“Experimental and Finite Element Analysis of Accelerometer Force Balance for Short Duration Applications”

A Project Report

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In partial fulfilment for the award of the degree

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In

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CERTIFICATE

We hereby certify that the work which is being presented in the B.Tech Project Report entitled **“Experimental and Finite Element Analysis of Accelerometer Force Balance for Short Duration Applications ”,** in partial fulfilment of the requirements for the award of the **Bachelor of Technology** in **Mechanical Engineering** and submitted to the Department of Mechanical Engineering of National Institute of Technology Meghalaya is an authentic record of our own work carried out during a period from **June 2017 to May 2018 (7^{th} and 8^{th} Semesters)** under the supervision of **Dr. P. Ramesh Babu**, Department of Mechanical Engineering National Institute of Technology Meghalaya.

The matter presented in this Project Report has not been submitted by us for the award of any other degree elsewhere.

DEEPAK KUMAR **GUDEPU SURESH** **CHIRIKI PAVAN SAI**

This is to certify that the above statement made by the student(s) is correct to the best of my/our knowledge.

Date 23/05/2018

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ABSTRACT

Force measurement techniques are used to measure the drag force, lift force and therefore to minimize the nose size of vehicle, noise emission and other causes of aerodynamic instability at high speed. Generally air is considered as fluid in this case. The measurement of forces in hypersonic flow is not possible using conventional techniques. Measurement of aerodynamic forces on a model open to hypersonic flow in shock tunnel must be performed during the period of steady flow which may be less than a millisecond. It is one of the crucial areas of research, which is requisite in the design of any mechanical or electromechanical systems. Due to lack of knowledgeable testing and force measurement on the scaled models in the design phase, a lot of failures are experienced over the decades for various vehicles such as ships, rockets, airplanes, internal combustion engines etc. But in the recent years, rate of failures of such kind have been reduced due to the development of different types of force measurement techniques. Force measurement in impulse facilities such as shock tunnel is one of the specialized areas useful for the design of hypersonic vehicles. These measurements are sophisticated due to their short test duration.

The supporting structure was tested using the impact hammer test from which the acceleration is measured for the applied input force. The test was done on model in free-flying condition and therefore rubber was used to provide the free-flying condition. Accelerometer force balance has been used by various researchers for force measurement in shock tunnel testing with the assumption of free-flying condition. Finite element modelling is carried out for one of the literature reported test model to evaluate the resistance offered by the rubber during the experimental test time. These studies are found useful to demonstrate the use of computational techniques in developing the force balance for a given test model. Accelerometer based force balances are seen to be directly used for force measurement as seen in the literatures. At the same time stress wave force balances are involved with detailed calibration procedure.

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Chapter-1
INTRODUCTION

1.1 INTRODUCTION

When two solid bodies interact in a mechanical process, forces are transmitted, or applied, at the point of contact. But when a solid body interacts with a fluid, things are more difficult to describe because the fluid can change its shape and the fluid can flow around the body and maintain physical contact at all points. Understanding the motion of air flow around an object enables the calculation of forces and moments acting on it. Force measurement techniques also used to measure the various Aerodynamic parameters such as drag force, thrust force, lift force, pitching & moment etc. Aerodynamics is important to understand when designing and constructing buildings, bridges, wind turbines as well as vehicles and aircraft, the later two in order to minimize fuel consumption and emissions.

Force measurement techniques in wind tunnel are used to measure the variety of aerodynamics performance parameters. Hypervelocity aerodynamic testing is generally used using impulse-type wind tunnel facilities. These facilities are capable of producing the high enthalpy flows necessary for aerodynamic simulation but are limited by the duration of the test flow. The typical test flow duration of a reflected shock tunnel is between one and three milliseconds.

Before conducting the wind tunnel test on any scaled model, calibration techniques are very essential for establishing the relation between the applied forces and the responses from the systems. Various techniques are proposed and tested experimentally for the measurement and prediction of the forces in the short test duration. In that kind there are well known techniques such as stress wave force balance and accelerometer force balance. Accelerometer force balance works on the principle that when transient force is applied on the body, which is considered as the lumped mass system, the measured acceleration can be useful for the prediction of the applied force. But in case of the stress wave force balance, the body is considered as distributed mass and the strain history measured can be used for predicting the force applied on the body.

Researchers have proposed many such techniques and methodologies for finding the applied forces using the measured responses. Some of the available techniques are studied from the literature before going to propose this novel technique for force prediction. The next section deals with the literature cited for establishing the present research work.

1.2 LITERATURE REVIEWS

Accurate measurement of the forces and moments acting on a model in short-duration hypersonic facilities remains a difficult problem. The time scales of such facilities are so short that stress equilibrium typically cannot be established within the model and support within the measurement time, rendering traditional force balance techniques impractical. While a variety of alternative methods have been developed, each has its limitations, and no existing standard has emerged. Surveying the techniques available for short duration force measurements three and a half decades earlier, Bernstein (1975) wrote ‘‘the present state of the art is such that reasonably reliable measurements can be made, but none of the methods developed so far can claim a very high overall precision.’’ Despite the major advances that have been made in sensor technology and electronics since this time, the same may be said to hold true today. Bernstein introduced the useful distinction between stiffness- and inertia-dominated methods. Within the first category, the stress-wave force balance, first proposed by Sanderson and Simmons (1991), is probably the best established method. While this initial work did not indicate a repeatability of better than 10%, the technique has since been developed, primarily by researchers at the University of Queensland, to the point that it is able to provide reliable measurements on models up to the scale of large scramjet geometries (Mee 2003; Robinson et al. 2006). Disadvantages of this technique include the need for careful model design and interpretation of results, and the complex support mechanism required can limit the applicability of the method.

One force measurement techniques named as ‘*stress wave force measurement technique*’ is used to overcome the limitation associated with short test time. This technique was proposed by Sanderson and Simmons and relies on measuring and interpreting the stress waves which propagates within a model and its support as a result of aerodynamic loading. Since its development, Daniel and Mee have extended the technique through finite element modelling of two and three component balance designs. This lead to the development of three component balance which permitted the measurement of lift force, drag force and pitching moments on a short conical model in a reflected shock tunnel.

Various techniques can be used to address these problems. The model can be made small and light and the force balance very stiff so that the natural frequency of the system is high (e.g. Jessen and Groenig, 1989). Accelerometers can be placed on the model and can be used to detect vibrations that can then be used to compensate the strain signals from the force balance (e.g. Carbonaro, 1993). Another possibility is to measure the acceleration of the model and use flexible supports for the model (e.g. Joshi and Reddy, 1986) or to let the model fly freely during the test (e.g. Naumann *et. al.,* 1993). This eliminates the effect of a support mechanism decreasing the natural frequencies of the system. The natural frequencies are set by the model size and the speed of stress waves in the structure of the model. A small model keeps these frequencies high and a light model leads to larger acceleration signals. When force measurements are required on models of larger size and mass in impulse facilities, the period of the lowest natural frequency of the force balance can become of similar order to the duration of the test flow. For such conditions, system identification and inverse techniques can be used. The system dynamics can then be included in the analysis of the force balance signals to determine the history of the aerodynamic forces on the model. One such technique, the stress-wave force balance (SWFB) technique, was proposed by Sanderson and Simmons (1991). This technique has been extended to larger sized models (Tuttle et al., 1995), shorter duration flows (Smith and Mee, 1996a), multiple-component force measurement (Mee *et. al.*, 1996) and has been used for measurements such as the performance of scramjet-powered vehicles (Paull *et. al*., 1995). An overview of dynamic testing is given by McConnell (1995) and the dynamic calibration of measurement systems is discussed by McConnell and Abdelhamid (1987).

Many experiments and analysis for measuring drag force in wind tunnels have been done to grasp the various aerodynamic effects in real environment. Hypersonic force balance techniques have been in use since the 1950's and have developed into different types, such as continuous and impulse types. Important model parameters are drag and thrust but their measurement is greatly complicated with short duration testing. A comprehensive review of the force measurement techniques used in short duration facilities has produced by Bernstein. The outline of this review says that the model act as a rigid body and the members of the force balance structure are simple element.

Balances are then divided as stiffness dominated force balance and inertia dominated accelerometer balances. Impulse facilities include shock tubes, reflected shock tunnels and expansion tunnels and these facilities are done for very short duration. These facilities are done into a shock tube which is a cylindrical tube in which there are two parts named as driver and driven separated by a diaphragm. The basic principle of these impulse facilities is to suddenly release a highly compressed gas in the so-called driver tube through rupturing a diaphragm. With the shock tunnel one of the major deficiencies that originally existed was the lack of suitable force balance. Traditional force balance could not be used as they are required to come to static equilibrium during the test period. With test times of the order of milliseconds in a shock tunnel, this is impossible to achieve with any reasonable size model, even if the models are constructed from carbon-fibre or beryllium, which have very high speeds of sound.

1.3 FORCE MEASUREMENT OR CALIBRATION TECHNIQUES

Force measurement is complicated in impulse facilities due to the short test duration that will likely prevent the force balance from attaining a steady state. This limitation of short test times in such facilities was overcome by applying the stress wave force measurement technique (SWFM), proposed by Sanderson and Simmons. Due to impulsive aerodynamic loading, stress waves that are created, propagate and reflect through the model and support structure, which are measured and analysed by this method. Extension of this work by Daniel and Mee using finite element modelling led to the design of a three component force balance. The SWFM technique is based on the principle that, when stress waves travels, no force equilibrium is reached in such a short duration of time so that the strain histories are the crucial feature for developing force measurement techniques. An investigation into internal and external force balances was undertaken by Robinson et al which showed that a higher accuracy of the recovered force and moment loads was attained using an external force balance. Also, for a blunt body, these authors found that the interaction of external balance on the model forces was negligible when compared to that of an internal balance. Some of the recent developments include comparing the experimental measurements with CFD calculations by Boyce and Stumvoll, which showed good agreement for a range of Mach numbers and test gases.

On the other hand, accelerometer-based force balances were used by Kulkarni and Reddy and Sahoo et al, which was a single-component accelerometer force balance. The data were in accordance with modified Newtonian theory. Sahoo *et. al*., found that the drag measured on a 30 degree semi-apex angle blunt cone model at Mach 5.75 with an accelerator based balance agreed closely to the SWFM technique.

1.3.1 Internal Force Balance

Internal force balances are defined as those that have the measuring instruments like strain gages, accelerometers placed inside the model. The mounting system (sting) has to adapt depending on the location of the force balance. Models are generally attached to a long sting and placed in the test section of the tunnel. The geometry of the model has to accommodate the sting. A common way to measure forces is by strain gages.

1.3.2 External Force Balance

External balances are those where the measuring instruments are located outside the model but may be within the test section. The definition of external balances used to be restricted those that are mounted outside the test section, which has been updated to balances that are specifically external to the model, but which can be within the test section. The principle of external balances is similar to that of internal balances but the difference is that the measuring devices are placed on a supporting structure, such as a sting. The forces on the model are transmitted as stress waves to the sting, which on deformation or bending creates strain that is measured by the attached strain gages. Specifically for hypersonic shock tunnels, external force balances that use stress wave propagation are named as Stress Wave Force Balances (SWFB)

1.3.3 Strain Gauges

Strain gauges are sensors that are used to measure strain or deformation. Strain gauges work by the principle that a strain in a metal or semi-conductor causes a change in resistance, which when measured can be related to the strain. There are different types of strain gagues, namely, metallic foil gages and semiconductor strain gauges, which can be either piezo-resistive or piezoelectric. All resistance-based strain gauges require an excitation voltage. A Wheatstone bridge arrangement increases the sensitivity of the strain gauge, thus allowing small changes in strain to be measured.

1.3.4 Piezoelectric Film

Piezoelectric film gauges are a type of transducer for measuring dynamic strain and are used in high-frequency applications. Some of the features of piezo film are its flexibility, varying thickness, lightweight and easy application. These gauges have a large frequency range of up to the order of 1 GHz. Some other properties include its dynamic range, high mechanical strength, and temperature and humidity stability. Piezoelectric film can be adapted to various shapes and can be bonded with commercial adhesives. Another feature is high voltage output, that can be as high as 10 times higher than normal strain gauges. Some disadvantages of piezoelectric films are that they are sensitive to electromagnetic radiation; in such cases shielding becomes important to avoid any kind of interference and ensuring a good signal-to-noise ratio. Piezoelectric film gauges do not require an external power source or excitation voltage. Marineau showed that a piezoelectric force balance has a higher frequency response than a strain gauge force balance. Both balances showed comparable levels of accuracy. The piezoelectric balance shows a 350% increase in frequency response and 400% increase in sensitivity.

1.4 STRESS WAVE FORCE MEASUREMENT TECHNIQUES

The stress wave force measurement technique depends on characterizing the dynamic response of the wind tunnel model and its support. This technique permits the simultaneous measurement of single and multiple force components.

Conventional force balances depend on the damping mechanisms and filters to reduce the effects of the vibrations, associated with the sudden application of the impulse/aerodynamic forces when the flow start or when the model is injected into the flow.

The model can be made small and light and the force is stiff so that the natural frequency of the system is very high.

Accelerometer can be placed on model to detect the vibration that can then be used to compensate the strain signal from the force balance.

Another method is to measure the acceleration of the model and for this flexible supports for the model are used or model flies freely during the test. This eliminates the effect of a support mechanism decreasing the natural frequency of the system. A small model keeps these frequencies high and a light model leads to larger acceleration signals.

When the force measurements are done on the model of larger size and mass then the period of the lowest natural frequency of the force balance can be of same order during the test. For such conditions, it is possible to use system identification and inverse techniques to include the system dynamics in the analysis of the force balance signals to determine the time history of the aerodynamic forces on the balance. One such technique, the stress-wave force balance (SWFB) technique, was proposed by Sanderson & Simmons (1991).

When an aerodynamic force is suddenly applied to a model, stress waves are initiated within the model. These waves propagate through the model and its support structure.

The principle of the SWFB lies on the fact that no steady state is achieved.

Therefore, during the short duration of the testing no equilibrium can be achieved between the model and its support.

If the model and support structure produce linear strains due to linear forces, then the dynamic behaviour of the system can be modelled as time-invariant, causal and linear with an output $\mathbf{y}(t)$ (the resulting strain signal), being related to the applied aerodynamic load, $\mathbf{u}(t)$, via an impulse response function, $g(t)$, as described by the convolution integral,

$$y(t)=\int_0^t g(t-\tau)u(\tau)d\tau \qquad (1)$$

If the system characteristics (in the form of the impulse response function) are known, then a deconvolution procedure can be used to determine the time history of the applied load from the time history of measured strain.

One method for experimentally determining the impulse response is to measure the output signal generated by a step change in the input to the system. This is called the step response of the system and the impulse response can be determined by differentiating the step response with respect to time and scaling the result appropriately. This can be shown by taking the Laplace transform of eq. (1) to obtain

$$Y(s) = G(s)U(s) \qquad (2)$$

where Y (s), G(s) and U(s) are the Laplace transforms of y(t), g(t) and u(t) respectively.

Let the input be a step of magnitude a starting at time t = 0,

$$u(t)=0 \quad \text{when } t < 0$$

$$u(t)=a \quad \text{when } t \geq 0$$

The Laplace transform of this input is a=s and eq. (2) becomes

$$Y(s)=(a/s)G(s) \qquad (3)$$

Inverting this gives

$$y(t)=a\int_0^t g(\tau)d\tau \qquad (4)$$

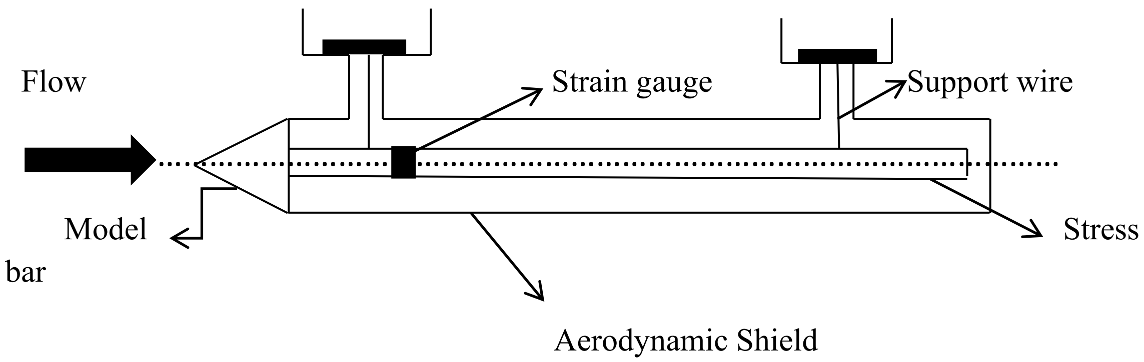


Fig. 1.1 Single-component stress-wave force-balance

The single stress wave force balance is generally a variation of original Hopkinson pressure bar experiment and consists of a model rigidly connected to an elastic bar. The stress bar serves as the model support and the arrangement is suspended in the flow so that there is no restriction to movement in the flow direction. Due to this aerodynamic loading on the model stress waves will propagate within the model. These waves reflect within model and are progressively transmitted into the supporting stress bar.

Force measurement is one of the vital areas of research, which is essential in the design of any mechanical or electromechanical systems. Due to lack of sophisticated testing and force prediction on the scaled models in the design phase, a lot of failures are encountered over the decades for various vehicles such as ships, rockets, airplanes, internal combustion engines etc. However in recent years, rate of failures of such kind were reduced due to the development in force measurement facilities and force measurement techniques. Force measurement in impulse facilities such as shock tunnel is one of the specialized area useful for the design of hypersonic vehicles. These measurements are sophisticated due to their short test duration. Computational techniques like Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) are generally used before actual design of the system. Recently evolved fluid structure interaction (FSI) is one of the emerging computational tools for the analysis of fluid and solid domains simultaneously. Here, the surface forces obtained from the fluid simulations are transferred to the fluid solid interface for obtaining the response from the structural simulation. Since increasing mission complexities and advanced technologies demand more accurate assessments, the experimental force prediction strategies are preferred since they provide golden mean between the accuracy and the cost effectiveness. Therefore, ground based facilities are essential for the purpose of proper understanding of the physics of the flow and the associated aerodynamic parameters. Encouraging developments in the short duration facilities like conventional shock tunnel free piston shock tunnel etc. has posed challenges in measuring forces and moments during the experiments. Two different techniques viz., *accelerometer* and *stress wave based force balances* are generally used for measurement of forces and moments in the high speed impulse (short duration) facilities. Therefore in the present work initial investigations deal with establishment of a non-intrusive force measurement technique using laser and development of the associated experimental set-up. This technique is then assessed with the well-established contemporary techniques for the step and impulse loading. Accelerometer force balance has been used by various researchers for force measurement in shock tunnel testing with the assumption of free-flying condition. Finite element modelling is carried out for one of the literature reported test model to evaluate the resistance offered by the rubber during the experimental test time. These studies show that the effective test time decreases with increase in the angle of attack due to increase in resistance of the rubber. These studies are also found useful to demonstrate the use of computational techniques in developing the force balance for a given test model. Accelerometer based force balances are seen to be directly used for force measurement as seen in the literatures. At the same time stress wave force balances are involved with detailed calibration procedure based on de-convolution technique.

Two possible calibration arrangements are shown in Fig. 1.2 and fig.1.3 (a) where a known mass is attached to the wire to apply a known load to the model. In Fig. 2 the model is supported horizontally (as it is in the test section of the wind tunnel) and the wire passes over a pulley to the mass. The wire is cut close to the model. In Fig. 1.3(a) the axis of the balance is vertical and the balance is supported by a wire attached to the end of the stress bar. Each of these techniques has been used to obtain step responses.

A deficiency of calibration arrangement in fig.1.2 & fig.1.3 (a)) is that the end of stress bar is supported. But in the fig.1.3 (b) is free.

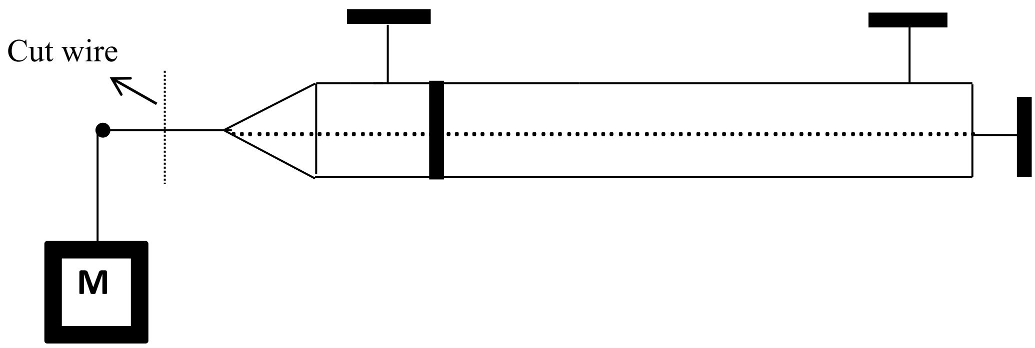
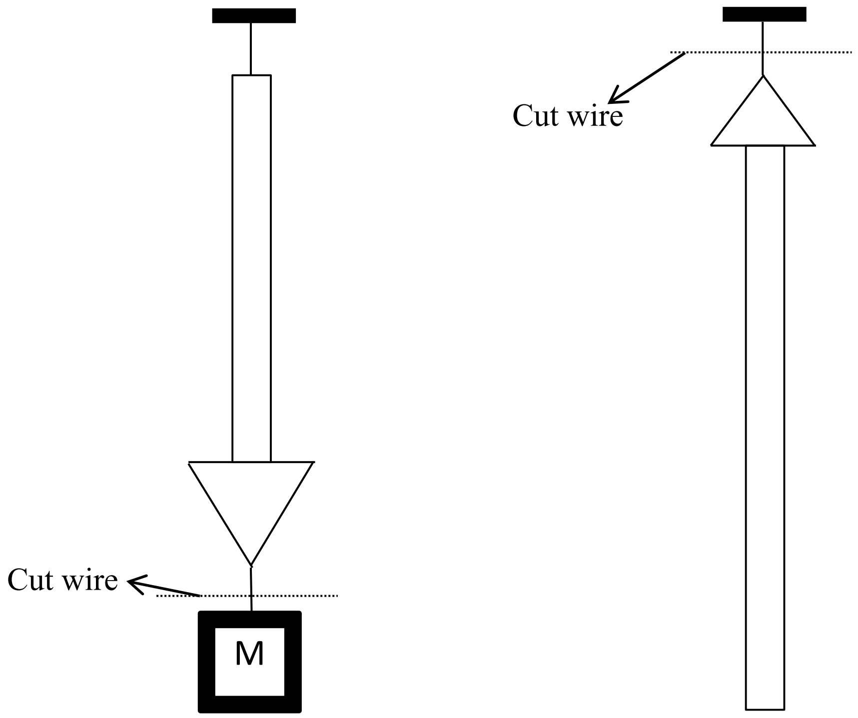


Fig. 1.2 Horizontal Calibration Technique



a) Vertical calibration b) Free-end calibration

Fig. 1.3 Vertical calibration techniques

This deficiency can be overcome by the calibration arrangement shown in fig.1.3 (b). Here the SWFB is again supported vertically but the load applied to the tip of the model is the weight of the SWFB and the end of the stress bar is free.

During the period of free-fall there is no load on the model and a step response valid for the tunnel experiments is obtained for a longer period of time. The magnitude of the applied step is set by mass of the model and stress bar. This deficiency can be overcome by the calibration arrangement shown in Fig. 1.3(b).

Here the SWFB is again supported vertically but the load applied to the tip of the model is the weight of the SWFB and the end of the stress bar is free. When the wire is cut, the load is suddenly removed at the tip and the arrangement falls. During the period of free-fall there is no load on the model and a step response valid for the tunnel experiments is obtained for a longer period of time. The magnitude of the applied step is set by mass of the model and stress bar.

1.5 AERODYNAMICS FORCE

It occurs on a body is immersed by the fluid or some other gas. The relative movement between the body and the gas caused the aerodynamics force. The force could be generated on the surface of the body owing to pressure and viscosity. The figure below shows the force on an aerofoil.

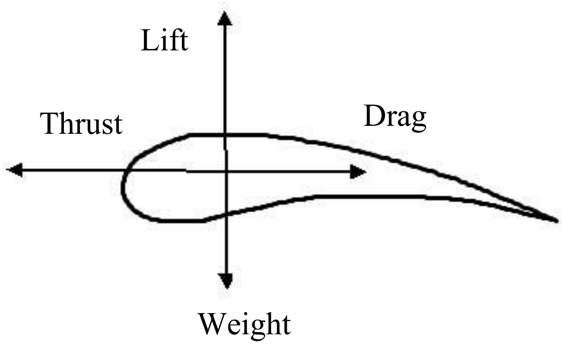


Fig. 1.4 Forces on an aerofoil

1.6 DRAG AND LIFT

1.6.1 Drag force

Drag force can be defined as in fluid mechanics, the force which exerted on the solid object in the upstream direction of the relative flow velocity.

Drag force depends on flow velocity and it decreases the fluid velocity. Therefore, drag force also called air resistance or fluid resistance.

1.6.2 Lift force

Contrasts with the drag force, lift force exerts when a fluid flowing pass through the surface of an object and the direction of lift is perpendicular to the flow velocity direction.

1.6.3 Drag coefficient

Drag coefficient is one of the most important factors in the field of fluid mechanics. It is often used in the drag equation. It is proportional to the drag force which act on the body immersed in the fluid; namely, less drag coefficient indicate less drag force.

1.7 OBJECTIVES

It is obvious from the above literatures review that the present work still need a lot of development, particularly in the flexible supporting system.

- The main objective of the present work is to design, fabricate hemispherical models and test a multi component force balance to be installed in wind tunnel with flexible support.
- To design and fabricate a free flying mechanism for constant force application
- Evaluate the mechanism with manual force application

These objectives are fulfilled by following the below steps

- Single component force balance design and experimental analysis.
- Multi component force balance design and experimental analysis.
- Validation of experimental results with FEM results.
- Fabrication and testing of a sliding system for uniform force application.
- Evaluation of manual and constant force application system.

Chapter-2

MODELLING AND SIMULATION

2.1 MODELLING

The model used in this project is a hemispherical model. The model needs to be of light weight and small to make high natural frequency of the system. Accelerometer can be placed inside the model by some glue, to measure the acceleration of the model and to provide free-flying condition and flexible support Neoprene rubber can be used. The natural frequencies are set by the model size and the speed of stress waves in the structure of the model. A small model keeps these frequencies high and a light model leads to larger acceleration signals. The model can be fixed on the Bench-vice and impulse force can be applied by impact hammer at different points and angles to get the reaction forces and accelerations of the model.

All of the models are designed in the PTC-Creo, designing software. The 2D and 3D drawings are shown in figures below.

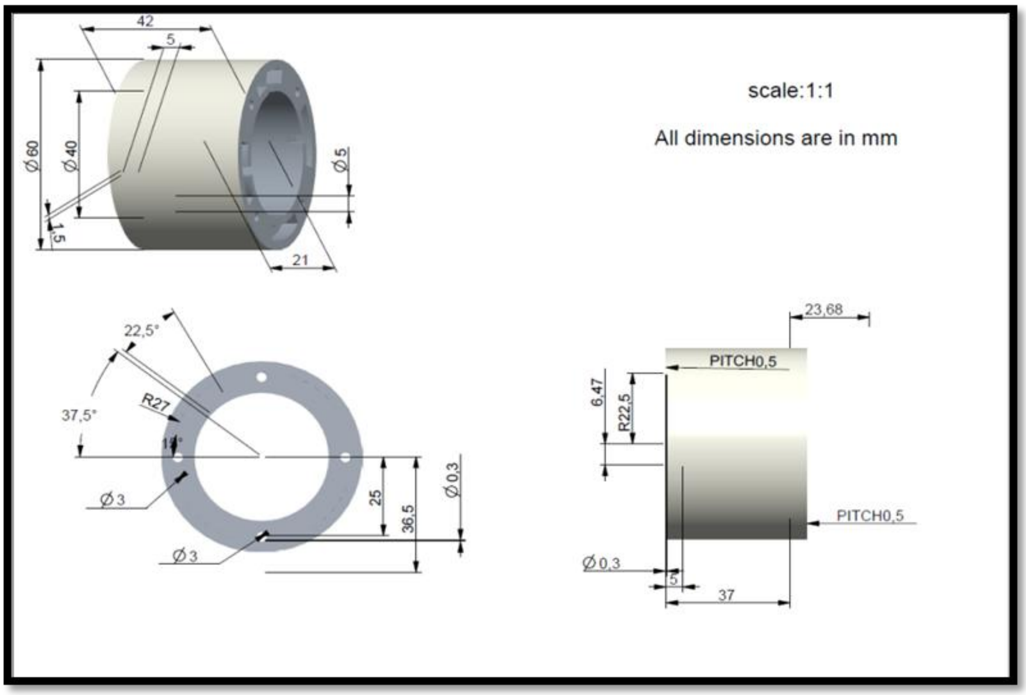


Fig. 2.1 Support structure of design

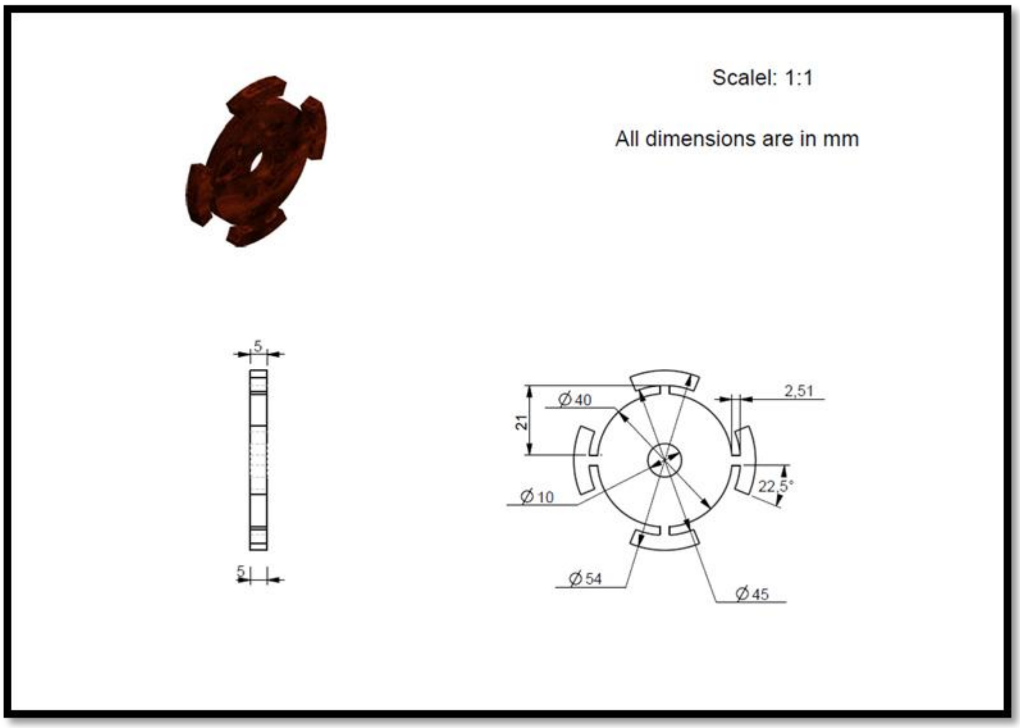


Fig. 2.2 Rubber support of design

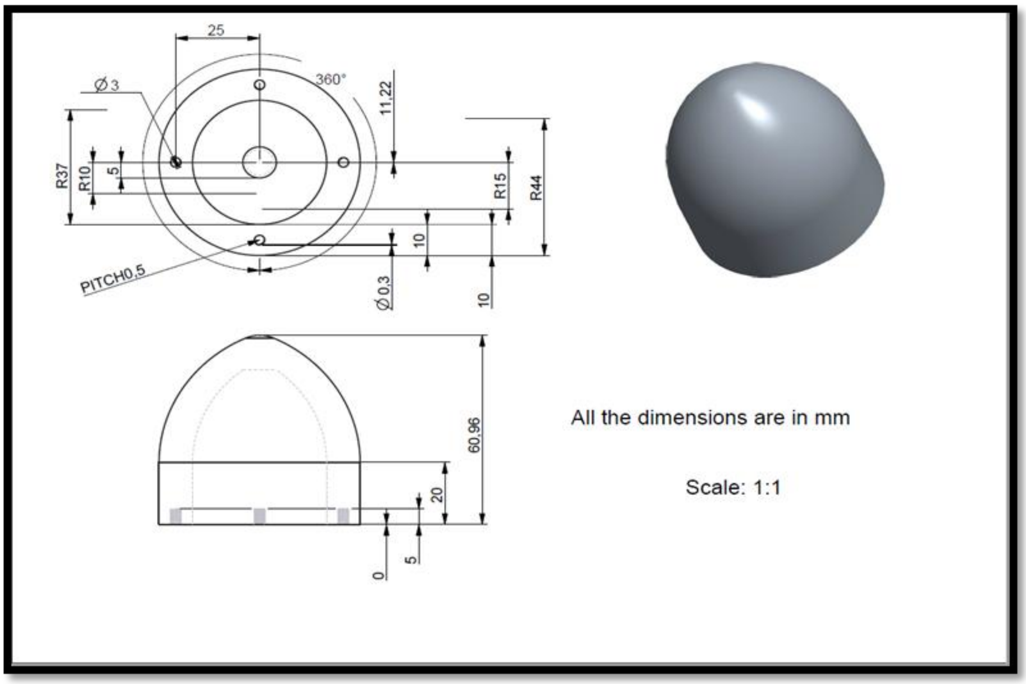


Fig. 2.3 Hemispherical model

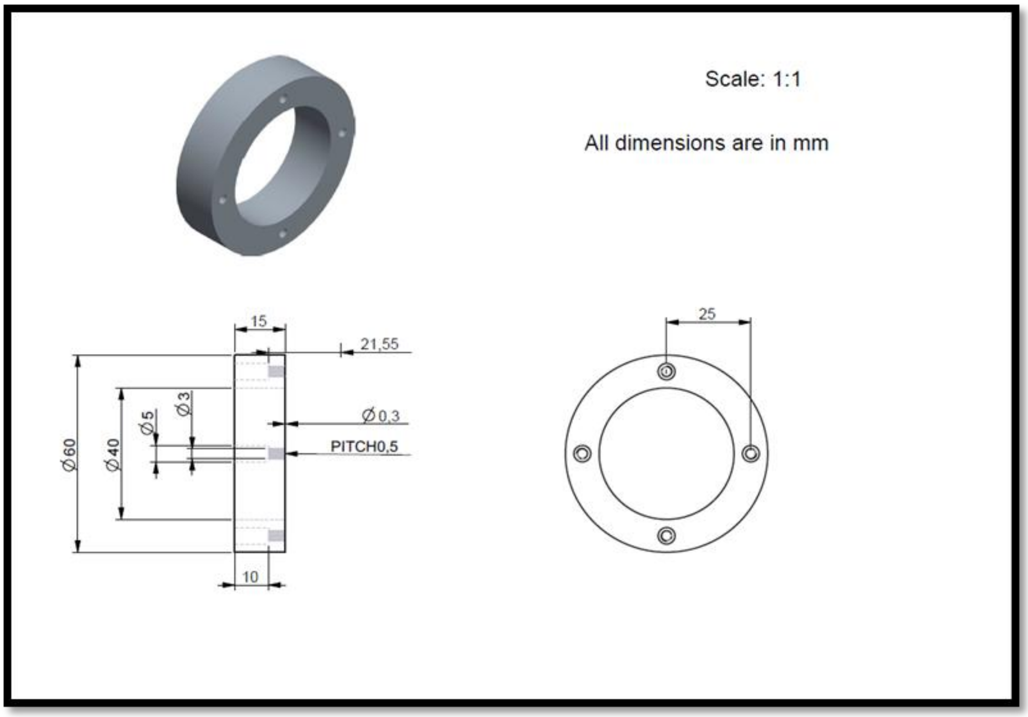


Fig. 2.4 Outer support of design

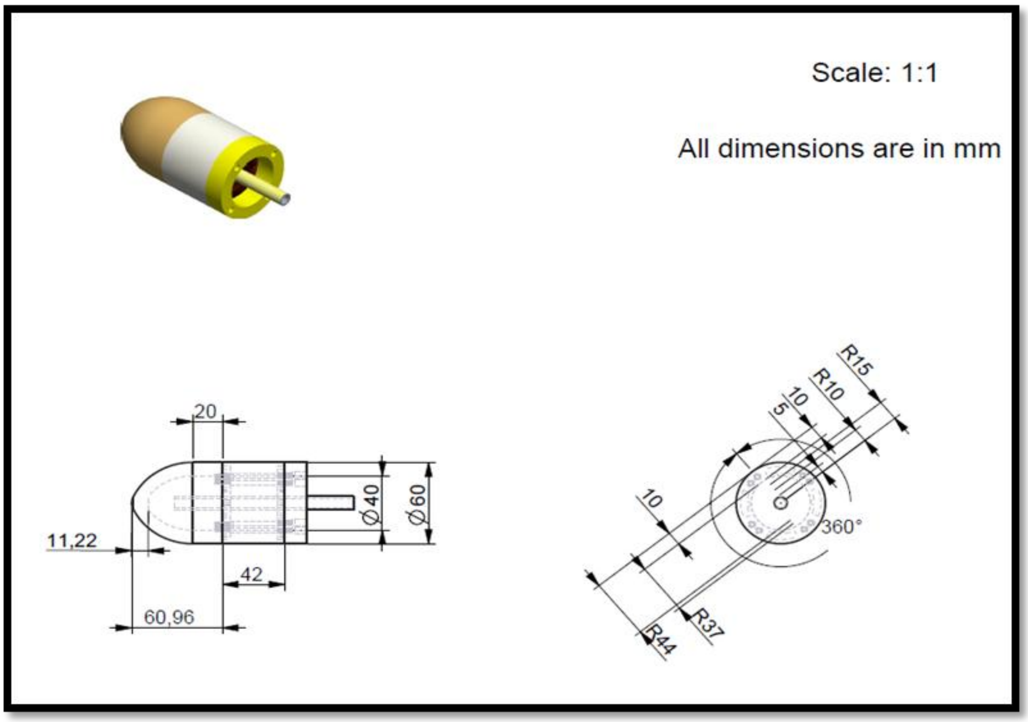


Fig. 2.5 Assembled design

2.2 FINITE ELEMENT ANALYSIS

Finite element (FE) modelling is used in the design process to analyse the dynamic behaviour of different force balance designs. FE modelling can also be used to provide insight into the nature of coupling between balance outputs and the sensitivity of the loading distribution.

Several factors influence the accuracy in computing the dynamic or transient response of a structural using FE modelling. These include; mesh refinement, mesh transition, internal/structural damping, integration time step and the distribution of applied loads. The material properties relating the deformations, stresses and the governing relationships are considered over these elements and are expressed in terms of unknown variables at the element nodes. An assembly procedure, duly considering the element boundary conditions (in terms of displacements or forces) and constraints, result in a matrix equation, which is called the equilibrium equation. Solution of this equation gives us the approximate behaviour of the continuum in a piece-wise continuous sense. Therefore, as the discretization of the domain is made finer with smaller element size, the energy of the system is equilibrated more accurately, and the result converges to the almost exact solution.

In particular, the FE method is useful in dynamic analysis, where exact analytical solutions are extremely difficult to obtain, and simply not tractable for complex problems involving arbitrary geometry and time-dependent boundary conditions. Dynamic analysis involves the analysis of the model subjected to time-varying loads and we can find the different characteristics like acceleration, strain, stress with respect to time at different locations of the model.

2.3 MATERIAL PROPERTIES

The model used in present work is manufactured using aluminium and support structure is manufactured using the neoprene rubber.

Table 2.1 Properties of materials

Material	Young's Modulus (Pa)	Poisson Ratio	Bulk Modulus(Pa)	Density (kg/m^3)	Shear Modulus (Pa)
Aluminium	7.1 e+10	0.33	6.9608 e+10	2770	2.96692 e+10
Neoprene Rubber	3 e+5	0.49	13.59 e+6	960	2.72 e+4

2.4 PROBES POSITION

Different magnitude impulse forces are applied on the models to find out the different characteristics like strain, stress, acceleration of the bodies. In particular, the acceleration is measured at 2 different points for tri-axial accelerometer. One point is at the tip and another point is at the centre of gravity and for 3-uniaxial accelerometers three probes have been used at three different positions.

The positions of accelerometer are shown in fig. 2.6 & fig. 2.7:

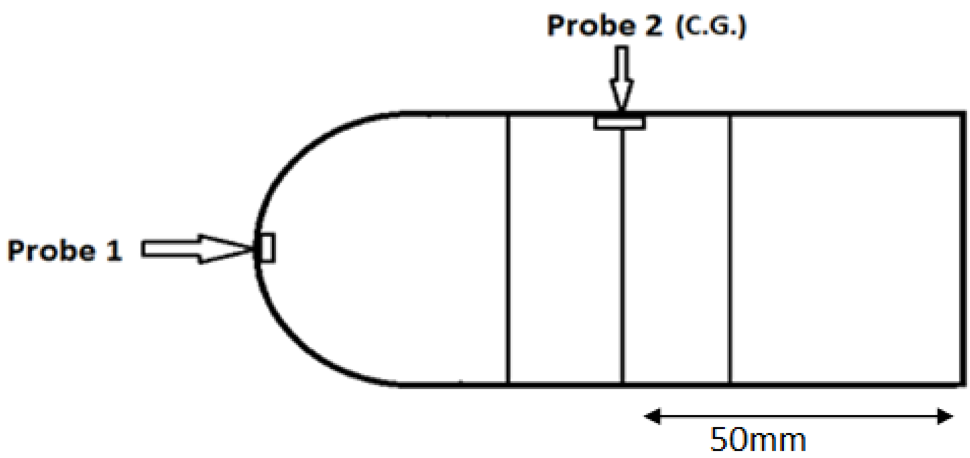


Fig. 2.6 Position of probes for tri-axial accelerometer

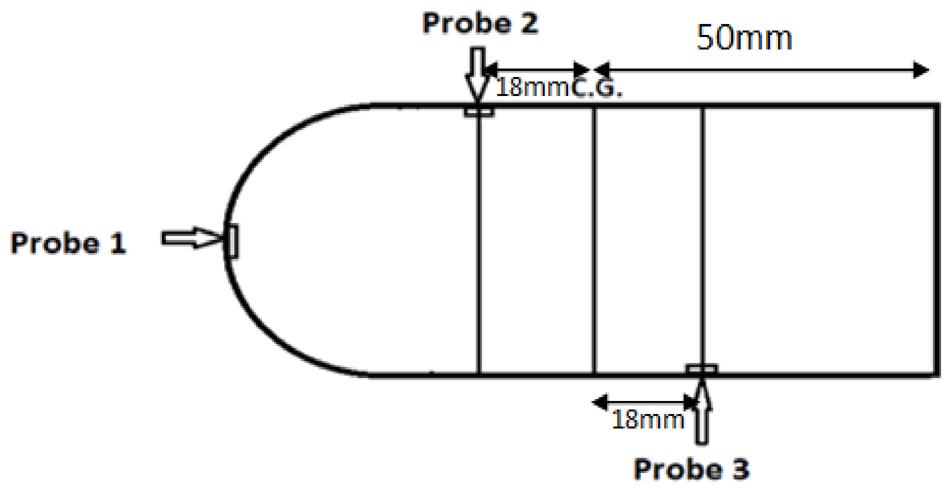


Fig. 2.7 Position of probes for three-uniaxial accelerometer

Chapter-3

EXPERIMENTATION

3.1 INSTRUMENTS USED

3.1.1 Accelerometer

An accelerometer is a device that measures proper acceleration. Proper acceleration, being the acceleration (or rate of change of velocity) of a body in its own instantaneous rest frame, is not the same as coordinate acceleration, being the acceleration in fixed coordinate system.

Here the accelerometer under application of load sense the acceleration and send the output voltage signal to signal conditioner where the amplification of the signal is done according to sensitivity and noise in the signal is discarded

Fig. 3.1 Accelerometer

3.1.2 Signal Conditioner

Signal conditioner is used to do the signal conditioning process. Signal conditioning is the manipulation of a signal in a way that prepares it for the next stage of processing. Many applications involve environmental or structural measurement, such as temperature and vibration, from sensors.

Fig. 3.2 Signal conditioner

3.1.3 Oscilloscope

An oscilloscope is a type of electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional plot of one or more signals as a function of time. Oscilloscopes are used to observe the change of an electrical signal over time, such that voltage and time describe a shape which is continuously graphed against a calibrated scale. The observed waveform can be analysed for such properties as amplitude, frequency, rise time, time interval, distortion and others. Modern digital instruments may calculate and display these properties directly.

Fig. 3.3 Oscilloscope

3.1.4 Bench vice

A Bench vice is a mechanical apparatus used to secure an object to allow work to be performed on it. Bench vice have two parallel jaws, one fixed and the other movable, threaded in and out by a screw and lever.

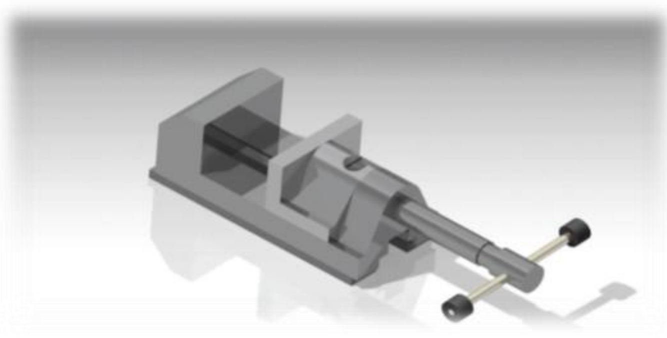


Fig. 3.4 Bench vice

3.1.5 Impact Hammer

Impact hammers are easy to use solutions for delivering impulse forces into test specimens and providing electrical measurement signals of the amplitude and frequency content of the applied force. Response accelerometers then accelerate the resultant motion of the test specimen for such requirements as resonance detection, modal analysis, transfer characteristics, and structural health determination.

Fig. 3.5 Impact Hammer

3.2 SPECIFICATION OF INSTRUMENTS

Table 3.1 Instrument specifications

Name of Instrument	Company Name	Sensitivity
Uniaxial accelerometer	PCB Piezotronics	10.2 mv/(m/s^2)
Triaxial accerelometer	PCB Piezotronics	1.02 mv/(m/s^2)
Impulse hammer	PCB Piezotronics	11.2 mv/(N)

3.3 EXPERIMENTAL PROCEDURE

1. Fabricate the model as per the dimensions.

2. Prepare the neoprene rubber rings as per the required dimensions to be fixed in the model to obtain the free flight condition of the model.

3. Neoprene rubbers are glued to the model.

4. Affix the tri-axial accelerometer with the help of glue and uniaxial accelerometer with the help of screw inside the model.

5. Mount the model on the rubber rings which are supported by central sting. The central sting is fixed in the bench vice and bench vice is fixed on the table with C clamps.

6. Connections are made from accelerometers to the to the signal conditioner input and output of signal conditioner is connected to the oscilloscope for display and collection of data.

7. Connect the impact hammer to the oscilloscope through the signal conditioner.

8. Set the all the values of oscilloscope and signal conditioner as per the requirement.

9. Apply force on the model with the impact hammer and measure the results of force and acceleration in different directions.

10. Save the results of acceleration and force for further processing.

11. Repeat the above process several times to obtain acceleration values for tri-axial and uniaxial accelerometers for 20N, 40N, 60N forces and save the results for further processing of results.

12. Apply the experimental force on the simulation model in ANSYS.

13. Validate the simulation results with the experiment.

14. Perform de-convolution for the prediction of the unknown force.

Chapter-4

RESULTS AND DISCUSSION

4.1 OBSERVATIONS OF THE FINITE ELEMENT ANALYSIS

4.1.1 TRI-AXIAL ACCELEROMETER AT TIP

Force at tip (In x-direction):

Experimental and Finite element analysis for three different forces have been conducted on hemispherical model with tri-axial accelerometer placed at tip of the hemispherical model and impulse forces are applied at tip in x-direction as shown in the fig. 4.1 and x, y and z accelerations have measured experimentally as well as by FEA and also comparison has done between these two results as shown in the fig. 4.2, fig. 4.3 and fig. 4.4.

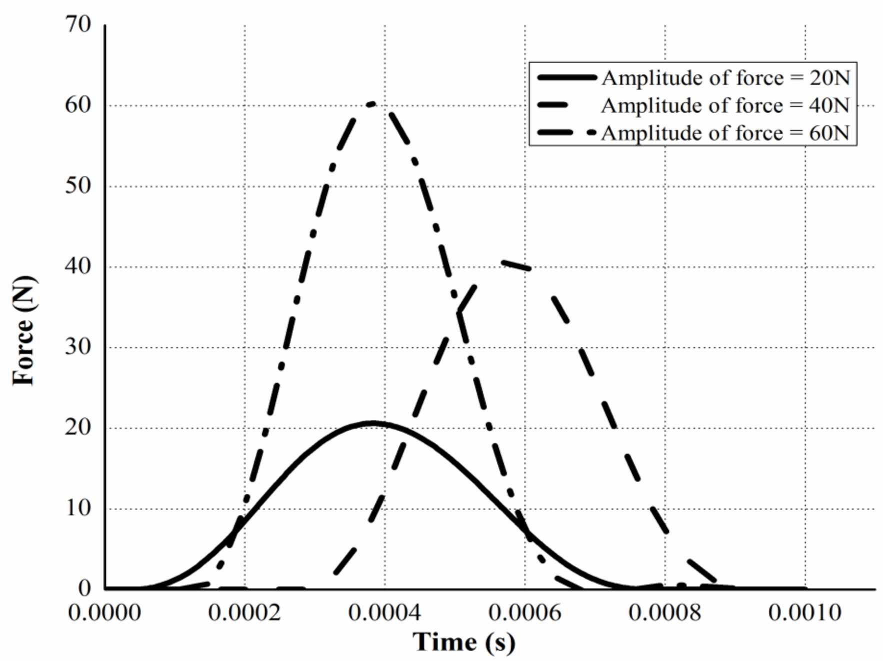


Fig. 4.1 Force at tip vs time for tri-axial accelerometer

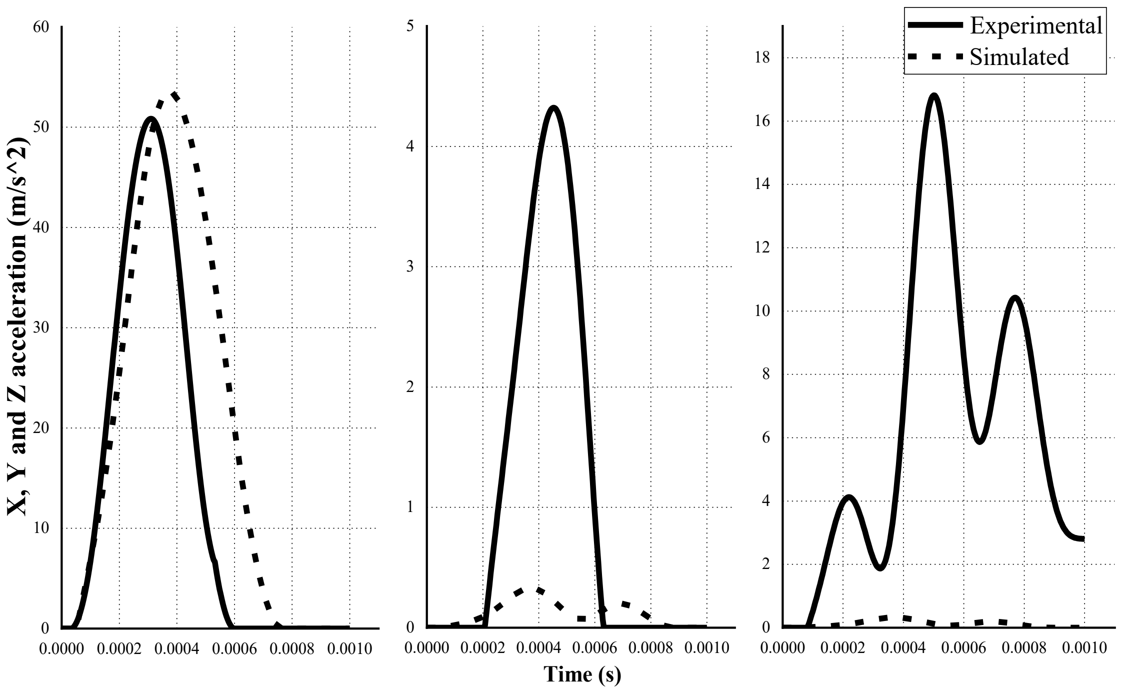


Fig. 4.2 Accelerations vs time graph for 20N Force

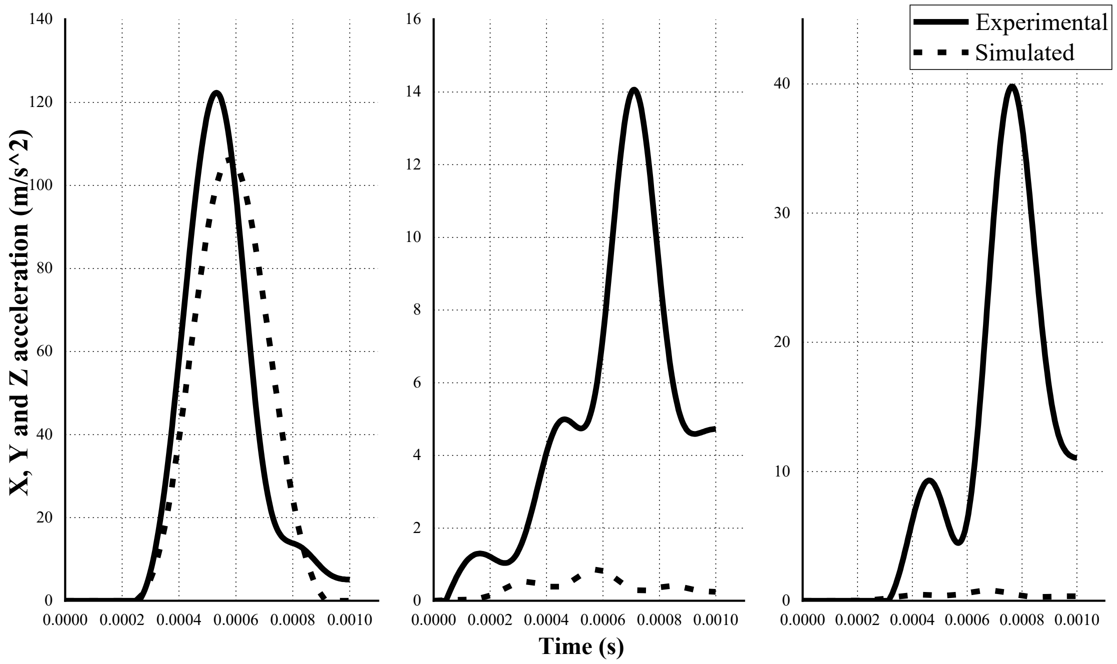


Fig. 4.3 Accelerations vs time graph for 40N Force

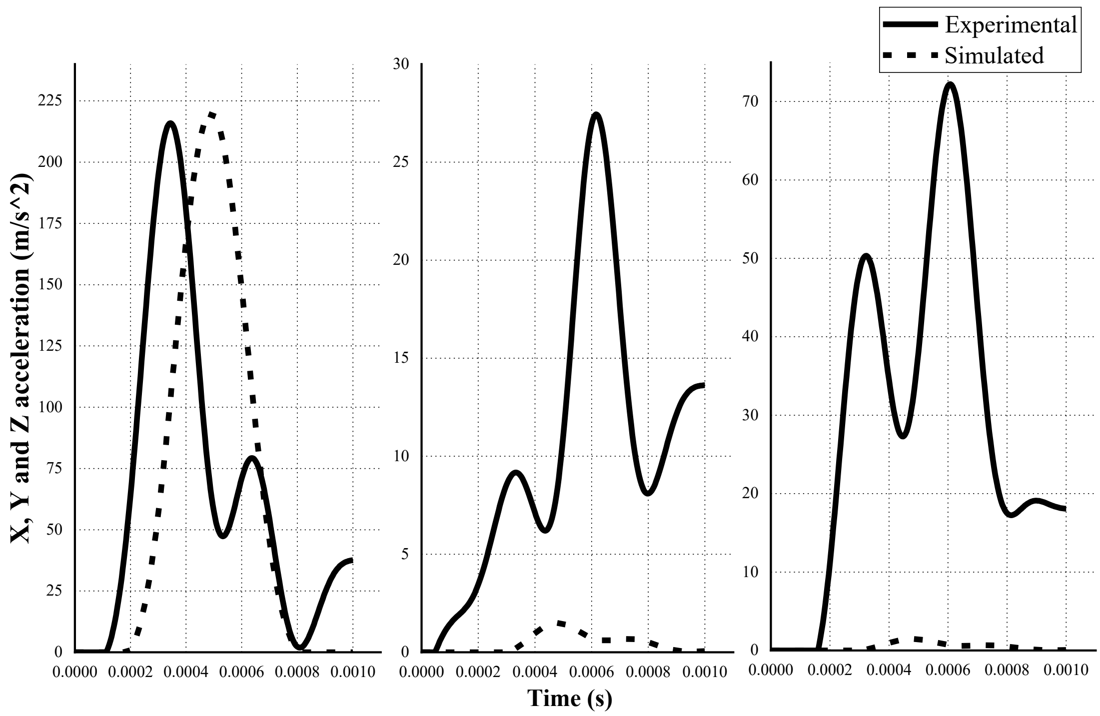


Fig. 4.4 Accelerations vs time graph for 60N Force

During the experiment impulse forces have applied by impact hammer and with the help of signal conditionar and ocsillascope corresponding accelerations are recorded. From the experimental results it has found that, in the direction of force, i.e. in x-direction, accelerations are more for all the applied forces compared to other two directions (y and z-directions) and it also has found that accelerations are not in sinosuidal form. But from the simulation accelerations in x-direction have found in a sinusoidal form and the magnitude are also in the acceptable range, but the accelerations in other two directions are almost zero which is correct because the forces have applied in only x-direction.

The experimental accelerations in other two directions (x and y) are having some values due the error in the alignment of model with x-axis and also due the improper cutting of neoprene rubber which provides the free-flying condition to the model.

The principal accelerations (in x-direction) in both the cases (experimental and simulation) are of almost same magnitude which says that experimental results are almost similar to the simulated results in x-direction and in other two directions they are not same beacause of the some errors with the experimental model.

4.1.2 TRI-AXIAL ACCELEROMETER AT CENTER OF GRAVITY (CG) OF MODEL

Force at CG (In z-direction):

In this case tri-axial accelerometer has placed at centre of gravity of the model and the forces also have applied at the centre of gravity, i.e. in the z-direction and due to these forces x, y and z accelerations have found experimentally as well as with the help finite element analysis and comparison has done between these two results as shown in the fig. 4.5, fig. 4.6, fig. 4.7 and fig. 4.8.

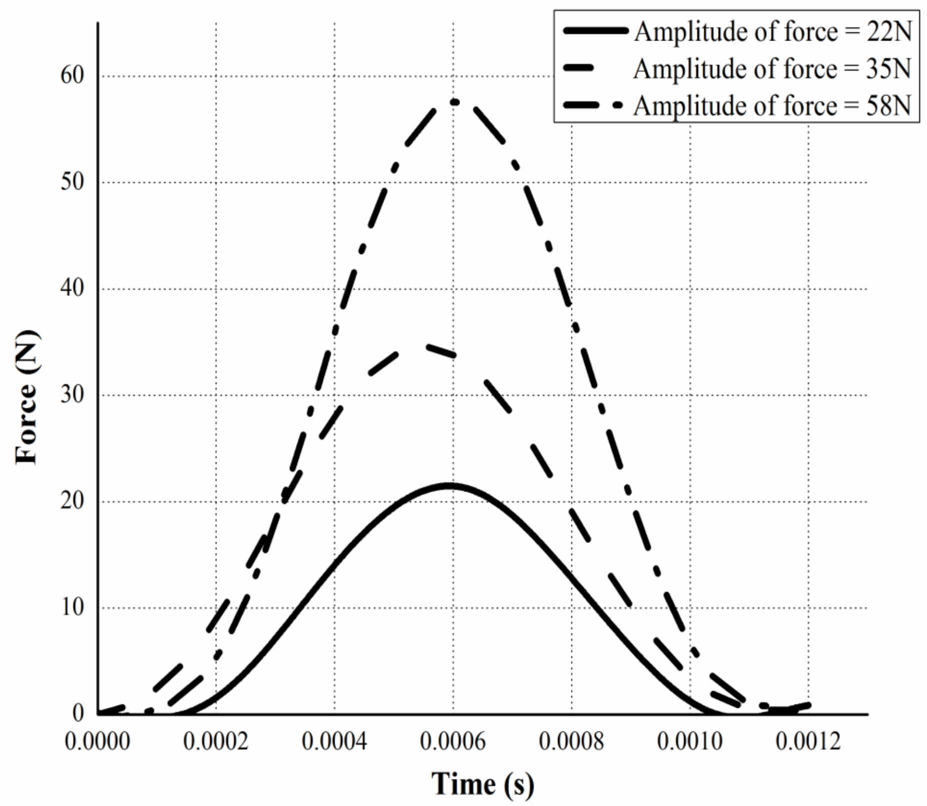


Fig. 4.5 Force at cg vs time for triaxial accelerometer at cg

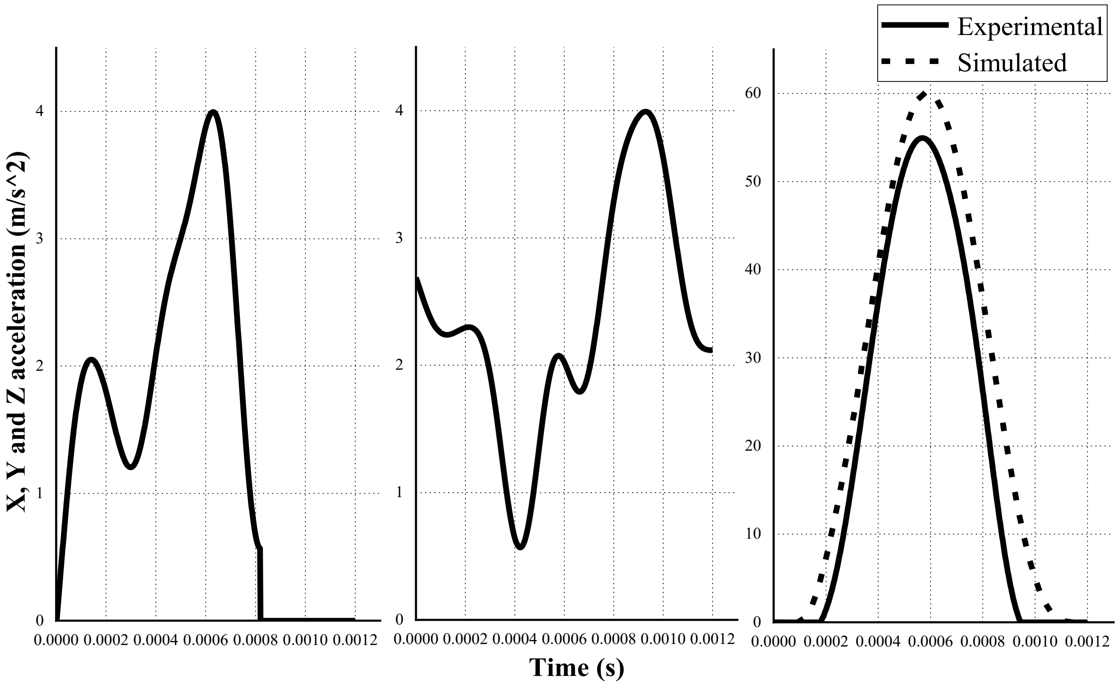


Fig. 4.6 Accelerations vs time graph for 22N Force

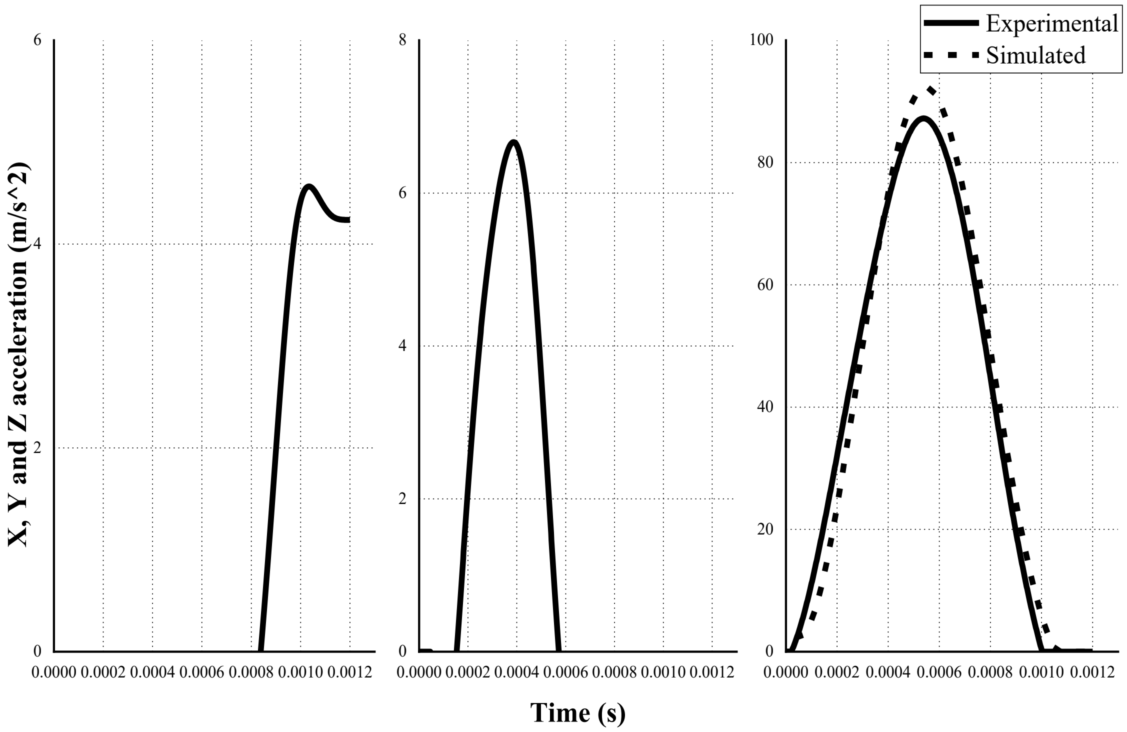


Fig. 4.7 Accelerations vs time graph for 35N Force

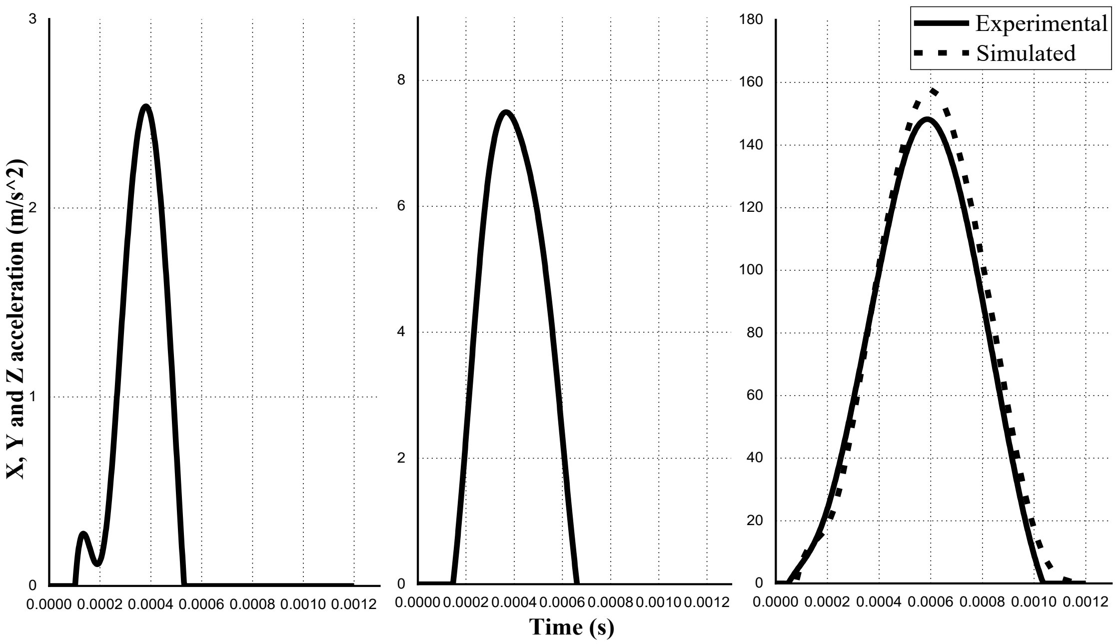


Fig. 4.8 Accelerations vs time graph for 58N Force

Experimentally, it has found that maximum accelerations for all the forces have found in z-direction and acceleration in other two directions are very small which are coming due misalignment of model and improper free-flying condition. But from the simulated results it has found that smooth and sinusoidal results come in the z-direction and in other two directions accelerations are zero.

From the above figures, it can be said that experimental and simulated accelerations for all the forces are of same magnitude and nature in the z-direction and in other two directions they are not same beacause of the some errors with the experimental model.

4.1.3 UNIFORM FORCE MECHANISM FOR TRI-AXIAL ACCELEROMETER

Force at tip (In X direction):

The forces have been applied with the help of proper sliding mechanism to remove human errors and to get uniform force profile and accelerations. In this tri-axial accelerometer has places at the tip of the model and forces have also applied at the tip in the x-direction and with the help of these forces accelerations have been calculated experimentally and by finite element analysis as well and comparison has been done.

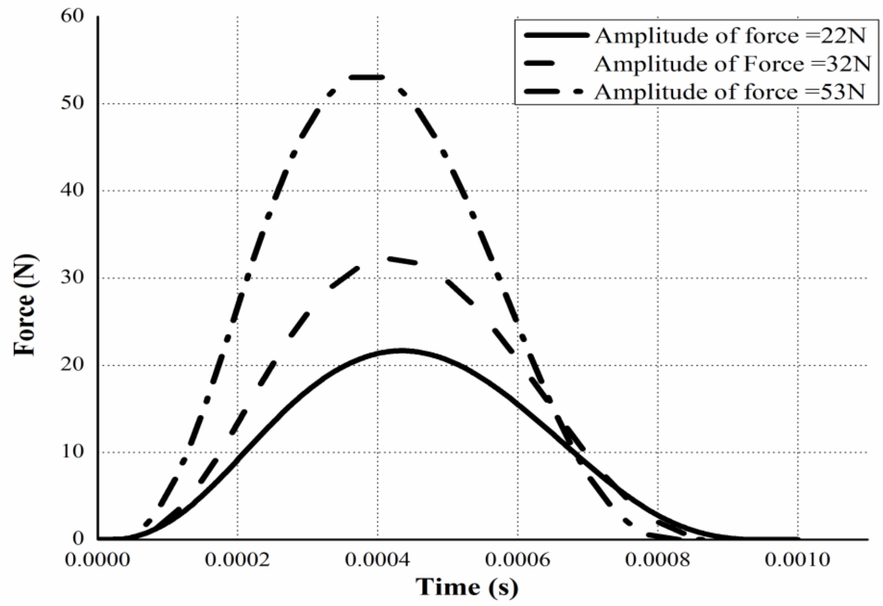


Fig. 4.9 Force at tip vs time for triaxial accelerometer at tip

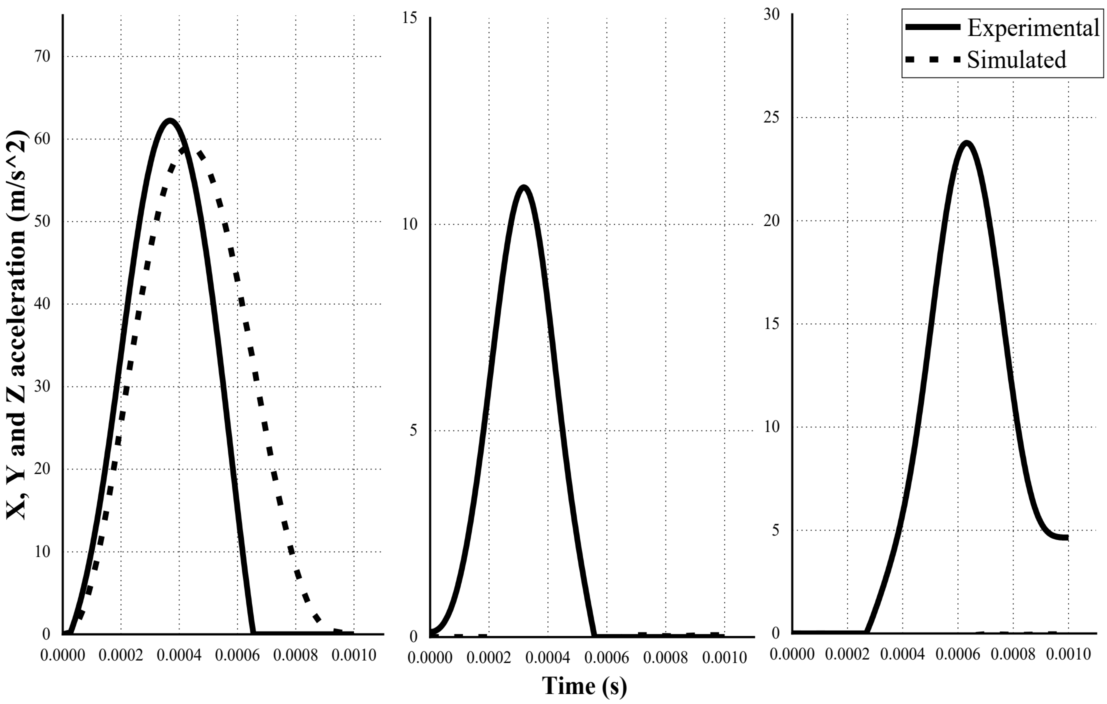


Fig. 4.10 Accelerations vs time graph for 22N Force

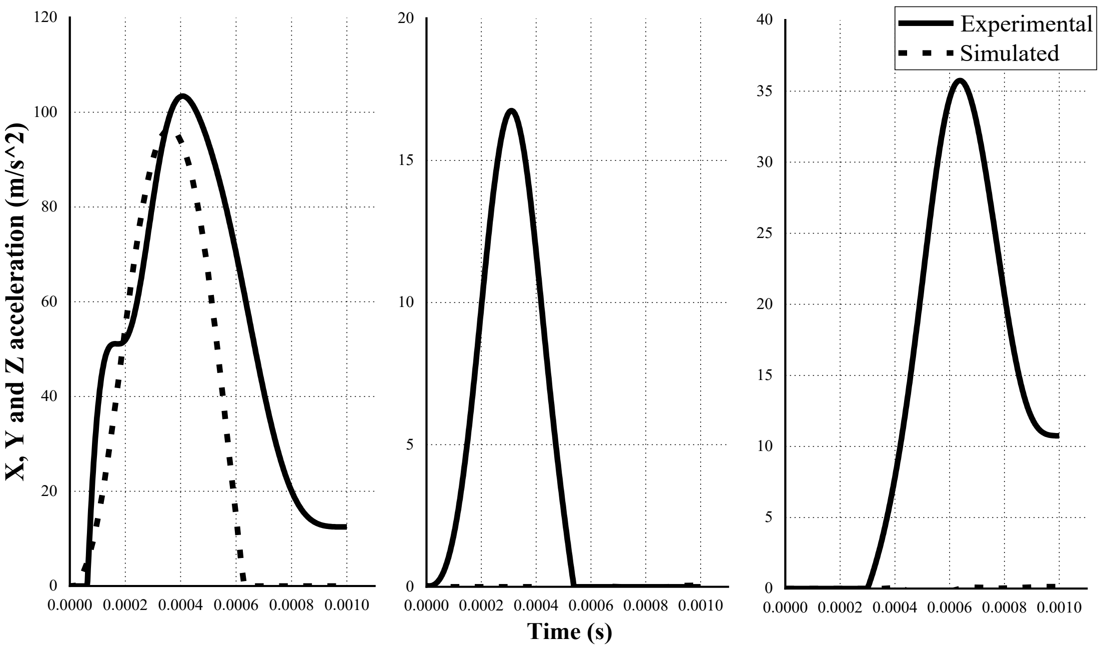


Fig. 4.11 Accelerations vs time graph for 32N Force

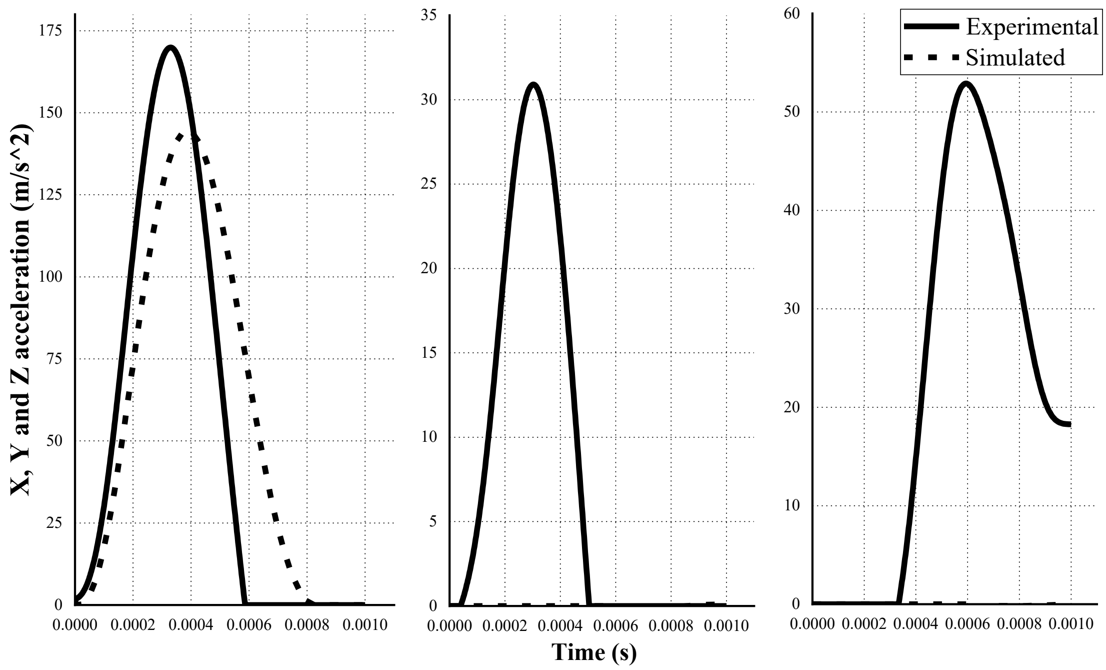


Fig. 4.12 Accelerations vs time graph for 53N Force

From the above figures and observation it has been found that forces with this technique are very accurate and also in same time interval, it also has found, accelerations in force direction is more compared to other directions in experimental data but in case simulated data accelerations are zero. The principal accelerations in both the cases (experimental and simulation) are of almost same magnitude which says that experimental results are almost similar to the simulated results in x-direction and in other two directional they are not same beacause of the some errors with the experimental model.

4.1.4 SINGLE UNIAXIAL AT TIP

Force at tip (In x direction):

In this case a single uniaxial accelerometer has fitted at tip of the model and forces have applied at tip in x-direction and due to these force accelerations have found. The force data is shown in fig. 4.13

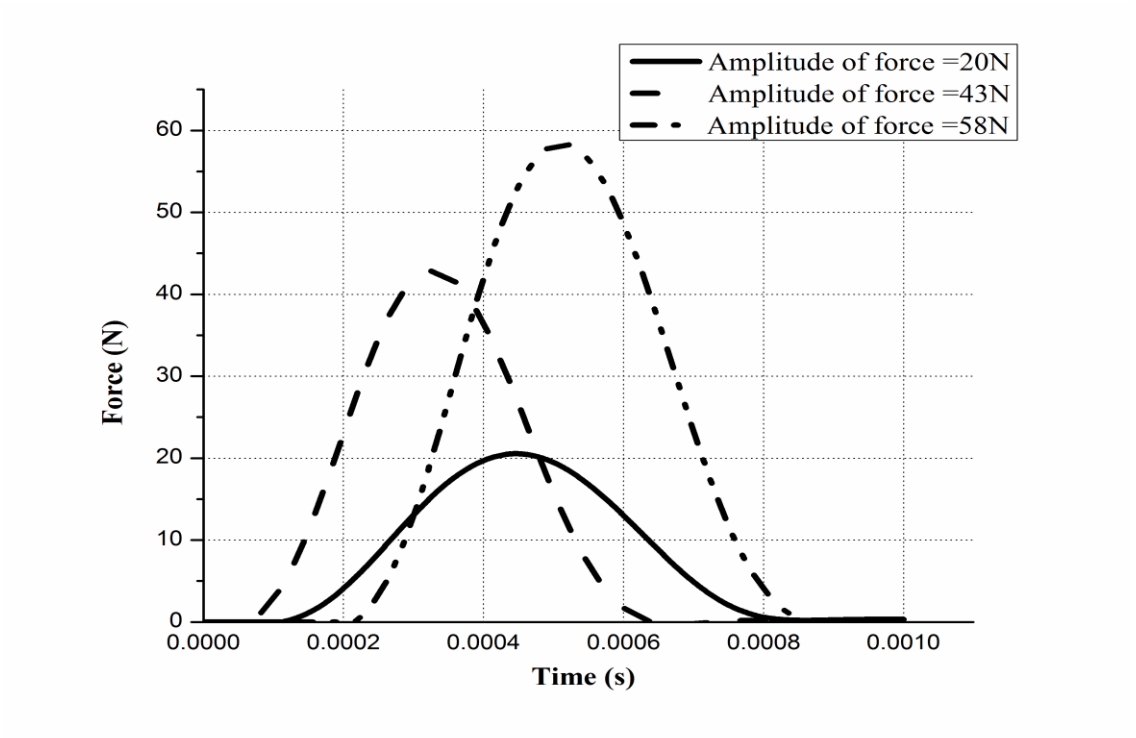


Fig. 4.13 Force at tip vs time for single uniaxial accelerometer

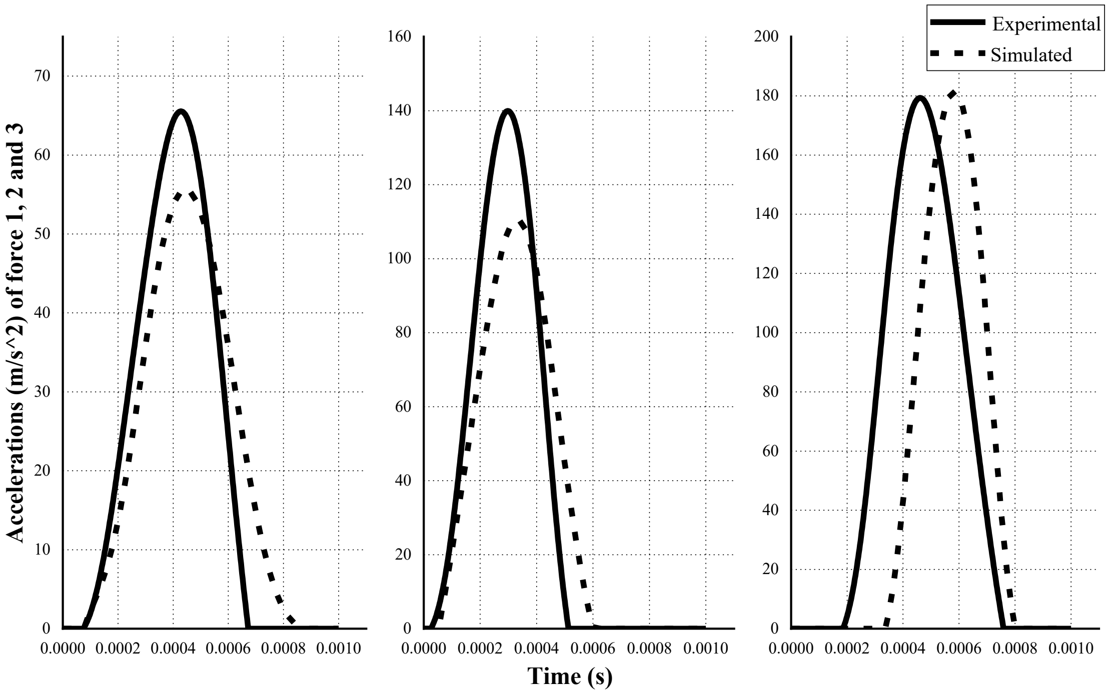


Fig. 4.14 Accelerations vs time for single uniaxial accelerometer

From the above figures it has seen that the accelerations in both the cases are of same nature and magnitudes for all the applied forces. Uniaxial accelerometer gives the acceleration in single direction in which the force or disturbance is given therefore it has given the acceleration in a single direction.

There is some deflection between the experimental and simulated results, it is because of error in free-flying condition and also due to some error in manually force application.

4.1.5 THREE UNIAXIAL ACCELEROMETER

Force at tip (In X direction):

In case of three uniaxial accelerometer, one is fitted at the tip of the model which gives x-acceleration and other two are fitted on y-axis opposite to each other with some eccentricity and the forces have applied at tip in x-direction. The force data is shown in fig. 5.15.

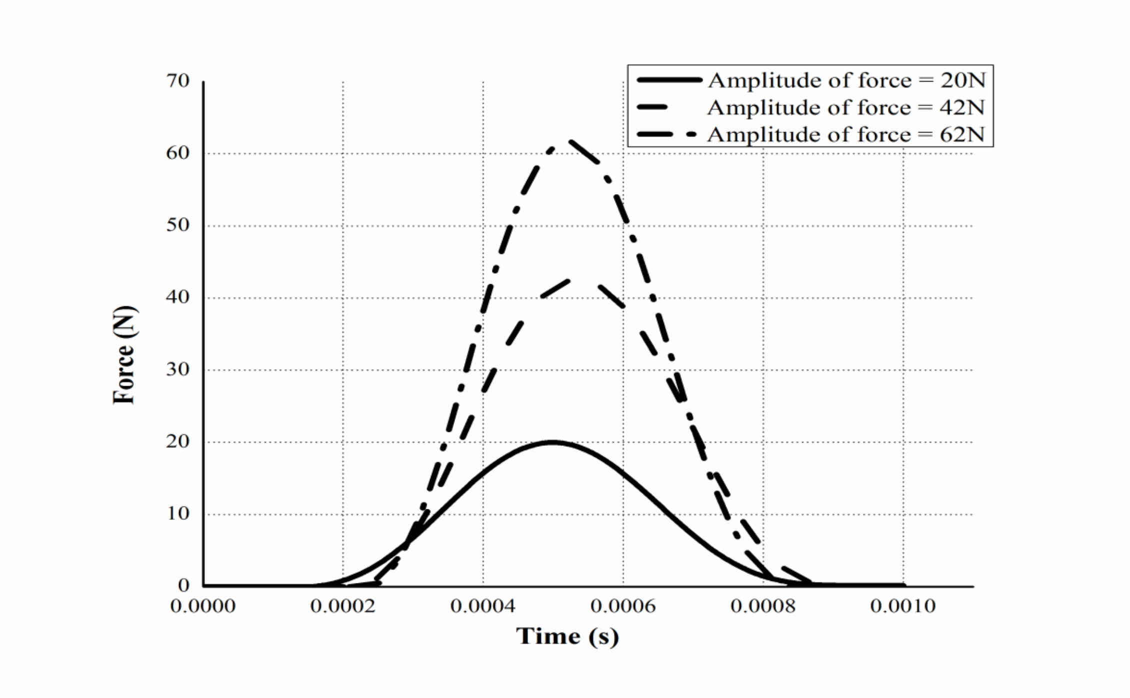


Fig. 4.15 Force at tip vs time for three-uniaxial accelerometer

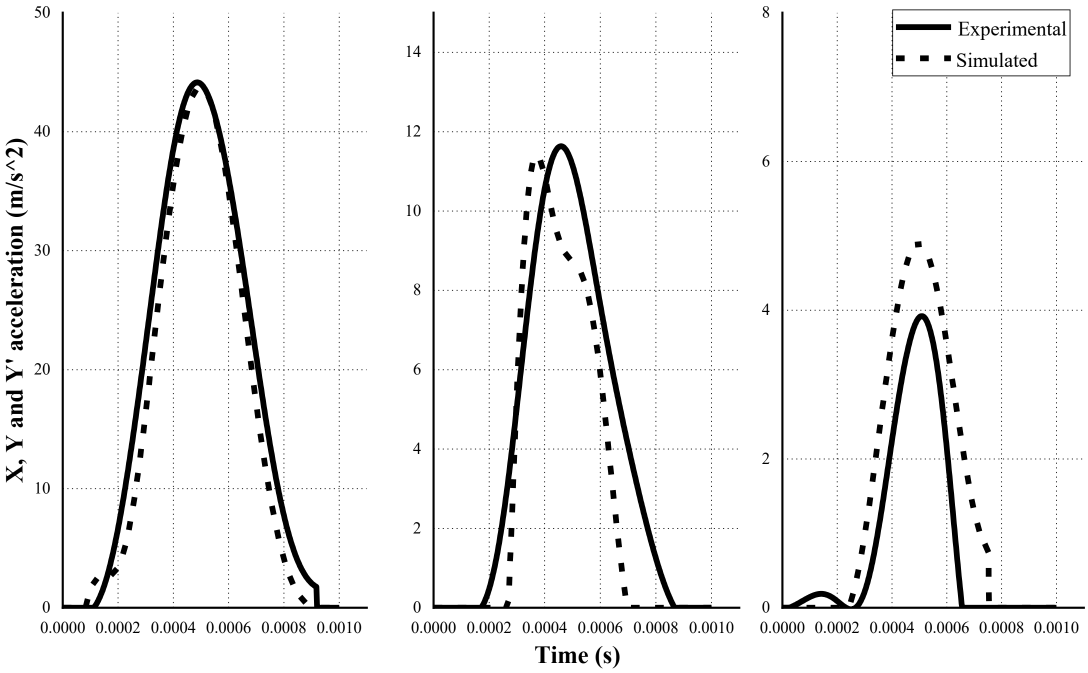


Fig. 4.16 Accelerations vs time graph for 20N Force

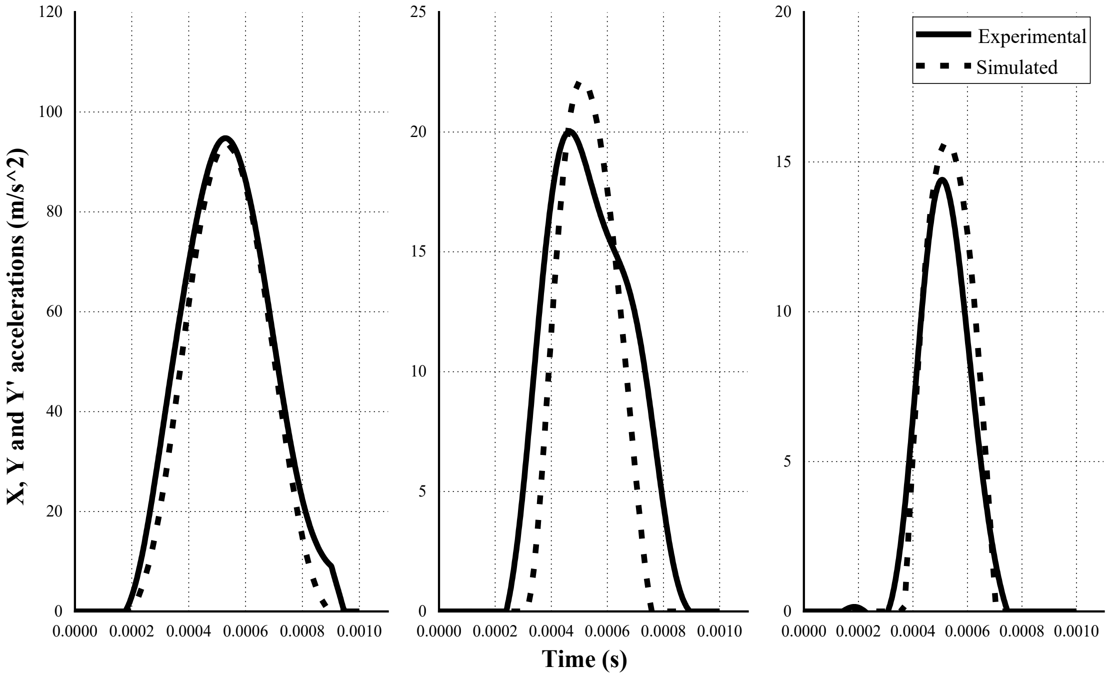


Fig. 4.17 Acceleration vs time graph for 42N Force

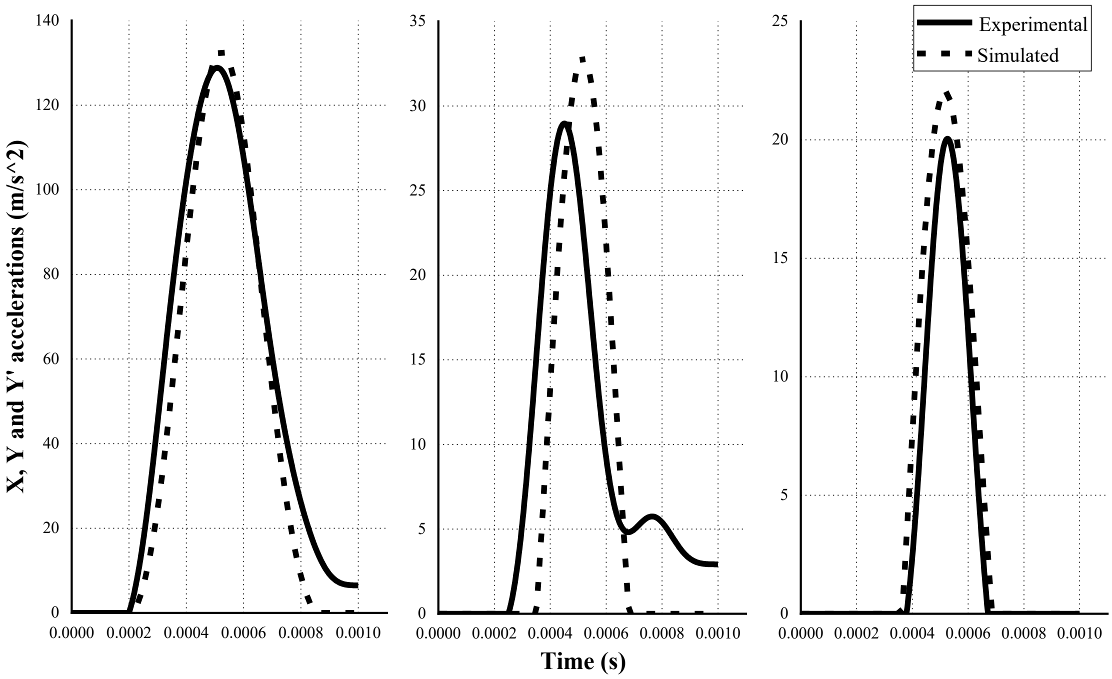


Fig. 4.18 Acceleration vs time graph for 62N Force

Analysis has done on three different forces as shown in fig. 4.15; it has seen that accelerations are more in direction of applied forces experimentally as well as simulative and in other direction its magnitude is small as shown in fig. 4.16, fig. 4.17 and fig. 4.18. It also has observed that simulated results are more precise and smooth compare to the experimental results but the magnitude of the acceleration in both the cases are almost equal.

4.1.6 DE-CONVOLUTION TECHNIQUE

De-convolution is an algorithm based process which is used to reverse the recorded data. In this technique with the help of experimental accelerations data, force data has found.

Force at tip for 3-uniaxial accelerometer:

In case of three uniaxial accelerometer two forces are de-convoluted with help of algorithm and experimental accelerations and it has observed that the de-convoluted forces are of same nature and magnitudes.

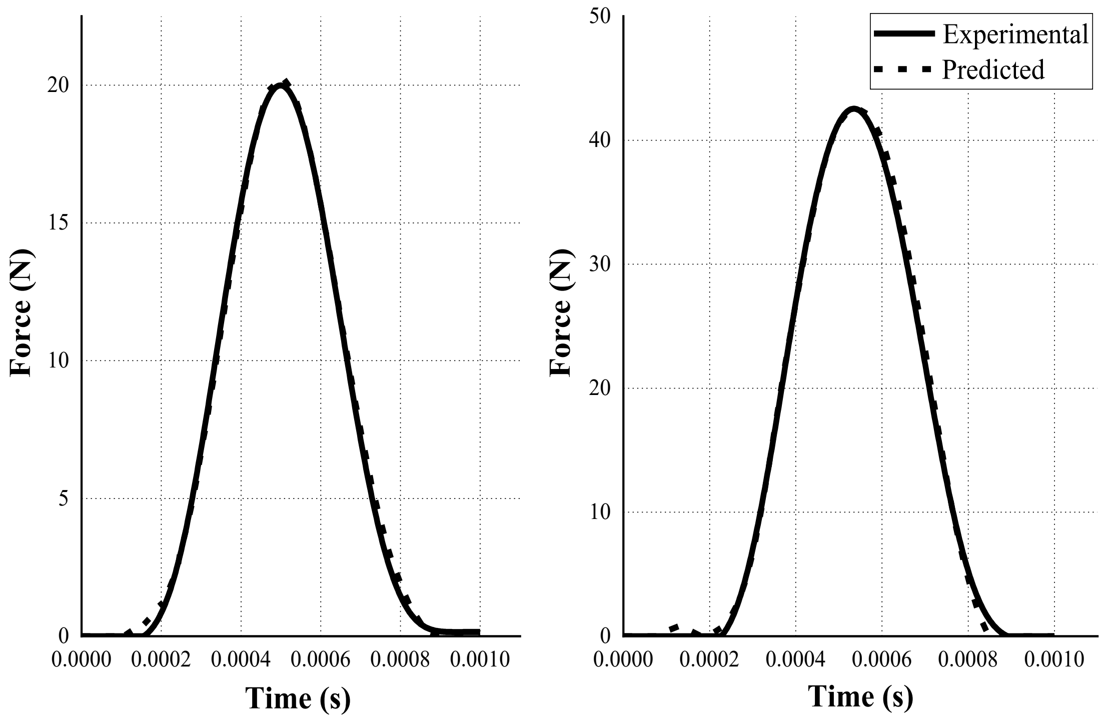


Fig. 4.19 Force vs time for 3-uniaxial accelerometer

Force at tip and triaxial accelerometer also at tip:

In case of tri-axial accelerometer also two forces are de-convoluted with help of algorithm and experimental accelerations and it has observed that the de-convoluted forces are of same nature and magnitude but in case of three uniaxial accelerometer it has seen that the predicted forces are more precise and accurate because the sensitivity of the uniaxial accelerometer is high compare to tri-axial accelerometer.

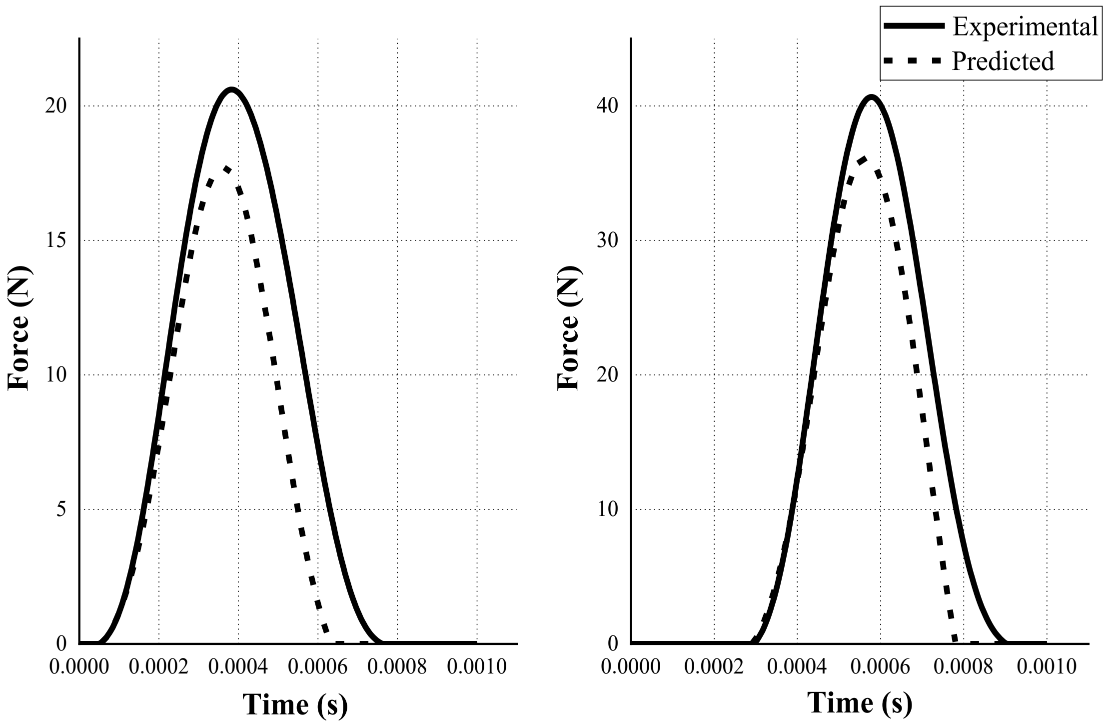


Fig. 4.20 Force vs time for tri-axial accelerometer

In the above figures two de-convoluted forces for tri-axial as well as three uniaxial have found with the help of experimental data.

It has also observed that the predicted forces are more accurate in the x-direction compared to other direction it is also because the applied force direction in experiment is x and therefore acceleration is also more accurate in this direction.

4.2 FINITE ELEMENT ANALYSIS OF FREE SLIDING MECHANISM FOR UNIFORM FORCE

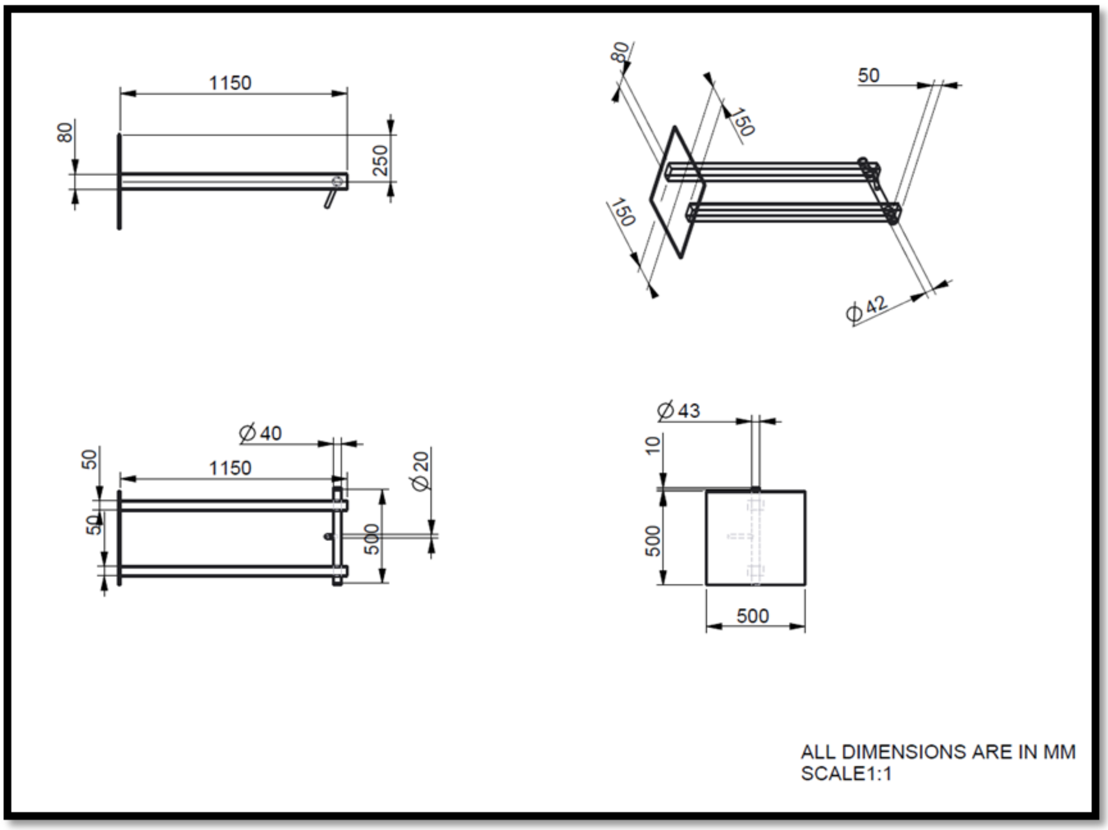


Fig. 4.21 Model of free sliding mechanism for uniform force applications

Table 4.1 Model characteristics

S.no	Dimensions	mm
1	Base Plate	500*500
2	Frame Height	1150
3	Rod Hole Diameter	22
4	Frame Length	50
5	Frame Breadth	40
6	Horizontal Rod Diameter	20
7	Vertical Rod Diameter	10
8	Vertical Rod Length	150

Case 1 (Material used Grey Cast Iron & Stainless Steel) *Force 10N*

Maximum value of Transverse Deformation 0.050696mm

Minimum value of Transverse Deformation 0.0mm

S.no	Horizontal Rod(mm)	Vertical Rod(mm)
1	1.24E-02	1.34E-02
2	1.37E-02	2.10E-02
3	1.28E-02	4.52E-02

Maximum value of Transverse Deformation 0.15209mm

Minimum value of Transverse Deformation 0.0mm

S.no	Horizontal Rod(mm)	Vertical Rod(mm)
1	3.70E-02	3.98E-02
2	3.86E-02	6.36E-02
3	3.82E-02	1.46E-01

Maximum value of Transverse Deformation 0.25348mm

Minimum value of Transverse Deformation 0.0mm

S.no	Horizontal Rod(mm)	Vertical Rod(mm)
1	6.26E-02	6.67E-02
2	6.44E-02	8.90E-02
3	6.37E-02	2.14E-01

4.3 COMPARISON OF FINITE ELEMENT ANALYSIS RESULTS OF

MODEL

Three models with different dimensions are made, aluminium alloy and grey cast iron and combination of cast iron & stainless steel are used for FEM analysis and FEM analysis was performed on three models to find the deformation and found the results as tabulated above for different forces i.e. 10N, 30N, 50N.
Looking at the above results found that model 1 with combination of stainless steel and cast iron the deformation results are less compared to other simulation results.

The deformation results of model 1 with combination of stainless steel and cast iron are as follows:

The maximum deformation for 10N is 0.050696 mm

The maximum deformation for 30N is 0.15209 mm

The maximum deformation for 50N is 0.25348 mm

Minimum deformation is 0 mm

4.4 FABRICATION PROCESS OF MODEL

1. As per the dimensions of model 1 cut a base plate with the help of plasma cutting.

2. Cut two frame rods of 1150 mm are and drill 25mm for both the rods with the help of drilling machine.

3. Do welding to join both the base plate and the frame rods.

4. Cut two stainless steel rods as per the dimensions and do turning and facing operation on lathe machine to get the required dimensions.

5. Do threading to stainless steel rods to join them together.

6. Use two bearing on both sides of horizontal rod to get free motion of the impact hammer.

7. Insert the stainless steel rods with bearings into the frame rods to obtain the complete model.

Chapter-5

CONCLUSIONS AND FUTURE SCOPE

5.1 CONCLUSIONS

- The experiments have been performed on a hemispherical model using multi component accelerometer balance.
- The experimental results have been consistent and encouraging with respect to the simulation.
- The balance can be used on complex aerodynamic models for measurement of forces and moments in ground-based hypersonic test facilities.
- It has been observed that the results obtained using uni-axial accelerometer is better than the tri-axial accelerometer since the sensitivity of uniaxial accelerometer is higher than tri-axial accelerometer.
- The free sliding constant force mechanism has also been designed, fabricated and tested for getting better impact force during the experiment.

5.2 FUTURE SCOPE

Means for integrating the various calibration methods and appropriate sets of parameters for describing the dynamic characteristics of general transducers will be strongly required.

These methods are in the initial stage of the development. The calibration of three component accelerometer balance based force measurement can be extended to six component force balance.

The stress wave force balance can be demonstrated for the three component forces.

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