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HYPERSONIC DRAG MEASUREMENT IN FREE PISTON SHOCK TUNNELS

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ABSTRACT

The paper describes a hypersonic drag measurement technique for free piston shock tunnels which interprets the stress waves propagating in a long model support. Knowledge of the system's impulse response allows the time-varying hypersonic drag on a cone at approximately Mach 5 to be deduced. The technique has been shown to work successfully on a short 15° cone and a long 5° cone on which skin friction was significant in flows ranging from 5 to 30 MJ/kg stagnation enthalpy with Reynolds numbers based on length from 0.5×10^6 to 6.5×10^6.

INTRODUCTION

Hypervelocity impulse facilities are important to the development of hypersonic flight technology. Free piston driver shock tunnels are an important class of these devices as they generate the high enthalpy conditions encountered at near-orbital velocities and in scramjet propulsion systems. Measurement of important parameters such as drag and thrust is complicated by the very short test flows of these impulse facilities. Test times are typically 1 millisecond or less.

Force balances may be either stiffness-dominated or inertia-dominated, the former suiting measurement in test flows of 200 ms or longer. The latter, employing acceleration compensation, may work in test flows as short as 10 ms. As the time scale over which the balance must operate reduces, the distributed mass and flexibility of the balance members must be considered. This is essential for force measurement in the free piston driver shock tunnel flows. Force measurements inferred from discrete surface pressure tappings cannot account for skin friction and become exceedingly difficult as model geometry increases in complexity.

THE NEW DRAG BALANCE

Figure 1 is a schematic of the drag balance configuration. The model is an aluminium cone, 425 mm in length, with a small stainless steel nose tip. It has a 5° semi vertex angle. The support or sting is a hollow brass cylinder 2 metres long. It is freely suspended by thin wires and aligned in the flow direction. The support structure is shielded from the tunnel flow. The time history of the drag on the cone is deduced from the output of strain gauges, situated near the upstream (model) end of the sting, which respond to the passage of the stress waves arising from the impact of the flow on the model.

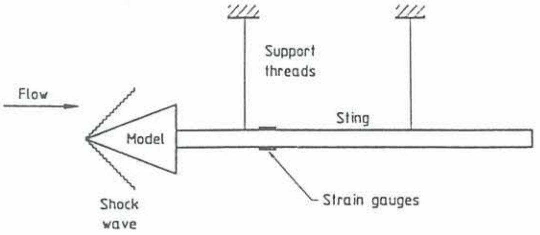

Figure 1. Drag balance configuration

The principle behind the method is that from a knowledge of the model-sting system's impulse response, any input loading of arbitrary time distribution may be determined from a single measurement of the response of the system. A dynamic system's response to excitation by an impulse is described by its impulse response. This is of great use in examining transients. For very large models, the spatial distribution of the loading will become important and may necessitate the measurement of other parameters. A finite element model of the system provides the required impulse response. It models internal material damping as Rayleigh damping.

The drag measurement is a typical dynamics inversion problem. It may be described by the following convolution integral

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

The cone on the freely suspended sting is a time-invariant, causal linear dynamic system. The forcing function, u(t), is the unknown drag which gives rise to the measured output strain, y(t), in a manner determined by the system impulse response, g(t). Finding the drag entails the inversion of the integral. This problem is highly sensitive to measurement noise, something quite prevalent in the impulsive free piston shock tunnel flows.

For this problem of uniaxial loading, simple stress wave theory (Kolsky, 1963) predicts an exponential stress (or strain) rise. Damping is very low in metals and the system may be regarded as a first-order one. The time constant of the system depends upon the impedance of the join between the model and the sting. A suitable choice of materials and a geometry which allows a smooth passage of the stress wave from the model to the sting results in a system which responds fast enough to enable force measurement in the shock tunnel test time. The system's mechanical time constant is approximately 380 microseconds. Figure 2 shows the finite element computed step response to a uniform pressure on the 5° cone. The part of the signal of interest is the initial exponential rise up to aproximately 1.1 ms, at which time the reflection from the free end returns to the strain gauge position. The output has been normalised by the static stress.

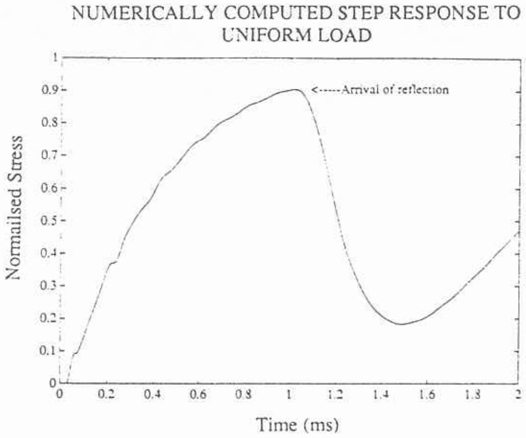
NUMERICALLY COMPUTED STEP RESPONSE TO UNIFORM LOAD

Figure 2. 5° Cone step response

Sanderson (1989) performed the initial investigation of the technique with a 200 mm long 15° semi-vertex angle cone. The solution of the complete inverse dynamics problem is a numerical one with both spatial and temporal discretisation. The unit impulse response is found by computing the step response to a pressure load applied uniformly to the cone surface, and then normalising this by the static stress and differentiating by a method based upon a Langrangian interpolation formula.

There are two approaches to the measurement problem when model flexibility is significant and the drag distribution over the surface determines the balance output. One is to condition the problem such that the loading distribution is described by a small number of parameters. This requires that there only be a limited number of wave reflections within the model. The second, and simpler, is to maximise the number of wave reflections within the model so that an accurate description of their propagation is unnecessary. This second approach was adopted. Aluminium has a high stress wave speed (speed of sound), while brass a much slower one. This maximises the observation time before the return of the stress wave reflected from the downstream free end of the sting.

Validation of the finite element representation of the system is performed using a step unloading of a mass attached to the cone vertex. There is no discernible difference between the output from this and that obtained for a uniform pressure load in the case of the 15° cone. With the longer 5° cone, wave reflections within the model become more apparent. For a model of this length, the effects of a small change in conditions at one point on the model will not be experienced instantaneously by other points on the model. Perturbations will propagate downstream at the speed of the flow plus the local sound speed. For this reason, the impulse response is determined from a pressure loading, uniform in magnitude but temporally swept over the cone surface at the speed of the flow plus the local sound speed. The deconvoluted result of this was compared with results obtained using impulse responses based upon a uniform pressure instantaneously applied to all the model surface, and a point load at the cone vertex (see Simmons et al (1992)). The overall results differed little; only the oscillations differed according to the manner of load application. The temporally swept manner, however, represents the tunnel loading most closely and has, therefore, been employed to produce the results shown here.

Sanderson (1989) initially solved the inverse problem in the frequency domain. This was for mathematical expedience. It is well known that measurement noise is amplified during the inversion process. For this reason the inverse problem was treated as a least squares minimisation problem by Sanderson (1989) in which some degree of measurement noise had been accounted for. This resulted in the use of a Wiener optimal filter in the frequency domain, just prior to the inversion of the integral. For the high signal-to-noise ratio 15° cone data, the results of this process agreed to within 10% of Taylor-Maccoll theory (skin friction and base pressure were neglected).

The harsher tunnel conditions required to produce detectable strains in the 5° cone led to an order of magnitude decrease in signal-to-noise ratio. Greater electronic amplification of the foil resistance strain gauge signals also decreased the signal quality. The initial solution method failed to yield sensible data, and this led to a revision of the solution algorithm. Deconvolution now takes place in the time domain and the data is filtered after deconvolution using a low-pass Butterworth six pole filter. The cut-off frequency is 3 kHz. The filter's response is completely adequate during the period of interest. Comparable agreement between theory and experiment is obtained.

The theoretical drag is predicted using the theory of Taylor and Maccoll (1932) for a specified Mach number and ratio of specific heats. For the 5° cone's surface-to-base-area ratio, skin friction may constitute up to 30% of the total drag. The base pressure on a slender cone may also be significant, depending on the method of support. The situation here is complicated by the presence of a buffer immediately behind the cone to prevent damage when it moves back during the test flow period. The test section is evacuated before the shot. To determine base drag, it is assumed that the flow in the gap between the cone and the buffer is choked and the pressure within the sting shrouding remains near vacuum during the test. The only back pressure then occurs in the gap region. This is typically half the free stream static pressure. Skin friction is determined for a laminar boundary layer, although it is recognised that transition may occur in some conditions. An approximate formula for low speed flow is used where the reference temperature of Eckert (1955) as described by White (1974) is used to evaluate flow properties.

The signal quality was the main difficulty encountered with the 5° cone. This was found to vary with tunnel conditions, as shown in Figure 3. The signal-to-noise ratio obtained at nine different operating conditions is plotted versus Reynolds number based on length.

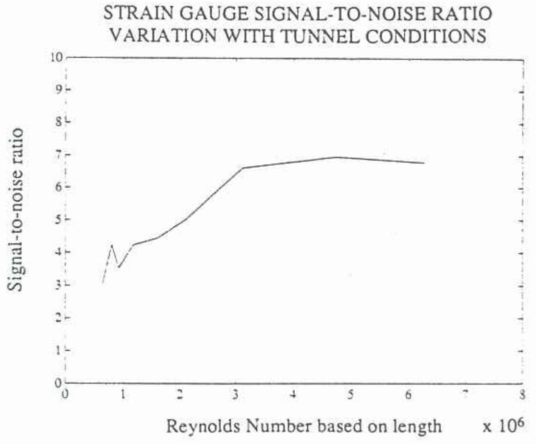

Figure 3. Signal quality variation with tunnel conditions

Results from the tests performed on the 5° cone in the University of Queensland's T4 free piston driver reflected shock tunnel are shown below in Figures 4 to 7. A Mach 5 contoured nozzle was used with nitrogen test gas (this was in order to minimise dissociation effects). The tunnel operates predominantly in the under-tailored mode. This means that the stagnation pressure falls with time. The period designated as the test time is when the ratio of pitot pressure to stagnation pressure is approximately constant.

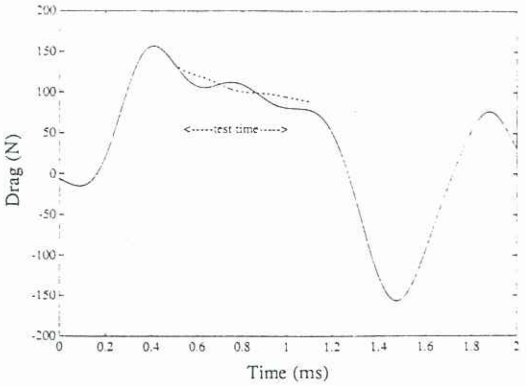

Figure 4. Stagnation pressure = 60 MPa; stagnation enthalpy = 7.8 MJ/kg; stagnation temperature = 5990 K; pitot pressure = 1058 kPa; shock speed = 2921 m/s; Mach number = 5.9

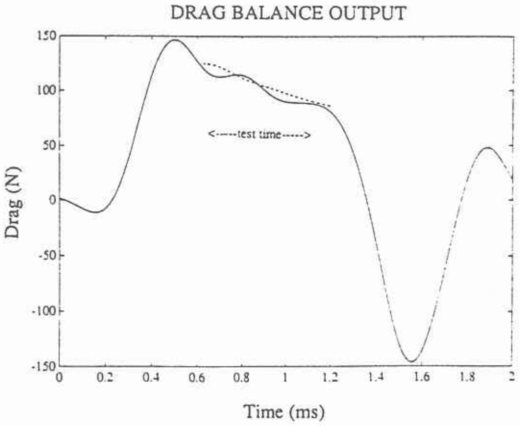

Figure 5. Stagnation pressure = 70.5 MPa; stagnation enthalpy = 10.8 KJ/kg; stagnation temperature = 7433 K; pitot pressure = 1103 kPa; shock speed = 2376 m/s; Mach number = 6.12

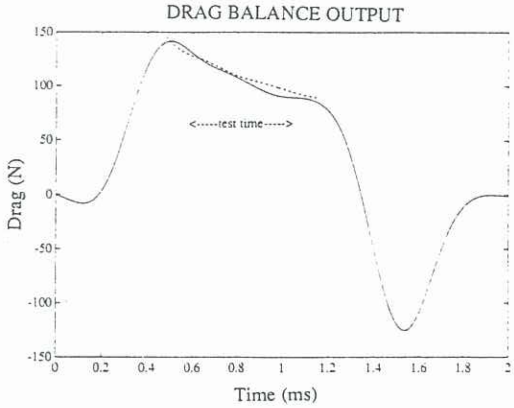

Figure 6. Stagnation pressure = 67.9 MPa; stagnation enthalpy = 6.01 MJ/kg; stagnation temperature = 4817 K; pitot pressure = 1156 kPa; shock speed = 2548 m/s; Mach number = 5.87

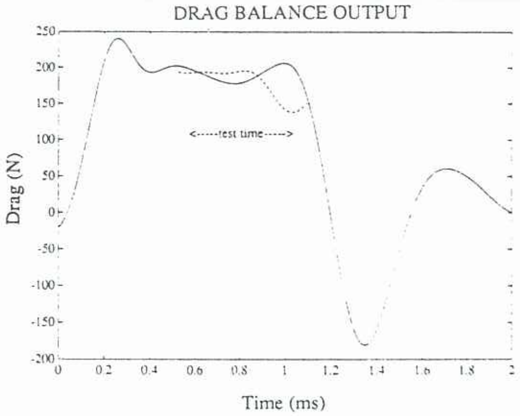

Figure 7. Stagnation pressure = 71.8 MPa; stagnation enthalpy = 21.8 MJ//kg; stagnation temperature = 9485 K; pitot pressure = 1167 kPa; shock speed = 4499 m/s; Mach number = 5.3

It can be seen that agreement between the net drag measured on the cone and that predicted by Taylor-Maccoll theory with base pressure and skin friction effects included is good.

CONCLUSION

Drag has been measured in a very demanding situation. The tunnel was driven very hard to produce sufficient drag on this slender cone with the result that the flow was often very noisy. A large amount of amplification was required for the foil resistance strain gauge signals which had to respond to strains of the order of 1 microstrain lasting for less than 1 millisecond with a signal-to-noise ratio which was often very poor due to flow conditions.

The main limitation of the method's usefulness in measuring uniaxial forces was the strain gauge technology. Subsequent work has shown semiconductor gauges to yield far superior signal quality. The model size is a useful one for realistic hypervelocity aerodynamic experimental work (approximately half a metre in length and two kilograms in mass). This size of model is still sufficiently insensitive to loading distribution for an approximate impulse response to yield satisfactory deconvoluted results. It has since been found that model size or mass may be increased at least by a factor of two while still achieving satisfactory results. The method is now being applied to the measurement of the net axial thrust produced in a two dimensional scramjet nozzle. Again, the effect of skin friction will be accounted for.

Drag has now been measured in a 1 ms test flow, with the skin friction component included in the measurement, on a practical sized model whose geometry approaches that of the forebody of a hypersonic aircraft.

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