Neural Networks for Smoothing of Helicopter Rotors

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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 not only the predicted vibration levels and track split but also the number of required adjustment moves. The neural network rotor smoothing system is a part of the VMEP (Vibration Management Enhancement Program) PC Ground Base Station program and has been successfully applied to the AH-64 Apache and UH-60 Blackhawk helicopters. Applications to other types of helicopters are under development.

Introduction

Rotor smoothing (rotor track and balance) is a routine maintenance task performed to reduce the helicopter vibrations at the fundamental (1/rev) harmonic of the rotor frequency. This procedure aims to reduce the rotor vibrations due to asymmetries in both the mass distribution and in the aerodynamic forces. It typically involves special purpose instrumentation, and a series of dedicated test flights followed by rotor adjustments that converge on an acceptable solution.

Vibration data for the rotor smoothing are typically acquired from sensors placed in the helicopter cockpit. Two orthogonal components of the vibrations at the fundamental (1/rev) rotor frequency are usually measured: lateral and vertical or, some equivalent of those two. The measurements are performed at a number of 'test states' including flat pitch on ground (FPG), hover and a number of pre-defined air speeds. The rotor smoothing procedure is performed in a number of distinct steps or, 'test modes'. For example, for a newly installed blade or, a set of blades, the usual procedure includes tracking of the rotor on ground at flat pitch (with pitch link adjustments to make the blades fly at approximately the same height), balancing the rotor on ground (with weight adjustments), and aerodynamic balancing at a number of air speeds up to the operational maximum speed (with tab, pitch link and weight adjustments or, a subset of those). A routine periodic 're-smoothing' of the aircraft may include only the flight test. The detailed scenario of the rotor smoothing procedure (modes, test states and sensors) varies for different types of helicopters.

The rotor adjustments change both the dynamic balance (weight moves) and the rotor aerodynamics (pitch link moves and tab bends). The adjustments are traditionally calculated with the use of a linear model, in which the helicopter vibration response to the rotor adjustments is represented by a set of linear coefficients. The rotor smoothing system uses the measured vibration data to calculate the rotor adjustments that are necessary to reduce the vibration magnitudes to below manufacturer's prescribed limits. As the number of possible adjustments is typically smaller than the number of tests states for which the vibration limits are defined, the optimum solution is usually found as the best fit (in the root-mean-square sense) to the measurement data. [1-3]

The linear model is a simplification of the actual rotor system as it is not capable to account for possible non-linear interactions. Usually, the accuracy with which the linear coefficients may be determined is not better than about 20% and in many cases it is much worse [4]. Thus, in practice, the rotor smoothing is completed in several

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

test flights, with consecutive sets of adjustments converging on an acceptable low vibration state of the aircraft. It is, of course, desirable to minimize the number of dedicated rotor smoothing flights.

Neural networks provide a non-parametric mapping between the vibration measurements and the rotor adjustments. [5,6] This relaxes the usual assumption of a linear relationship between the two. The mapping is extracted from empirical data in the neural network training process. Model dependencies (linear or non-linear) may be also included in the neural network training, which is especially useful when the experimental data is not exhaustive. The neural networks may be easily updated (retrained) to include new data thus allowing the system to evolve and mature during the course of its use.

In this paper, we describe a general, neural network based software system for helicopter rotor smoothing. The software has been developed as a part of Vibration Monitoring Enhancement Program (VMEP).[7] VMEP is a low-cost, commercial off-the-shelf (COTS) onboard rotor smoothing and vibration monitoring system based on embedded PC technology. It provides a continuous monitoring of the helicopter components through the use of permanently installed sensors and onboard data collection. Besides the rotor smoothing, the system includes advanced data processing for detection and prediction of failures in flight critical components such as engines, gearboxes and drive train. Emphasis is being placed on open architecture design that will facilitate growth and flexibility and addition of other health usage monitoring (HUMS) functionalities, as well as on the technician-machine interface and on the easy field usage of the VMEP system. The main aim of the rotor smoothing functionality is to: (a) decrease the number of dedicated rotor smoothing test flights; (b) enable rotor system "tweaks" to maintain low aircraft vibrations without a need for dedicated flight tests.

Overview of the rotor smoothing algorithm

A schematic representation of the neural network based rotor-smoothing algorithm is shown in Figure 1 and the main components of the algorithm are described below. Information about the database is provided in the following sections.

Adjustment Evaluation Networks

Adjustments necessary to smooth the aircraft are evaluated, based on the vibration data, by a series of neural networks. Separate networks are used to produce corrections involving different subsets of allowed correction moves. These networks produce 'reduced' solutions, represented by complex numbers.

Vibration Prediction Network

The predicted vibration level (after the correction) is evaluated for each of the solutions obtained by the adjustment evaluation networks. This network provides an empirical mapping from the adjustment space to the vibration space.

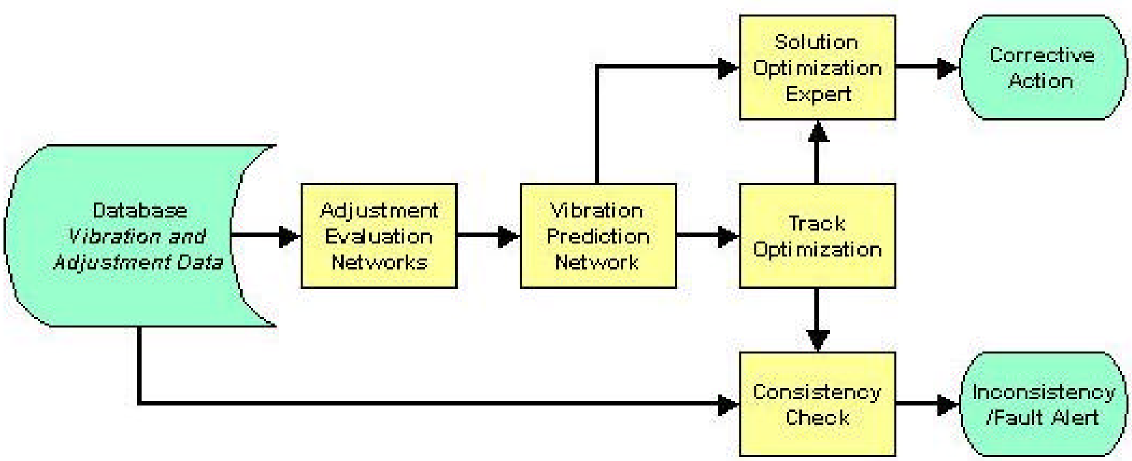

Figure 1. *Flow chart for the neural network based algorithm for rotor smoothing*

Track Optimization – Detailed Solution

The reduced (complex) adjustment solutions have to be implemented as real adjustment moves on particular blades (detailed solution). In general, there are numerous detailed solutions that correspond to a single reduced solution. For example, for a four bladed rotor, a +5 pitch link move on blade 1 has the same effect on the vibration change as a –5 pitch link move on an oppositely placed blade 3. However, these two moves may result in a very different relative track split. Thus, the detailed solution is selected (optimized) to minimize the predicted track split. The predicted track split is calculated for all available detailed solutions and the solution with the lowest track split (averaged over the whole test envelope) is selected. Here, the track split is defined as the maximum observed deviation from the average track.

It should be stressed that the present system puts the main emphasis on the reduction of vibration magnitudes and the track optimization is secondary to that goal. That is, a smooth aircraft may be produced even if the track split is not ideal or, outside the recommended limits, as has been often observed in real-life smoothing procedures. This opens the possibility of routine in-field smoothing of the main rotor based on the vibration data collected periodically by the VMEP on-board data collection unit, without the need for temporary installation of the tracker device.

Solution Optimization Expert

From the operational point of view it is desirable to reduce not only the vibration levels but also the number of adjustment moves. This reduces not only the time required to implement the corrections but, even more importantly, the chance of implementation error. Also, with fewer correction moves, the resulting vibration levels may be predicted more reliably. Thus, a smoothing solution with a small number of moves is more attractive than a solution with many moves even if the predicted vibration levels are somewhat larger with fewer moves.

The optimization module effectively selects a solution that produces low predicted vibrations and track split, and involves a small number of moves. The available solutions are evaluated using a fitness function that includes contributions from:

- The predicted vibration levels,
- The number of actual corrective moves,
- The predicted track split.

All these quantities should be minimized and the fitness function provides a weighting of their relative importance. The fitness function is obtained through an analysis of a large number of real-life examples, for which the optimal solution was selected by human experts.

Consistency Check

Additional function of the smoothing system is the consistency check, which detects errors in the implementation of adjustments. Vibration changes between the most recent flights are compared with the adjustment information stored by the user. A large discrepancy between the measured change in vibrations and the change predicted from the stored adjustment moves indicates that either the correction moves were recorded incorrectly or, an error was made in the implementation of rotor smoothing adjustment. An inconsistency between the recorded corrections and measured vibration changes that persists for a number of subsequent test flights indicates a mechanical fault.

Our experience indicates that mistakes are often made in the actual field operations. For example, in a data set of 23 test flights collected for a number of AH-64 helicopters, we found strong evidence that the correction moves were incorrectly implemented (or, recorded) in five of the tests (error rate of about 20 per cent). The consistency check feature alleviates the user frustration due to apparently unexpected response of the aircraft when the adjustment moves are implemented incorrectly.

Ground Based Station (PC-GBS) Software

The rotor smoothing software is implemented as a component of VMEP PC-GBS (ground based station), a Microsoft Windows application. The PC-GBS program provides an easy to use interface to the helicopter diagnostic measurements and maintenance recommendation. It is designed primarily for the helicopter maintenance personnel but it also provides a number of advanced interactive data analysis tools. The data collection and analysis functions include: determination and display of the status of individual aircraft and of the aircraft fleet, processing of measurement results and display of resulting maintenance recommendations for the rotors and other components of the aircraft, and data transfer (from and to local PC-GBS database), including data exchange between Ground Based Stations.

Database

The vibration data collected during dedicated rotor smoothing flight and during routine operation of the aircraft are stored on board the Vibration Monitoring Unit (VMU), which is permanently installed on the helicopter. Periodically, the data is transferred to a PC class computer and stored in the PC-GBS database (Microsoft Access).

Although designed primarily for the onboard VMEP data acquisition, PC-GBS also accepts data from the AVA (Aviation Vibration Analyzer), a portable system currently deployed on US Army aircraft, and its commercial counterpart RADS/AT (Smith Industries, Inc.). This provides the necessary backward compatibility and facilitates extensive testing of the rotor-smoothing methodology before a complete VMEP system is installed on the aircraft.

In the future, the VMEP data will be archived at three distinct levels: (i) crew-chief's laptop for the immediate after-flight data analysis and rotor smoothing, (ii) unit's ground station for permanent storage of data for all unit's helicopters, and (iii) Internet (Web) based VMEP repository of historical data. For each aircraft, the data, including all maintenance/corrective actions, will be recorded in the crew chief laptop PC. The data from several laptops, corresponding to several aircraft, will be concentrated in the unit's ground station. Data from the ground stations of various units will be transferred to the Web-based VMEP data repository for long-term interpretation and correlation with other data items.

User Interface

The PC-GBS provides an intuitive graphical user interface (GUI) to the rotor smoothing and other helicopter diagnostic functions. Once the data is imported into the system from the onboard collection hardware, the GUI displays the status of different components, (self-explanatory) color coded as red, yellow or, green. The status is determined based on exceedance of prescribed vibration levels and on other condition indicators. The GUI provides also an overview of the status for all helicopters for which the data was collected (e.g., all helicopters in the given unit).

For the aircraft of interest, the rotor smoothing solution is obtained by double-clicking on its rotor icon. The smoothing solution may be viewed at different levels of detail from a text message describing the recommended adjustment moves to detailed graphs of measured and predicted vibration and track values. Interfaces designed for an experienced user permit editing of the solution and viewing of the predicted results. The following options are available:

- Detailed editing of the solution, adjustments on all blades may be manually modified.
- The user may specify the maximum number of adjustments, the best solution with the number of adjustments less or equal to the specified limit is returned.
- 'Resolve to vibration limits' option returns a solution with the smallest number of moves, for which all predicted vibration measurements are below the limits.

The consistency check functionality of the software depends on the availability of the rotor adjustment history. The user is prompted to save in the database all the correction actions performed on the aircraft.

Model 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 the generic rotor-smoothing software described above. These models are constructed off-line and may be easily updated and/or expanded as the available knowledge base increases. The system training, updates and customization to different types of helicopters are facilitated by a set of specialized software tools. Thus, an application to a new helicopter type may be developed quickly and without a programming effort. Inclusion of new helicopter types or test scenarios in the PC-GBS program is accomplished through PC-GBS database setup.

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.

We have collected an extensive database documenting the responses of the aircraft to the main rotor adjustments for the Apache (AH-64), Blackhawk (UH-60) and Kiowa Warrior (OH-58D) helicopters. Generally, the initial data were collected in a series of dedicated maintenance test flights, which, up to date, were conducted for all three types of the helicopters. In these dedicated tests, we have applied both single-type adjustments (weight, pitch link or, tab) and adjustments including a combination of moves of different types. Historical data, if available and deemed reliable, as well as data from ongoing maintenance procedures are also included in the training database.

Linear Model

Traditionally, a linear relationship is assumed between the adjustment magnitude and the resulting change in vibration magnitude. The determination 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. (Variations in higher harmonics do not show a linear correlation with the correction magnitude.)

Our database of rotor smoothing procedures was analyzed using the linear approach. Calculation of linear coefficients, based on the data for single type moves, 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. [4] The statistical error of determination of track coefficients (linear dependence between the adjustment magnitude and change in blade height) is of the same order. The linear coefficients (vibration and track) that were used (when appropriate) in this work were determined from the analysis of our database. Small but possibly significant differences were noted between the newly determined coefficients and those used in the standard (AVA) implementation of the linear system.

Neural network models

Artificial neural networks have been extensively used in complicated classification and multi-dimensional function approximation problems.[5] Neural networks are nonparametric and make weak or no assumptions about the shapes of the underlying distributions of the data. Thus, the neural network paradigm provides a generic, nonlinear mapping of the input-output relationship. Moreover, calculation of the output of a trained neural network represents, in essence, several matrix multiplications. Thus, the model encoded in the network during the training process may be calculated quickly and with a minimum of computing power. Several network configurations are commonly used. They share the common feature of being built from a large number of simple processing elements that are exhaustively interconnected to form processing layers. In the present work, we have employed the radial basis function (RBF) neural networks and standard training algorithms. [5]

Neural networks are trained by example. The training process requires a set of data, for which the input-output relationship is known. In the present case, the training data consists of rotor adjustment moves and resulting changes in the aircraft vibrations. The training set is selected to exhaustively cover the known input feature space. An independent data set, also with known input-output relationship, is used to verify the network performance.

In an initial development of the neural model, the data requirement may be somewhat relaxed by incorporation of parametric models. The commonly used linear model is expected to provide 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. For example, 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 purely simulated (i.e., trained solely on the parametric model data). The use of a 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 the 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 implementations described here, the neural networks for adjustment prediction were trained mainly 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.

It is worth noting that the neural network applications developed up to date required only a modest amount of test flight data (typically, 20-30 test flights). The training was based both on the data collected during specially designed series of test flights, in which the adjustment space of the aircraft was fully explored, and on the data obtained during regular maintenance procedures.

Results of Verification Tests

The rotor-smoothing program has been successfully applied to Apache (AH-64) and Blackhawk (UH-60) helicopters. We have also developed an application of this program to the Kiowa Warrior (OH-58D) helicopter. Data for all these helicopter types (either from the AVA or VMEP VMU data collection hardware) may be archived and analyzed by the PC-GBS program. Most of the verification tests were performed on the AH-64 helicopter, admittedly one of the most difficult aircraft to smooth with a linear method. In general, the verification tests demonstrated that the main rotor can be smoothed in, typically, 2-4 flights (1-3 adjustment sets). Also, the neural network approach produces adjustment solutions with smaller number of moves than recommended by the traditional linear method, low predicted vibrations, and small track split. We have also demonstrated the system ability to detect errors in the implementation of the rotor adjustment moves.

AH-64 Apache

Smoothing of the Apache helicopter involves, besides the usual weight and pitch link moves, adjustments of individual pockets (segments) of the blade tab. Pockets 4-10, 6-10, and 8-10 (with the entire tab divided into 10 pockets) may be adjusted separately to produce distinct aerodynamic responses of the blade at high air speeds.

The vibration data are collected at seven test states: Fpg100 (flat pitch on ground), hover, and forward level flight at 60, 80, 100, 120, and 140 knots (60K, 80K, 100K, 120K, 140K). The vibration detectors are denoted as LAT (lateral) and VERT (vertical).

The smoothing procedure is performed in three steps (test modes):

- Ground test, with data collected at Fpg100 (the initial pitch link adjustment, only).
- Initial test, with data collected at Fpg100 and hover (weight and pitch link adjustments, only).
- Flight test, with data collected at all test states and all five adjustments allowed.

The first two tests are rather straightforward algorithmically as they involve a system of linear equations with the numb er of unknowns equal to the number of equations. The flight test set, on the other hand, is over-determined (in the linear approximation approach) and presents a more complicated computational problem. Thus, verification test for the neural network approach are conducted for the flight mode.

Table 1. Main rotor smoothing adjustment for AH-64 tail #008. The rotor corrections were made after the corresponding flights.

Flight #	Max (LAT) (ips)	Max (VERT) (ips)	Correction moves	
1	0.28	2.84	Pitch Link	(blade 3): -1 flat
				(blade 4): +3 flats
			Tab 6-10	(blade 1) : -2 deg
				(blade 4): -5 deg
			Tab 4-10	(blade 2): +2 deg
				(blade 3): -1 deg
2	0.24	0.68	Tab 8-10	(blade 3): -2 deg
3	0.28	0.28	None, procedure completed	

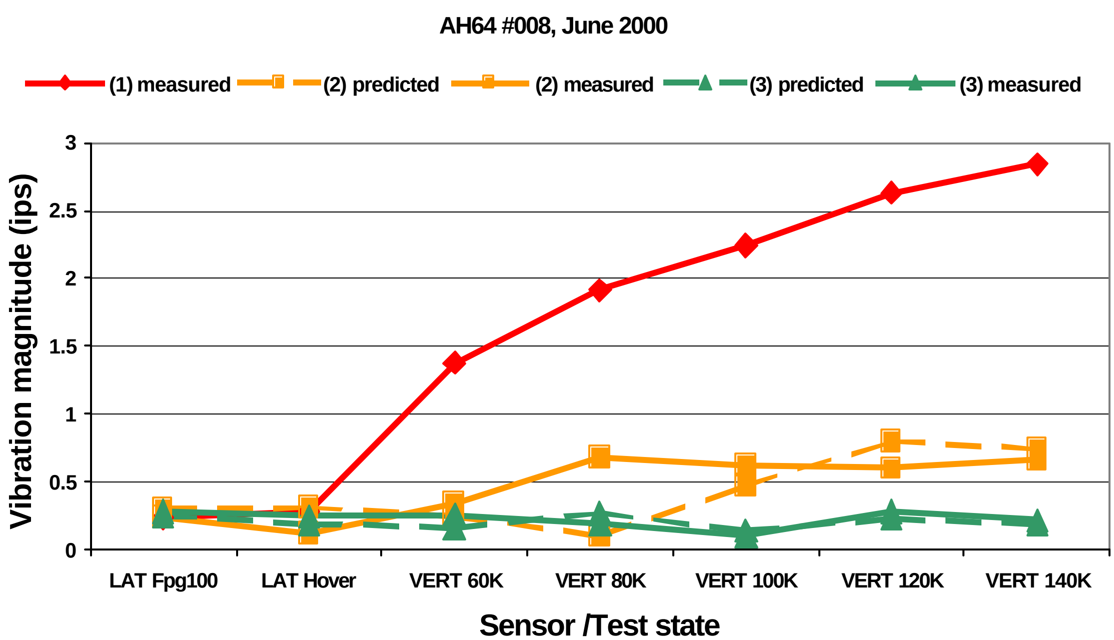

Figure 2. *Main rotor smoothing for an Apache helicopter. The plot shows vibration data for three consecutive test flights (1 through 3) – solid lines. The vibration levels predicted for flights 2 and 3, for the corrections given in Table 1, are shown by dashed lines. There is generally a very good agreement between the predicted and measured values. The recommended vibration targets are 0.2 ips for LAT, and 0.25 ips for VERT measurements.*

Table 1 and Figure 2 summarize an Apache smoothing procedure performed with the use of the neural network system. The aircraft started with unusually high vertical vibrations (the target levels for AH-64 are 0.2 ips and 0.25 ips for LAT and VERT measurements, respectively). Thus, the first set of adjustments (flight #1) involved a rather large set of six moves: two pitch link moves and four tab moves. It became apparent after the moves were implemented that two of the tab corrections were put on wrong blades: the system recommendation of Tab6-10 (blade 3) = -2 move was implemented on blade 1, and Tab4-10 (blade 1) = -1 move was implemented on blade 3. (Table 1 lists the actual corrections implemented on the aircraft and Figure 2 shows the predicted values corresponding to the actual moves). After flight #2, only one correction move was recommended by the smoothing software. This move appears to be consistent with the implementation error for flight #1. The smoothing procedure was concluded after the third flight despite small exceedances of the recommended targets. It should be noted that, perhaps with an exception of VERT 80K point for flight #2, the neural network system performed very well in predicting the vibration magnitudes.

Overall, the neural network approach was used in ten smoothing procedures of the Apache main rotor performed at SCANG Army Aviation Facility in Columbia, SC. In all of the verification procedures, the main rotor was smoothed in two to four test flights (one to three sets of adjustments). On average, the smoothing required two sets of adjustments or, three flight tests.

The verification tests were started in the early stages of the VMEP system development and thus, the initial tests used a prototype version of the smoothing program. We believe, that through continuous 'real-life' testing of the system, a significant improvement has been achieved in the program accuracy and reliability, with the later versions of the program producing better smoothing solutions.

UH-60 Blackhawk

Preliminary verification tests of the neural network smoothing approach were performed for the UH-60 Blackhawk helicopter. Similar to the Apache helicopter, the main rotor smoothing for the Blackhawk includes three test modes:

- Ground track, with track data collected at Fpg100 and track corrections with the pitch link moves,
- Ground balance, with vibration data collected at Fpg100 and weight adjustments.
- Flight, with vibration data collected over the flight envelope and adjustments involving up to three types of correction moves: weight, pitch link, and tab.

The vibration data is collected by sensors A and B placed on two sides of the cockpit and linear combinations of these signals, A-B (roll) and A+B (vertical), are used in the smoothing procedure. The vibration measurements are made at the following test states: Fpg100, hover, and forward level flight at 80, 120 and 145 knots (80K, 120K, and 145K).

Figure 3 shows a result of an application of the rotor smoothing software to the UH-60 main rotor. The recommended corrections are given in Table 2 and involve a rather large number of 6 correction moves. (The subsequently improved and currently implemented optimization model for the Blackhawk produces a solution with only four correction moves and overall lower predicted vibrations). We note, however, that the standard linear algorithm was incapable of producing a reasonable solution for this flight. The measurements made on a subsequent flight indicated all vibrations were within the recommended targets except the A-B/Fpg100 point. These measurements agree very well with the predicted values, indicating that the prediction accuracy of the system is very good, even with a large number of corrective moves.

Table 2. Main rotor smoothing adjustment for UH-60 tail #330, August 2000

Flight #	Max (A-B) (ips)	Max (A+B) (ips)	Correction moves		
1	0.51	0.36	Weight	(blade Red, 3):	-20 Oz
				(blade Black, 4):	-65 Oz
			P/Link	(blade Red, 3):	-7 notches
				(blade Black, 4):	-2 notches
			Tab	(blade Blue, 2) :	+2 mils
				(blade Red, 3):	+12 mils
2	0.29	0.25	Aircraft within targets, except A-B/Fpg100		

Conclusions

We have developed a general, neural network based approach to helicopter rotor smoothing. The neural network paradigm provides the capability to learn from actual smoothing data and to include effects that are not well described by the traditional linear approach. Parametric models of the aircraft vibration response to the corrective actions can also be accommodated within this framework. We expect that the intensive data collection effort made possible with introduction of VMEP on-board data collection will provide a wealth of information relevant to the rotor smoothing process and will lead to an evolutionary improvement in the algorithm accuracy. As new data becomes available, the neural network system may be easily retrained to model the newly encountered dependencies.

The smoothing software is a part of the VMEP PC-GBS (ground based station) program. The software may be easily reconfigured, through the PC-GBS database setup, for application to different helicopter types. Similarly, new test states conditions (test states, test modes, vibration measurements) may be incorporated into the rotor smoothing procedure. Neural networks are easily retrained to accommodate such revisions. Up to date, the system performance has been extensively verified for the Apache AH-64 helicopter and verification tests have been initialized for the UH-60. The OH-58D implementation of the neural network rotor smoothing software has been completed and the verification test will begin shortly. Applications to other helicopter types are being considered.

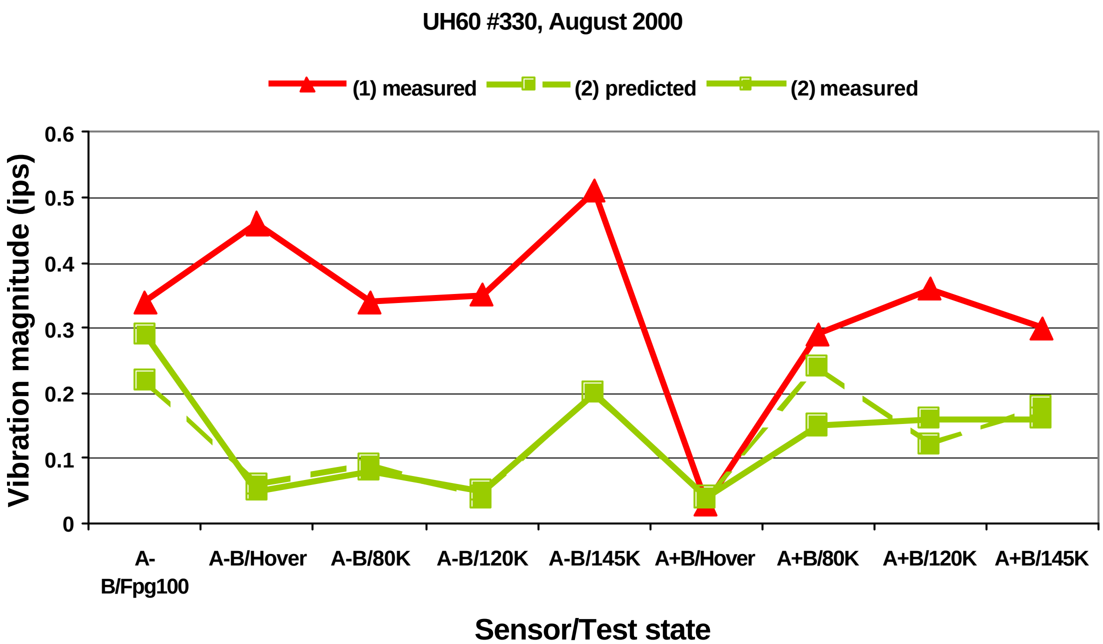

Figure 3. *Main rotor smoothing for a Blackhawk helicopter. The plot shows vibration data for two consecutive test flights – solid lines. The vibration levels predicted for the second flight, corresponding to the corrections given in Table 2, are shown by the dashed line. There is an excellent agreement between the predicted and measured values. The recommended vibration targets are 0.2 ips for A-B, and 0.25 ips for A+B measurements.*

Acknowledgments

We would like to express our gratitude to CW5 Lem Grant and the personnel of the South Carolina Army National Guard Aviation Support Facility in Columbia, SC for their continuing support of the VMEP program. CW5 Bob Caldwell and the personnel of Mississippi National Guard Aviation Support Facility in Tupelo, MS, provided invaluable help in collecting the OH-58D test data.

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