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A Balance for Measurement of Yaw, Lift and Drag on a Model in a Hypersonic Shock Tunnel

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Abstract— **This paper describes the design of an accelerometer balance for the measurement of Yawing moment, Lift and Drag on a lifting model with typical control surfaces, in a hypersonic impulse facility. The model used in the present study is a blunt-nosed triangular plate attached with flaps. The experiments were carried out at a freestream Mach number of 8 in a hypersonic shock tunnel, with air as the test gas, where the test time was about 1.2 milliseconds. The experiments were repeated at different angles of incidence of the model and the coefficients of Yawing moment (C_Y), Lift (C_L) and Drag (C_D) were deduced based on the acceleration signals obtained from the balance. Measured values of the moment and force coefficients were compared with the theoretical results predicted using the Newtonian theory.**

Index Terms— **Accelerometer balance, Force measurement, Shock tunnel, Yawing moment**

I. INTRODUCTION

ACCURATE information on the aerodynamic forces and moments of a lifting hypersonic vehicle is essential in order to predict its aerodynamic behavior and stability in a flight. The forces and moments on a scaled down model of a hypersonic vehicle can be measured in ground based hypersonic test facilities using force balances, such as stress wave [1] and accelerometer balances [2]. An accelerometer balance is a simple, yet an accurate device, requiring a one-time calibration, thereby reducing the complexity of the measurement process.

Accelerometer balances were so far used for measuring forces and pitching moments in hypersonic test facilities on axisymmetric bodies of revolution. When the shape and the application of the geometry are changed, the balance design and its orientation also undergo a change and so is the entire measurement technique.

In this paper, we are presenting an accelerometer balance designed to measure yawing moment, lift and drag on a blunt-nosed triangular plate model, attached with flaps. The model used is that of a typical hypersonic lifting body that can find applications in hypersonic cruise/transport and re-usable launch missions.

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II. MATERIALS AND METHODS

The experiments were carried out in IIT Bombay–Shock Tunnel (IITB–ST) [3], at a hypersonic freestream Mach number of 8. The tunnel is operated by exploding a metallic diaphragm in a shock tube of inner diameter 51.5 mm. Air was used as the test gas and the nitrogen was used as the driver gas in the shock tube. The shocked test gas was expanded through a converging-diverging conical nozzle attached between the shock-tube end and the tunnel test section. The shock strength, the total pressure of the flow and the freestream at the exit of the nozzle in the tunnel test section were monitored by high-frequency pressure transducers, located at the end of the shock tube and at the nozzle exit. The schematic of the IITB–ST is presented in Fig. 1. The test conditions in the tunnel are given in Table I. The test time in the tunnel was about a millisecond.

The test model is a blunt, triangular plate with two rectangular flaps at its trailing end. Figure 2 describes the test model–balance assembly. The model was fabricated out of aluminum. The force balance consists of a structure made of stainless steel, which has an arrangement to hold 4 cubical rubber bushes. These rubber bushes in the balance offer the model a soft suspension that makes it unrestrained (free-floating) during the test in the tunnel. The soft suspension system has a combined stiffness of 10528 N/m in axial direction, 5128 N/m in normal direction and 10528 N/m in yawing direction. These values of stiffness were obtained by subjecting the suspension to deformation in appropriate directions on a Universal Testing Machine (UTM).

The accelerometers in the balance were appropriately oriented to sense the acceleration of the model in the desired directions. Accelerometer 4 was located along the axis of the model, with the model and the accelerometer axes coinciding with each other, to sense the acceleration corresponding to drag. Accelerometer 3 was located vertically, at the Center of Gravity (C.G.) of the model, to sense the model acceleration corresponding to lift. Accelerometers 1 and 2 were positioned horizontally, on either side of the model C.G., with the centers of the accelerometers falling on the line passing through the model C.G. laterally. The arrangement of the accelerometers is shown in Fig. 2. The difference of the magnitudes of accelerations sensed by the accelerometers 1 & 2, positioned in this way, would read the pure yawing moment on the model. The model was tested for aerodynamic forces and moments at various angles of attack such as 0, 5, 10 and 15 deg. The accelerometers used in the balance were miniature in size, uniaxial in sensing and were of PCB Piezotronics

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(USA) make. The specifications of the accelerometers are given in Table II.

The model was suspended on a soft suspension system, but the bushes had a finite stiffness, which could restrain the model during the test. But, it can be shown [4] that for a test time of about 1 millisecond, the restraint offered by the rubber bushes is negligible and consequently the model can be assumed to be in a state of free-flight during the tunnel run. With this assumption it can be shown that the yawing moment (Y(t)), normal force (N(t)) and axial force (C(t)) on the model can be deduced from the following expressions:

$$Y(t) = J \cdot \left[\frac{\xi_1 - \xi_2}{a' + b'} \right] \quad (1),$$

$$N(t) = m \cdot \xi_3 \quad (2),$$

$$C(t) = m \cdot \xi_4 \quad (3),$$

where ξ_1, ξ_2, ξ_3 and ξ_4 are the outputs of the accelerometers 1, 2, 3 and 4, respectively; a′ and b′ are the distances of locations of the accelerometers 1 and 2, respectively, from the center of gravity (C.G.) of the model; m is the mass (0.5112 kg) and J is the mass moment of inertia (1.2876×10^{-3} kg.m^2) of the model. The coefficients of yawing moment (C_Y), lift (C_L) and drag (C_D) for the model can be deduced from the equations below:

$$C_Y = \frac{Y(t)}{q_\infty \cdot A_{ref} \cdot L_{ref}} \quad (4),$$

$$C_L = \left(\frac{N(t)}{(q_\infty A_{ref})} \right) \cos\alpha - \left(\frac{C(t)}{(q_\infty A_{ref})} \right) \sin\alpha \quad (5),$$

$$C_D = \left(\frac{C(t)}{(q_\infty A_{ref})} \right) \cos\alpha + \left(\frac{N(t)}{(q_\infty A_{ref})} \right) \sin\alpha \quad (6),$$

where q_∞ is the freestream dynamic pressure, A_{ref} is the reference area (base area) of the model; L_{ref} is the model base length and α is the angle of incidence of the model.

III. RESULTS

Typical signals obtained from the accelerometers in the balance are shown in Fig. 3. Pitot tube signal is included in every case to indicate the test time in the tunnel, which is about a millisecond.

A theoretical, local surface inclination method called Newtonian Theory [5] has been used to estimate the force and moment coefficients for the model. This theory is an inviscid theory, but predicts quite reasonable results for the force and moment coefficients for models in hypersonic regime.

Figure 4a shows the variation of coefficient of drag (C_D) for the model with its angle of attack to the freestream. A good agreement has been observed between the measured and the estimated (Newtonian Theory) values of C_D at lower angles of attack, but at higher angles, a small deviation has been observed between the values. This deviation is attributed to the viscous effects that become prominent at higher angles of attack, which are not considered in the theoretical analysis, as the theory is inviscid.

Figure 4b presents the variation of coefficient of lift (C_L) for the model with angle of attack. At 5 deg angle of attack, the measured and the estimated C_L match well, but at higher angles, a difference in the two methods is noticed. At angles of 10 and 15 deg, the flaps bring about viscous effects such as flow separation on the leeward side and the strong/detached shock (at 15 deg AOA) on the windward side. These effects are not included in the theoretical analysis and hence, the minor deviations in the values and the trend are justified.

Figure 4c gives the variation of coefficient of yawing moment for the model with its angle of incidence. The trend of variation of yaw is similar to that of drag as both of these movements occur in the same plane. The flaps enhance the yawing moment on the model at higher angles of attack. A strong shock effect occurs at the windward flap at an AOA of 15 deg, and due to this, yawing moment is comparatively large at this angle. The Newtonian theory does not consider this detached shock effect and hence predicts comparatively lower values of yawing moment at higher angles.

The agreement between the theoretical and the experimental data is within the expected limit of deviation. Several experimental runs were conducted and the data presented is repeatable within the indicated bands of scatter.

IV. CONCLUSION

An accelerometer balance for the measurement of yawing moment, lift and drag on a lifting model in a hypersonic shock tunnel has been developed and tested. The data obtained from the balance is compared with the data generated using Newtonian Theory. A good agreement has been observed between the measurements and the theoretical data. The balance developed is a very useful tool to measure forces and moments on complex aerodynamic models in ground based hypersonic test facilities.

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TABLE I
FREESTREAM CONDITIONS IN THE TUNNEL TEST SECTION

Test Gas	Air (γ = 1.4)
Pressure (Pa)	61 ± 4.48 %
Temperature (K)	62 ± 1.26%
Mach No.	8 ± 0.25%
Total enthalpy (MJ/kg)	0.83 ± 1.26%
Unit Reynolds number (/m)	1.04×10^6 ± 2.85%

TABLE II
PROPERTIES OF ACCELEROMETERS

Accelerometer Model No. (PCB)	Location in test model	Sensitivity (mV/(m/s^2))	Operating Frequency (kHz)	Peak Load (g)
352C67	1	9.94	10	50
352C67	2	10.25	10	50
353B17	3	1.015	10	500
353B17	4	1.028	10	500

FIGURES

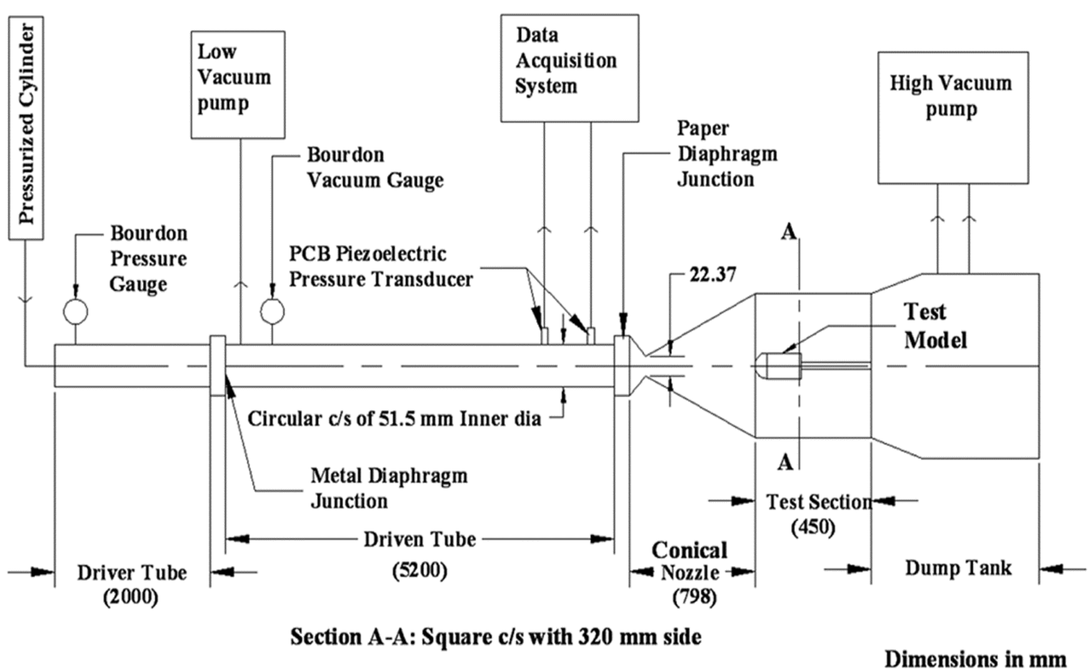

Fig. 1. Schematic of the IITB-Shock Tunnel.

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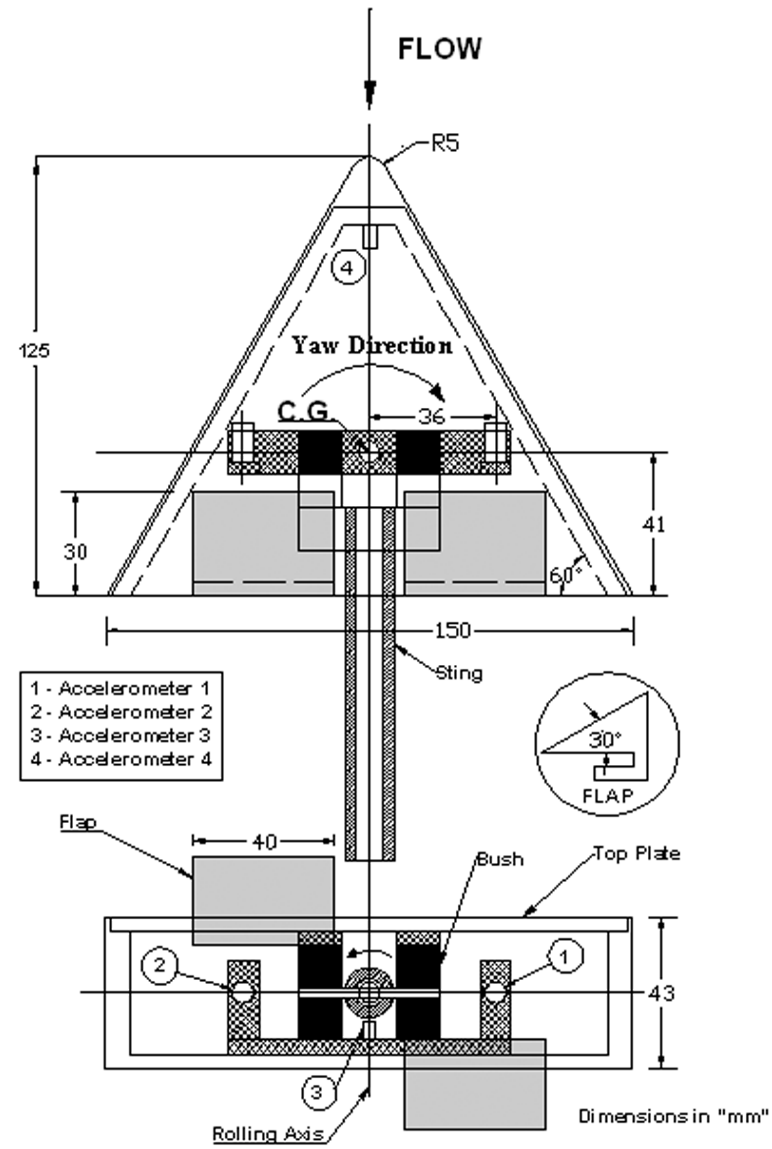

Fig. 2. Schematic of the test model-balance assembly.

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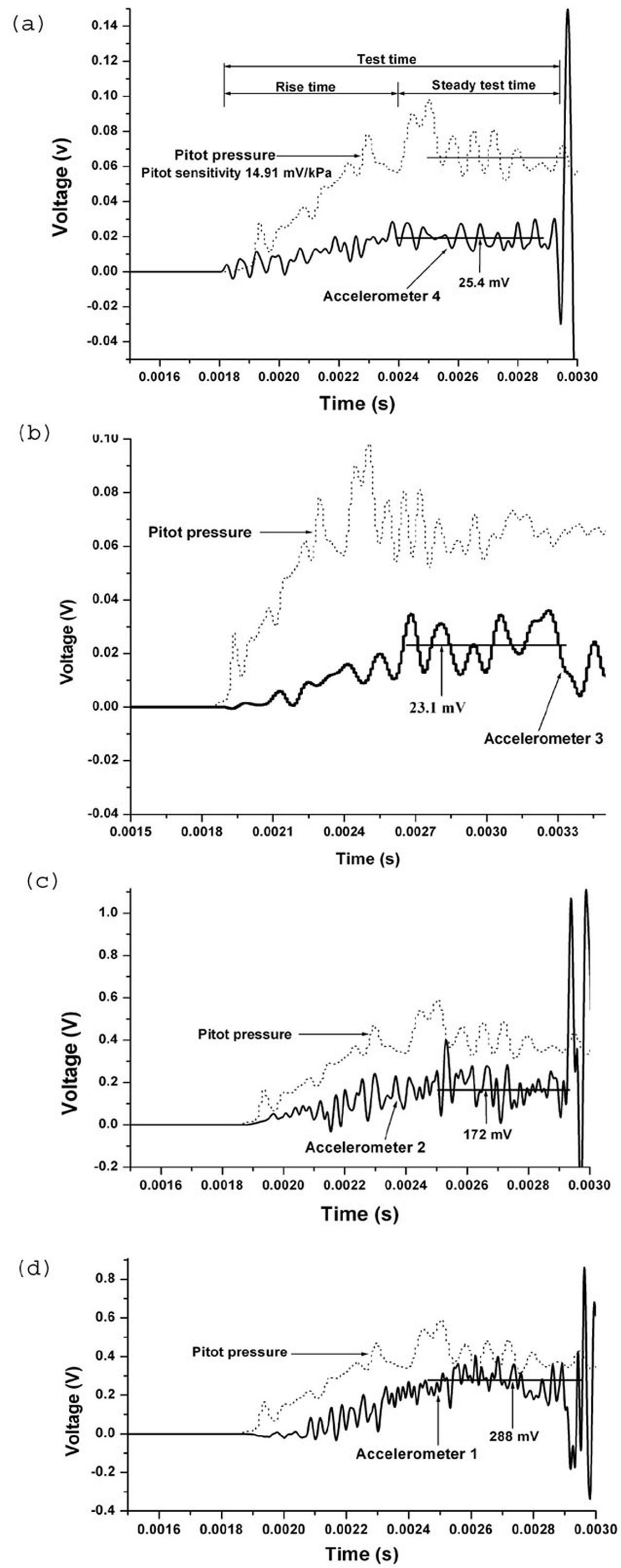

Fig. 3. Signals of the accelerometers for a model AOA of 15 deg. (a) Accelerometer 4, (b) Accelerometer 3, (c) Accelerometer 2 and (d) Accelerometer 1. Pitot signal included in each case to indicate the duration of steady freestream.

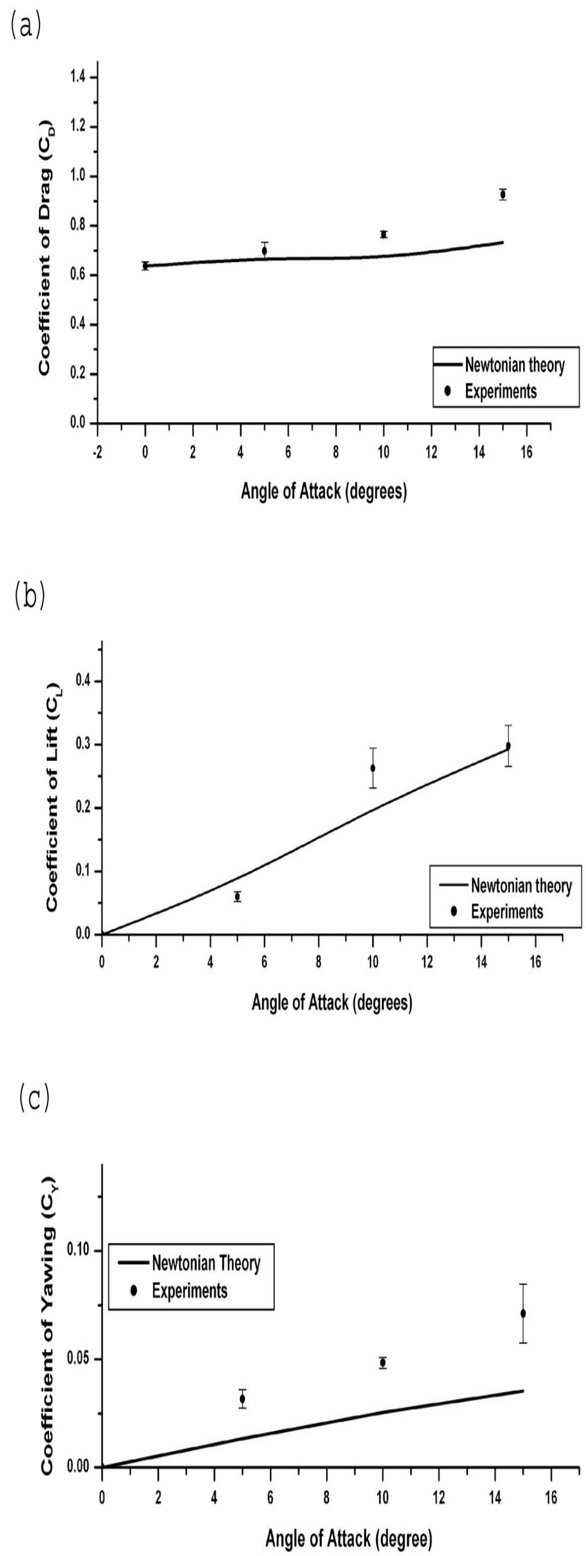

Fig. 4. Variation of coefficients of (a) drag, (b) lift and (c) yawing moment with model angle of incidence.

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