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# NEURAL NETWORKS FOR ROTOR TRACK AND BALANCE OF HELICOPTER

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## ABSTRACT

Rotor Track & Balance (RTB) process is performed to bring the Vibrations to acceptable limits in identified steady flight regimes of a helicopter. Vibrations at 1/rev (1P, 1R) manifests due to mass differences between the Main Rotor blades and differences in aerodynamic forces on the blades. The process of correcting the mass differences between the blades (in plane vibrations) and the aerodynamic forces (out of plane vibrations) of the blades is called the Rotor Tracking and Balancing process. The RTB process can be optimised using Artificial Neural Networks. Number of vibration flights will increase if RTB process is not optimised. The inputs for the neural network algorithm would be in terms of mass changes, track changes and tab changes based on established sensitivities of these inputs and cross sensitivities between them. The outputs are vibration changes of MR. Change in vibrations is the difference between the vibration values of two successive flights / ground runs. For Main Rotor, there are 12 inputs to adjust 2 outputs (MR Lateral and MR Vertical) for satisfactory vibrations during regimes - ground run, HOGE and two steady speed forward flight regimes. Artificial Neural Network (ANN) feed forward back propagation algorithm was used to predict the change in vibrations for the given inputs. Three types of Neural Networks for MR system were made to predict the vibrations of helicopter. The inputs and outputs were fed into neural networks tool of MatLab for predicting vibrations. The regression values obtained in ANN simulation of MatLab obtained are more than 0.9. The neural networks are predicting vibrations for given input corrections and found satisfactory. This research work recommends for the implementation of Artificial Neural Networks algorithms and its applications for vibration predictions in helicopter to reduce vibration flights.

**KEYWORDS**: Rotor Track and Balance, Vibrations, Helicopter, Neural Networks, Back Propagation.

## 1. INTRODUCTION

The helicopter, a versatile mode of aerial transportation primarily due to its unique capability to take-off and land vertically as well as its ability to hover. These characteristics of helicopters enable many unique tasks such as rescue operations and reconnaissance in military applications. Helicopter Major Servicing is carried out on a time based maintenance routine presently & intent is to adapt Condition based maintenance in future. As part of maintenance routines the 1/rev vibrations of the rotor and N/rev vibrations of the rotor are addressed. The other multiple harmonics of the rotor are part of design of the rotor. The 1/rev vibrations generally are measured in terms of Velocity (inch/sec) & N/rev (where, N is the number of blades) vibrations are measured in terms of acceleration (g) as its response of the structure. The RTB process takes care of 1/rev vibrations of the rotor and N/rev vibration is addressed by tuning the vibration isolation system embedded on the helicopter. The N/rev Vibration isolation system could be a passive vibration isolation system or an active vibration isolation system. And, the deficient blade tracking can be an additional source of vibrations. Helicopter rotor smoothing procedure is performed to bring vibrations to acceptable limits. Vibration magnitudes (in inch per second) and phase angle (as clock angle) are recorded during ground run and flights.

## 2. PROBLEM STATEMENT

The helicopter uses flexible rotating wings which provide Lift, Propulsion and Control forces. Vibrations at 1/rev (1P, 1R) manifests due to mass differences between the Main Rotor blades and differences in aerodynamic forces on the blades. RTB process is performed to bring the 1/rev vibrations to acceptable limits in identified steady flight regimes of a helicopter. The problem here is large no. of ground runs and flights for getting acceptance of helicopters and the difficulty in manual calculations of input parameters (mass changes, track changes and tab changes) to obtain satisfactory output (change in vibrations) during RTB process. For main rotor, there are 12 input parameters to adjust 2 outputs (MR Lateral and Vertical). Change in vibrations is the difference between the vibration values of two successive flights / ground runs. During each flight / ground run, the main rotor vibrations magnitude (i.e., velocity in ips) and phase angle (i.e., clock angle) are recorded. Number of vibration flights will increase if RTB process is not optimised. The RTB process can be optimised using Artificial Neural Networks by prediction of change in vibration before vibration flight. The methodology adopted for vibration predictions using Neural Network tool of MatLab is shown in Fig-2.

## 3. LITERATURE SURVEY

Helicopter main rotor smoothing is performed to minimize vibrations due to non-uniform mass and aerodynamic distributions in the main rotor and tail rotor systems. It is time consuming, expensive. The relationship between adjustments and vibration response is assumed as Linear. Artificial neural networks have been designed to recognize non-linear mappings [1]. Present AVA for military applications is a portable maintenance aid, which is not permanently installed on the helicopter, and needs to be installed and removed every time vibration readings are taken. Vibration Management Enhancement Program (VMEP) of Helicopters AH-64, UH-60 and Kiowa Warrior (OH-58D) contains on board vibration monitoring unit, which is permanently installed on the aircraft, on board data storage, periodic downloads into pilot's laptop computer. Radial Basis Function in Neural Networks toolbox of MatLab is used for this purpose [2]. Systems such the Goodrich IVHMU can give good solutions. However, it requires a high degree of user expertise in selecting Rotor Track and Balancing (RTB) control adjustments. Bayesian Classifier expert system is one, based on a multiple hypothesis testing and demonstrates the ability to deliver an improved RTB adjustment [3]. The drawback of traditional approach is it neglects the nonlinearity and vibration noise. A Probability based approach neural network model has four inputs and one output [4]. Perfect track is the starting point for the vibration smoothing process. [5]. The VMEP objective is to develop a low cost and effective maintenance tool for rotor smoothing (track and balance) and vibration monitoring. 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 system has been operational on 18 AH-64A and 8 UH-60L aircraft since September 2001 [6]. Neurocomputing offers a collection of alternative computational techniques in Aerospace Industry [7]. Aviation Engineering Directorate (AED) has noted more difficulty in rotor smoothing the Chinook than either the Blackhawk or the Apache. This inefficiency was suspected to be caused by inaccurate sensitivity coefficients associated with the CH-47 adjustments. Current sensitivity coefficients for the CH-47 are based upon a relatively small sampling of aircraft, unlike the UH-60 and AH64 whose coefficients are based upon a more extensive sampling. In addition, the coefficients may have changed as the airframes and blades have accrued flight hours and various repairs [8]. A Neural Network based algorithm has been developed for rotor smoothing of AH-60 Apache and UH-60 Blackhawk helicopters. 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 [9]. An adaptive method of helicopter track and balance improves the search for the required blade adjustments. In this method, an interval model is used to represent the range of effect of blade adjustments on helicopter vibration, instead of exact values, to cope with the nonlinear and stochastic nature of aircraft vibration [10].

## 4. METHODOLOGY

The methodology used in this research work involves: helicopter vibration data analysis and applying Network Manager / Neural Network toolbox of MatLab for vibration predictions by Modelling, Training, Validating and Testing of the vibration data in order to reduce vibrations and number of vibration flights before acceptance by customer. Inputs for NN tool are mass, track link, tab adjustments and track. Outputs for NN tool are change in vibrations of Main Rotor. Fig-1 shows a two–layer feed-forward network with sigmoid hidden neurons and linear output neurons used in this study.

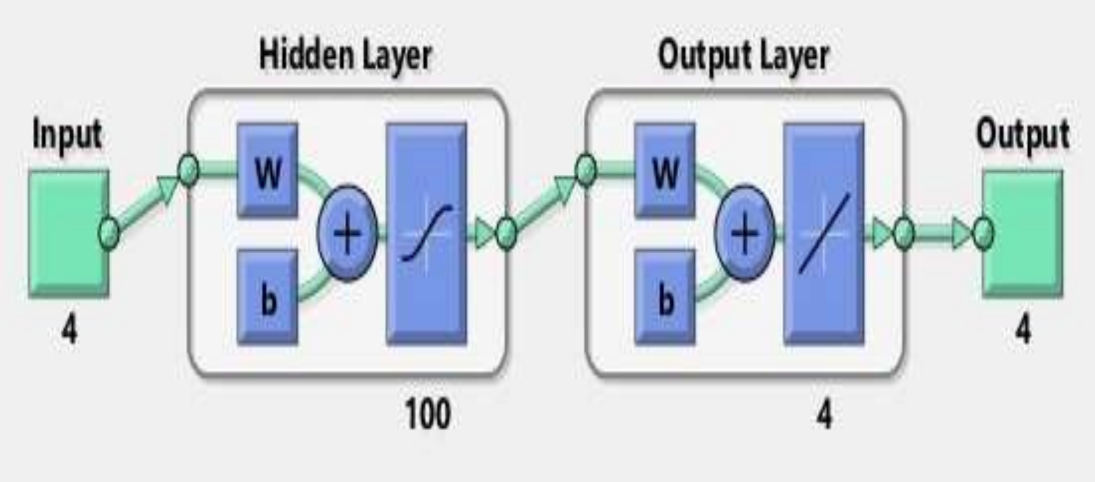

*Fig-1: Network Architecture (with 4 inputs and 4 outputs) using Neural Networks tool of MatLab.*

Fig-2 shows the flow chart of the methodology adopted for vibration predictions using Neural Network tool of MatLab.

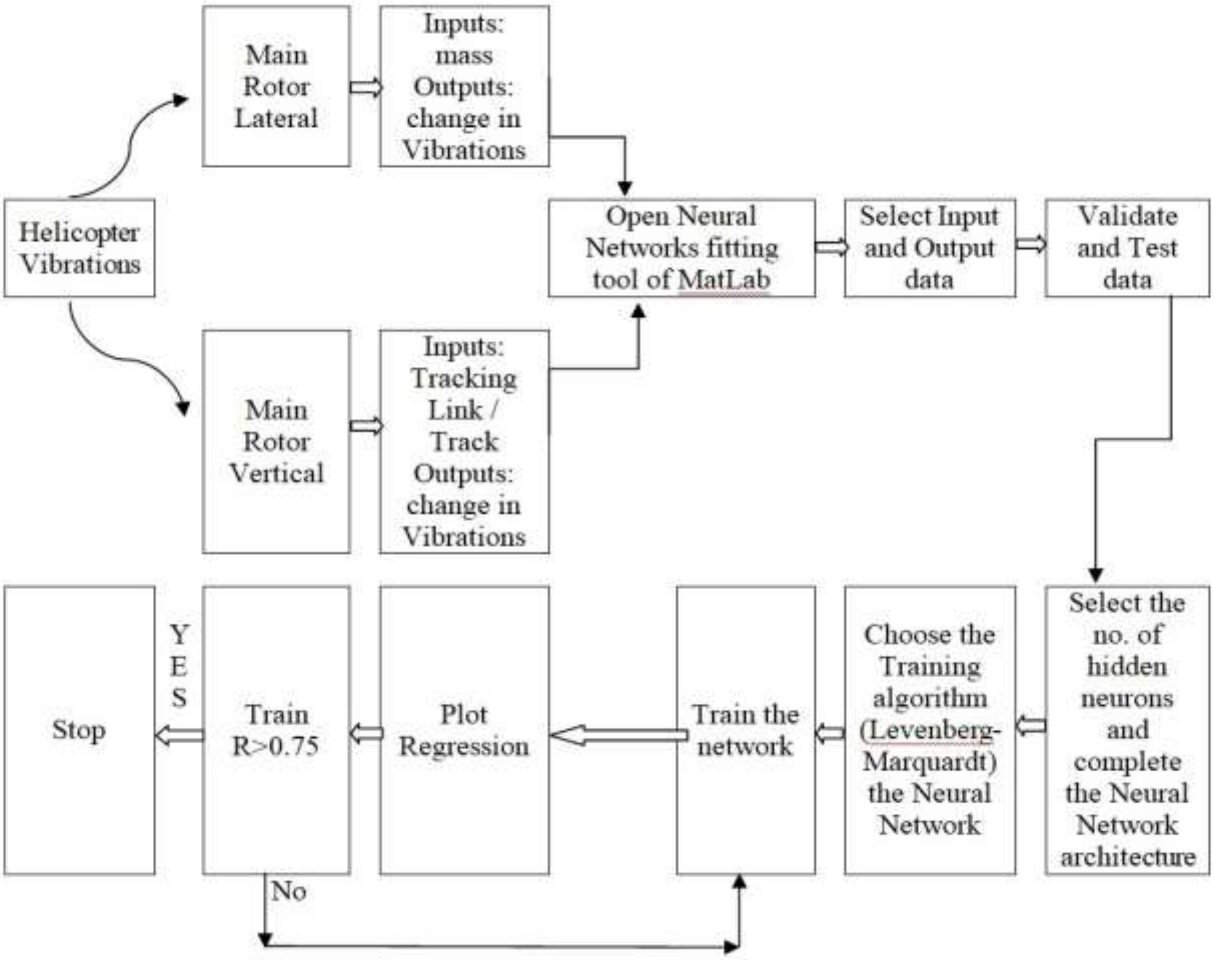

*Fig-2: Flow chart for Training, Testing and Validation of Network Network using MatLab for vibration predictions of main rotor of helicopter.*

## 5. EXPERIMENTATION AND VIBRATION DATA ACQUISITION

Helicopter Main Rotor vibrations are in the vertical and lateral planes. A vertical vibration is a result of unequal lift produced by the main rotor blades or out of plane rotation. Lateral vibrations are due to in plane unbalance of the rotor masses. D-Form is the document which gives the details of vibration snags and rectification action taken during each ground run / flight. The D-forms were analyzed and MR-Lateral, Vertical vibrations observed during Ground, HOGE, two steady speed forward flight regimes with corrections given were tabulated. Let $V_1$ and $V_2$ be the vibrations recorded before and after giving correction of mass, $m_1$. The response of helicopter to correction is change in vibration, $\Delta V$ equal to $V_2 - V_1$. The acceptable limit of vibration is below 0.3ips for main rotor i.e., $V_2$. Input corrections applied to control the main rotor vibrations in neural networks are as follows:

| **Type of Vibrations** | **Inputs to NN tool** | **Outputs (prediction of vibrations)** |
|---|---|---|
| Main Rotor Lateral | Mass, m (in grams) | Change in Vibration, ΔV (in ips) |
| Main Rotor Track / MR Vertical | Tracking Link (in flats) / Track split, t (in mm) | Change in Vibration, ΔV (in ips) |

Hence, Vibration in next flight is $V_2 = V_1 - \Delta V$. Input mass is in grams and track is in mm.

## 6. NEURAL NETWORKS OF MATLAB FOR ROTOR TRACK AND BALANCE OF HELICOPTER

The problem of multiple Inputs and multiple outputs for controlling the vibrations on helicopter can be solved by using Neural Networks. The development of statistical regression for establishing relationships removed the burden of solving complex mathematical equations with the solution of a simple system of linear equations. The Artificial Neural Network (ANN) is a result of extensive research carried out on machine learning algorithms through artificial intelligence. ANN mimics the human brain in its approach to solving problems. The term "neural network" refers to a collection of neurons, their connections, and the connection strengths between them. Fig-3 shows an idealized neural network where the artificial neurons are shown as circles, the connections as straight lines, and the connection strengths (or weights) as calculations derived during the learning process for a problem. This network contains three layers - an input layer, an output layer, and a hidden layer with each layer consisting of several neurons or nodes. The adaptation scheme used is based on the delta error back-propagation algorithm. In error back-propagation, the weights are modified to perform a steepest- descent reduction of the sum of the squares of the differences between the generated outputs and the desired outputs as indicated in the training pairs. The optimal number of nodes in the hidden layer and the optimal number of hidden layers can be problem dependent. These numbers, however, should be kept low for computational efficiency. The activation function determines the response of the neuron and is the only source of introducing nonlinearities in the input-output relationships. The type of activation function that was used in the present study is a ‘sigmoid function’. The sigmoid function is given by the expression shown in Fig-4. In equation, H is the weighted input to the node, and ‘b’ is a bias parameter used to modulate the element output. The principal advantage of the sigmoid function is its ability to handle both large and small input signals.

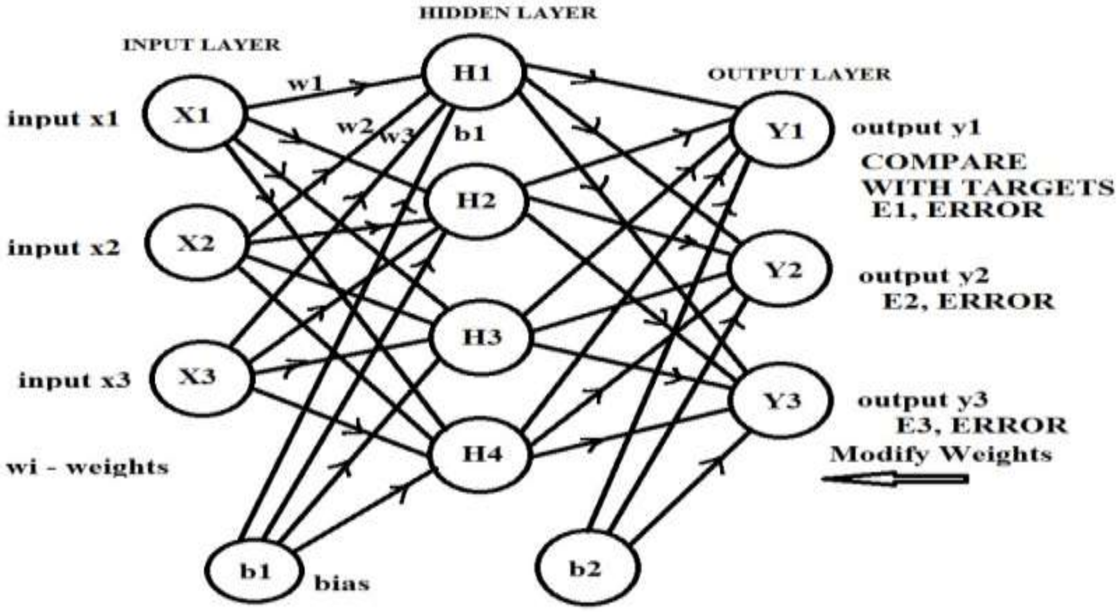

**Fig-3: Architecture of Artificial Neural Network**

$$F(H) = \frac{1}{1 + e^{-(H + b)}}$$

$$H = w1*x1+w2*x2+w3*x3$$

**Fig-4: Sigmoid function (Activation Function)**

The process of modeling with ANN begins with identification of input parameters and the output parameters to be predicted by the network. After entering the data, the Network / Data Manager shall be used to generate several types of networks and tuning each type of network for better performance until the most suitable one is identified. The entire data should be divided into a training pair which contains large amount of data and a testing pair which contains a small portion (about 10% to 20%) of the total data. The training pair is supplied to the network to help it set up the connection weights and bias values. The testing pair is used to evaluate the performance of the network against input data. Regression, R values measures the correlation between outputs and targets. An R value of 1 means a close relationship, 0 a random relationship. Mean Squared Error (MSE) is the average squared difference between outputs and targets. Lower values are better. Zero means no error.

For the present case, the neural network toolbox available in MatLab software was used for the modeling and vibrations prediction. The type of algorithm used was feed forward back propagation of neural networks. For main rotor, there are 12 inputs (corrections) to adjust 2 outputs (main rotor vibrations). ANN for RTB is used to predict the MR vibrations with input parameters in the form of mass (in grams), tracking link (as flats)/track(mm). A Neural network models the transfer function between the adjustment parameters and vibrations of the main rotor. The vibration data and corrections given during RTB of 10 helicopters were processed to obtain input and output pairs for ANN. The input variables (12Nos) - mass, tracking link and tab corrections on main rotor blades were used in obtaining the vibrations as output variables (2Nos) (main rotor lateral and vertical in each regime). The model sets required to train the neural networks for all regimes are generated and Training, Validation & Testing was done using MatLab. Corrections to be given for a new vibration conditions were predicted by using the Trained Network. The neural network vibration predictions for given inputs were found to be satisfactory. The number and the location of the accelerometers are deciding for

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the quality of the optimization phase. The research for the parameters is carried out by minimizing the function $|H(\beta^i_j + \delta^a_h)|^2$ where $\beta^i_j$ is the adjustment parameter to be determined and $\delta^a_h$, is the vibration level before adjustment.

## 7. TRAINING, VALIDATION AND TESTING OF VIBRATION DATA USING ANN

ANN Analysis was done based on the Inputs (mass, tracklink, tab, track) and obtained outputs (MR and TR Vibrations). The three types of neural networks were modeled and analyzed from vibration data – MR. The neural network simulation data / results were shown below:

Table-1 shows the mass added / removed (inputs) on MR Blades and MR-Lateral Vibrations (outputs) during Ground Run, HOGE, two steady speed forward flight regimes. Input & Target data is obtained from existing vibration data. Once this data is fed to NN tool of MatLab, the predicted output and error obtained are tabulated. Fig-5 shows the graphical representation of helicopter vibrations and neural network simulated vibrations.

| **Input** (mass in gms added / removed on blades) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Blade | Training | | | | | | | Validation | | Testing | |
| Red | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 |
| Yellow | -15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 0 | 20 |
| Blue | 0 | 0 | 0 | 0 | 0 | 10 | 20 | 0 | 0 | 0 | 0 |
| Green | 15 | 30 | 15 | -10 | 0 | 0 | 0 | 10 | 0 | 25 | 0 |
| **Target** (observed vibrations ips on helicopter) | | | | | | | | | | | |
| Ground | -0.463 | -0.453 | -0.253 | -0.199 | -0.081 | -0.072 | 0.043 | -0.009 | 0.198 | 0.074 | 0.235 |
| HOGE | -0.188 | 0.105 | -0.053 | -0.019 | -0.168 | -0.007 | 0.072 | 0.063 | -0.054 | 0.024 | -0.195 |
| ISSFF | -0.136 | -0.190 | 0.046 | -0.123 | -0.001 | 0.018 | 0.073 | 0.119 | 0.004 | -0.160 | -0.038 |
| BRFV | -0.185 | -0.048 | 0.061 | 0.031 | -0.043 | 0.027 | -0.018 | 0.049 | 0.006 | -0.164 | -0.080 |
| **Output** (vibrations ips after simulation in NN tool of MatLab) | | | | | | | | | | | |
| Ground | -0.463 | -0.453 | -0.253 | -0.199 | -0.081 | -0.072 | 0.043 | -0.352 | 0.809 | -0.312 | 0.846 |
| HOGE | -0.188 | 0.105 | -0.053 | -0.019 | -0.168 | -0.007 | 0.072 | -0.343 | -0.483 | 0.191 | -0.564 |
| ISSFF | -0.136 | -0.190 | 0.046 | -0.123 | -0.001 | 0.018 | 0.073 | -0.025 | -0.010 | -0.122 | -0.021 |
| BRFV | -0.185 | -0.048 | 0.061 | 0.031 | -0.043 | 0.027 | -0.018 | 0.043 | 0.252 | 0.022 | 0.186 |
| **Error** (=Target – Output), ips | | | | | | | | | | | |
| Ground | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.343 | -0.611 | 0.386 | -0.611 |
| HOGE | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.406 | 0.429 | -0.167 | 0.369 |
| ISSFF | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.144 | 0.014 | -0.038 | -0.017 |
| BRFV | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.006 | -0.246 | -0.186 | -0.266 |

***Table-1: ANN simulation model of Mass inputs to Main Rotor Blades and outputs as Main Rotor Lateral Vibrations during Ground Run, HOGE, two steady speed forward flight regimes.***

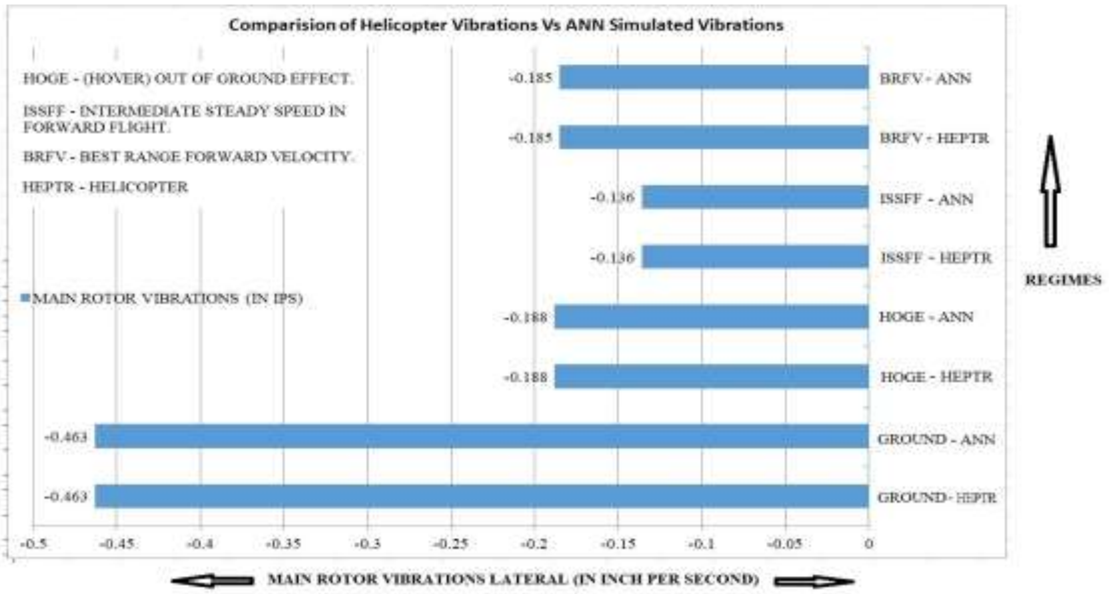

***Fig-5: Graphical representation of helicopter vibrations Vs NN simulated vibrations using MatLab.***

**Regression Results of RTB using ANN:**

**Case-1:** Neural Network for Mass added / removed (inputs) on MR Blades and MR-Lateral Vibrations (outputs) during Ground Run, HOGE, two steady speed forward flight regimes. Refer Table-1 for values. Fig-1 shows the network architecture generated in MatLab and used for this case.

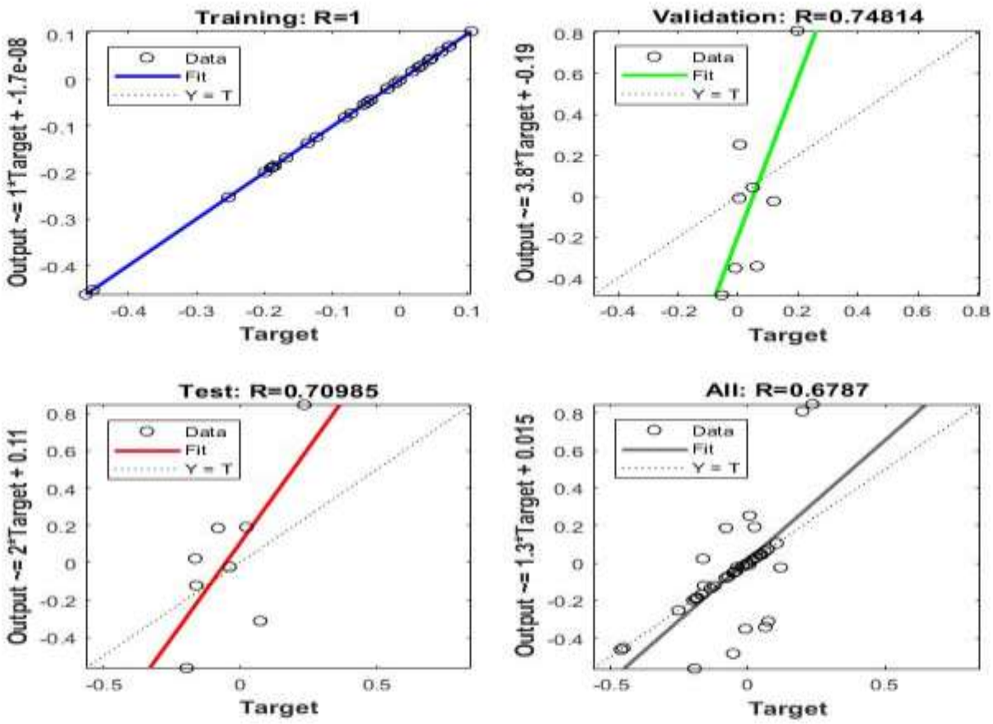

*Fig-6: Regression Graphs (R-values) – Main Rotor Lateral Vibrations all Regimes.*

*Table-2: Regression Values of MR-Lateral Vibrations all Regimes ANN Simulation using MatLab.*

Type of Vibrations : Main Rotor –Lateral

Parameter : All Regimes

(Ground, HOGE, two steady speed forward flight regimes)

No. of inputs : 4 (masses on blades)

Targets / Outputs : 4 (change in vibrations)

No. of Trials : 11

No. of Trial Points : 11

Training : R=1

Validation : R=0.748

Testing : R=0.71

Overall : R=0.679

**Case-2:** Neural Network for the Track values (inputs) of MR Blades and MR-Vertical Vibrations (output) during Ground Run. (values not shown in this paper)

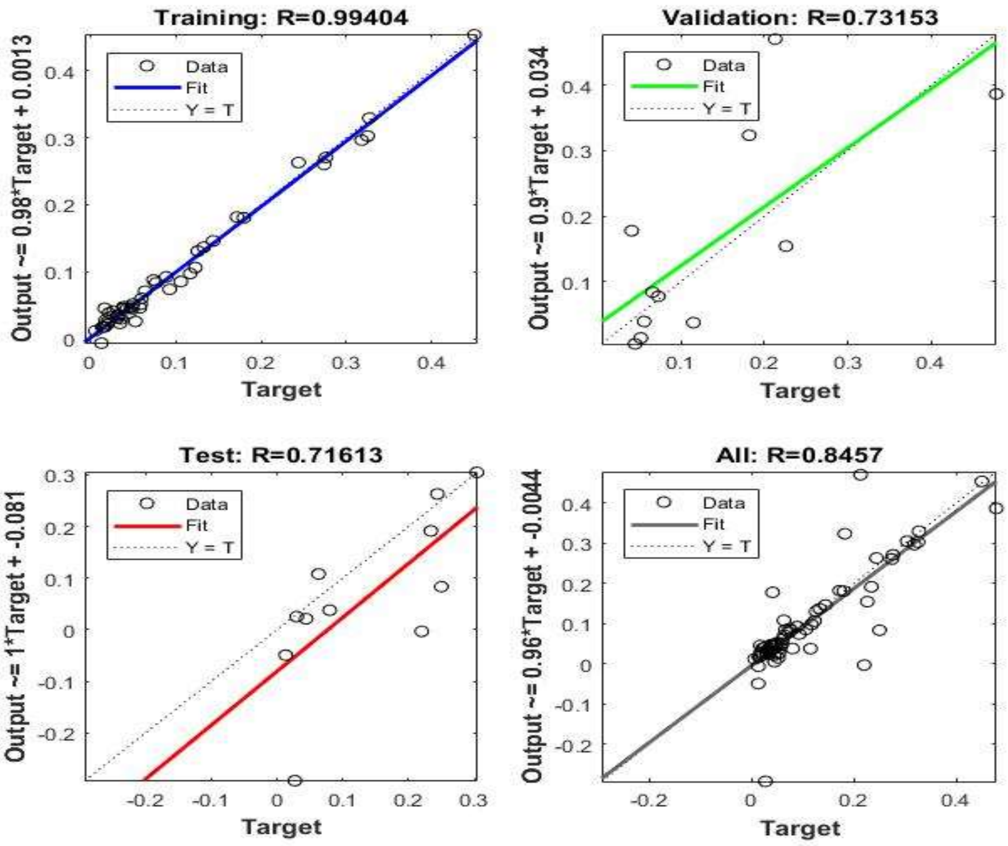

*Fig-7: Regression Graphs (R-values) – Track and Main Rotor Vertical Vibrations during Ground Run.*

*Table-3: Regression Values of MR-Vertical Ground Vibrations ANN Simulation using MatLab.*

Type of Vibrations : Main Rotor –Vertical

Parameter : Track-Ground run

No. of inputs : 4 (track values)

Targets / Outputs : 1 (change in vibrations)

No. of Trials : 70

No. of Trial Points : 70

Training : R=0.994

Validation : R=0.732

Testing : R=0.716

Overall : R=0.846

**Case-3:** Neural Network for the Track values (inputs) of MR Blades and MR-Vertical Vibrations (output) during HOGE. *(values not shown in this paper)*

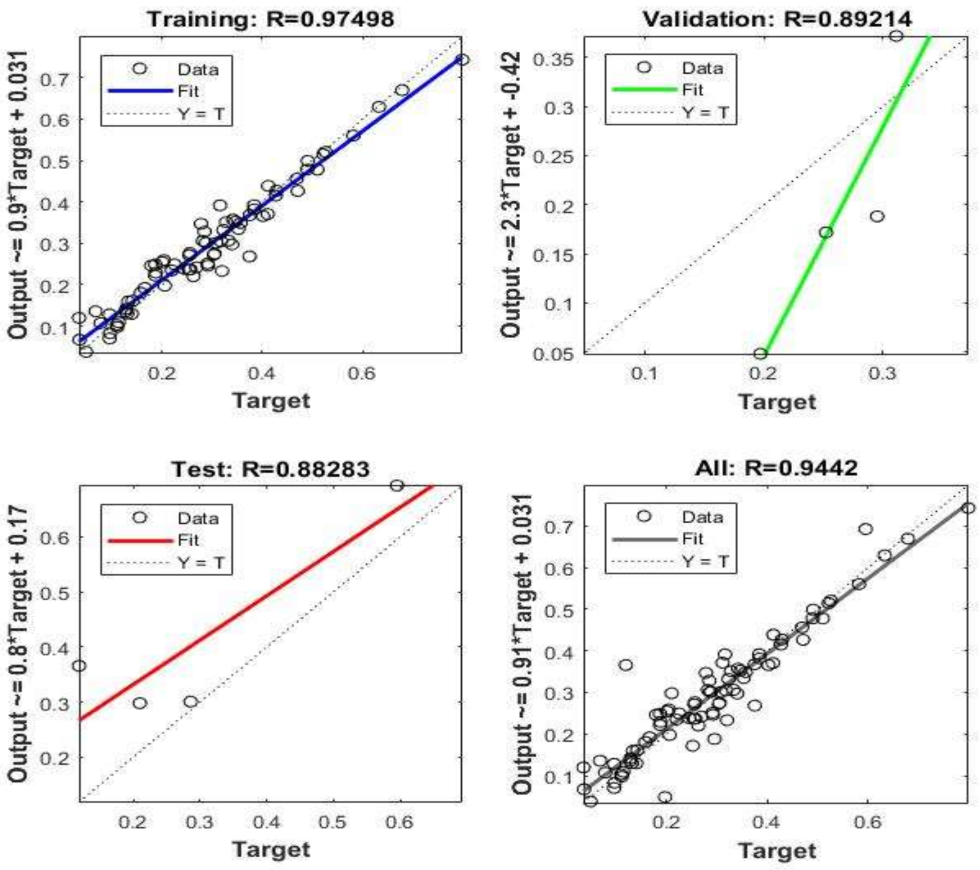

*Fig-8: Regression Graphs (R-values) – Track and Main Rotor Vertical Vibrations during HOGE.*

***Table-4: Regression Values of MR-Vertical HOGE Vibrations ANN Simulation using MatLab.***

Type of Vibrations : Main Rotor –Vertical

Parameter : Track-HOGE

No. of inputs : 4 (track values)

Targets / Outputs : 1 (change in vibrations)

No. of Trials : 85

No. of Trial Points : 85

Training : R=0.975

Validation : R=0.892

Testing : R=0.883

Overall : R=0.944

## 8. RESULTS, CONCLUSIONS AND RECOMMENDATIONS

The Vibration data of 10Nos of serviced helicopters was Trained, Validated, Tested and Simulated through Feed Forward back propagation algorithm of neural network tool of MatLab and aimed at controlling the vibrations of helicopter. Vibration in second flight, $V_2 = V_1 - \Delta V$. Change in vibration, $\Delta V$ is the predicted vibration by neural networks tool. The Regression value achieved was more than 0.9 in neural network simulation tool of MatLab (Refer Fig-6, 7 & 8, Table-2, 3 & 4). Summary of Regression Values obtained during ANN Simulation is shown in Table-5. However, the values can be further improved by increasing vibration data during training.

***Table-5: Summary of Regression values (R-Value in NN tool of MatLab) of Vibrations of helicopter.***

| Type of Vibrations | Parameter | No. of Trials | No. of Trial Points | Training | Validation | Testing | Overall |
|---|---|---|---|---|---|---|---|
| MR Lateral | Mass | 11 | 44 | 1 | 0.748 | 0.710 | 0.679 |
| MR Vertical | Track - Ground | 70 | 70 | 0.994 | 0.732 | 0.716 | 0.846 |
| MR Vertical | Track – HOGE | 85 | 85 | 0.975 | 0.892 | 0.883 | 0.944 |

## 9. FUTURE WORK

ANN results depends on, how best the training is done with enough and accurate vibration input and output data. Similar Study can be done for batch of new helicopters for generation of Vibration data at regular 300hrs intervals from Induction date. Intervals – 0 to 300, 300 to 600, 600 to 900 and so on. A Graphical User Interface (Vibration Management Enhancement Program) for retrieving data from the ANN Model developed using MatLab and simulate the corrections by entering the present vibration values can be made. This GUI may be facilitated with vibration predictions, polar plots, dynamic addition / deletion of the new set of corrections. Graphical User Interface can be developed using App designer of MatLab Neural Network tool, Web page using HTML for improving the Serviceability, reducing the Turn Around Time of helicopter. The Research concept may be applied to any helicopter project of HAL.

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