HELICOPTER HEALTH MONITORING AND FAILURE PREVENTION THROUGH VIBRATION MANAGEMENT ENHANCEMENT PROGRAM

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ABSTRACT

A Vibration Management Enhancement Program (VMEP) effort is currently under way at the South Carolina Army National Guard, Army Aviation Support Facility (SCARNG-AASF) in cooperation with the University of South Carolina (USC). The purpose of the program is to minimize aircraft operation cost, reduce maintenance flights, augment aircraft availability, and increase safety through in-flight vibrations monitoring, on-line data processing and artificial intelligence based decisions. The program is targeting Apache (AH-64), Blackhawk (UH-60), and Kiowa Warrior (OH-58D) helicopters. The instrumented aircraft are at the SCARNG-AASF at McEntire Air National Guard Station in South Carolina. University of South Carolina is responsible for the cost and effectiveness analysis of the VMEP program, the establishment of a data repository for the collected data, and the development of long-term helicopter health monitoring and failure prevention methodology based on in-flight vibrations measurements.

This paper presents the general methodology adopted in the VMEP programs, the new neural network based rotor smoothing processing principles, and cost and effectiveness analysis approach. Technical details of the algorithms are succinctly presented, and projection of program development over the next period is briefly discussed.

Key Words: Vibration Monitoring, Damage Detection; Health Monitoring; Failure Prevention; Neural Networks, Smoothing Algorithms, Rotor Track and Balance, Non-destructive Evaluation; Incipient Damage; Progressive Deterioration, Cost Reduction, Helicopter Maintenance, Artificial Intelligence, Apache, Blackhawk, VMEP, AVA, HUMS.

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1. INTRODUCTION

Vibration Management Enhancement Program (VMEP) project, sponsored by the US Department of Defense through the South Carolina Army National Guard and the US Army, is developing advanced Rotor Track and Balance (RT&B) procedures and helicopter Health and Usage Monitoring System (HUMS) capabilities. The VMEP system includes a number of sensors placed on the aircraft and advanced signal-processing algorithms for the failure prevention in crucial aircraft components such as rotor, engines, gearboxes, and drive train. An important system component is the automatic rotor smoothing (rotor track and balance) that uses an imbedded, onboard data acquisition and processing system. Even a slight imbalance of the helicopter rotor may lead to large vibration levels in the aircraft structure and associated premature failure of components. The rotor smoothing process typically involves installation of special purpose instrumentation and a series of maintenance test flights, in which the vibration data collection is followed by rotor adjustments. The adjustments usually involve changing the dynamic balance (weight moves) and rotor aerodynamics (pitch link adjustments and tab bends).

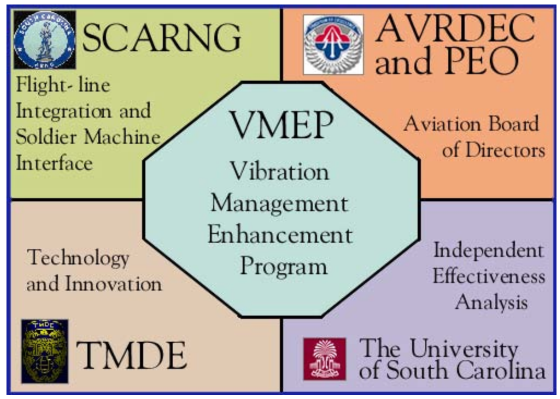


Figure 1 The VMEP government-industry-academic partnership

2. OVERVIEW OF THE VMEP PROJECT

The starting point (and basis for comparison) for the VMEP system is the fully functional Aviation Vibration Analyzer (AVA) and its commercial counterpart RADS/AT that is currently deployed on US Army aircraft. In the VMEP system, rotor smoothing (RT&B) as well as vibration collection and surveying will be fully supported, including the monitoring of all sensors for capture of exceedances (high condition indicators). The main objective of the VMEP project is to develop a low-cost commercial off-the-shelf (COTS) onboard rotor smoothing and vibration monitoring system based on embedded PC technology. Emphasis is being placed on open system design that will allow for growth and flexibility with the addition of other health usage monitoring (HUMS) functionalities. Emphasis is also placed on the soldier-machine interface and on the easy field usage of the VMEP system. The RT&B functionality incorporates the development of advanced rotor smoothing algorithms based on both linear methods and advanced non-linear methodologies. The RT&B functionality will: (a) decrease the number of dedicated Rotor Track and Balance test flights; (b) enable rotor system "tweaks" to maintain low aircraft vibrations. The vibration monitoring HUMS functionality is aimed at the engine, gearbox, and drive- train components. Its immediate purpose is to: (a) give advanced warning of mechanical faults; (b) perform continuous monitoring of critical AH-64 components and of UH-60 input shaft and oil cooler; (c) implement advanced fault detection and diagnostic algorithms. To identify the operational cost savings, a statistical data collection, and analysis study is being performed using side-by-side comparison of VMEP *vs.* non-VMEP and aircraft.

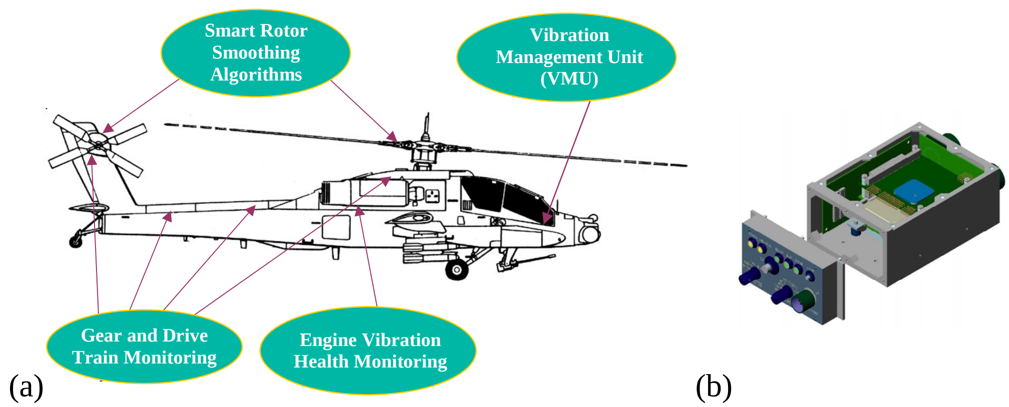


Figure 2 The VMEP configuration for the AH-64 Apache helicopter: (a) placement of sensors and major components; (b) the onboard VMEP unit.

3. HELICOPTER ROTOR SMOOTHING

Helicopter Rotor Smoothing (Rotor Track and Balance, or RT&B) is a periodic maintenance task required to minimize rotor induced aircraft vibrations at the fundamental (once per revolution) rotor frequency. We have designed and implemented a general, neural network based software system for rotor smoothing. Neural networks provide non-parametric mappings between the spaces of adjustments and vibration measurements.

The neural network system has been applied to Apache (AH-64) and Blackhawk (UH-60) helicopters as part of the VMEP project. Preliminary results are very encouraging. In the verification tests, we were able to significantly shorten the smoothing time for the AH-64. All the rotor-smoothing procedures were completed in 2 to 4 flights. In all cases, the neural network approach produced solutions with experimentally verified low vibration levels and small track split.

3.1 Application Development

The general approach to the rotor-smoothing problem is based on empirical models of aircraft response to the correction moves. Thus, an application to a particular aircraft type consists of two principal steps: (a) development of a database of flight data; and (b) construction of parametric and neural network models, which are used by a generic rotor-smoothing algorithm. These models are constructed off-line and may be easily updated and/or expanded as the available knowledge base increases.

3.2 Database development

Development of a robust empirical model requires a large database of experimental measurements, which covers as much as possible the operational envelope of the aircraft. As we are modeling the aircraft response to rotor adjustments, the database must contain at least three types of information: vibration data before the correction, adjustment (correction) information, and vibration data after the correction.

Generally, the initial data are collected in a series of dedicated maintenance test flights. Historical data, if available and deemed reliable, are also included. Dedicated maintenance test flights are expensive and thus it is important to design the test procedure that maximizes the content of resulting data set. This may be accomplished by using a sequence of flights and associated adjustment moves.

3.3 Linear Models

The calculation of linear coefficients requires experimental (flight test) data with a single adjustment type (e.g., weight, pitch link, tab). The linear response coefficients are calculated by comparing the vibration data before and after the correction. The coefficients are determined for the fundamental harmonic of the rotor. (Higher harmonics do not show linear correlation with the correction magnitude.) Calculation of linear coefficients provides an assessment of the statistical significance of the linearity assumption. Typically, the statistical error for the linear coefficients determined from a significant number of measurements is in the range of 20-30%. Often, for some flight states and diagnostic signals, the statistical uncertainty is much larger and there is no clear linear trend in the response data.

3.4 Neural network models

The VMEP HUMS system is to collect and archive the relevant data for the entire fleet of serviced helicopters. Thus, it is fully expected that the data requirement will be eventually met. For initial neural network development, the data requirement may be somewhat relaxed by building parametric models. The commonly used linear model is expected to be inaccurate at extremes, but it provides a reasonable first approximation. Other parametric models may be developed as needed. Such models are easily encompassed by the general neural network architecture through inclusion of model (simulated) data in the network training. In the limit, if only simulated data from linear model are used for training, the neural network will reproduce the linear model. Thus, the neural network models may range from purely empirical (no model data) to

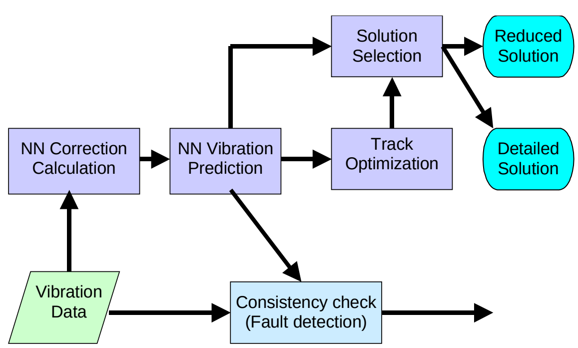
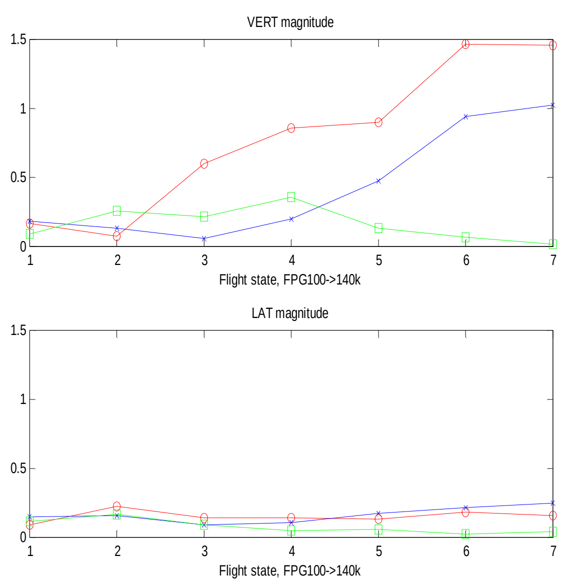


Figure 3 Rotor-smoothing algorithm flowchart.

purely simulated (i.e., trained solely on the parametric model data). The use of general computing paradigm allows the user to refine the model (e.g., to include the non-linear effects) as relevant data becomes available. That is, as the system matures and more data becomes available, the content of model data may be changed in favor of empirical data. The rotor smoothing models used here are derived from a combination of experimental and model (linear approximation) data. This approach allows us to avoid the difficulties in training the neural networks in the absence of a comprehensive empirical database. In the prototype implementation described here, the neural networks for adjustment prediction were trained solely on the linear model data. The vibration prediction networks were trained mainly on experimental data with the model (simulated) data providing information only about the boundaries of the adjustment space.

3.5 RT&B Verification Tests

The rotor smoothing system was demonstrated in eight actual RT&B procedures of the AH-64 helicopter at the South Carolina Army National Guard (SCARNG) in Columbia, SC. In all tests, the aircraft rotor was smoothed in two to four test flights (i.e., one to three sets of adjustments). Two aircraft required only one adjustment set (two test flights), two aircraft required two adjustment sets (three test flights), and four aircraft required three adjustment sets (four test flights). Thus, on average, the smoothing procedure required about two adjustment sets (three flights). Some of these tests were conducted during the development of the smoothing algorithm. As an example, we show the details of the smoothing procedure for Apache AH-64 aircraft (tail # 460) performed at SCARNG AASF in Columbia, SC (Figure 4). This aircraft was smoothed in 3 flights with two sets of adjustments.



RT&B adjustments

Date and time	Main Rotor Adjustments		
05/18/99; 14:48	Weight	Blade 2	+100 grams
	Tab 6-10	Blade 1	+2.0 deg
	Tab 6-10	Blade 4	+2.5 deg
05/19/99; 08:54	Pitch Link	Blade 3	+0.5 flats
	Pitch Link	Blade 4	-1.25 flats
	Tab 8-10	Blade 3	+1.5 deg
	Tab 8-10	Blade 4	-1.0 deg

Figure 4 Preliminary tests at SCARNG on the AH-64 Apache tail number 460: Vibration magnitudes is shown for the first (o), second (x), and third ( ) flight in the series.

4. HUMS FUNCTION OF THE VMEP PROJECT

Statistical data will be collected to compare the vibration-monitored aircraft with the aircraft in the rest of the fleet. Aircraft will be initially evaluated over a 1-phase (250 h) period to verify that the evaluation procedure is operational. The total period of time needed to obtain irrefutable proof of VMEP effectiveness is estimated to be around 10,000 total flight hours. This could be achieved over a 36 to 60 month period, depending on intensity of usage.

4.1 Design of the Statistical Experiment

Two statistical sets of helicopters, one of AH-64 Apache, and one of UH-60 Blackhawk, are planned. Each set will be split into "treatment" and "control" groups. The "control" group will contain monitored helicopters on which all the data is recorded, but only normal corrective action is taken. The control group will be operated and maintained in strict accordance with the normal regulations practice. The "treatment" group will contain monitored helicopters on which corrective action is taken based on the feedback from the onboard and ground station components of the VMEP. Such feedback will refer to both the T&B and the HUMS functions of the VMEP system. The size of the statistical sample will be 12 helicopters, half in the "treatment" group, and half in the "control" group. A build up period in which the size of the statistical sample will be gradually increased is expected. Predictions for the current year are that 4 VMEP systems will be available, 2 for AH-64 and 2 for UH-60 helicopters. This sets the initial set size at the value $N = 2$ for the 2000-2001 period. As more VMEP systems become available, the set size will be gradually increased to the planned value of 12. Several data collection considerations are important in experimental design. The parts monitored in the VMEP project are categorized into: (a) primary systems and (b) collateral systems. The *primary systems* are those that produce a vibration signature. In this category we include: (a) main rotor, which has immediate vibration effects; (b) generators, gearboxes, and other rotating machinery, that are candidates for extended vibration monitoring. The latter will identify subtle changes in the intrinsic vibration signature of these components, changes that can be indicative of incipient failure. The *collateral systems* are systems that do not have a vibration signature of their own, but are affected by ambient vibration. Typical examples of collateral systems on the AH-64 Apache helicopter are: TADS/PNVS, avionics, blade structure.

4.2 Data Repository

University of South Carolina is the data repository for the data collected during the VMEP project. USC has allocated office space and resources (hardware, software, and IT personnel) to develop the VMEP data repository center. Electronic links are being established with the McEntire SCARNG Air National Base, as well as with other units that will be added in the project. USC intends to become a node in the RITA-HUMS network database system. The Unit Level Logistic System – Aviation (ULLS-A) database will be utilized to trace parts usage and aircraft unavailability/down time. We are researching methods to incorporate the VMEP data into the local ULLS-A database system. Data will also be extracted from the Aviation Mission Planning System (AMPS) database. Coordination with TADS-PNVS visionics maintenance database (Lockheed-Martin) will be established. Vibration data from the VMEP system, track and balance system, and voice data information will be recorded for each aircraft (e.g., 15-min long). Baseline data and data after corrective actions will be recorded.

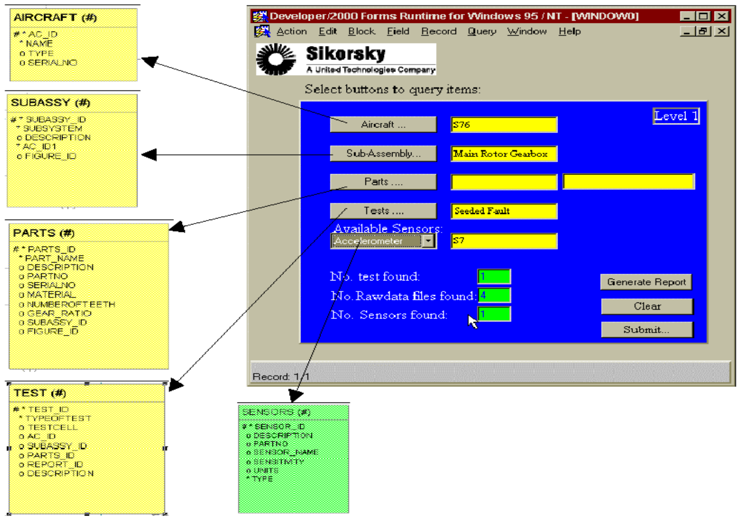


Figure 5 Level 1 form query selection relationship to tables for the RITA-HUMS Diagnostic Database (Rozak, 1999).

4.3 Data Usage - Helicopter Diagnosis and Prognosis Database System

At USC, data will be stored in the RITA-HUMS Diagnostic Database format. The RITA HUMS Diagnostic Database is a product of the National Rotorcraft Technology Center (NRTC) and Rotorcraft Industry Technology Association Inc. (RITA). It is one of the products of a multi-year, multi-company RITA cooperative project on HUMS industry-wide technology. RITA member manufacturers have invested considerable time and effort in developing a maintenance database for this assembly. Access to the RITA-HUMS database is permitted with the approval of RITA. The RITA HUMS Diagnostic Database is an ORACLE-format database that consists of two parts: a data library, and a diagnostic algorithm library. The data library hosts HUMS related data contributed by NRTC/RITA members in a standardized format and intended to be shared among NRTC/RITA members. The diagnostic algorithm library contains a set of 34 public domain benchmark diagnostic algorithms, which are also resident on each distributed database node. The combined data and diagnostic libraries can provide RITA members with the capability to cost effectively evaluate and compare current and advanced diagnostic algorithmic methodologies.

For analysis, MATLAB toolkits are used. The database allows an end-user an environment to apply several algorithms to actual raw test data. To that end, the database catalogs the raw test data and provides documentation of the meta data that describes the raw test data. The database also stores the benchmark algorithms, and the math or system functions needed to support the execution of the algorithm(s). The results from the application of the algorithms to a single or a set of raw data files are stored in the database. A separate form is used to compare data between the applications of the algorithms to different raw data files. The database structure is a client-server relationship between the Oracle database server and the primary Oracle form. The Oracle Client form launches the analytical tool application, i.e., MATLAB (that analyze raw data files). The database table structure is illustrated in Figure 5. All of the database tables reside in a single tablespace. The interface between MATLAB and ORACLE is presented in Figure 6.

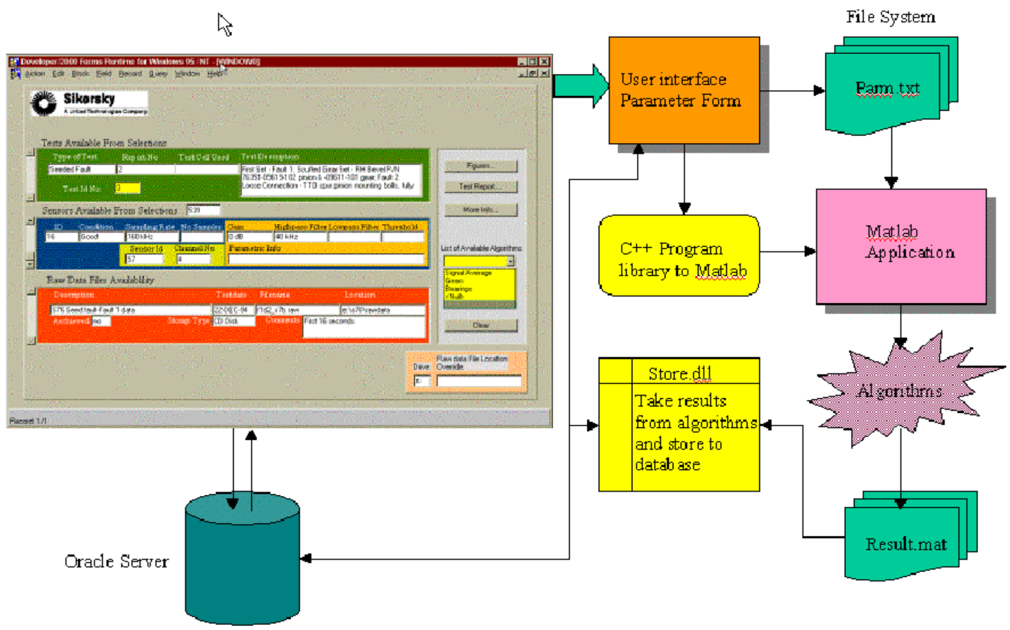


Figure 6 Interface between MATLAB and ORACLE in the RITA-HUMS Diagnostic Database (Rozak, 1999).

5. EVALUATION OF THE VMEP PROJECT

The University of South Carolina (USC) is tasked to perform the evaluation of the AH-64A/UH-60L vibrations monitoring (VMEP) program. Over the length of the program, USC will develop the complete evaluation/assessment of the VMEP program and will extract irrefutable conclusions based on scientific statistical analysis of the collected data. The evaluation will cover both technical and economical aspects of the program such as: (a) evaluation of the Rotor Track and Balance function; (b) evaluation of the HUMS function; (c) cost benefits analysis.

Cost benefit analysis is an important aspect to be considered during VMEP project evaluation. A number of overall cost and reliability outcomes will result from the collected data, such as: (a) time between failure (TBF) and time between maintenance action (TBMA) on critical and/or high cost components; (b) inventory costs; (c) flight time allocated to maintenance actions; (d) downtime. Besides these general trends, we will apply a systematic evaluation of the dollar costs/saving associated with the VMEP program implementation. To this purpose, the RITA-HUMS Cost Benefits Analysis Model (CBAM) will be utilized (Figure 7). CBAM analysis results include: return on investment (ROI), present value analysis, flight hour cost reports, and a graphic representation of payback point.

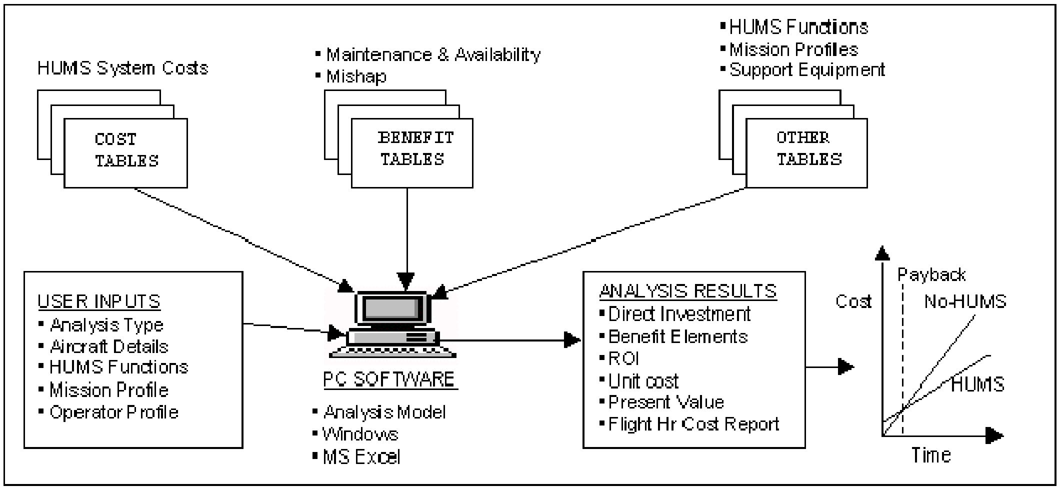


Figure 7 Overall architecture of the RITA HUMS Cost Benefit Analysis Model (RITA, 1998).

6. CONCLUSIONS

This paper briefly presented the Vibration Management Enhancement Program (VMEP) effort currently under way at the South Carolina Army National Guard Army Aviation Support Facility (SCARNG-AASF) in cooperation with the University of South Carolina (USC). The purpose of the program is to minimize aircraft operational cost, reduce maintenance flights, augment aircraft availability, and increase safety through in-flight vibrations monitoring, on-line data processing, and artificial intelligence based decisions. The program is targeting Apache (AH-64), Blackhawk (UH-60), and Kiowa Warrior (OH-58D) helicopters. The instrumented aircraft are located at the SCARNG-AASF at McEntire Air National Guard Station in South Carolina. University of South Carolina is responsible for the cost and effectiveness analysis of the VMEP program, the establishment of a data repository for the collected data, and the development of long-term helicopter health monitoring and failure prevention methodology. Cooperation and guidance from USAAMCOM, AVRDEC, and TMDE in Huntsville, AL is provided.

The initial main rotor track and balance results, using neural networks is exceedingly promising. An estimated 40 percent improvement in lower vibration levels and 40% reduction in the number of test flights have been realized. A large amount of vibration data, on individual components, has been collected. Faults, to include in flight failures, have been recorded. The ground stations ability to identify faults, establish trends and automatically alert maintenance personnel has been realized. The use of the Internet link to update software, train personnel, monitor for accuracy and archive data is very exciting. This endeavor will provide the military with new and innovative ways to prevent unscheduled maintenance events, improve reliability, and reduce operational costs.

Operational flights of first the fully functional VMEP components installed on one AH-64 and one UH-60 are scheduled to take place in Spring 2000.

7. ACKNOWLEDGEMENTS

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