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Design of Artificial Neuro-Fuzzy Based Methodology for Six Component Force Balance

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Abstract

A blunt cone model of 60° apex angle and 15° flare with internally mountable accelerometer balance has been considered for the present investigation on six component force balance. The finite element method (FEM) has been incorporated at predetermined angles of the applied force to obtain multiple accelerations in three spatial directions so as to replicate a six component force balance system. A novel intelligent soft computing technique, Artificial Neuro-Fuzzy Inference System (ANFIS) has been implemented for accurate prediction of the magnitude and trend of aerodynamic forces and moments from the transient acceleration history. The same method is also used to validate the universal approximation nature of the impulse force by accurate prediction of the hat and ramp forces from the training of the impulse forces. Furthermore, a training algorithm is deduced so as to predict the force and moment magnitude for the three and single component force balance from the six component training data. Henceforth, novelty of this study involves in deduction of a universal training method and successful implementation of it to predict short duration transient force and moment histories.

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Keywords: ANFIS; FEM; Impulse; Transient; Accelerometer balance.

1. Introduction

Hypersonic aerodynamics has been a topic of interest for many researchers. Analysis of the fluid flow in this domain usually requires both ground based and flight based experiments but due to low cost and less risk the ground based experimental facilities seems to be reliable. During ground based experiments the stability and aerodynamic
behavior of a vehicle can be properly addressed by accurate estimation of forces and moments acting on the body. For an exact estimation of the behavior of the body subjected to certain flow condition can be analyzed fully by a six component force balance system through prediction of the coefficients of forces and moments viz. coefficient of drag, lift, side force, pitching, yawing and rolling moment. The forces and moments on a body during experiment in hypersonic ground based test facilities can be measured with the help of either accelerometer force balance system [1] or stress wave force balance system [2]. A stress wave force balance system incorporates the stiffness based measurements which can represent a system more accurately but accelerometer force balance system is preferred due to its simplicity and less complexity during measurement. Conventionally, de-convolution technique is used for accurate prediction of drag force in a single component force balance system [3]. However, the implementation of this algorithm for three and six component force balance system is a cumbersome task. The extension of this technique is rather more difficult for a complex geometry and as well as involves extensive mathematical formulation and various assumptions. The basic assumption of non-achievement of steady state between the model and supporting system makes the measurement and prediction more complicated.

Hence, present study deals with implementation of ANFIS for short duration transient force and moment prediction for multi degree of freedom system. Soft computing technique has been successfully implemented in many research areas like rapid damage detection in automobile sector [4], flank wear prediction during turning process [5] etc. Artificial intelligent techniques like neural network, fuzzy logic, genetic algorithm and combination of the above stated algorithms are the current research of interest. But comparison of the data prediction type of soft computing techniques like multiple regression, artificial neural network and ANFIS provides an affirmation to outperformance of ANFIS [6]. In view of the wide acceptance of the soft computing technique, an attempt has been made to incorporate it as a part of prediction purpose in hypersonic flow aerodynamics. An accelerometer force balance has been taken into consideration for implementation of ANFIS due to its simplicity. In the succeeding sections a blunt conical model has been considered as it can precisely represent a hypersonic vehicle configuration. The model has been analyzed in FEM under various kinds of loading conditions and transient acceleration responses are measured. Further, these acceleration data are used to obtain a universal training data for ANFIS and a parametric study has been done to obtain the optimum parameters for ANFIS architecture. Then, with the usage of this training data and optimized architecture, various forces and moments has been accurately predicted within certain error bands.

2. Numerical modeling

2.1. Finite element simulation

A Blunt cone model having 60° apex angle and 15° flare with internally mountable accelerometer based balance is shown in Fig. 1. The model is made out of aluminum and the balance system is prepared from stainless steel rings with circular cross-section (40 mm outer diameter and 30 mm internal diameter). The balance is also comprises of two annular neoprene rubber bushes (30 mm outer diameter and 12 mm internal diameter) having 4 mm thick, which is bonded with inner steel rings as well as with a sting.

Transient finite element analysis has been carried out for the above model using ANSYS 14.5 for a simulation time of 2 ms which corresponds to the range of experimental test time. During meshing for the test model, 10-noded tetrahedral (Solid 187) element is used. After the detailed mesh independence studies, the number nodes are obtained as 58985. The material properties assigned to different parts of the model during simulation is given in Table 1. The boundary conditions for this test model are given as inner surface of the rubber as “fixed”. The detailed mesh of the model is shown in Fig. 2. During simulation, different trend, orientation and magnitude of forces are applied at point ‘P’ on the model as shown in the Fig. 1. Acceleration signals corresponding to the forces are obtained at six discrete points viz. two acceleration in each spatial direction. Some of the acceleration histories are employed for training of the ANFIS network while the other signals are used for prediction purpose. Sample filtered acceleration signals (Cut-off frequency = 12.5 kHz) of 10 N force applied at 100 inclination to both X and Y-axis is shown in Fig. 3.
Fig. 1. Schematic diagram of the model.

Fig. 2. Meshed model during FEM analysis

Fig. 3(a). Filtered axial acceleration responses

Fig. 3. (b) Filtered normal acceleration responses  (c) Filtered side acceleration responses.
Table 1: Material properties assigned during simulation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (E) in GPa</th>
<th>Density (ρ) in kg/m³</th>
<th>Poisson’s Ratio (υ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>70</td>
<td>2700</td>
<td>0.32</td>
</tr>
<tr>
<td>Steel</td>
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<td>7850</td>
<td>0.27</td>
</tr>
<tr>
<td>Rubber</td>
<td>0.003</td>
<td>960</td>
<td>0.49</td>
</tr>
</tbody>
</table>

2.2. Implementation of ANFIS for force prediction

The present investigation deals with an extensively recognized artificial intelligence technique viz. ANFIS for short duration transient force and moment prediction for a six component force balance system. This soft computing technique is basically combination of Fuzzy Logic (FL) and Neural Network (NN) as a result of which it has universal approximation capability as well as a sense of adaptability for tuning the fuzzy controlled parameters. ANFIS is a Multi Input Single Output (MISO) system which comprises of one input layer, one output layer and four hidden layers and each layer is connected by the other with help of model weights. In this method, an initial fuzzy model containing input and output variables along with the rules extracted from input output data is created which is further fine-tuned to optimize the model weights with neural network so as to optimize the network parameters and henceforth the ANFIS architecture.

Generally, the existing ANFIS module of MATLAB usually handles normalized input and output data. So, different types of input and output membership function (MF) are available for normalization. These MFs more often normalize the data between 0 and 1 which basically relays on the shape of MF. The input MFs are categorized into five group viz. Piecewise linear, Gaussian, Bell-shaped, Sigmoidal and Polynomial based whereas linear and constant MFs are also available for normalizing the output data. The input and output MF to be considered, depends upon the type of data to be trained or, it can also be chosen based upon user’s experience. Incorporating either of the MFs for training, two types of training method (hybrid or back propagation) can be employed in ANFIS architecture. The back propagation method uses gradient descent algorithm whereas hybrid method follows gradient descent algorithm along with least square method to evaluate the model weights. As hybrid training strategy incorporates both the technique, it seems to be converging to the global optimal model weights. However, back propagation is slow and likely to be trapped in local optimal solution. Also, output of the back propagation training strategy depends upon the number of epochs (number of iteration up to which training is performed) whereas, hybrid training method seems to be independent of it.

Now, considering the input MF, output MF and training strategy as the varying parameter for obtaining optimized ANFIS structure, a parametric study is done which results in input MF as “Gaus”, output MF as “constant” and training method as “hybrid” with 500 epochs. For the above parametric variation analysis, transient accelerations are considered as input whereas forces and moments corresponding to a resultant force having magnitude of 10N and 50N has been fed as the output to the network. The transient accelerations, forces and moments corresponding to a resultant magnitude of 20 N have been taken into account as the testing data for the optimized ANFIS network.

3. Results and discussions

3.1. Six component force prediction

The present investigation emphasizes on prediction of impulse, ramp and hat force having resultant magnitude of 20 N and 30 N, by employing the pre-obtained ANFIS structure. The network is executed with same set of training data as earlier. A universal training data sets comprising of two transient accelerations along each axis can be considered irrespective of the force and moment to be recovered; however considering computational cost and accuracy of prediction as the important factor, a modified training data set selection strategy has been adopted. For more accurate prediction of forces, a training method is employed which uses transient accelerations corresponding to the spatial direction along which force has to be recovered. The training of moment about certain axis employs a method where single transient acceleration in each spatial direction is fed as input to the network. With this training
data set initially an attempt has been done to recover three forces and moments corresponding to an impulse force of resultant magnitude 20 N and 30 N which is shown in Fig. 4. As discussed earlier the forces are applied at $10^\circ$ inclination to both X and Y-axis and moments are calculated about center of gravity.

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Fig. 4. Prediction of forces and moments of various magnitudes with “impulse” nature.
Since, ANFIS has universal approximation capability, the “impulse force” is considered as for training purpose, while attempt has been made for the validation of the network with “hat and ramp forces” by incorporating the transient acceleration data sets. Keeping the training data sets same; forces and moments corresponding to a resultant hat and ramp force of 20 N and 30 N is recovered (Figs. 5 and 6). Further, the actual and predicted value of forces and moments for impulse, ramp and hat forces along each axis has been given in Table 2.

Fig.5. Prediction of forces and moments of various magnitudes with “hat” nature.
Fig. 6. Prediction of forces and moments of various magnitudes with “ramp” nature.
From all the above figures and tables, it can be clearly observed that all the forces and moments corresponding to various magnitude and trend, have been successfully predicted with an accuracy of ± 7%. Henceforth, the detailed analysis resulted in good agreement between actual and predicted as well as validates the universal representation capability of impulse force and ANFIS architecture for a six component force balance.

3.2. Three and single component force recovery

One of the objectives in the present study is to validate this training data as the universal data for training. As in the preceding section the training data is successfully implemented in prediction of force and moment data for a six component balance, so an attempt is done to recover the forces and moment corresponding to a three and single component balance with the same training data as earlier. For the simulation of three component balance for the model and support structure, force has been applied at same location as earlier but with inclination of 10° with X-axis only and acceleration responses are obtained at predefined location which is same as of the former one. However, single component force is achieved by applying the force on the model at zero degree angle of attack (i.e. force is applied horizontally but at the same location ‘P’ as shown in Fig. 1). Now, for the prediction purpose, the training data and optimized ANFIS architecture remains same while the transient acceleration data obtained is set as the testing data. The drag force, lift force and pitching moment recovery for three component force balance and drag force recovery for recovery for single component has been shown in Fig. 7.

From the Fig. 7 a deviation of 3.7% and 4.4% in peak magnitude can be estimated for drag force recovery of 20 N and 30 N correspondingly in case of three component force balance whereas over prediction of 3.2% and 4% can be found for lift force recovery of 20 N and 30 N. Similarly, the moment prediction for 20 N and 30 N impulse force results in a deviation of 8.1% and 3.6%, simultaneously. In case of drag predication for single component system, under prediction of 4% and 4.7% in peak magnitude has been noticed. Thus, from the above analysis it is clear that using the same training data incorporated for six component force balance and ANFIS structure, it is also possible to predict the forces and moment for three and single component force balance with an accuracy of ± 8%.

<table>
<thead>
<tr>
<th>Nature</th>
<th>Impulse</th>
<th>Hat</th>
<th>Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Predicted</td>
<td>Actual</td>
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4. Conclusion

Current study revealed the successful implementation of ANFIS for transient force and moment prediction using acceleration histories of a six component force balance system. A set of optimized ANFIS parameter and training data obtained from the FE simulation has been incorporated for deducing a universal strategy and data for training of the ANFIS architecture. Different trends of forces are predicted with a deviation of ± 7% which validates the training data and ANFIS structure. Furthermore, three and single component forces and moments are also predicted with a minimum accuracy of 92% which generalizes the calibration process. Thus, this method provides an alternative to de-convolution technique as well as this implementation is independent of any assumption and rigorous mathematical formulation.

References