for the other two). The current and suggested values of the 'goal' (green), 'caution' (yellow), and 'exceedance' (red) are shown.

The *Recommended Settings* are found directly from the collected normal data using the box plot processing similar to that described before. Figure 22 indicates that the Recommended Settings for the first CI (SP2 FPG100 Aft HB Drive Shaft), are considerably above the current settings. Indeed this particular CI was a problem because of the low threshold settings which created numerous false alarms.

As seen in Figure 22, the user has the option to accept each of the recommended settings, fill in (and accept) their own settings, or do nothing.

Set CI Limits

Aircraft type: AH64

Component: **Drive Shafts**

SP2 FPG100 AFT HB Drive Shaft

Limit type:	Current Settings:	Recommended Settings:	Modified Settings:
Goal:	1.5	2.4669	
Caution:	1.5	2.5363	
Exceedance:	3	3.7508	

○ Accept recommended settings for this CI
○ Accept modified settings for this CI
◉ Accept NOTHING! (Make no changes)

SP2 FPG100 AFT HB OA

Limit type:	Current Settings:	Recommended Settings:	Modified Settings:
Goal:	10	3.5876	
Caution:	10	3.7807	
Exceedance:	20	3.8402	

○ Accept recommended settings for this CI
○ Accept modified settings for this CI
◉ Accept NOTHING! (Make no changes)

Figure 22 CI detection threshold setting

To gain more insight into the data the user may bring up additional plots for the data. Figure 23 shows some of the additional plots for the first CI for the Drive Shaft. The top shows the boxplot for the original data. The bottom plot is a histogram of that data. As described previously the boxplot gives an indication of the self consistency of the data, the spread of the data, and a poor man's detector of outliers. All the data that was used in plots of Figure 23 had previously been labeled as "good".

The box plots contain sets up upside down and right side up triangles. The triangles are colored green, yellow, and red and indicate the current threshold setting (the upside down triangles that appear above the center line in the plots) and the automatically generated thresholds (the right side up triangles that appear below the center line in the plots). For this particular CI as seen all of the recommended threshold settings are to the right of the current threshold settings. It is clear from this plot why false alarms would likely be occurring.

For the second CI shown in Figure 22 (SP2 FPG100 Aft HB OA) we can see that the recommended settings are much lower then the current settings. Thus with the current settings there will be no false alarms, but also no detections! Again the recommended settings would greatly improve the system's performance.

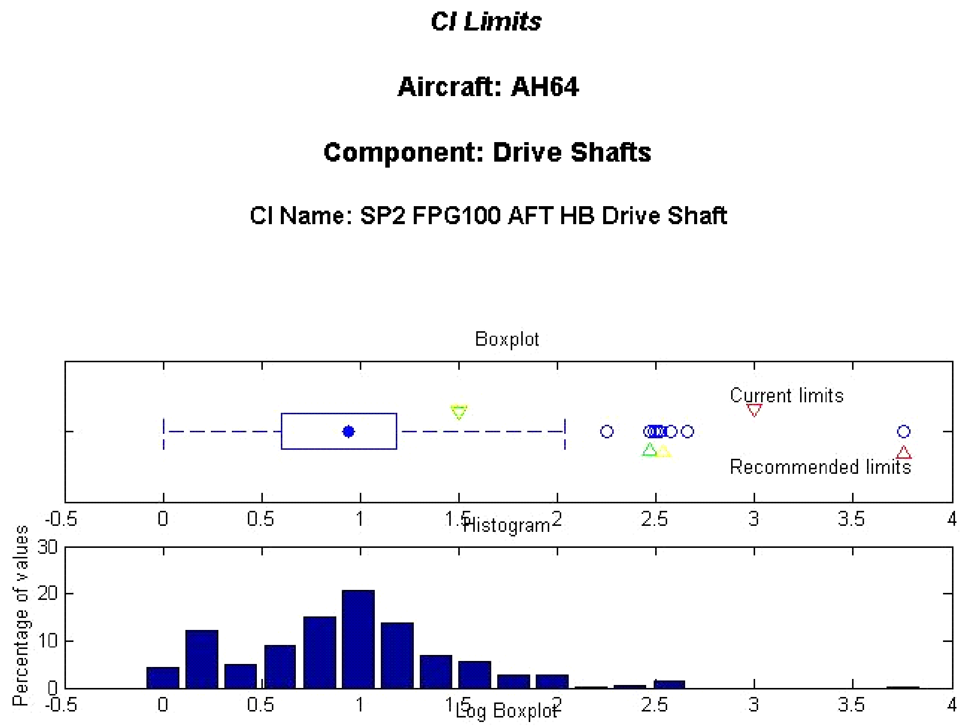

Figure 23 CI automated detection threshold

Gold Standard Data Set Development

As one can imagine, building models from examples of real data, requires that the real data be representative of the normal and fault classes that are being considered. Miss labeling of data or allowing outlier points to be included as "good" points, results in models that will not be good. Thus tools have been included in the website for viewing and including new data as it enters the system to be labeled as 'normal' or assigning a specific fault class. This is used in forming what we've called the *gold standard* data set. All new data entering the system must be reviewed by qualified personnel before being included in the gold standard database.

The Server has tools built into it to be able to bring up new data for individual components, display that data overlaid with current gold standard data. Some of those tools are described here. The data and results presented so far have been on data that has been previously reviewed and labeled as "good" or not. That same data is presented below, but <u>before</u> it has been labeled.

When data first enters the system, it is labeled "new." It is not known if the data is "normal" or has some known fault condition, or is just a bad data point (i.e. equipment turned off so no vibrations generated for example). It is up to the engineer to apply a label to the data. Figure 24 shows a screen for reviewing and assigning as "good" new data that enters into the system. The data is the AH64 Engine #2 data that has been examined previously.

In the display shown the data has been rank ordered according to its *distance* [5] from a single multi-dimensional Gaussian model fit to a transformed version of the multi-dimensional CI data. The transform converts the data from its original distribution, so that it is Gaussian in each of its CI dimensions [6]. This transformation ensures a better model fit to the data. An example of original data and transformed data is shown in Figure 26. Ensuring that the data and the form of the model fit are in agreement is often overlooked and "bad" models usually result. That transformation becomes part of the modeling information and used for all future processing (i.e. the data is first transformed, the anomaly detection of other processing applied, and the results are transformed back into the original domain). Note at the bottom of the display, the data can be sorted in a variety of other ways.

Individual points can be accepted or rejected. However a more automated approach is to use the "Rejection threshold" shown at the bottom of the display. Figure 25 shows the results of a roughly 10% rejection rate; that is that the top 10% of the points that are farthest from the nominal model are rejected. Those points are colored red in the plot; accepted points are green.

Modify Class
Aircraft: AH64
Component: Engine 2

New points

Tail Number	SP2 FPG100 #2 Eng GG	SP2 FPG100 #2 Eng PT	SP4 FPG100 #2 ENG OA	Date/Time	Status
86-08996	0.427637	0.327462	4.866620	03-Nov-2001 10:33:41	⦿ Accept ○ Reject
86-08996	0.411514	0.327072	4.683140	02-Nov-2001 13:15:15	⦿ Accept ○ Reject
86-08996	0.395290	0.337388	4.498500	03-Nov-2001 11:00:19	⦿ Accept ○ Reject
86-09031	0.000036	0.000399	0.000724	05-Jan-1999 00:40:21	⦿ Accept ○ Reject
86-09036	0.053707	0.329181	5.077570	23-May-2002 14:16:42	⦿ Accept ○ Reject
• • •					
86-08992	0.068153	0.038869	0.775602	02-May-2001 09:25:42	⦿ Accept ○ Reject
86-08992	0.087866	0.125816	0.014492	01-Apr-2002 11:57:23	⦿ Accept ○ Reject
86-08992	0.081643	0.159876	0.011818	01-Apr-2002 12:26:20	⦿ Accept ○ Reject
86-08992	0.072278	0.062366	0.010277	11-Apr-2002 09:12:42	⦿ Accept ○ Reject

⦿ Accept changes above ○ Accept all ○ Reject all ○ Rejection threshold: 0.300000

Sort by: (Saves changes to satus column)

○ Tail Number ○ SP2 FPG100 #2 Eng GG ○ SP2 FPG100 #2 Eng PT ○ SP4 FPG100 #2 ENG OA ○ Date/Time ⦿ Value

Figure 24 Golden data set specification

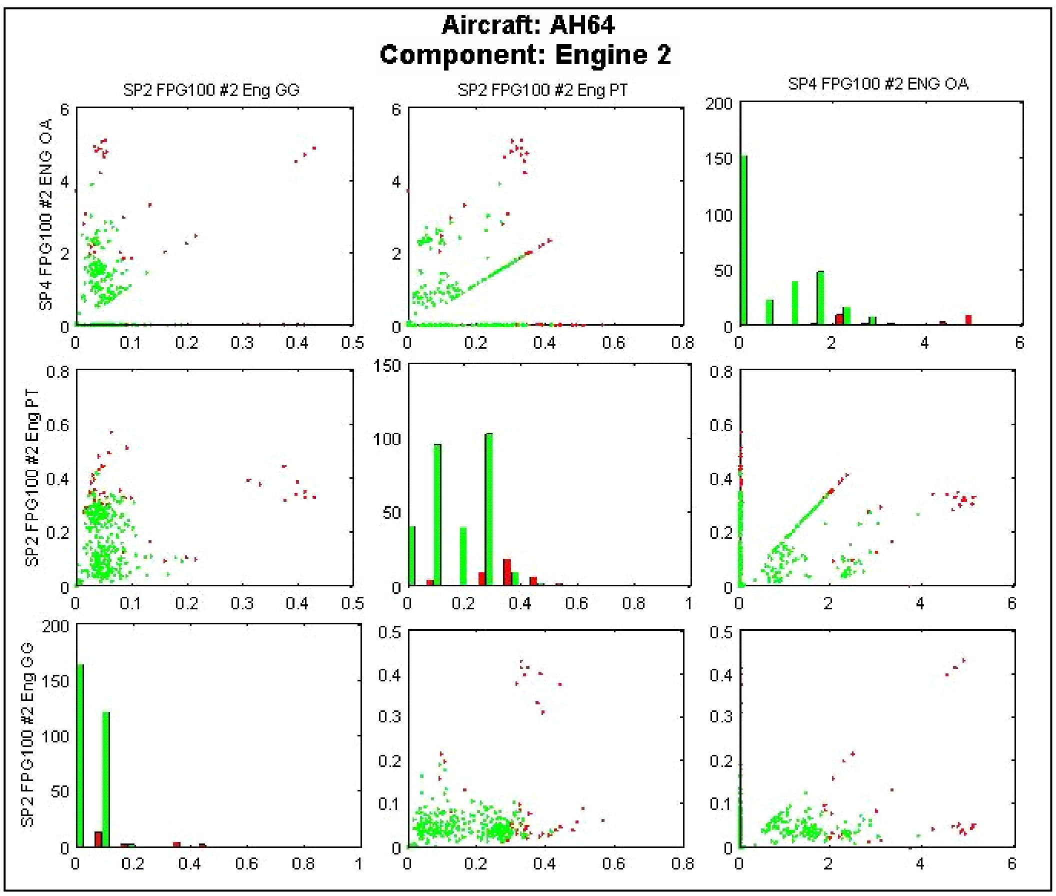

Figure 25 Labeled data

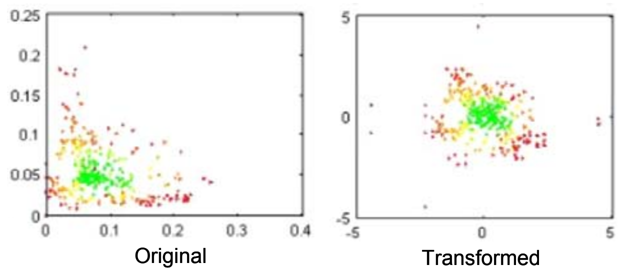

Figure 26 Gaussian transformation example

The histograms along the diagonals contain red and green bars that correspond to the red and green points. At this point the user can blow up individual displays, highlight single points to determine which tail number / flight that data was collected from, and then pull up the data as originally collected for even more detailed review.

Once the data has been validated, the user pushes a button to accept the labeling, and those new samples will be included into the gold standard database. As more samples are collected, the automated portion of the processing will become more reliable.

Data in the tails of the normal vs. fault distributions will start to be filled in!

7. SUMMARY AND RECOMMENDATIONS

The US Army has fielded a prototype system for monitoring of Army helicopter vibration, with expansion to include engine performance, and aircraft structures. The processing being fielded was developed as part of the Army's Vibration Management Enhancement Program (VMEP).

VMEP is composed of three primary components; (1) an on-board system, (2) a ground-based station, and (3) a web server. The Server is used to collect and process data from all Army helicopters that have the VMEP on-board system. The server can also collect information from fielded Aviation Vibration Analyzers by importing the data to the VMEP PC-GBS.

An extensive set of Rotor Smoothing tools have been implemented to aid the maintainer in keeping the main and tail rotor vibrations low. These tools are being used to maintain the aircraft at SCARNG. The VMEP system is used on a daily basis for vibration troubleshooting and fault diagnostics.

Additions to the system not discussed here include engine performance data collection / monitoring and flight regime recognition in support of structural life monitoring and automated triggering of vibration data collections. Almost all of the tools developed for processing data are based on the Matlab and Simulink processing environment. IAC has developed an extensive set of Matlab based tools that include data import, vibration data analysis, performance and prediction models, statistical models, regime recognition, and reasoning tools.

Collection of large amounts of data is required to capture both normal and known fault events. All the action in prognosis occurs in the tails of distributions of "normal" vs. "fault" measurements – precisely the areas where not much data has been collected. This data is required for empirical model development but also for validation of detailed physics based models. The tails are a scary place. A slight change in a threshold can mean a drastic change in times.

The VMEP system is an ideal data collection and processing testbed for the continuing collection and analysis of large amounts of real data in support of automated diagnostic and prognostic system development. The VMEP Server included tools to automatically screen "normal" and known fault data so as to detect off-nominal events that are of interest. It includes tools to systematically and continuously update existing model parameters to improve overall detection and classification performance.

8. REFERENCES

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