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Novel Calibration Approach For Prediction of Aerodynamic Coefficients Over Large-Size Aerodynamic Configurations in High-Speed Flow

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Abstract

In proper design era of any hypersonic spacecraft, such as space shuttles or missiles, has a serious problem with aerodynamic heating and drag force. Having an approximation of this drag force is desirable. For these calculations, any appropriate force balance is used in conjunction with ground-based test facilities. To anticipate the force inversely from recorded responses, these force balances must be calibrated. There are many calibration techniques reported in the literature. Multi point calibration is found to be convenient and effective technique. However, conventionally a multi-point calibration has been carried out over a test model. But there is no any evidence in literature that effect of number of points changes during calibration on a recovered forces. Hence experimental studies focus on different set of loading points over a test model for calibration. Therefore, a blunt bicone model has been fabricated in-house for present studies. The associated three component accelerometer balance has also been made with the concern of achieving free flying condition.

Keywords: Hypersonic Flow, Blunt body, Inertia force balance, ANFIS.

1. Introduction

When a hypersonic flow encounters with aerodynamic configuration results as uncertainty arises to understand the behaviour of flow around the body. In general, fluid flows having a Mach number more than 5 are considered to be in hypersonic flow. This flow has some unique characteristics, viz., narrow shock layer, entropy layer, viscous interaction, and low-density flow. Furthermore, two important design parameters for a vehicle of that flows in this domain are aerodynamic drag and heating. Aerodynamic forces are the primary focus of this study for the proper design of space vehicles. There are two main methods to quantify the force for a hypersonic vehicle, i.e., Stiffness or stress wave-based force measurement and Inertia or accelerometer based force measurement. Sahoo et. al. discussed about this two techniques in the literature [1]. Additionally, Sahoo et al. used two methods to quantify drag force and compared the recovery [2]. In this instance, two different force-measuring methods were used at Mach number 5.75 in an experiment to forecast the forces on a blunt cone model with a 30° semi-apex angle. It is clear from the literature that improvisation is necessary to enhance prediction in accelerometer-based force measurement. This means the measuring technique capability for force prediction is highly desirable. In accordance with this, as an alternate method to accelerometer force balancing theory, another method for recovering force from the aggregate responses is to use artificial intelligence technology as well as a de-convolution algorithm that requires intricate mathematical modelling. As already known, It is highly important to forecast the drag force over a hypersonic vehicle. Therefore, each step taken to recover forces is crucial. So, calibration is an important step in all steps. This step is responsible for determining the impulse response function (IRF) or constant system parameters dynamical system. Furthermore, the forces from various recovery methods are recovered by using this IRF or parameters of the system. Aerodynamic forces are recovered using a variety of calibration techniques, including single point and multi point. A hemispherical model was designed by Nanda [3], and it has been incorporated into an impulsive test facility, i.e., a Shock tube with stress wave force balance. In dynamic calibration experiments, the strain time histories have been acquired by half bridge and quarter bride circuit configurations with two and three wire methods. The single point calibration technique was used to recover the force over a model. The half bridge circuit was shown to be appropriate for applications involving impulsive loads [4]. As a drawback of single point calibration, multi-components cannot be measured, since this method is limited to drag force or single component only. However, when multiple components come into the picture, the force recovers in a normal direction, i.e., lift can not be measured from the single point method. On the other hand, in a real shock tunnel test, the load applied to a model or aerodynamic body is distributed naturally over the test model. Therefore, using a single point calibration technique for force recovery does not yield a valid result. Additionally, recovered forces have a lower level of precision. At first, Kulkarni and Reddy [4] have been performed a dynamic calibration on an accelerometer force balance-model assembly by employing the suggestions of Abdel-Jawad et al. [5]. However, this calibration is valid and gives better results for a single component, i.e., drag force only. Further, this calibration methodology has also been employed for stress wave force balance by integration of with acceleration measurement [5], but this integration is unnecessary and becomes insensitive. Sahoo and Reddy [6] have gone through several techniques of static as well as dynamic calibration for the evaluation of system response function; as a result, these methods show a wide agreement with axial force instead of normal force. To overcome this problem, a novel soft computing approach, i.e., ANFIS, was precisely employed for the recovery of aerodynamic forces developed during actual shock tunnel tests at hypersonic environmental conditions, i.e., Mach 8.0. Shock tunnel tests were conducted with a hemispherical test model with three component force balance assembly at 0° and 15° angle of attack [7]. Ramesh et al. [8] have employed this soft computing approach, i.e., ANFIS (Adaptive Neuro Fuzzy Inference System), to predict the aerodynamic forces and their corresponding moments acting over the test model from the set of collected acceleration data. The proposed approach is better than the previous suggestive improvisations with some drawbacks. The key limitation of this suggestive approach is that the applied force at a point over the model is impulsive in nature during calibration; the obtained calibration data is used to train this approach, i.e., ANFIS. As a result of finding the constant system parameters for the current dynamical system. However, these evaluated system parameters are not unique due to dependency on the choice of calibration point. This means that this training strategy does not consider the whole dynamics of the system. Thus, it would inevitably induce lapses in the estimation of true aerodynamic loading, which is primarily caused by surface forces, whereas the force balance banks are calibrated based on point force response Even though, a multi-point loading is preferred for calibration, which is reported in a literature [5] requires precise computations and a deliberate selection of loading points to determine the desired orthogonal inputs and their corresponding calibration data responses for determining the system response function or training of any soft computing approaches.

It is evident in the literature that a multi-point calibration approach [9] is found to be consistent and also enhances the accuracy of force prediction for accelerometer-based force measurement techniques. It is also anticipated that this approach may be mathematically streamlined to evaluate the system response function and also simplify the training procedure. With this approach, initially, the multiple hits are applied to the test model at different points to acquire force time histories and their corresponding acceleration responses during the calibration process. Additionally, these force time histories and concomitant acceleration signals are superposed using an associated weightage factor in order to obtain responses due to orthogonal forces. These calibration location weights are computed by using an optimization methodology, and further, the obtained resulting responses are then input into ANFIS for training purposes. As a result, it is clear that the multi point calibration methodology much closer to accurate force prediction than the single point calibration method. When compared to single point calibration. However, the number of points across a test model increases as its size increases to enhance force accuracy during calibration. Due to the large size of the test model, it is difficult to consider all points that are marked on the surface of the model for calibration. Therefore, the primary emphasis of the current study is the comparison of recovered axial and normal force for the aerodynamic model from several sets of calibration sites. A model with an accelerometer force balance fitted inside is taken into consideration for the experiment in order to measure the calibration forces. Additionally, these signals have been utilized for force recovery using the neuro-fuzzy logic-based method known as ANFIS. The subsequent sections cover the fabrication of a blunt bi-cone test model, three-component accelerometer force balance, and its dynamic calibration tests along with their results.

2. Description of Aerodynamic Model and Force Balance

A blunt cone test model has been designed in-house. The test model configuration is of blunt bi-conical shape which is a scale model of the "DASA CTV" re-entry spacecraft capsule [10]. Aluminium as a material has been chosen for fabrication of test model. The nose cone angle is 21.37° while another yaw angle of 5.9° is also present making it a lifting capsule. An accelerometer force balance comprising steel rings and rubber bushes has been equipped inside the model to achieve free flying conditions. Three uniaxial accelerometers are attached in the test model to monitor the temporal variation of acceleration during calibration experiments. A diagrammatic diagram of the test model with accelerometer force balance is illustrated in **Figure 1.**

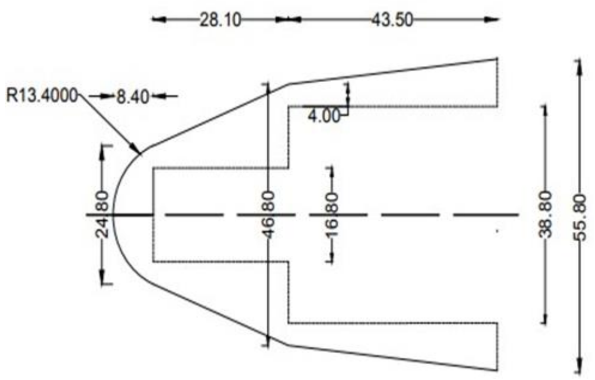

Figure 1: Diagrammatic representation of 'DASA CTV' scaled test model.

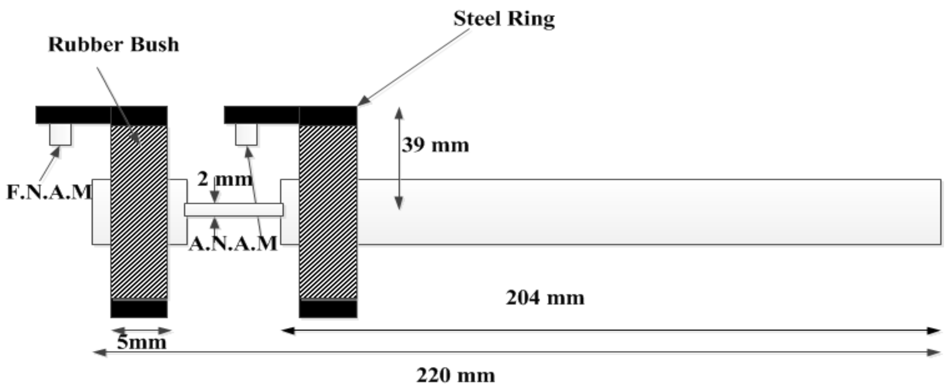

Figure 2: Schematic of Accelerometer Force Balance system

Three uniaxial accelerometers have been installed at different positions inside the test model to record responses using an accelerometer force balance system. This force balance system consists of two steel rings and rubber bushes imposed on a hollow steel rod with the help of glue [11]. These steel rings are 5 mm in thickness and 38.40 mm in outer diameter. This accelerometer force balance system is fastened with test model by the help of screws The rubber bushes present in the accelerometer balance system are accountable for achieving the free-flying motion of the complete support system during the experiments. The outside diameter of the rubber bushes is 31 mm, and their thickness is 5 mm, respectively. The accelerometers, which are placed in their respective direction, are responsible for recording the acceleration responses during tests. The axial accelerometer, which is mounted at the nose of the model, measured the axial acceleration while the acceleration measured in normal direction has been done other two accelerometers which are mentioned as front and aft lift, respectively. These two accelerometers are located ahead and behind the center of gravity of the model respectively. Further, the test model integrated with accelerometer force balance has been mounted on a bench vice to conduct calibration experiments. The details of calibration experiments are given in subsequent sections. A diagrammatic representation of the three component inertia based force balance system is illustrated in **Figure 2**, and the details of each uniaxial accelerometer [Model: 352C67 SN109747 Make: Piezotronics] which is associated with force balance are shown in **Table 1.**

Table 1: Specification of accelerometer used in force balance

Locations	Accelerations	Sensitivity (mV/m/s^2)	Frequency (kHz)
1.	Axial	10.15	10
2.	Front Normal	9.97	10
3.	Aft Normal	10.34	10

3. Calibration setup and Experiments

For dynamic calibration, the test model integrated with the accelerometer system is initially fixed on a bench vice. **Figure 3** provides information regarding the location of the normal forces employed during calibration. The location of each accelerometer is found in **Figure 4**. These mounted accelerometers have been connected with a signal conditioner as input, and its output is further connected with the oscilloscope, which records all impulsive applied force and its corresponding acceleration responses. The impulsive force has been applied on nine different locations over a test model at normal to the local surface using impulse hammer. Here, typical diagrams of impulse force and acceleration signals for particular location (Location 1) are shown in **Figure 5** and **Figure 6.**

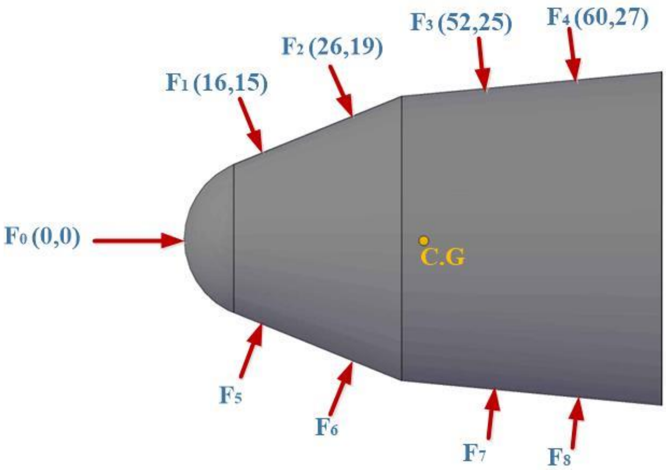

Figure 3: The coordinates of calibration locations of the test model.

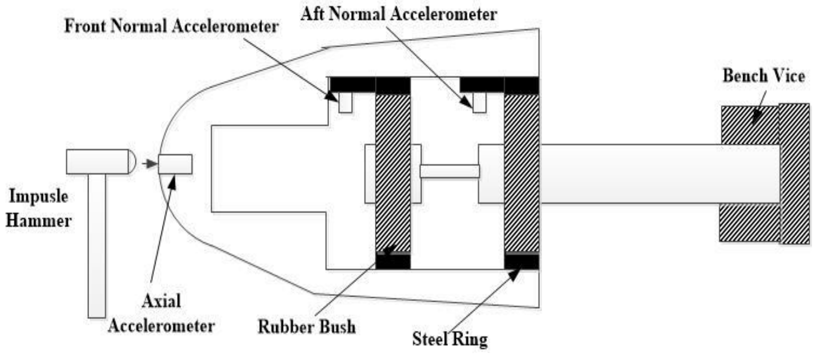

Figure 4: Calibration Setup.

It is clear from Figure 4 that when the force is applied at location 1 or nearer to the front normal accelerometer, then the front normal acceleration is prominent compared to other acceleration.

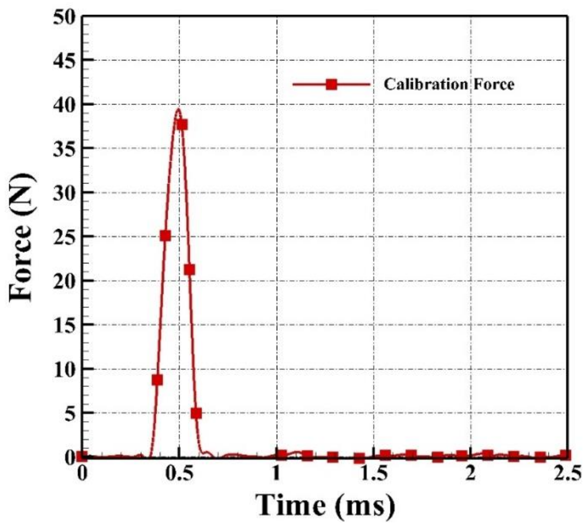

Figure 5: Calibration force signal for location 1

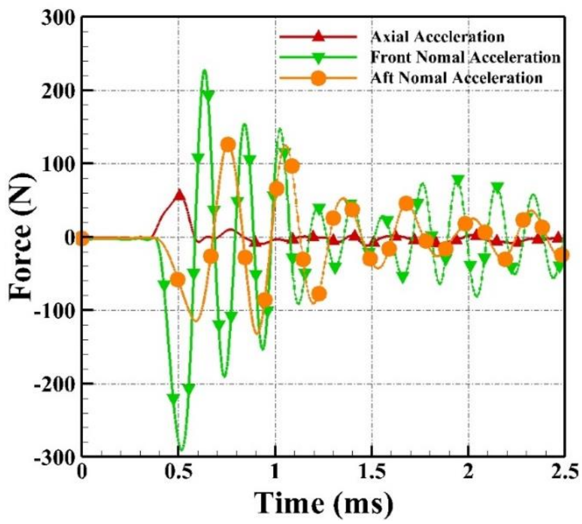

Figure 6: Calibration acceleration signals for location 1

4. Optimization of Calibration Orthogonal Inputs

Calibration tests are performed to get the acceleration responses for the corresponding orthogonal input of impulse forces. The responses of orthogonal inputs, such as axial force and normal force, should be noted carefully . In order to determine the associated responses for those orthogonal inputs, this component first evaluates orthogonal inputs in the frame of reference fixed with the model using the applied local normal forces. As a result, it marks the beginning of the new force balance calibration method that uses the Genetic Algorithm (GA), an established optimization tool. In order to derive pure axial and normal forces from dispersed point forces, this approach is mainly used to compute the weights corresponding to various calibration points (**Figure 2**). Eq. (1) indicates the mathematical connection between pure axial force, pure normal force, and induced moment in terms of applied force location coordinates as well as each cone angle of test model (**Figure 2**).

$$\left.\begin{aligned} F_x &= F_1 + \sum_{i=2}^{5} \alpha_i F_i \sin\theta_1 + \sum_{i=6}^{9} \alpha_i F_i \sin\theta_2 \\ F_y &= \sum_{i=2}^{5} \alpha_i F_i \cos\theta_1 + \sum_{i=6}^{9} \alpha_i F_i \cos\theta_2 \\ M_z &= \sum_{i=2}^{5} \alpha_i F_i (x_i \cos\theta_1 + y_i \sin\theta_1) + \sum_{i=6}^{9} \alpha_i F_i (x_i \cos\theta_2 + y_i \sin\theta_2) \end{aligned}\right\} \qquad (1)$$

Figure 1 shows the consistency in cone angles and the direction of applied forces, while **Figure 3** explains various subscripts of input forces. Furthermore, the force Fi exerted in the local normal direction has an associated weight which is denoted by αi. The equation above clarifies that if an impulse force is applied at location 1 (nose of test model), the resulting normal force is zero since it is a strictly axial force at that point. After that, GA is used to determine the weights that correlate to the calibration points, which ultimately aids in estimating the pure axial as well as normal force. As the result, initially, the Genetic Algorithm (GA) approach set the objective function as maximize for axial force (Fx) by taken the normal force (Fy) and induced moment (Mz) are set as zero for constraint. Similar to this, genetic algorithm (GA) is once more used to assess the weights for maximizing the normal force (Fy) while limiting the axial force (Fx) and induced moment (Mz) to zero amount. GA can then be used to maximize the induced moment (Mz), but this is not desirable because the coefficient of drag, lift, and pitching moment can be predicted using the standard accelerometer force balance theory by estimating the pure axial force and normal force [12]. The optimization toolbox in MATLAB [13] is used to accomplish the aforementioned goal. For the current studies, a population size of 20 and a crossover proportion of 0.8, the selection function is stochastically uniform, the mutation function is typically employed as constraint dependent, and the cross-over function is typically scattered for computations. However, the estimated model weights for each calibration locations for individual calibration tests are given in **Table 2.** Furthermore, these model weights are fed in Eq. 1 to evaluate the pure axial as well as normal forces and their respective acceleration responses. Finally, these obtained forces in axial as well as normal direction and its responses are fed to train the prediction algorithm i.e. ANFIS, to monitor its performance. During training of this soft computing algorithm, the ANFIS network parameters has been also checked and reaches its optimize value for ANFIS architecture.

4. Soft computing-based force Recovery Algorithm

The current study focuses on using the widely utilized soft computing method ANFIS [14] to the prediction of temporal force and moment histories. Jang has shown a thorough working philosophy of this approach

[15]. The combination of fuzzy logic (FL) and neural networks (NN) in this artificial intelligence technology gives it a feeling of flexibility that contributes to its universal approximation capabilities. Additionally, ANFIS is a Multi Input Single Output (MISO) system, as shown in **Figure 4**, in which the input, output, and intermittent layers are coupled by weights. This technique optimizes the ANFIS architecture by adjusting the consequent and premise parameters, which in turn fine-tunes the model weights. In order to meet the current goals, the MATLAB ANFIS toolbox is utilized. The current MATLAB ANFIS module supports normalized input and output data, which may be accomplished by using different kinds of membership functions (MF) that make it easier to normalize data between 0 and 1. The user's experience must be taken into consideration while choosing these MFs. The ANFIS architecture must be trained using either the hybrid or back propagation training methods in addition to the MF type. However, because the hybrid approach combines the least squares method for function evaluation with the gradient descent process, it often yields global optimum model weights. Now, a research is conducted utilizing the data sets derived from the multi-point calibration approach, taking into account the variability of factors, such as input MF, output MF, and training strategy. This aided in determining the parameters that would be most effective in accurately predicting the moments and coefficient of forces based on the obtained experimental responses. Therefore, by tracking the accuracy during training, when one of the impulse hammer test data is used for recovery of the other, optimal ANFIS input parameters are established. As a result, 500 epochs viz. iterations with the hybrid training method, sigmoid (psig) type of input MF, and constant type of output MF have been chosen for the train of the ANFIS network. Figure 7 depicts the whole flowchart of the proposed calibration process, which consists of initial GA-based optimization for assessing pure orthogonal inputs and further ANFIS based training and recovery for the experiments.

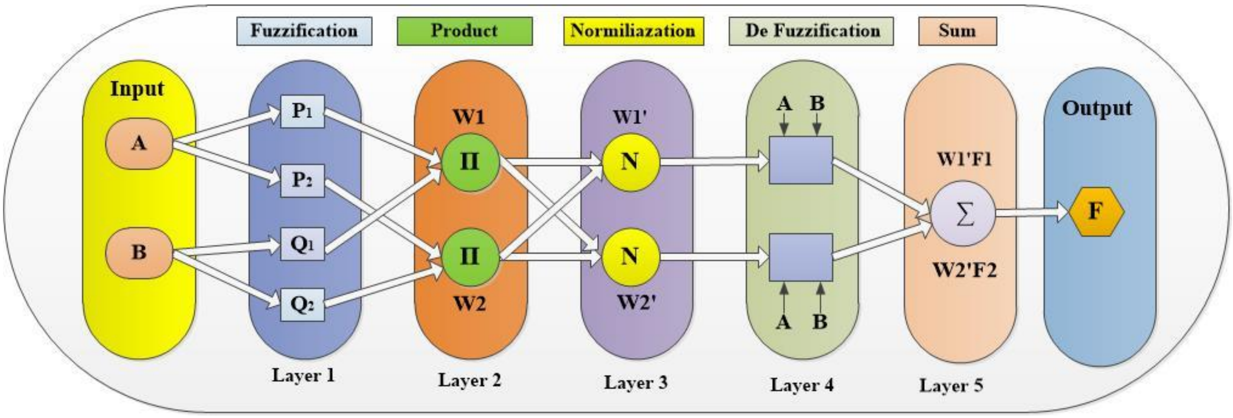

Figure 7: ANFIS Architecture

5. Results and Discussion

In a real shock tunnel experiment, a test model is subjected to a distributed load. Nevertheless, the load has been delivered at certain points during calibration. Several points on a model's surface have undergone calibration. It has been observed that a better prediction is obtained when the applied calibration force is normal and also closer to the center of the pressure plane. Although the acceleration responses of calibration signals correspond to locally applied normal forces are always present, the responses for forces purely in axial as well as normal direction must be known in order to be used as input for force prediction techniques. A novel solution to this issue is the Genetic Algorithm (GA), which determines the relative

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importance of several calibration sites in order to derive forces in axial as well as normal direction from dispersed point forces. There are three individual equations for force and moments for corresponding locations i.e. pure axial, pure normal, and moment are used in this approach. It is evident that the net normal force is zero if the force is applied at the model's nose or position 0. The weights of the additional calibration points are then determined by using GA, which aids in estimating the pure axial and pure normal force. Hence, the GA's goal function is configured to maximize the axial force while taking into consideration the restriction to set the induced moment and normal force to zero. In a similar way, one more time Genetic Algorithm (GA) is utilized to evaluate the weights in order to maximize the normal force while simultaneously lowering the axial force and induced moment magnitude close to zero. Afterwards, GA can also be used to maximize the induced moment value, although this is not ideal because the coefficient of drag, lift, and pitching moment can be predicted using the standard accelerometer force balance theory by estimating the forces in purely in axial as well as normal direction respectively.

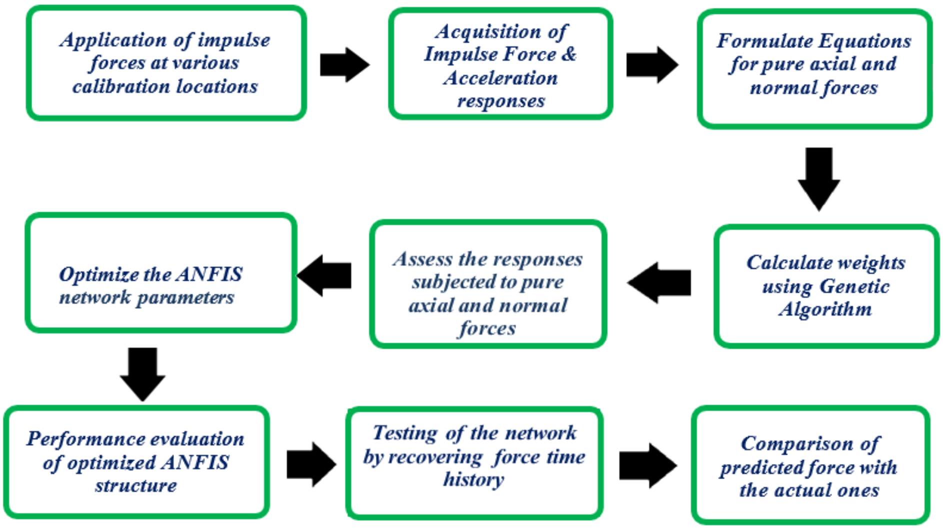
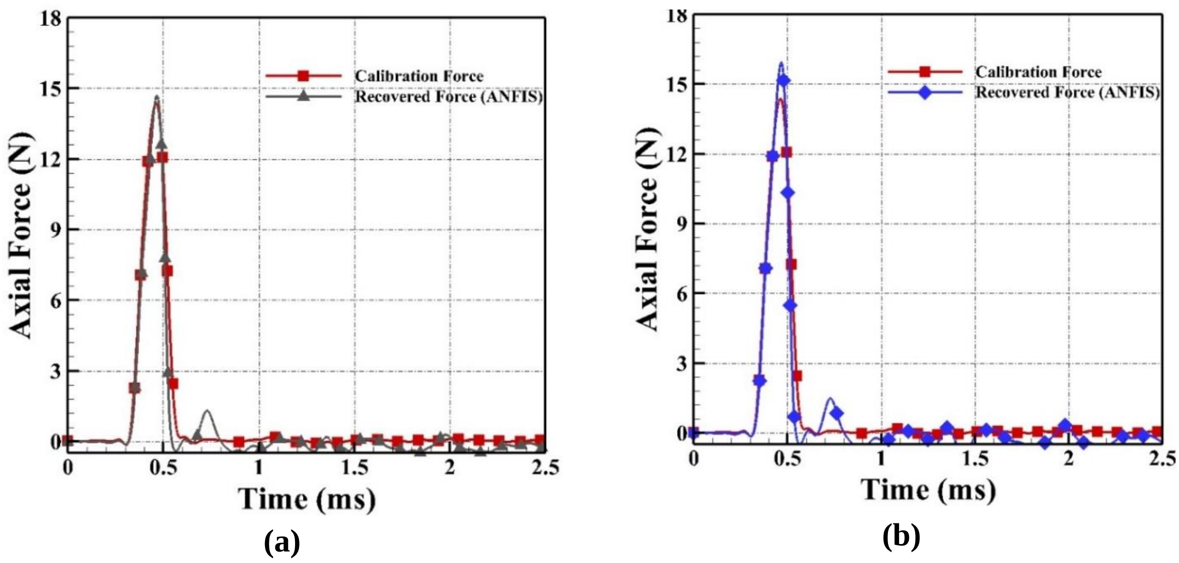
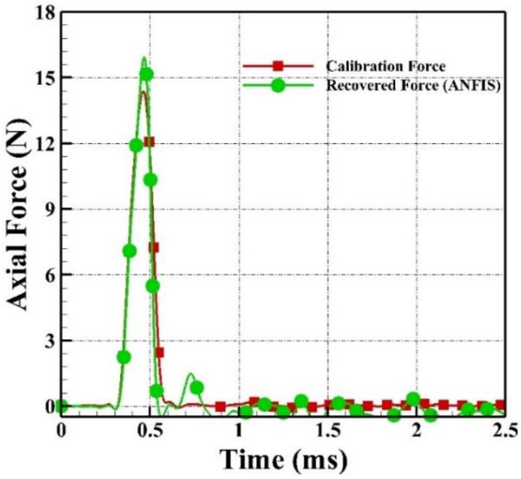
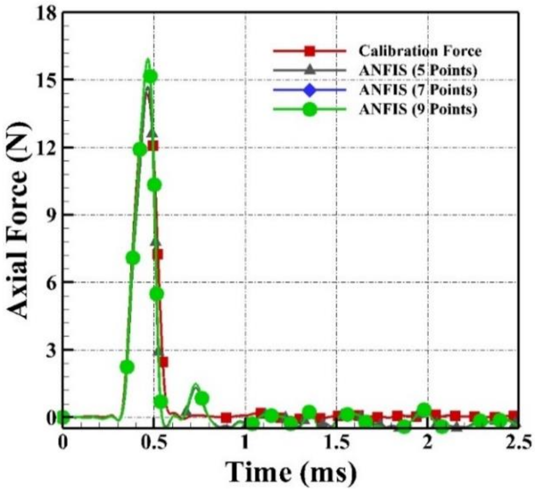


Figure 8. Flowchart of the multi-point calibration methodology.





(c)



(d)

Figure 9: Recovered Axial force signals for location 1 from (a) 5 Point, (b) 7 Point (c) 9 Point calibration using ANFIS technique (d) Combined plot for all recovered axial forces

The weights have been estimated for the three different sets of locations, viz. 5 points (Even points), 7 points, and 9 points. Now, these weights are used to estimate pure axial, pure normal, and their respective acceleration responses. In order to recover a force, these forces and responses were further input into a prediction technique termed as ANFIS. For such computations, MATLAB [13] based functions are used in the current investigations. Additionally, the well-known soft computing approach, ANFIS, is used to achieve a similar recovery procedure. ANFIS is a hierarchical structure of multiple inputs and a single output. And, this architecture has been trained and optimized with the help of force and acceleration time histories of calibration tests. Afterward, without altering these consequent and premise parameters, an attempt has been made to recover the experimental force. Thus, present calibration tests boost the confidence of force recovery processes.

Here, an only location 1 force (i.e. axial as well as normal) has been predicted from different set of calibration points. And it has been observed that the recovered normal force magnitude for location 1 is good agreement with its own force magnitude for 9 points calibration then 5 and 7 points calibration. Oscillations are also less in case of nine point calibration. Axial force recovery has for same location has also a well matched with its own actual axial force. There is no so much difference in magnitude from different set of calibration. So it concludes that the prediction of pure axial force for a location does not so much effects with multi point calibration. The comparison of recovered axial and normal fore location 1 with their respective actual force are illustrated in **Figure 9** and **Figure 10**.

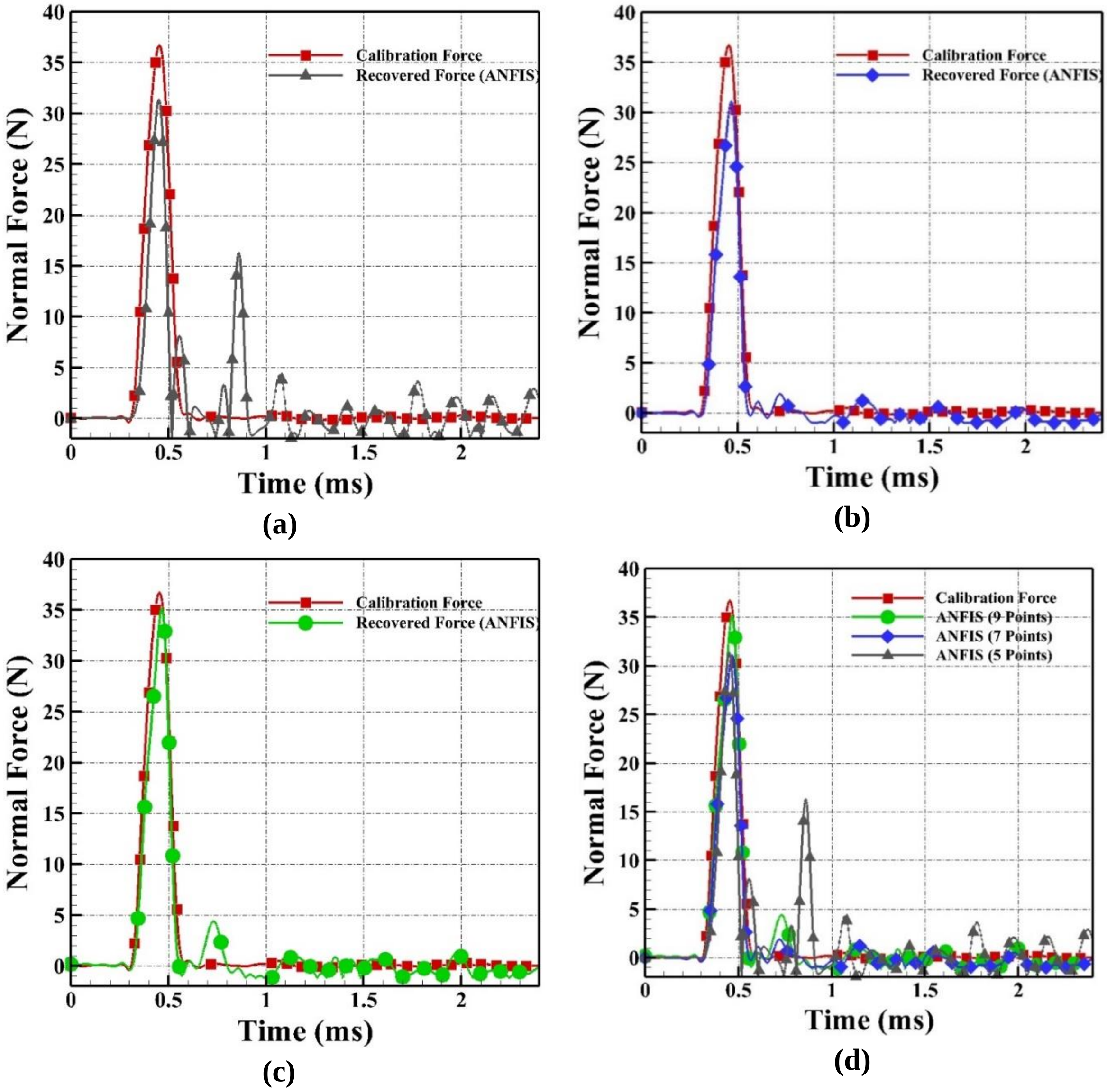


Figure 10: Recovered Normal force signals for location 1 from (a) 5 Point, (b) 7 Point (c) 9 Point calibration using ANFIS technique (d) Combined plot for all recovered normal forces

6. Conclusion

A blunt bicone model has been successfully calibrated at multiple locations of the test model. Using the GA and ANFIS techniques, the normal and axial forces of location 1 have been predicted using a various set of calibration locations data (5, 7, and 9 points). On the basis of result, it can be concluded that recovered force i.e. Axial which is predicted from five point calibration gives a better agreement with actual calibration force for location 1 while normal force well matched with nine point calibration. However, nine point calibration for axial force also have good agreement with experiment. The percentage error for force recovery is around less than 10%. GA along with ANFIS technique gives a better response for multi component in field of force prediction. Further, this technique can be used for force recovery purpose in shock tunnel experiment.

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