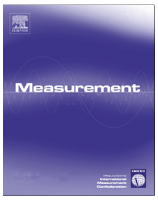
Measurement 46 (2013) 2110–2117

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement



Design and testing of an external drag balance for a hypersonic shock tunnel

P. Vadassery, D.D. Joshi, T.C. Rolim, F.K. Lu *

Aerodynamics Research Center, Department of Mechanical and Aerospace Engineering, University of Texas at Arlington, Arlington, TX 76019, USA

ARTICLE INFO

Article history:
Received 3 July 2012
Received in revised form 14 February 2013
Accepted 17 March 2013
Available online 26 March 2013

Keywords:
Force balance
Hypersonic shock tunnel
Drag measurement
Finite element analysis
Stress wave force measurement technique

ABSTRACT

An external force balance for a hypersonic shock tunnel was developed. The design utilized finite element analysis that identified the dynamics of the balance. A simulated impulse and a step load were applied to the design, the former for determining the simulated transfer function and the latter to validate the design. The numerical modeling showed the feasibility of this approach for designing stress wave force balances. A force balance based on the design was fabricated, calibrated statically and dynamically, and implemented in a shock tunnel for measuring drag of a blunt cone at Mach 9.4. The measured drag compared well with modified Newtonian theory.

1. Introduction

Short-duration facilities such as shock tunnels and their variants are well-known for their hypersonic testing capabilities. Unfortunately, such facilities have test times in the micro to millisecond range which complicates force measurement [1]. Of particular concern is the dynamics of the force balance when subjected to sudden aerodynamic loading. The short test time also likely prevents the force balance from attaining a steady state. A unique consideration related to the test environment and the short test time is that the sensors must be robust and fast. Typical sensors are fast-response accelerometers and strain gages.

A method known as the stress wave force measurement technique (SWFM) [2] can address the complications from the short test duration by measuring the stress waves propagating within the force balance. Another force measurement approach is accelerometer based [3], which requires the model to be free floating. This type of internal balance requires springs and rubber flexures mounted in a model suspension system [4,5]. The measured acceleration–time history can then be related to obtain the force history.

As with conventional aerodynamic facilities, force balances for impulse facilities are either internal where the sensing elements are placed within the test model or external otherwise. Robinson et al. [6] showed that high 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 an external balance on the model forces was less than that of an internal balance. Moreover, authors in [7,8] have discussed the possibilities of using finite element modeling techniques in the design process for developing aerodynamic force measurement devices in hypersonic flows.

The present work involves a further development of the SWFM technique. The emphasis is to apply finite element analysis (FEA) in designing a drag balance through investigating the propagation of stress waves. A number of preliminary designs were evaluated using FEA. Other than developing an understanding of stress wave propagation, FEA identified stress concentrations and was used to identify suitable locations for strain gage placement. A drag balance was fabricated as a monolithic item and it was cal-

---

* Corresponding author. Tel.: +1 817 272 2083.
E-mail address: franklu@uta.edu (F.K. Lu).

0263-2241/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2013.03.011

ibrated dynamically to obtain the system transfer function. This transfer function was used to recover the force acting on the model by a deconvolution procedure [9]. The balance was used to measure the drag of a spherically blunted cone mounted in a hypersonic shock tunnel in a nominal Mach 10 flow. The measured drag was compared against the modified Newtonian theory.

2. Force balance

The SWFB technique utilizes the wave reflections in a so-called stress bar for determining model forces in impulse facilities. The force balance is considered to be a linear system. The general approach, therefore, is to perform a dynamic calibration to determine the system transfer function. The force of a subsequent test can then be obtained from the stress measurement and the established transfer function. The design of the present force balance is facilitated by finite element analysis and will be summarized next.

2.1. Force balance design

A requirement for the force balance is its ability for mounting a variety of models. Design requirements such as size (to fit into the test core of the shock tunnel), strength of balance, model and support attachment, strain gage/transducer placement and machining simplicity were considered. For ease of manufacture, reduced weight and high strength, aluminum (Al-6061) was chosen as a suitable material. A rigid support was made using hardened steel.

The design made use of finite element analysis (ANSYS® Workbench™ 12 explicit dynamics solver) to assist in selecting a suitable force balance design amongst a number of candidates. (Details of the selection process can be found in [10].) This novel approach was carried out to understand the propagation of stress waves in solids. An impulse and a step load were applied to the front of the balance. In some of the designs, stresses concentrated more at joints where members are fastened together. Therefore, it was decided to fabricate the force balance as a single solid piece. Details of the analysis settings are seen in Fig. 1. The top surface remained as a fixed support. Location 1 is just behind the tip of the axial bar while location 2 is 25 mm up the forward leg from the axial bar as indicated in Fig. 1. These two locations are potential sites for strain gages.

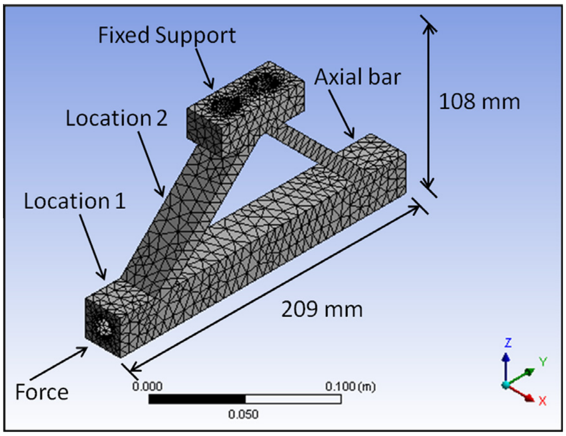


Fig. 1. Mesh generated with explicit dynamics solver.

The mesh was initially generated with a total of 34,088 uniform tetrahedral elements. The size of the elements was dictated to respond to high frequencies associated with the stress wave. Mesh refinement was then applied for computational efficiency, by maintaining larger elements to insignificant areas and increase density in areas of higher stress concentration. FEA solves the general differential equation of motion in structural dynamic analysis

$$m\ddot{u} + c\dot{u} + ku = f(t) \tag{1}$$

where m is the mass of the system, c is the damping coefficient, k is the stiffness constant, u is the displacement vector and $f(t)$ is the vector of the time-varying load. Forces at nodes are calculated by a central difference time integration scheme used by the solver with a uniform time step of 0.08 μs. The time step is limited by the smallest element in the mesh. Simulations were carried out on an Intel Pentium 4, 2.6 GHz machine with 2 Gb of RAM. The simulation required 16,250 steps to converge, which required approximately 2 h. Damping was not included in the simulation so as to capture the high-frequency stress waves.

The dynamical behavior of the force balance depends solely on the impulse response which ideally is the output when an impulse load is applied. The output $y(t)$ is given by the convolution of the input $x(\tau)$ and the impulse response $g(t-\tau)$, namely,

$$y(t) = \int_0^t g(t-\tau)x(\tau)\mathrm{d}\tau \tag{2}$$

It is more convenient to express Eq. (2) in the Fourier domain and after rearranging one obtains

$$G(f) = Y(f)/X(f) \tag{3}$$

Eq. (2) or (3) provides the key for determining the transfer function. In practice, an ideal impulse $x(t) \equiv \delta(t)$ cannot be achieved. However, such an ideal impulse can be approximated to a high degree by a narrow triangular loading [11]. For the present, a triangular loading with a peak of 350 N and pulse width of 220 μs is applied at the front of the force balance. A few frames of the simulation are shown in Fig. 2. The time after the application of the impulse is indicated in the individual frames. The frames show primarily the propagation of stress waves within the force balance, omitting most of the subsequent reflections. The forward slant member is considered for strain gage placement and hence it is named the “stress bar.” The initial stress wave at the front face transmits to the rear of the axial bar as well as to the forward and aft stress bars. The strain histories observed on the axial bar at locations 1 and 2 are shown in Fig. 3. This figure shows that the strain history at location 1 follows closely the trend of the impulse with minor reflection right after the pulse. Location 2, however, shows that there are numerous wave