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The aerodynamic stability of superorbital reentry craft

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ABSTRACT

This paper presents the results of preliminary experiments and analysis performed on a generic sphere-cone reentry capsule at superorbital speeds in an expansion tube. The passive stability of flight vehicles is realised by placing the mass centre upstream of the centre of pressure. However for axi-smetric vehicles at zero incidence, the line of action of the force and the vehicle axis are coincident, and no centre of pressure is defined. Stability is then determined by the behaviour of the vehicle at small perturbation angles to zero incidence. The resulting centre of pressure of the inclined craft is found from the intersection of two nearly parallel lines, and is hard to measure experimentally without using a large angular perturbation, which alters the flow field around the axismmetric body. The measurement thus obtained may not give a true indication of the stability of the vehicle at zero incidence. The approach taken in this paper is to split the capsule into equal halves, and to measure the lift and lift centre of the two half-bodies. The measurement obtained is sensitive to the same parameters which determine the location of the aerodynamic centre, (i.e. the distribution of surface forces), and is therefore useful for validating analytical and computational models of the flow field.

INTRODUCTION

Thermal protection is a vital component of all spacecraft which are required to make hypervelocity transits through planetary atmospheres. Heat shields constitute a significant fraction of the weight of such craft, which detracts considerably from the useful payload which can be carried, and reduces the overall value of the mission. In the event of heat shield failure, total loss of the spacecraft will occur, so heat shield survival is of paramount importance. For entry speeds of low Earth orbital velocity and below (7.9 km/sec), reusable insulation, such as seen on the US space shuttle, may be used. However for higher flight speeds, and where the reusability is not required, sacrificial ablative insulation is used. Ideal heat shield design incorporates minimum mass of insulating material, whilst achieving adequate thermal protection on all exposed surfaces. Such optimised designs are not possible at the moment for superorbital speeds, because the aero-thermo-dynamic processes of high speed reentry are not understood sufficiently to give accurate predictions of the surface heating and ablation rates involved. Where such heat shields have been made and successfully flown in the past, it has only been possible by means of very conservative engineering design factors, and the resultant heat shields have been excessively heavy and inefficient.

From a thermal point of view, the best shape for a reentry vehicle is a very blunt body, with the windward surface normal to the incoming flow. This maximises direct energy transfer to the gas through the normal shock, and minimises heat transfer to the spacecraft structure. However, from an aerodynamic point of view, this is unstable, as the centre of drag is well forward of the mass centre. Therefore to use this sort of configuration, an active control system is required. This is quite satisfactory if the space craft is sufficiently large to house the control apparatus, as for example, the Apollo return capsule which used multiple jet thrusters. However, an increasing number of spacecraft now involve small entry capsules, with diameters of the order of a metre or less, in which it is not practical to install active control systems. For such systems, an intrinsically stable aeroshell is required.

The generic sphere-cone shape provides a simple means of doing this, (Ivanov et al 1998). The large area of the downstream section of the cone moves the centre of drag towards the rear of the craft, which at the appropriate cone angle gives stability. Such a configuration was used in the successful Galileo craft (Jupiter entry at 47.4 km/sec), and the Huygens probe for Titan entry. This shape, as well as being effective for practical flight vehicles is also amenable to simple parametric optimisation, the complete windward geometry being defined by only three parameters (cone angle, nose radius and base diameter).

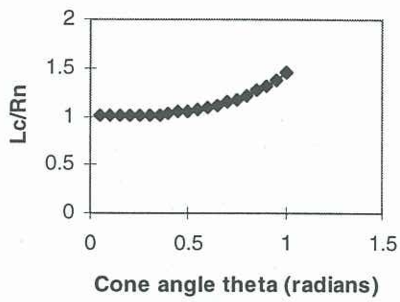

Figure 1

The geometry chosen for this study is that of the Japanese 'MUSES C' asteroid sample return mission reentry capsule, Ahn 1997. It is a 45-degree sphere cone with a nose to cone base radius ratio of 1. Newtonian theory has been used to indicate the sensitivity of location of the aerodynamic centre to cone angle for this configuration, Figure 1. For the purposes of this paper, the aerodynamic centre is defined as the limit of the centre of pressure as the craft approaches zero incidence, which as mentioned below cannot be easily measured. The trend is to some extent counter intuitive, but can be explained by noting that as the cone angle goes to zero, the body shape approaches a sphere, and the static pressure force vectors all go through the sphere centre. As the cone angle approaches 90 degrees, all the force acts at the nose, but the direction of the force is along the line of flight, giving a theoretical centre of pressure at infinity, with apparent stability. That the 90° cone is not stable can be seen by inspecting the restoring moment created by the different shapes, Figure 2.

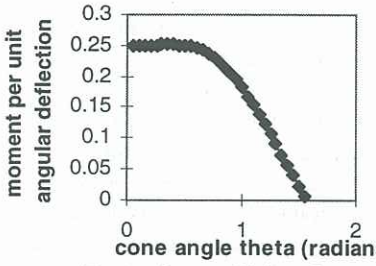

Figure 2 sensitivity of restoring moment to cone angle

Because the pressure generated on the windward surfaces closely follows the Newtonian approximation of $\sin^2(\theta)$, the near-normal surfaces associated with the blunter cones generate higher pressures. However, at zero incidence on an axisymmetric body these forces are balanced and generate no torque. The restoring torque scales with the angular derivative of pressure, or the $\sin(\theta)\cos(\theta)$ product, which goes through zero at 90 degrees and has a maximum at 45 degrees. The value of 45 degrees is seen to have good restoring torque, and a relatively aft centre of pressure, but is less effective as a braking body than the blunter shapes. It is of interest to know just how blunt they can be made, and still be amenable to passive control. The Newtonian analysis above is only approximate, and is not adequate on its own to verify a design. Of particular interest on the bodies at the limits of stability, with cone angles around 45 to 60 degrees, is the location of the sonic point, which may lie on the flank of the cone adding uncertainty to the dynamic response of the capsule. At the superorbital speeds pertaining to this study, real gas effects have a strong influence on the sound speeds and Mach number of the shock layer. The purpose of the experiments is to provide data for the evaluation of analytical and numerical models of the flow.

Having selected an axisymmetric body, a problem now arises in experimentally measuring the aerodynamic properties, in particular the centre of pressure. At zero incidence the centre of pressure is undefined, so measurement requires the body to be placed at some small but finite angle to the flow. The centre of pressure of the inclined capsule is given by the intersection of the axis of symmetry with the line of action of the aerodynamic forces, which diverge from parallel lines at increasing incidence. As the deviation from zero incidence increases, the accuracy of the experimental measurements improves (we are no longer trying to find the intersection of two 'parallel' lines), but the flow field may change significantly.

The objective of this work is to devise an experiment which measures the distribution of aerodynamic forces with the craft in the position and orientation at which it is intended to fly, i.e. zero incidence. This is done by splitting the axisymmetric body, (which experiences no lift) into two matching halves generating equal and opposite lifts. By means of force transducers fabricated from pietzoelectric film, the magnitude and distribution of the lift force can be measured. The stability of the capsule is not determined by lift alone, as the drag experienced by a craft perturbed from its intended orientation is also important in creating a restoring torque. However, all the factors which determine the location of the centre of pressure are involved in determining the centre of lift, i.e. the local distribution of static and shear stresses. The half-body lift measurement is therefore useful for validating the analysis used to estimate the centre of pressure.

EXPERIMENTAL METHOD

A schematic of the models used for the experiments is shown in Figure 3. The model is constructed from two equal and opposite halves, with 3 force transducers connecting them. The tripod mounting arrangement, Figure 5, ensures good contact between the sensing films and the anvils, and all sensors are preloaded by a bolt located at the centroid of the contact points. A small gap, (approximately 0.01 mm was found to be optimal), prevents contact and force transmission between other parts of the model. The gap is sealed around the edges by a thin layer of RTV 'Silastic' to protect the sensors from the high enthalpy flow. Dynamic calibration decouples the effect of any force transmitted through the Silastic sealant and the preload bolt, Stewart 1998.

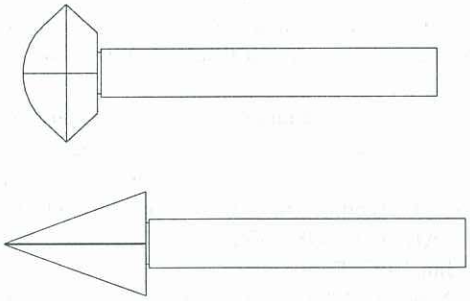

Figure 3 Models used for half-body lift measurement

Two models were used for the experiments. The first was a two dimensional wedge with a half angle of 19.2 degrees. This model was chosen as it has supersonic flow throughout, and a nominally uniform surface pressure distribution for which the magnitude and location of the lift forces could be predicted with confidence. The purpose of this model was to prove the viability of the technique in a simple configuration. The second model was a 1/6.66 scaled copy of the MUSES C capsule, chosen as a case study to use the technique on an important configuration with non-uniform and unknown surface pressure distribution.

The models are mounted loosely on the support sting through a nylon bush, and are effectively in free flight for the duration of the test flow, which is between 40m to 80 microseconds depending on enthalpy. The purpose of this is to eliminate any shear forces between the matching halves of the models which would arise if either of the components was rigidly mounted. Both halves see the same longitudinal force and acceleration, and so the films are loaded in pure compression, with no corrupting signals due to shear. The films generate charge in proportion to compressive load, which generates a voltage inversely proportional to the capacitance to which they are connected. For some of the tests charge amplifiers were used, but adequate signals were also obtained by direct connection to the recording device, with appropriate calibration for the associated capacitance.

Transient force measurements in short duration facilities can rely on reaching an equilibrium between the applied load and the measured signal if the response time is sufficiently short, or they may require a deconvolution of transient data to reconstruct the input function, Mee et al 1996. The models used were constructed to be as mechanically stiff as possible, in the hope that the simpler and less noisy first technique would apply. When the response of the sensors to dynamic loading was tested using a dynamic calibrated hammer, Mee 1998, it was seen to follow the input signal closely with a small delay.

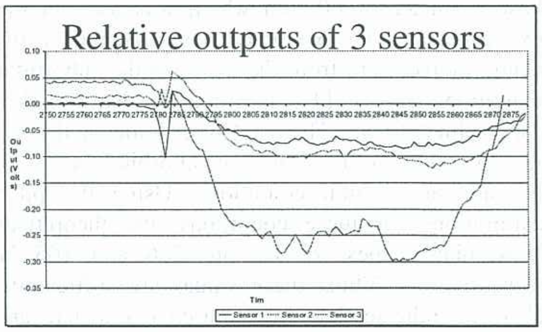

Figure 4. MUSES C capsule, equivalent flight speed 7.3 km/sec. 125 microseconds full display.

In Figure 4 the output from a test on the MUSES C capsule at a suborbital condition is shown.

This condition has approximately 90 microseconds of test flow, and the sensor outputs are seen to be constant after about 30 microseconds, giving a good indication of the steady force levels during the useable test time. It is noted that filtering was required to remove an oscillation from the signals during the flow. The two symmetrically placed sensors are seen to give good agreement, Figure 4.

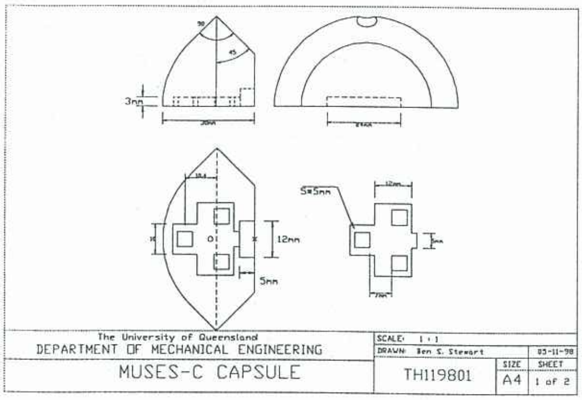

Figure 5 Layout of sensors in capsule.

The tests were repeated with a superorbital test condition at 10.5 km/sec, and having a steady flow duration of approximately 30 microseconds. This is right on the limit of the response time of the gauges, and is a condition which really requires the deconvolution techniques of Mee (1996) to achieve adequate response. However, the values to which the signals are approaching are sensible, indicating the technique may be worth refining further to improve the dynamic response.

Newtonian analysis of the windward surfaces of the MUSES C capsule puts the centre of lift at a distance of 9.7 mm from the leading edge for the base diameter of 60 mm which was used in the experiments. The experimental results put the lift centre at 10.7 mm from the nose for the suborbital condition, and at 11.1 mm for the less reliable superorbital flow. The total magnitude of the lift was measured at 267 N for the suborbital and 83 N for the superorbital conditions. Using the pitot calibrations for these conditions, the theoretical Newtonian values for lift are 286 and 105 N respectively. Whilst these values are sufficiently close to indicate that the required parameters are being effectively measured, the technique is not yet refined enough to definitively state that a measurable deviation from Newtonian flow has been detected. This will require a more extensive testing program, and signal conditioning such that filtering is not required during the test flow.

CONCLUSION

A technique has been developed which measures the lift magnitude and distribution for symmetric half-bodies in two dimensional and axisymmetric flows at zero incidence. The technique has been demonstrated at superorbital and high suborbital speeds, with the response time for the superorbital flows being marginal for currently available facilities. At suborbital speeds steady force measurements are obtained well within the calibrated flow duration. The instrumentation has been tested on the Japanese MUSES C asteroid sample return mission capsule in the X2 superorbital expansion tube at The University of Queensland. The measured total lift values agree with Newtonian predictions to 7% for suborbital flows, and 20% for superorbital flows. The location of the lift centres from the stagnation point is within 10% of Newtonian for suborbital and 13% for superorbital flows. The method needs more refinement and development before the results can be taken to give a definitive and quantitative indication of departures of analytical theory and CFD from experiment. However, it is a potentially useful technique for measuring the aerodynamic force distribution of axisymmetric bodies at zero incidence in pulsed facilities. Because it does not disturb the airflow from the designed flight condition, and it is sensitive to all the parameters which determine the location of the center of pressure of flight craft at near-zero incidence, it is potentially a very useful technique for experimental validation of computational and analytical models of reentry body stability.

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