Design of a force balance for shock tunnel measurement of aerodynamic forces on HYFLEX

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Abstract: The design of a new balance for the measurement of multiple force and moment components on a scaled model of the HYFLEX vehicle is described. The technique used is an extension of the stress wave force measurement technique, initally proposed by Sanderson and Simmons (1991). This technique relies on the interpretation of stress waves propagating within the model and its support, as a result of impulsive aerodynamic loads generated through shock tunnel testing. Dynamic finite element modelling was used to evaluate proposed force balance designs. The distribution of aerodynamic loads was obtained from a Newtonian code in which the model scale and test flow conditions were determined using binary scaling. The results from preliminary modelling were used to produce a final balance design. Simulations show this design to be capable of measuring aerodynamic loads on a model of the HYFLEX vehicle.

Key words: Hypersonic flow, Shock tunnel, Force measurement, Force balance, Deconvolution, Hyflex

1. Introduction

The ground-based testing of hypervelocity flight vehicles is typically conducted using impulse-type test facilities. While these facilities are capable of producing the high-enthalpy flows necessary for simulation, they 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. Consequently traditional force measurement techniques cannot be used as there is insufficient time for the aerodynamic forces acting on the model to reach static equilibrium with the support.

The stress wave force measurement technique has been found to be effective in overcoming the limitation of short test times. The technique relies on the measurement and interpretation of stress waves propagating within the model and its support as a result of aerodynamic loading. Originally this technique was developed by Sanderson and Simmons (1991) for the measurement of drag on a conical model in a free piston shock tunnel. Since then this technique has been extended by Mee et al. (1996) to allow the measurement of drag, lift and pitching moment on a short conical model.

This paper describes the design and simulated results obtained from a new stress wave force balance. The new design is a futher extension of the measurement technique that permits the measurement of multiple force and moment components. The new design has been developed to permit the measurement of aerodynamic forces acting on a scaled model of the Japanese hypersonic flight experiment HYFLEX (Shirouzu et al. (1996)). It is anticipated that measured force and moment components will be compared to flight data obtained from the HYFLEX vehicle.

2. Force measurement technique

The stress wave force measurement technique permits impulsive aerodynamic forces acting on a model to be measured. The technique relies on characterising the dynamic response of the model and its support. The technique permits multiple force components to be measured simultaneously. However the principles of operation are introduced using a single component force balance.

The single component force balance is essentially a variation on the original Hopkinson pressure bar experiment (Davies (1948)). It consists of a model connected to an elastic stress bar. The arrangement is suspended in the test flow so that there is no restriction to movement in the flow direction. Stress waves produced in the model due to the sudden arrival of the test flow are transmitted into the stress bar. The time history of these stress waves is measured using strain gauges mounted on the stress bar. By treating the dynamic behaviour of the arrangement as a linear system, a convolution integral (Eqn. 1) may be used to describe the system.

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

In Eqn. 1, $u(t)$ is the input to the system (aerodynamic force time history), $y(t)$ is the resulting output (measured strain time history) and $g(t)$ is an impulse response function. The impulse response function describes the relationship between the system input and output. When the data are discretised Eqn. 2 can be represented using matrix notation.

$$\mathbf{y} = \mathbf{G}\mathbf{u} \quad (2)$$

Typically in experiments the unknown aerodynamic drag force on the model is determined from solution of Eqn. 2 using the measured strain time history and by knowing the impulse response function of the system. Thus the problem becomes an inverse one and the drag force may be found using a numerical deconvolution procedure.

In extending the technique to multiple components, there must be at least as many measured outputs as there are unknown inputs. Ideally the outputs would be directly related to the inputs and therefore independent of one another. In this situation each component could be treated separately using deconvolution. Force balance design generally attempts to minimize coupling, however in practice some coupling always exists between different components. For instance, a pure drag force acting on a model may produce primarily a signal in drag output, but also a signal on the lift output. This is a problem in the recovery of different inputs but can be overcome by determining impulse responses for all outputs subject to all inputs. Therefore a complete description of the system is obtained and may be assembled into a matrix form. An example for a three component system is given in Eqn. 3.

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} \tag{3}$$

Here u_n and y_n are vectors of the system inputs and outputs, assembled sequentially. Matrix G_{nn} contains the impulse responses from the individual component matrices, as in Eqn. 2. The off-diagonal terms in Eqn. 3 represent coupling between the outputs and are generally undesirable.

The solution of Eqn. 3 is achieved using a time domain deconvolution technique developed by Mee et al. (1996) for an n-component system. The solution algorithm is based upon a technique proposed by Prost and Goutte (1984).

3. Simulation strategy for shock tunnel testing

The T4 free piston shock tunnel, located at The University of Queensland, is capable of producing high enthalpy flows over a wide range of conditions. It is therefore suitable for the simulation of the *real gas* effects experienced during the re-entry of the HYFLEX vehicle. The simulation strategy used to ensure accurate simulation of real gas effects is based on Eqn. 4. Here Q represents any dimensionless quantity, such as drag coefficient.

$$Q = Q(\frac{U^2}{2D}, \frac{l_D}{L}, \alpha_\infty, R_e, \frac{T_W}{T_0}) \tag{4}$$

Here U is the free stream velocity, D is the dissociation energy, l_d is the dissociation distance, L is the characteristic vehicle length, α_∞ is the mass fraction of the dissociated gas, R_e is the Reynolds number of the flow, T_W is the surface temperature of the vehicle and T_0 is the free stream temperature of the flow.

To satisfy all quantities in Eqn. 4 binary scaling was used. This requires that the free stream velocity, the quantity ρL (ρ is the free stream density) and the gas composition be matched between the flight and test conditions. (This is to some extent a simplification of the quantities given in Eqn. 4, but is a practical engineering approximation that has been used extensively for hypervelocity testing.) Then by assessing the range of test conditions available in the T4 facility and the HYFLEX vehicle's flight conditions, a basic model size was determined. The test flow conditions chosen corresponded to a point 120 seconds after separation in the HYFLEX flight. This became the nominal size around which the model and force balance were designed.

4. Newtonian Modelling

An estimate of the aerodynamic forces acting on a scaled model of the HYFLEX vehicle was obtained using a Newtonian flow solver (refer to Smith et al. (1996)). An example of the surface mesh used in the modelling is illustrated in Fig. 1.

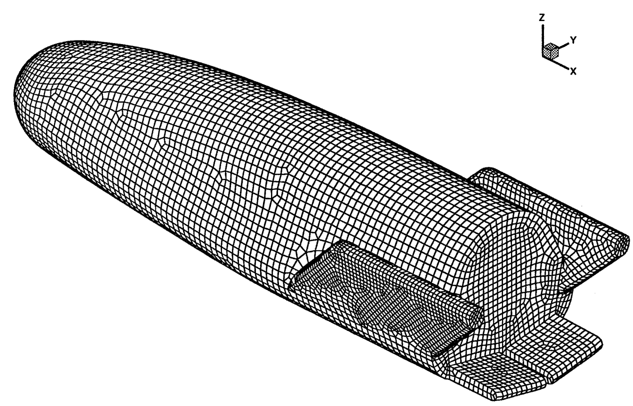

Figure 1. Surface mesh of HYFLEX vehicle used for Newtonian modelling.

The expected test flow conditions in the T4 facility were used in the Newtonian modelling with the flow direction set from the orientation of the HYFLEX vehicle during flight. The force distribution obtained from the Newtonian solver was resolved into components distributed along the major axis of the HYFLEX vehicle. This distribution of force is illustrated in Fig. 2 where the axial direction corresponds to the x-axis in Fig. 1.

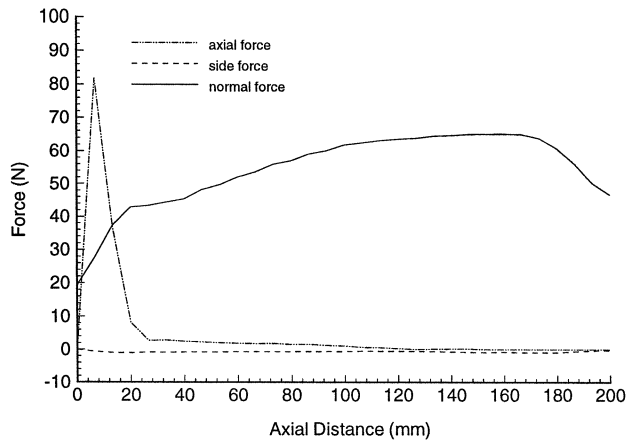

Figure 2. Distribution of force components acting on a scaled model of the HYFLEX vehicle in test flow produced by the T4 facility.

5. Finite Element Modelling

The central role of finite element (FE) modelling in the design process is the dynamic analysis of different force balance designs. The FE model is used to determine the dynamic response of a proposed force balance. The dynamic response is then used to assess the suitability of the force balance to deconvolution and give insight into the extent of coupling between outputs.

5.1. General modelling considerations

FE Models were developed using MSC/PATRAN and were solved using MSC/NASTRAN. Both of these packages were run on a Silicon Graphics Power Challenge Array. Although MSC/NASTRAN permits solution of transient linear problems through both modal and direct integration methods, only the latter was used because of the short times and high frequency content of the responses. The post-processing was preformed using a variety of programs developed by the authors.

Several factors influence the accuracy in computing a dynamic or transient response of a structure. These include: mesh refinement, mesh transitions, internal/structural damping, integration time step and the distribution of applied loadings. These issues and others were addressed by Daniel and Mee (1995) where similar FE modelling techniques were used in the design of a stress wave force balance. The suggestions made there were employed to ensure the accuracy of computed results.

Initially a large number of different configurations were examined. These provided valuable insight into the dynamic behaviour of the different arrangements. Some of the basic design principles established from this modelling are outlined below.

The effect of symmetry in the balance geometry was found to be significant. This is because decoupling of force and moment components relies on similarity in the response time histories from the balance outputs. Therefore balance symmetry with respect to the model and the measured force components is important.

Lower frequency modes often tend to supress the transmission of higher frequency components by dominating the response. This causes problems in the deconvolution of such signals as there is insufficient frequency content to permit full recovery of the original signal. Dominant modes were minimised by altering the relative stiffness of sections of the model and the installed force balance. This approach was found to also be effective in reducing unwanted high frequency noise in the output signals originating from flexural vibration of the model.

In previous work by Mee et al. (1996) the force balance/model was supported in the test section by a long stress bar suspended from threads. This *free end* condition is useful for calibration and experiments as it may be modelled accurately. For the case of the HYFLEX model the incident angle is approximately 49°. At this angle the size of the test section limits the length of the stress bar to around 150 mm. This reduction in length also corresponds to a reduction in mass which consequently reduces the measureable strain level because of reduced inertia in the stress bar. Therefore it is necessary to use a *fixed end* stress bar. The fixed end condition is produced by connecting the end of the stress bar to a relatively large mass, rigidly mounted in the test section. This serves to reflect stress waves back from the end of the stress bar enabling measureable strain levels to be developed in the force balance.

These design aspects were used in the development of a preliminary FE model. This model was simple and permited changes to be easily made which allowed optimisation of force balance geometry and configuration.

5.2. Preliminary FE model

The preliminary FE model was based on a cylinder of the same aspect ratio as the HYFLEX vehicle, except scaled so as to be representative of the final shock tunnel model. The force balance consisted of two cruciforms attached to a central bar incorporated into the model. The ends of the central bar were connected rigidly into the model at each end. The arrangement is illustrated in Fig. 3.

Although different materials were tested, Aluminium was choosen due to its high elastic wave speed and relative stiffness. The FE model was fully constrained at the down stream end of the stress bar. This represents the *fixed end* condition discussed in Section 5.1. Loads were applied as surface pressures to the model for the

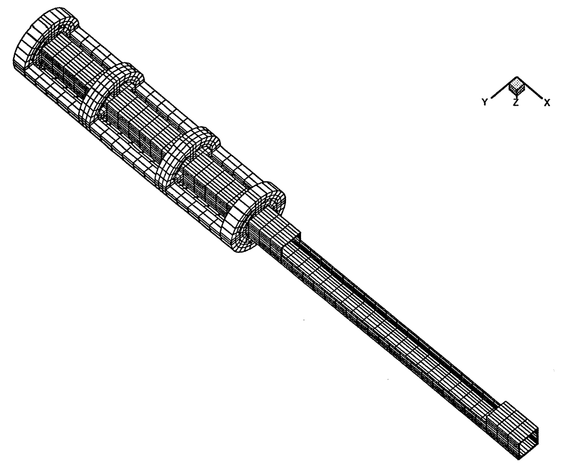

Figure 3. Finite element mesh of preliminary force balance design. Sections of the mesh have been removed to reveal internal details of the force balance.

six force and moment components. The magnitudes of these loads were obtained from the Newtonian modelling (discussed in Section 4.) and were initally distributed uniformly along the model.

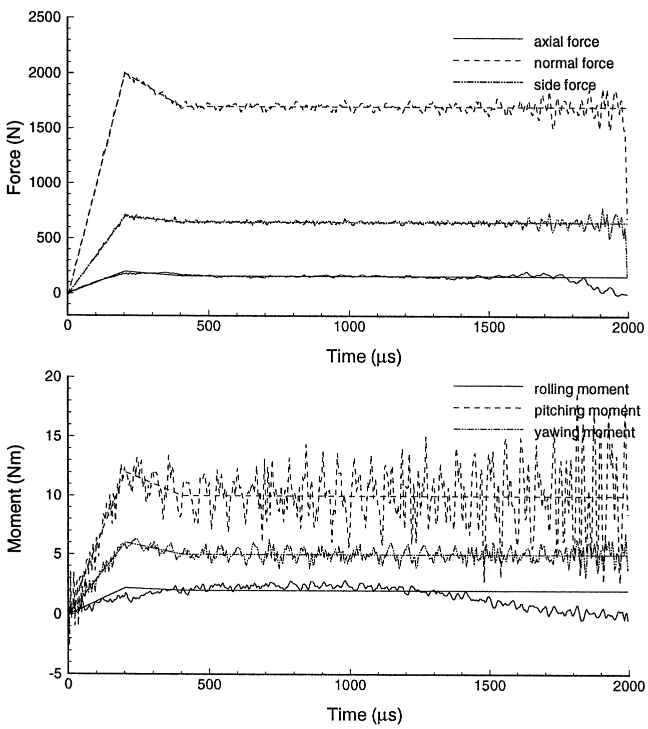

Figure 4. Original and recovered loads for all six force and moment components obtained from the preliminary FE model. Note: The side force has been scaled for illustration purposes.

Six force and moment outputs were obtained from the FE model by combining the computed step responses at 12 different locations. The step responses were determined from axial strain measurements in the eight bars along with axial and shear strain measurements in the stress bar.

To assess the suitability of the response of the force balance to expected loading time histories, simulated outputs were generated and then deconvolved to ensure that the original load time history could be recovered. The simulated outputs were generated by convolving the impulse response function (obtained from differentiation of the step responses) with an assumed *tunnel-type* loading time history. The impulse response function was then used to deconvolve the simulated output. Agreement between the applied *tunnel-type* loading time history and the deconvolved/recovered loading time history verifies the suitability of the force balance. An example of this comparison is illustrated in Fig. 4 for the FE model illustrated in Fig. 3.

The results shown in Fig. 4 demonstrate good signal recovery from all force and moment components apart from the rolling moment. Problems arise in the measurement of this component as the time history of the response is very slow in comparison to the other components. This problem remains unresolved as there is little that can be done to increase the torsional stiffness of the present model/balance configuration.

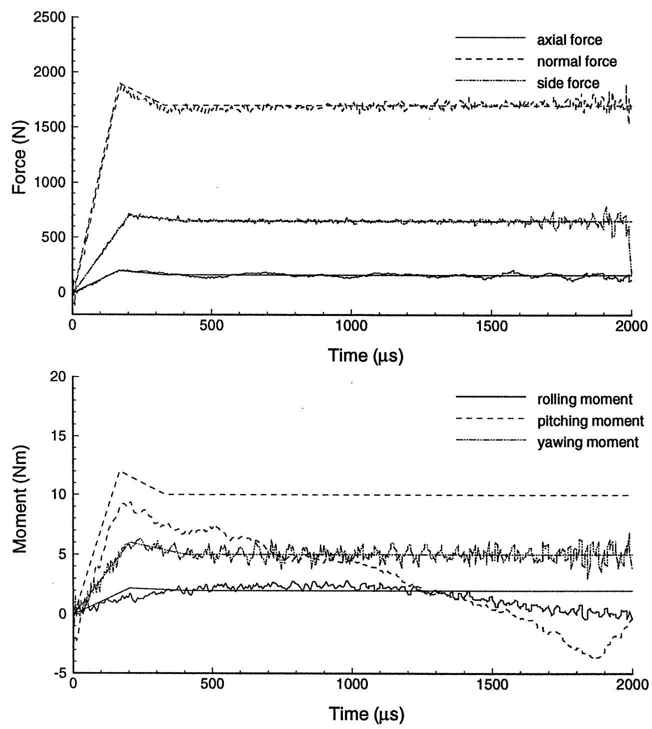

Figure 5. Original and recovered loads for all six force and moment components.

Although the signal recovery is good from this model, problems arise in the measurement of the pitching moment when the applied loads are distributed according to the Newtonian modelling (illustrated in Fig. 2). This distribution of loading causes stronger coupling between the normal force and pitching moment outputs resulting in poor signal recovery, as illustrated in Fig. 5. To overcome the problem of coupling, a variety of modifications to the force balance configuration were tried. These included altering the position of the force measurement bars along the central bar, changing the distribution of mass within the model, reducing the length of the stress bar and examining different output locations and combinations. The most effective modification was changing the position of the force measuring bars. This was found to give a reduction in the coupling between normal force and pitching moment and therefore improved signal recovery. Reducing the length of the stress bar also improved the decoupling as the dominance of low frequency oscillations within the balance/model is reduced. With these design features in mind a new FE model was developed using the actual HYFLEX geometry.

5.3. HYFLEX FE model

The HYFLEX FE model (illustrated in Fig. 6) incorporated the modified force balance design into the actual HYFLEX vehicle geometry. Only minor features, such as the wings and the tail flaps, were omitted from the model. The internal geometry was kept as close as possible to the preliminary balance designs, however some asymmetry resulted from the HYFLEX vehicle geometry.

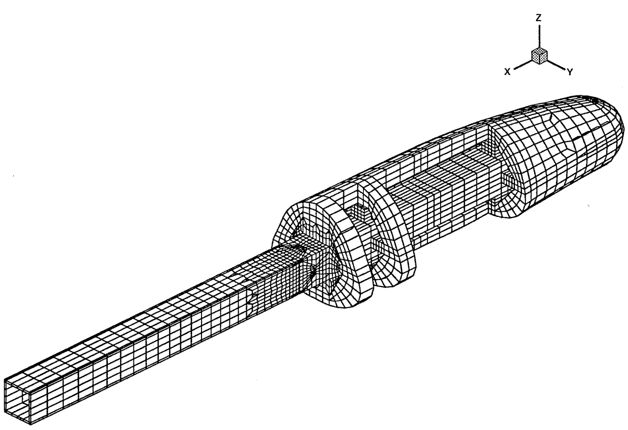

Figure 6. Finite element mesh of the HYFLEX vehicle with portion of mesh removed to show internal force balance.

The HYFLEX FE model was constrained in the same way as the preliminary model. The loads were applied again as surface pressures and were distributed according to the Newtonian modelling. The results of the original and recovered loads for this force balance are illustrated in Fig. 7. Here the results demonstrate that the current force balance design is capable of measuring all simulated aerodynamic forces and moments on the HYFLEX vehicle, apart from the rolling moment.

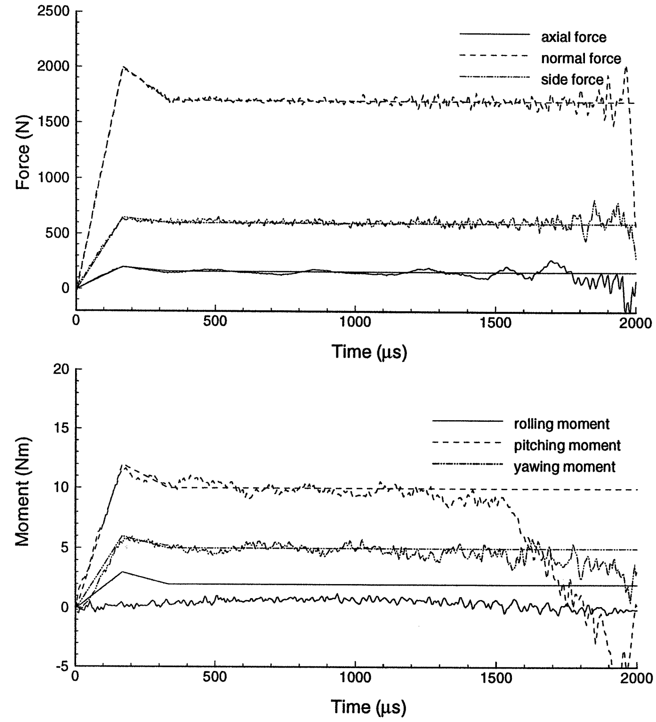

Figure 7. Original and recovered loads for all six force and moment components.

6. Mechanical Design Aspects

The layout drawing, shown in Fig. 8, illustrates the main features of the final force balance. Work in progress is concentrated on the manufacture of the force balance, model, stress bar and the shock tunnel mountings. The balance was machined from one piece of aluminium with the four quadrants of the model attaching around the outside. The final HYFLEX geometry was then machined using a five axis numerically controlled (NC) mill. The wings and the tail flaps were also NC machined and are to be attached to the model. The force balance will be instrumented with semiconductor strain gauges while the stress bar is to be instrumented with both shear pattern and piezoelectric film strain gauges.

7. Summary

The FE analysis and balance-performance simulations indicate that it should be possible to apply the stress wave force balance technique to measurements on an aerospace-plane configuration in a free piston shock tunnel flow. The results demonstrate some of the difficulties which arise in dealing with the more complex geometries of such vehicles, asymmetry of the model about the balance being one of the major considerations. The modelling indicates that the present balance design should be capable of measuring three force and two moment components, but that it is unsuitable for accurate measurement of rolling moment. Only axial and normal forces

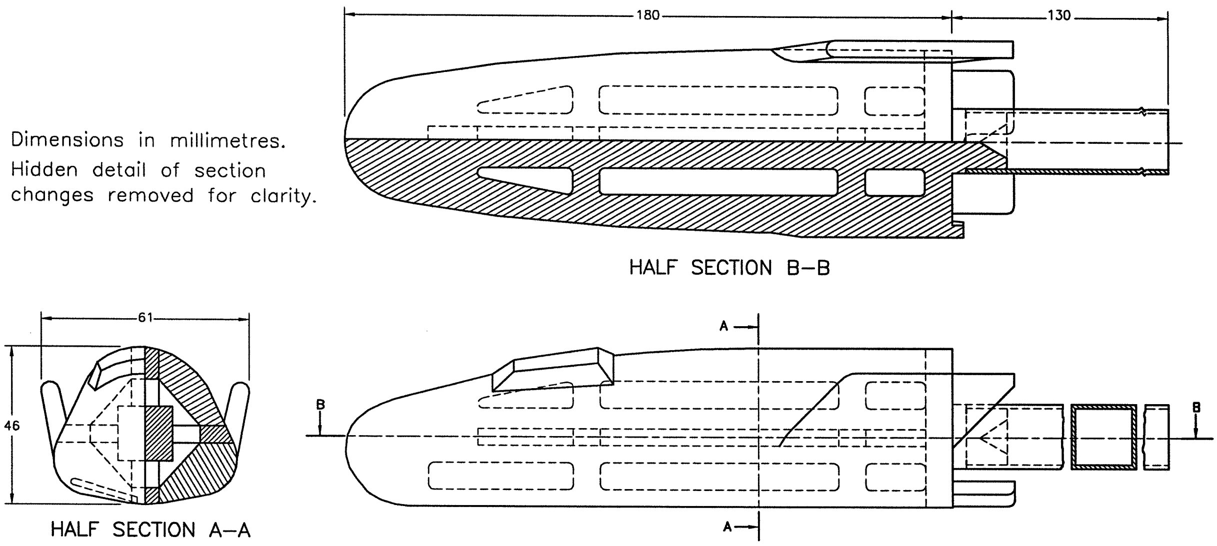

Figure 8. Layout of force balance mounted inside HYFLEX.

and pitching moment are of interest in the proposed testing of HYFLEX in the T4 free piston shock tunnel facility.

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