Shock Waves (2004) 13: 409–412
Digital Object Identifier (DOI) 10.1007/s00193-003-0225-y

Shock Waves

Original article

A new free floating accelerometer balance system for force measurements in shock tunnels

R. Joarder, G. Jagadeesh

Department of Aerospace Engg., I.I.Sc., Bangalore 560012, India

Received 1 July 2003 / Revised version 27 August 2003 / Accepted 15 October 2003

Communicated by K. Takayama

Abstract. In order to overcome the interference of the model mounting system with the external aerodynamics of the body during shock tunnel testing, a new free floating internally mountable balance system that ensures unrestrained model motion during testing has been designed, fabricated and tested. Minimal friction ball bearings are used for ensuring the free floating condition of the model during tunnel testing. The drag force acting on a blunt leading edge flat plate at hypersonic Mach number has been measured using the new balance system. Finite element modelling (FEM) and CFD are exhaustively used in the design as well as for calibrating the new balance system. The experimentally measured drag force on the blunt leading edge flat plate at stagnation enthalpy of 0.7 MJ/kg and nominal Mach number of 5.75 matches well with FEM results. The concept can also be extended for measuring all the three fundamental aerodynamic forces in short duration test facilities like free piston driven shock tunnels.

Key words: force measurements, shock tunnel, accelerometer balance

1 Introduction

The traditional force balance systems used for measuring aerodynamic forces in hypersonic wind tunnels are built using fast response strain gauges. The strain gauge techniques rely on static measurement of the reaction forces produced in the model-support structure (Rae and Pope 1984; Euwald 2000). In most of these measurements the steady state test time is considered only after the initial unsteady model oscillations due to the interaction of the hypersonic stream with the model and mounting system damps out. On the other hand, in shock tunnels only negligible amounts of damping is possible during the entire flow duration. Hence, the experimental methodology and aerodynamic force measurement techniques used in long duration hypersonic wind tunnels will not be suitable for shock tunnel applications. This problem is more pronounced when one tries to measure forces on generic hypersonic vehicle configurations like waveriders, hypersonic space recovery modules or the thrust generated by a scramjet engine.

For shock tunnels and free piston driven tunnels either miniature accelerometer balance (Sahoo et al. 2002) or the stresswave balances (Mee et al. 1996) are used. But in the case of complex 3-D models the inadequacy of rubber-based support systems in accelerometer balances and the complexity of calibration procedures in stress wave based balances impose severe restrictions in realistic force measurements. For example the rubber bushes used in the accelerometer force balance for ensuring the unrestrained motion of the model during tunnel testing is not suitable for measuring the thrust generated by scramjet models. Moreover when long and slender models are to be tested then it is still not clear whether rubber springs will ensure unrestrained movement during tunnel testing. In this backdrop there is an urgent need to come up with simpler yet reliable techniques for measuring aerodynamic coefficients in complex configurations like hypersonic waveriders, space recovery modules and generic hypersonic reusable vehicles. The present work describes a novel free-floating balance system for force measurement around bodies in shock tunnels. The experimental methodology, details about the balance system, along with important results are explained in the subsequent sections.

2 Experimental methodology

The experiments are carried out in the IISc hypersonic shock tunnel at nominal Mach number of 5.75. Nominal

---

Correspondence to: G. Jagadeesh
(e-mail: jaggie@aero.iisc.ernet.in)

Table 1. Nominal free stream conditions in IISc. shock tunnel HST2

D*rivergas*	M_s	P_0 (kPa)	T_0 (K)	H_0 (MJ/kg)	P_∞ (kPa)	T_∞ (K)	ρ_∞ (kg/m^3)	U_∞ (m/s)	R_e
N_2	2.15	180	720	0.72	0.15	95	0.005	1120	9×10^5
H*e*	3.1	485	1200	1.2	0.4	140	0.01	1360	1.25×10^6

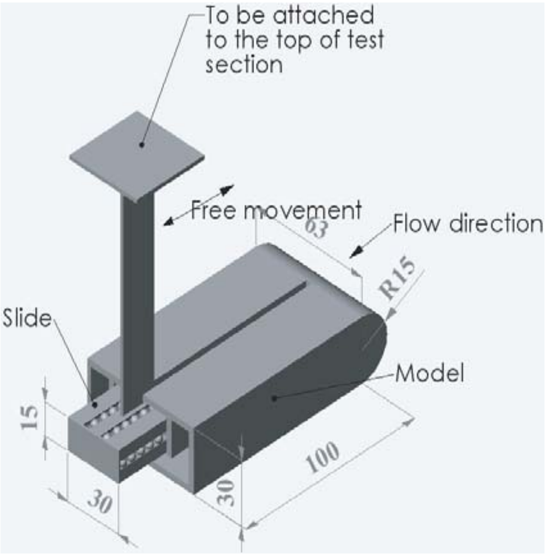

Fig. 1. Schematic diagram of free floating balance system mounted inside the flat plate model (all dimensions are in mm)

test conditions in the tunnel during experiments are shown in Table 1.

Before fabrication of the balance system exhaustive parametric FEM studies were carried out to optimize the design. The idea behind the present balance system is to mount the model on frictionless rollers and then measure the unrestrained model acceleration induced by the hypersonic flow. Figure 1 shows the schematic representation of the balance system along with the flat plate model. The model is free to move on the steel slide block with spherical grooves on the top and side surfaces. Steel rollers (4mm diameter) are inserted into these grooves from the end. These steel balls ensure point contact between the model and slide, thereby minimizing the friction. A steel strip with chamfered edges connects the slide with the top of the test section. Thus the slide with strip welded to it remains fixed during test, while the model moves in the horizontal direction with a certain velocity and acceleration depending upon its mass and free stream conditions during the shock tunnel testing. An accelerometer (PCB Piezotronics, 10 KHz) mounted along the central axis of the flat plate model is used for measuring the drag experienced by the model exposed to hypersonic flow stream.

Some of the salient features of the present model and balance system are:(a)The thickness of the steel strip is 2mm. This is to ensure minimum flow disturbance during the experiment. Although not shown here this has been confirmed by 3-D CFD simulation studies at Mach 5.75. The width of the strip is 20mm. The model and the strip interacts only through frictional force. This width is sufficient to guarantee adequate stiffness of the strip.(b)Length of slide is dependent on the anticipated movement of the model under test condition and the position of center of gravity of the body. One can determine the anticipated movement by finding the initial acceleration of the body and then using the relation $S = ut + \frac{1}{2}ft^2$, where S is the anticipated movement, u is initial velocity (= 0 in present case), f is the initial acceleration, and t is the test time. Here

$$f = \left[\frac{P_s \times A}{m}\right] \tag{1}$$

where P_s is the free steam static pressure, A is the projected frontal area, and m is the mass of the body.

A body remains in stable equilibrium as long as the vertical line drawn through the C.G cuts the supporting area of the body. Accordingly if this vertical line falls outside the slide, the model will not move in a stable manner. Taking all these factors into account, the slide length has been chosen to be 50mm for a model dimension of $110mm \times 60mm \times 30mm$.(c)The radius of the front portion is tentatively kept at 15mm, which can be changed according to requirement.

3 Calibration of the balance system

In order to estimate precisely the values of friction coefficients, both static and dynamic calibration of the balance system was carried out before the actual tests in the shock tunnel. For static calibration the model was rigidly fixed in an horizontal plane with the help of the vertical metallic strip (see Fig. 1). One end of a cotton thread was attached to the blunt leading edge of the flat plate model in the vertical plane of symmetry while an arrangement for loading known standard weights was provided at the other end. The thread was also supported by a steel rod between the two ends. By gradually increasing the load on the model the minimum weight at which the model started moving was determined. The average total weight at which the model started moving was found to be 10.15 gm. The coefficient of static friction is given by

$$\text{Cw}=\frac{\text{friction force}}{\text{weight of the model}} = \frac{10.15}{203} = 0.05.$$

The coefficient of dynamic friction can be considered to be equal to about sixty percent of Cw i.e. $0.05 \times 0.6 = 0.03$.

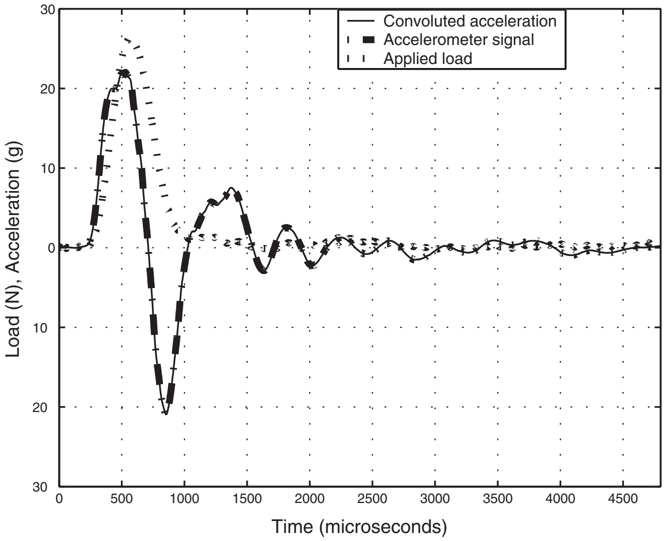

Fig. 2. Typical signal from hammer and accelerometer with convoluted output acceleration

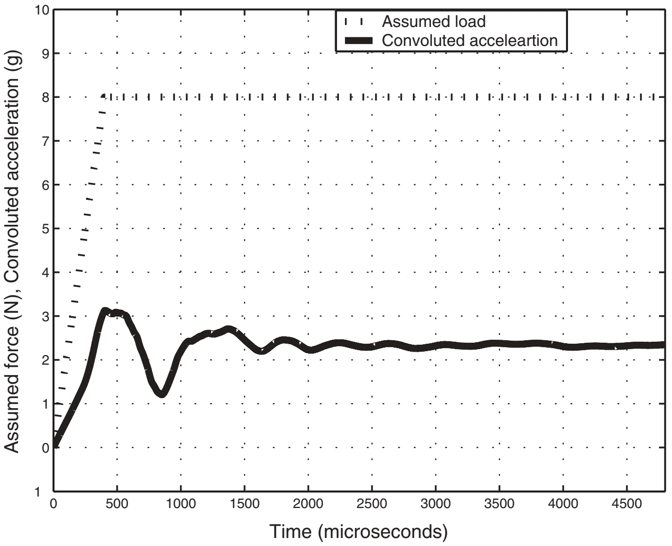

Fig. 3. Assumed variation of drag force and the corresponding convolved acceleration history

This indicates that the roller slide on which the model is mounted virtually ensures unrestrained motion during testing.

The dynamic calibration of the force balance system is quite essential, especially when we are trying to measure aerodynamic forces in impulse facilities like shock tunnels. It is necessary to obtain a system response function from dynamic calibration so that the forces from the measured acceleration history in experiments can be easily obtained. For further details on the dynamic calibration and the associated procedure for obtaining aerodynamic forces from the system response function refer to Mee et al. (2003).

Conventional impact hammering technique was used for the dynamic calibration of the balance system. An impulse hammer (PCB Model No. 208A03, sensitivity 10 mV/N) was used to apply dynamic force on the model. A 99 μs moving average filter was used for minimizing the higher frequency noise. Response of the force balance was found to be very sensitive to the nature of the applied force. The system response function for the force balance was obtained by deconvoluting the impulse hammer signal from accelerometer signal. The hammer signal which closely matches with pitot signal in nature i.e. in terms of rise time to its peak value was used for deconvolution. Using the system response function the impulse hammer signal was convolved to asses the fidelity of the dynamic calibration process. The convolved signal matches well with the original accelerometer signal as seen from Fig. 2.

Ideally this system response function should be used to deconvolute the accelerometer signal from the force balance system in experiments to obtain the drag force experienced by the flat plate model. However in most dynamic measurements the measured accelerometer signals are noisy, and deconvolution of these signals directly leads to erroneous estimation of the drag force. Hence in the present experiments, initially a force variation for typical free stream condition in the shock tunnel was assumed based on the the modified Newtonian theory. Then through an iterative process the assumed force signal was convolved using the system response function obtained from dynamic calibration to arrive at an acceleration history. The iterative process was terminated when the experimentally obtained acceleration history matched well with that estimated from the system dynamic approach.The assumed force variation along with the convolved acceleration history is shown in Fig. 3. The fluctuation in acceleration obtained at the beginning of the steady state can be attributed to the assumption of instantaneous variation of drag force.

4 Results and discussion

Typical signals from the drag accelerometer along with the recorded pitot pressure history in the test section with N_2 as the driver gas are shown in Fig. 4. About 255 μs of steady state test time is available for force measurement before the collision of the model with the stopper, while about 800 μs steady state test time is actually available in the HST2 shock tunnel (Gaydon et al. 1963).

In order to complement the experiments finite element modelling of the balance system, along with the flat plate model for the experimental free stream pressure conditions, was carried out using the commercial FEM package NISA (LINEAR TRANSIENT). The equation of equilibrium governing the linear dynamic response of a system of finite elements can be written as,

$$M\ddot{U} + C\dot{U} + KU = R$$

where M, C, and K are the mass, damping and stiffness matrices; R is the vector of externally applied loads; $U, \dot{U}, \ddot{U}$ are the displacement, velocity, and acceleration vectors of the finite element assemblage. 3-D wedge elements were used to model the blunt leading edge of flat plate while the rest of the hyperpatch were filled with 3-D hexahedral elements. Some of the important features of

Table 2. The tabulated values of drag around a flat plate with blunt leading edge at Mach 5.75

	Acceleration (g)	Drag (N)	Friction (N)	Net (N)
FEM	2.53	7.288 (steady state)	0.0358	7.3238
Experiments	2.4	8 (steady state)		8

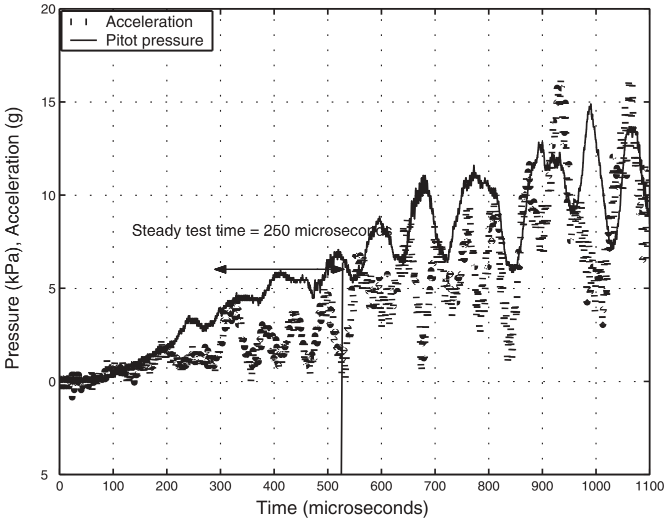

Fig. 4. Typical outputs from the drag accelerometer and the pitot pressure probe mounted inside the test section

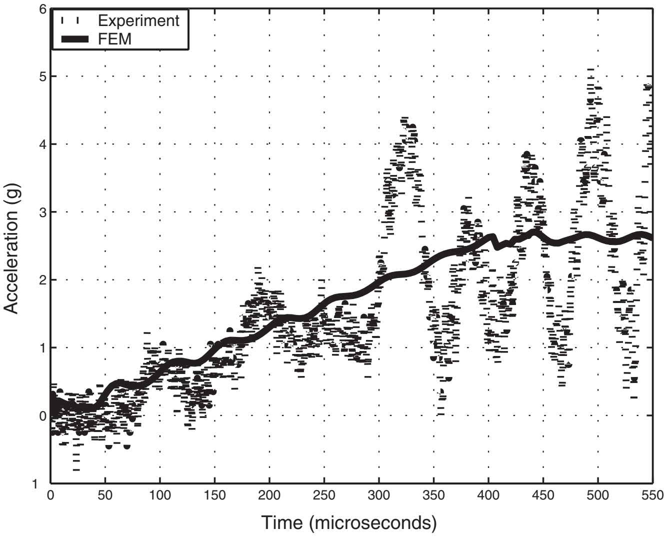

Fig. 5. The accelerometer output superimposed with the simulated acceleration time history using finite element modelling

the FEM analysis are (a) Total force on model was calculated by multiplying the frontal projected area of the body with steady pressure value. This was then equally subdivided according to the number of nodes at the front portion of the body in FEM. (b) The variation of force with time in FEM input was applied in the same manner as that of the pitot-signal. (c) The friction force was then calculated by multiplying 0.03 with the weight of the model. Figure 5 shows the typical acceleration histories from experiments and FEM simulations. The experimentally measured drag force at Mach 5.75 along with the FEM results are tabulated in Table 2.

In FEM studies the variation of the static pressure was assumed to be linear and the initial fluctuations associated with the static pressure in actual experiments was not modelled. Hence the FEM simulated acceleration history is smoother compared to the experimental result. Notwithstanding minor deviations the steady state values of the acceleration history from FEM simulations match well with experiments. In any case there will be some friction (0.0358 N) offered by the steel rollers during the motion.

5 Conclusion

A new single component, free floating force balance system has been designed and fabricated, and the drag force on a blunt leading edge flat plate has been successfully measured, in the IISc hypersonic shock tunnel HST2, at a nominal Mach number of 5.75. In the present configuration the balance can measure only the axial force and attempts are underway to extend the idea to measure all three fundamental aerodynamic coefficients. This novel force measurement concept for shock tunnel testing will be useful for thrust measurements in scramjet engines and other next generation hypersonic vehicles like waveriders.

References

Euwald, B.F.R.:Multi-component force balances for conventional and cryogenic wind tunnels. Meas. Sci. Technol. **11**, 81–94 (2000)

Gaydon, A.G., Hurle, I.R.:*The shock tube in high temperature chemical physics.* NY: Reinhold Pub., pp. 60–67 (1963)

Mee, D.J.: Dynamic calibration of force balances for impulse hypersonic facilities. Shock Waves **12**, 443–455 (2003)

Mee, D.J., Daniel, W.J.T., Simmons, J.M.: Three-component force balance for flows of millisecond duration. AIAA J. **34**, 590–595 (1996)

Rae, W.H., Pope, A.: *Low-speed wind tunnel testing.* NY: Wiley, pp. 165–213 (1984)

Sahoo, N., Mahaptra, D.R., Jagadeesh, G., Gopalakrishnan, S., Reddy, K.P.J.: Aerodynamic Force Measurement on 60 deg. Apex Angle Blunt Cones Flying at Mach 5.75 Using a 3-Component Accelerometer Balance. Meas. Sci. Technol. **14**, 260–272 (2003)