THE SIMULATION OF A PROPULSIVE JET AND FORCE MEASUREMENT USING A MAGNETICALLY SUSPENDED WIND TUNNEL MODEL

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SUMMARY

Models featuring the simulation of exhaust jets were developed for magnetic levitation in a wind tunnel. The exhaust gas was stored internally producing a discharge of sufficient duration to allow nominal steady state to be reached. The gas was stored in the form of compressed gas or a solid rocket propellant. Testing was performed with the levitated models although deficiencies prevented the detection of jet-induced aerodynamic effects. Difficulties with data reduction led to the development of a new force calibration technique, used in conjunction with an exhaust simulator and also in separate high incidence aerodynamic tests.

INTRODUCTION

The aerodynamics of base flows are particularly subject to support interference and it is desirable for the Magnetic Suspension and Balance System (MSBS) to be capable of such investigations. The influence of the propulsion system on flight vehicle base flows leads to the conclusion that a commercial wind tunnel equipped with an MSBS should be capable of propulsion simulation tests. Performing these tests with a magnetically suspended model presents a particular challenge, given the complexities of achieving such simulation, of inlet and exhaust flows simultaneously for some models, even in a conventional wind tunnel.

The aim of the work outlined in this paper was to address the issue of providing an exhaust flow from a magnetically suspended model free from an umbilical. The overriding design consideration for this simulation, as no support exists through which to supply a gas, became the need to incorporate a gas generator within the levitated model.

An evaluation of exhaust flow simulators was undertaken as a cooperative venture between Physical Sciences Inc. (PSI) of Andover, Mass. and the University of Southampton, England, funded under the NASA LRC SBIR scheme NAS1-17496. In terms of hardware PSI contributed a complete model for the work described in this paper, based on the use of stored liquid CO_2 as a gas source, while the University provided a model featuring a solid propellant gas source, the magnetic suspension system and associated wind tunnel.

The wind tunnel is horizontal and its magnetic suspension system comprises a set of ten actively controlled copper wire electro-magnets, some with air and some with iron cores, positioned around the test section, acting upon a magnetised model. The coil and model geometries allow the control of up to six degrees of freedom. The system is stabilised by the action of an optical system which senses model

position and attitude, feeding to digital control software in control loops which generate demands for current from individual power supplies for each electro-magnet. The computer allows also the control of position and attitude by change of set point. A schematic of the magnets and model is shown on figure 1. The test section is 7 inches across and allows the testing of models of length about 5 to 8 inches depending on angle of attack. The role of the electro-magnets is to magnetise the model, support its weight and resist aerodynamic and propulsive system force and moment components. The sum of each of the force and moment components acting on the model during a test is measured by establishing a relationship between them and the set of currents, by means of calibration.
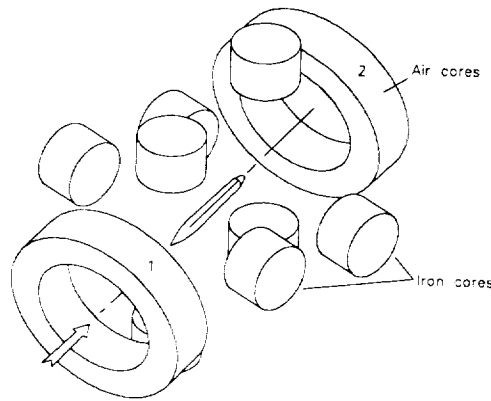

Figure 1. Wind tunnel magnetic suspension and balance system.
Array of electro-magnets around the test section.

Prior practice had been to levitate model designs comprising a non-magnetic outer aerodynamic shell normally containing permanent magnets, although we had experience in suspending models with iron cores and also a superconducting core. In view of the demands of the propulsion simulation experiments, namely a need to withstand a reasonably high force, to provide gas storage space, a nozzle and perhaps controls, it was decided to avoid the non-magnetic shell and instead to use iron for the whole of the model to easily allow a complex internal geometry, the maximum magnetisable volume and a high force capability provided the model was well magnetised. Essentially the model would be axi-symmetric and therefore need active control in only five degrees of freedom, rolling being prevented passively by an offset centre of gravity.

MODIFICATIONS TO THE SOUTHAMPTON MSBS TO ALLOW PROPULSION SIMULATION

The major change required was provision for the magnetisation of ferrous models, by means of current components in appropriate electro-magnets. The magnetisation method was novel in that the magnetisation vector was rotated to match the instantaneous angle of attack of the model. This was the first use of an adaptive magnetisation procedure, allowing the suspension of iron models over the full angle of attack range available with the Southampton MSBS[1].

Normally the streamwise position of the model is monitored with a laser light beam directed across the base of the model. This region was now to be occupied, at least in part, by exhaust gas which we could not be sure would not affect the beam. Therefore this component of model position was monitored

at the nose, requiring a software trigger to be installed to switch off electrical power to the electro-magnets when the model was absent.

EXHAUST SIMULATOR SPECIFICATION

The notional design would comprise a gas generator, controls and rear-mounted nozzle all contained in iron. The propulsive force vector would be along the model axis and generally horizontal, resisted partly by the air-cored electromagnet pair 1,2 on figure 1. Force capability was limited by current to about 1 lb. The good resolution of forces and moments required, in our experience, a steady model and currents. Good resolution was necessary if the aerodynamic effects of exhaust flows were to be separated. A minimum thrust-on duration was therefore set by the need to allow time for model motion transients to die away following firing. The model position control system had a natural frequency of order 10Hz with fairly good damping not far short of critical and therefore as a minimum the thruster needed to run steadily for about a half-second for the model to steady with another half second or so to allow data sampling and averaging.

Exhausts are often characterised by nozzle pressure ratio. The ratio of specific heats of the jet γ is also an important parameter[2]. The importance of other jet properties such as temperature, pressure, Mach number and Reynolds number depends on the particular propulsion simulation test to be attempted, which typically might be a rocket or jet engine exhaust. The test engineer is forced to compromise, selecting a small number of parameters to be correctly scaled for each investigation. Reference 3 is a review of requirements. Thrust duration and time profile were the main design drivers in this exploratory work.

A review of safety, cost and convenience issues eventually narrowed down the several options for on-board gas generator and led to the use of two commercially available generators. In turn this decision introduced constraints on the available generator size and therefore total mass of stored gas. The combination of design considerations led to the use of small diameter exhaust jets in relation to the body diameter, compared with many flight vehicles.

CARBON DIOXIDE THRUSTER

A compressed gas thruster was selected by PSI for proof of concept propulsion simulation trials. The decision to develop the compressed gas thruster was based on the perceived simplicity[4]. In the absence of any source of heating this type of thruster would by its nature generate a low temperature jet in comparison with many engines, but could be fairly representative in terms of γ and jet Mach number.

A thruster was proposed containing a small disposable CO_2 bottle, the contents of which could be exhausted via a nozzle. The major difference between the initial proposal and the design eventually tested was that the initial proposal incorporated a control valve to regulate gas flow. However no fast-acting valve was commercially available to match the small scale of the model and PSI were forced to omit a valve from the final design. Figure 2 is a simplified sketch of the layout of the model showing the important components. To initiate the gas discharge a laser beam was shone into a window on the forward

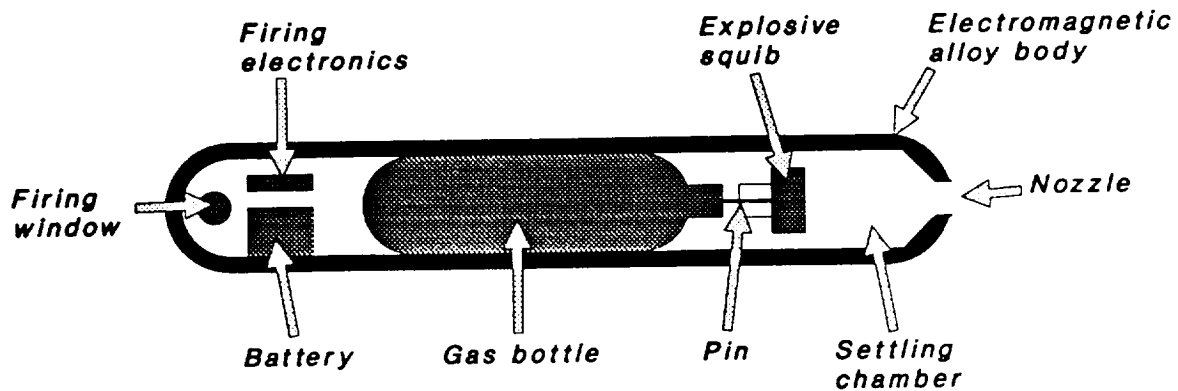part of the model, firing a squib to puncture the bottle.

Figure 2. Schematic of compressed gas exhaust simulator model.

Thruster Performance

In the design study for the small scale carbon dioxide propulsion simulator[4], PSI envisaged a stepped (or top-hat) thrust profile of two to three seconds duration. Such a profile would have been suitable for exhaust simulation in the Southampton MSBS. A typical profile from the actual thruster is shown in Figure 3. A peak corresponding to puncturing the gas bottle is followed by an almost exponential decay in thrust over a period of around one second.
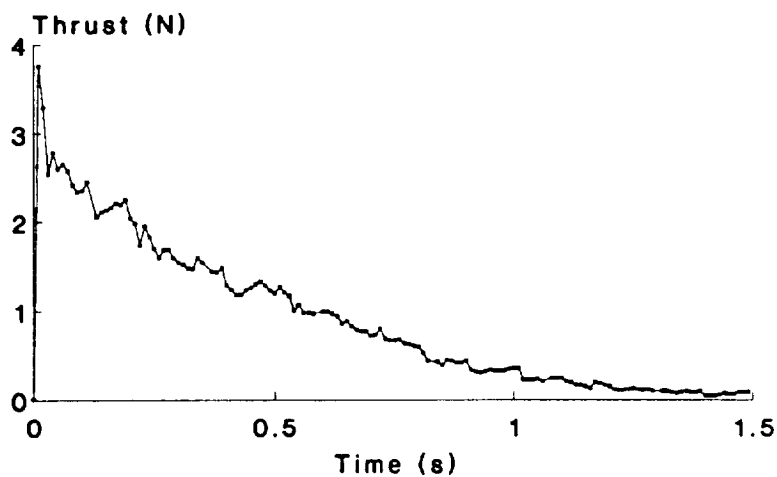

Figure 3. Thrust profile produced by the compressed gas exhaust jet simulator.

The critical factor leading to the discrepancy between the expected and actual thruster behaviour was the assumption that the propulsion simulator model had enough thermal mass to maintain the temperature of the carbon dioxide bottle and contents during a firing. The observed thrust decay is a result of rapid cooling of the thruster as the carbon dioxide absorbs heat for vaporisation and expansion from the model structure. This cooling reduces the vapour pressure and consequently the rate of CO_2 vaporisation.

The ultimate aim of the wind tunnel tests conducted using the suspended CO$_2$ thruster was to measure the difference in drag coefficient caused by the presence of an exhaust plume. To make this measurement it was expected that the following three parameters would be evaluated:

1. Installed thrust: Probably inferred from bench tests of the thruster.
2. Total external force: This comprises thrust and drag, and for tests at incidence also includes effects of lift and pitching moment.
3. Zero-thrust total external force: Aerodynamic loads alone.

Thrust was found to be sensitive to the initial temperature of the model and to attitude, factors which contributed to inconsistencies in the thrust. The resulting unsuitable thrust-time profile combined with the unsatisfactory repeatability of this thruster caused severe control and data interpretation problems. In the form tested the small-scale CO$_2$ thruster was judged as being poorly suited to the needs of exhaust simulation in the MSBS.

However once it had been shown that the capability of the MSBS to apply static axial force to the compressed gas exhaust simulator exceeded the level of the expected thrust peak, a series of firings of the thruster in suspension proceeded at zero angle of attack. The thrust peak tended to cause a large transient axial motion of the model. A large peak would often cause the model to move out of range of the axial position sensor. This event usually caused a loss of control. If the initial disturbance did not exceed the allowable limits, the MSBS was generally able to regain control of the thruster[1].

The MSBS with CO$_2$ model was calibrated statically for three components. The aim was to use the results of the calibration, that is the variation of system current with lift, drag, and pitching moment, to allow the extraction of these components from run-data obtained during thruster trials in suspension.

In view of the relatively violent motions of the model following its firing, a new computer program, TRANSIENT, was developed to deduce the forces and moments acting on the model from the observed changes in system current and model position. The aim was to derive the time history of the heave force, axial force and pitching moment from recorded data, the analysis accounting for inertia and acceleration[5]. The results obtained were generally disappointing. The axial force extracted from a wind-*off* thruster firing should have resembled a typical thrust profile such as that of figure 3. However, the output of the analysis appeared badly corrupted, as shown in Figure 4. A number of position-dependent factors were thought to have combined to denigrate the results. Some of these factors were identified and modifications made in attempts to reduce their effects but without a satisfactory outcome.
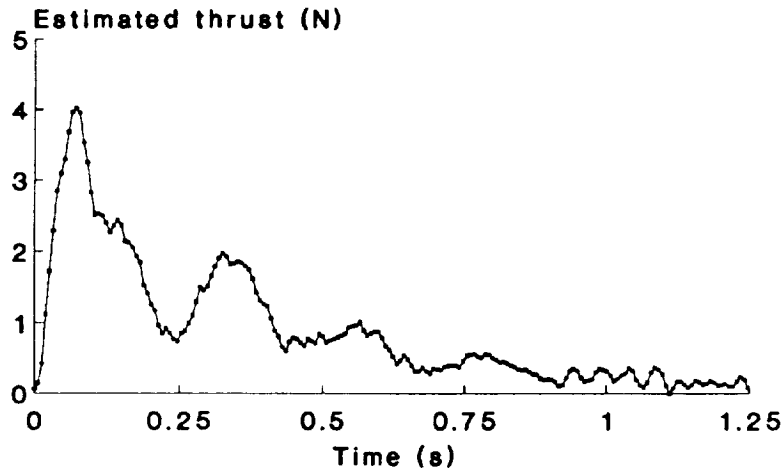
Estimated thrust (N)

Figure 4. A typical thrust history calculated from position and current data.

It became clear that given the available apparatus, two of the parameters introduced above, whose evaluation would allow measurement of a change in thruster drag coefficient, could not be accurately assessed. The thrust level (1) was uncertain and variable for this model, while as described above, attempts to extract three force and moment components simultaneously were not successful. This prevented accurate assessment of parameter (2). Parameter (3) could be found with more confidence.

Further investigations into the subject of the transient-dependence of the analysis were not deemed worthwhile. The performance of the compressed gas propulsion simulator was considered to be so far removed from that of a device acceptable for use in production wind tunnel testing as to draw into question the benefit of the further development of strategies to cope with its unpredictable and peaky thrust profile.

The disappointing results helped prompt a review of force measurement practices employed with MSBS facilities. This led directly to the development of the DFM technique described later in this paper.

SOLID ROCKET PROPELLANT

The use of a solid rocket grain to generate an exhaust plume in an MSBS was first considered by PSI in their initial proposal to NASA for the propulsion simulation contract[4]. The idea was rejected but doubt arose later over the objections in the light of the availability of small solid propellant motors from various sources, including rockets from hobby shops for use in model rockets and aircraft. It was decided to pursue the solid rocket option at Southampton.
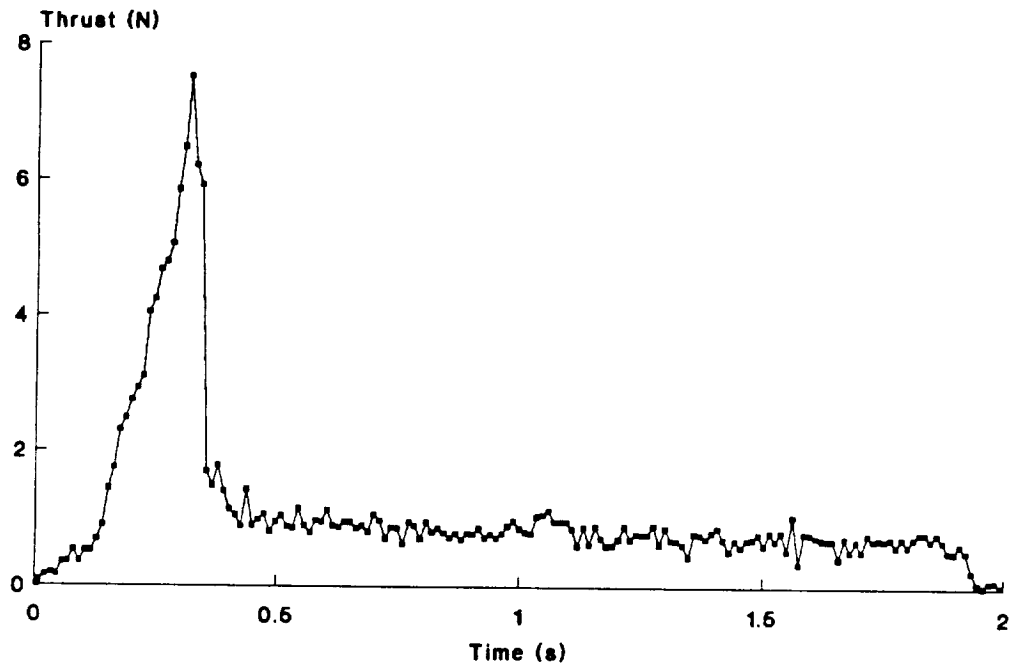
Figure 5. Thrust profile for solid propellant rocket motor

Hobby rocket motors generally have a peaky thrust profile. Figure 5 shows a typical profile featuring a substantial boost peak followed by a cruise phase. This same source of rocket motor was developed to a form more suitable for use for propulsion simulation with an MSBS. The development paid particular attention to the ignition and burn-out phases[1]. Figure 6 shows the performance of the same grain material but developed for this application and is typical of the developed performance. The profile is essentially top-hat as desired, of sufficient duration and suitable maximum thrust. The only criticism of the profile is the time variation of thrust, small but still judged to be too high, and a variability between motors which seems inevitable, discovered later during the test series.
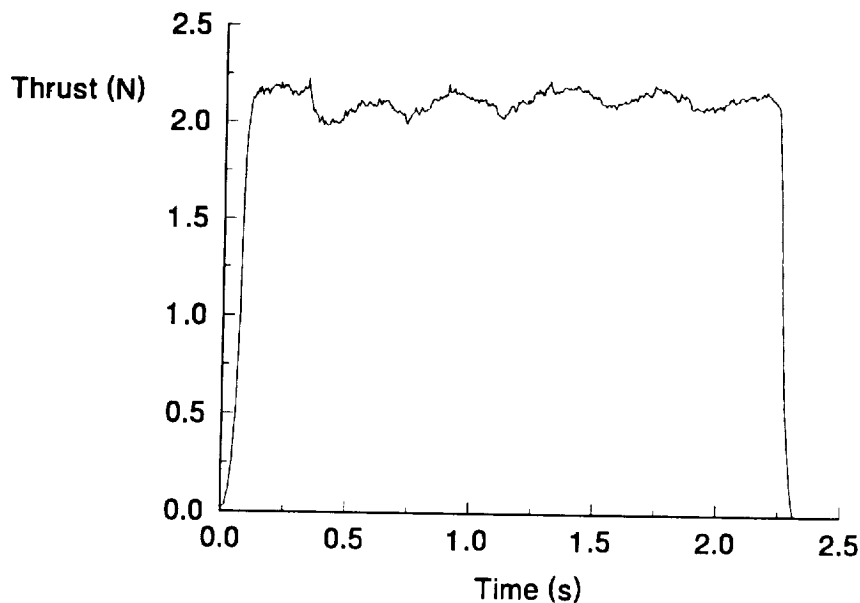

Figure 6. Thrust profile of improved solid propellant generator and model

Figure 7 is a sketch of the solid propellant cartridge and mild steel model designed for it. The settling chamber and nozzle diameters were 0.5 and 0.165 inches respectively.
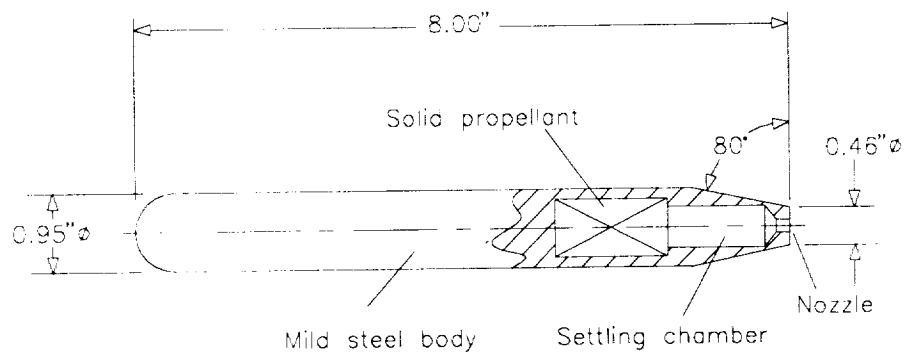

Figure 7. Solid propellant gas generator model

Rocket Exhaust Pressure Measurement

To allow a comparison of rocket thrusters with other propulsion simulation techniques and full scale exhaust flows, it was necessary to more completely characterise the exhaust. Parameters such as ratio of specific heats of the exhaust and density of the propellant (used to estimate mass flow rate from thrust duration) were available from data published by the manufacturer, given the commonality of propellants. One of the remaining characteristics which had to be measured directly was exhaust stagnation pressure, information not common with the off-the-shelf rockets because we removed the standard nozzle and provided our own as part of the model. A pressure measurement would also make possible the estimation of Mach number. It was decided also to try to relate thrust to another measurable, pressure being an obvious candidate.

Measurements of stagnation pressure during bench tests of using a pitot probe positioned in the exhaust plume close to the nozzle and a static tapping in the settling chamber downstream of the motor gave similar readings. For practical reasons the static tapping became the preferred method.

Figure 8 shows settling chamber pressure plotted against thrust for the rocket bench test of Figure 6. The data for the full-thrust period, concentrated in the upper right hand corner of the figure, suggests that thrust is linearly related to static pressure during nominal steady running. The mean chamber pressure, at about 1.3 bar gauge, would give an ideal exit Mach number of about 1.2 from a convergent-divergent nozzle. This introduces the possible alternative to the development of a thruster with a highly reliable and repeatable thrust profile. A propulsion simulator could be developed with pressure telemetry yielding an instantaneous thrust signal. An infra-red pressure telemetry system has been developed for the NASA Langley 13-inch MSBS[6], as a refinement of the radio telemetry techniques used at Farnborough in the 1960's. Pressure measurement could prove to be an attractive method for acquiring more precise data on installed thrust.
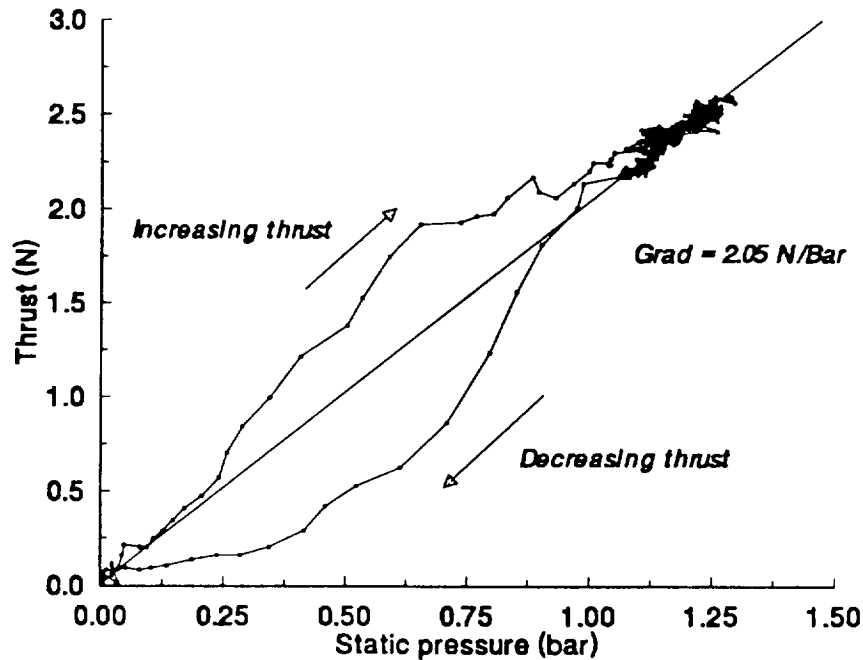
Figure 8. Chamber static pressure and thrust for solid propellant model

Rocket Thruster in Suspension

A typical axial position response to the 'top hat' thrust profile is shown in Figure 9. The start and finish of the rocket firing, at times 0.2 and 2.3 seconds, provoke a similar but opposite transient response in axial position, that is movement of the model away from its datum axial position, as the control system compensates for the changes. Once the starting response is damped out by the controller, the desired condition of a stationary model with the thruster firing is achieved in the interval 1.5 to 2.3 seconds. The electro-magnet current shown on this figure is the source of axial force data available from the MSBS. The evident transients are similar in character to the bench calibration of figure 6. A feature of these motors is the production of considerable solids and smoke which could constitute a problem in a closed circuit wind tunnel.

The external vertical heave force, axial force, and pitching moment experienced by the model were measured by the DFM rig described below. These components represent the summation of the instantaneous aerodynamic loads, motor thrust and model weight. As these tests were conducted wind-*off* at zero incidence, it was expected that motor thrust alone would dominate as the applied external axial force. The loads experienced during the firing illustrated in Figure 9 are shown in figure 10. The axial force recorded between 1.5 and 2.3 seconds is around 2.25 N, in good agreement with the levels of motor thrust measured during bench tests, figure 6. Much smaller levels of heave force and essentially zero pitching moment were recorded, as would be expected.
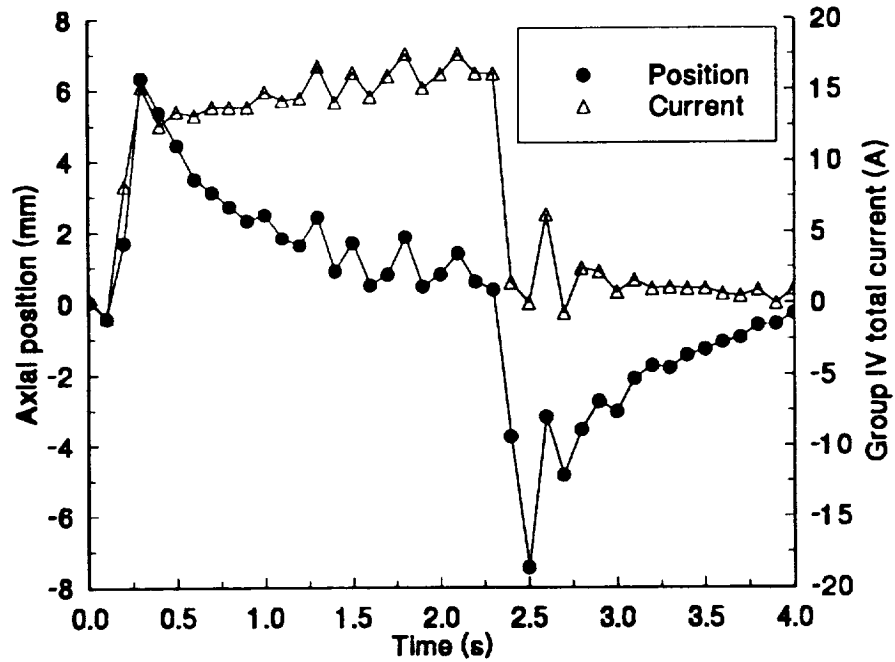
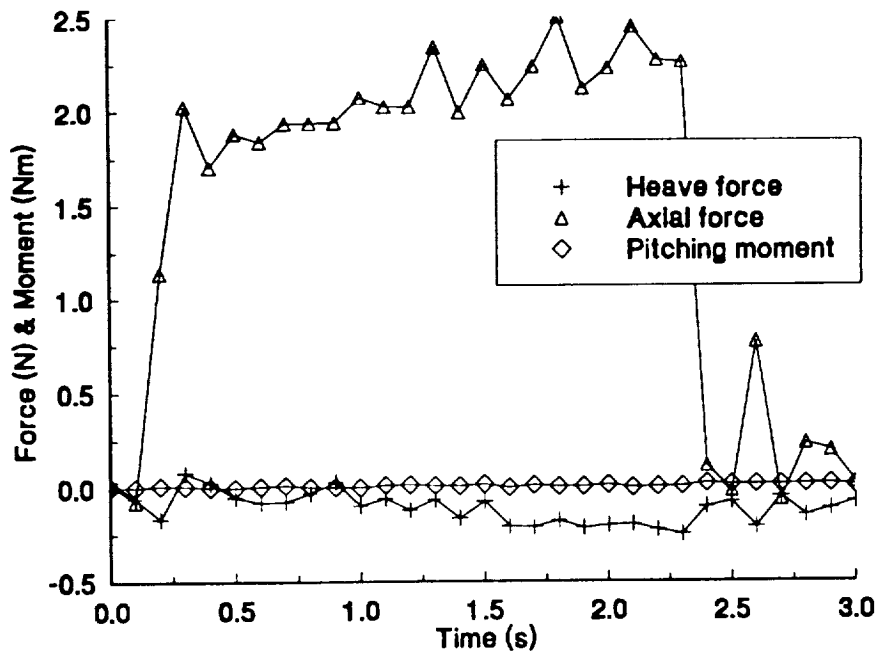Figure 9. Responses to firing levitated solid propellant model

Figure 10. Measured loads on solid propellant thruster in suspension

Solid rocket cartridges have proved a moderately successful gas source for simulating an engine exhaust for a model in a small MSBS. There remains a number of aspects of their performance which need to be addressed before firm conclusions can be drawn as to the suitability of this simulation

technique for use in a larger facility. The areas of question include safety, thrust profile, repeatability and smoke reduction. There are other sources of solid motor which might overcome some restrictions and offer a higher specific impulse. This, combined with the elimination of the separate motor case feature of model rockets, which is entirely feasible, could lead to a useful increase in jet diameter but in turn would require modifications to the MSBS equipment.

LOAD MEASUREMENT

Introduction

For an MSBS to be effective as an aid to wind tunnel testing, it is vitally important for it to be able to perform its 'Balance' function. The aim is to convert run-time coil currents into loads. The tradition has been to pre-calibrate a model/coil array by applying known loads to the model wind-off and recording current sets to allow calibration constants to be derived for the subsequent analysis of wind-on data. The evaluation of multiple force and moment components for a model suspended in an arbitrary position can, however, involve a particularly time consuming calibration procedure. Each of the force and moment components, six in all, is dependent on the currents in each of the ten electro-magnets of our suspension array, also on the position and attitude of the model and on the type and geometry of magnetic core inside the model. There can be appreciable non-linearities.

Simplifications are adopted because complete pre-calibration is too daunting a prospect for contemplation even for the case of one model core. For example the calibration matrix is reduced by using integrators in the control system to return the model to its nominal position following changes of applied load. Previous MSBS experience had demonstrated that the accurate assessment of aerodynamic loads by pre-calibration is straightforward for simple cases such as the measurement of a single force component applied to a centrally suspended model, and is possible in a reasonable time for up to three load components.

A review of the available load-extraction techniques[7] identifies five categories: (1) static or (2) dynamic pre-calibration of the MSBS load-current relationship, direct measurement of aerodynamic load using (3) an internal or (4) an external balance, and (5) calculation of the loads from first principles. The latter is quite impractical to the precision required for aerodynamic testing when using iron cores, but is attractive otherwise because the operation does not demand tunnel time. This is a feature it shares with (3), a method in which the model contains a balance[8] telemetering directly the force and moment data. The internal volume of the model occupied by the balance, processing electronics and telemetry compromises the maximum force capability. In contrast the other calibration methods (1), (2) and (4) do require tunnel occupancy time but with no compromise on model design. Dynamic calibration (2) involves the deliberate oscillation of the model to allow currents to be related to inertia forces and aside from avoiding the friction which might be associated with static calibration, it has no operational advantage.

The issue of tunnel occupancy for calibration purposes must be considered during studies into the appropriate measurement techniques for a commercial MSBS. The external balance notion (4) is a compromise solution much reducing the tunnel time devoted to calibration.

Previous research into external balances has been of limited scope, the major example being the construction of a force balance for use with an MSBS by Vlajinac[9]. He designed a rig to support a model in air bearings. Force and moment components in six degrees of freedom were deduced from air pressure measured inside the bearings. A static calibration of the rig away from the tunnel related bearing pressure to applied load. This rig appears to have performed well, exhibiting good linearity between load and pressure.

Since this work, miniature force transducers have become available, giving an electrical signal in response to load and it was decided to adopt this approach in a similar calibration rig, the Direct Force Measurement (DFM) rig. The notion was to carry out a wind tunnel test, recording all data as usual, then to extract the load information post-test. This would be by means of mounting the rig in the tunnel, with the model mechanically fixed to it at the proper position and attitude, then to play back the electro-magnet currents and record actual forces and moments.

DFM Rig Design

A DFM rig for use in a commercial MSBS was conceived as a starting point for the design of the new equipment, with the emphasis on automation[1], but was simplified to a three-component rig for the purposes of the actual demonstrator.
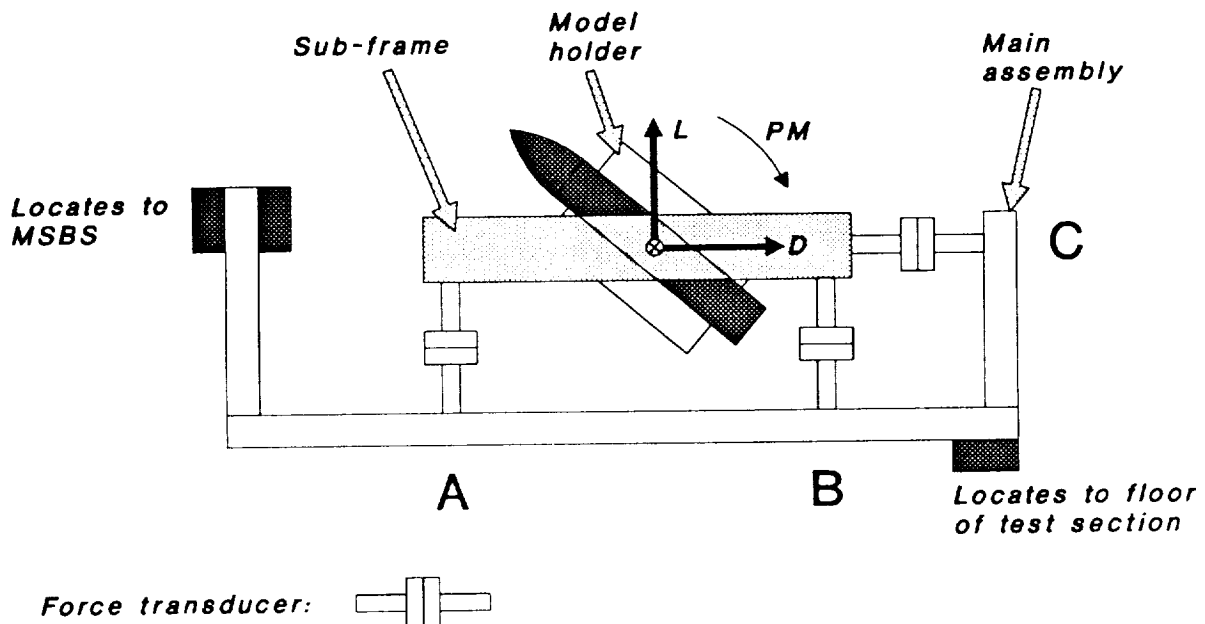

Figure 11. DFM rig schematic

A schematic of the DFM rig produced is shown in Figure 11. Layout was partly dictated by the need for compatibility with the position sensing system. The structural materials were primarily

aluminium and brass. A model restraining yoke allowed micro-adjustment of position and attitude which were checked by play-back of the recorded optical system data. Between the yoke and ground is a set of three pre-calibrated force transducers. Support electronics, software and test procedures were developed in parallel with the design and construction of the rig. Play-back of the currents then yielded the history of variation of the loads. Lift force and pitching moment are available from the sum and difference of outputs from transducers A and B, and drag force directly from C. The transducers have an accuracy of ±2%, adequate for a first build but not of a satisfactory standard for normal aerodynamic measurements.

DFM Applications

This equipment came along too late to be widely used in the propulsion demonstrator work but its usefulness was exploited several other ways, two of which are outlined below.

The DFM rig was used to improve the way force and moment components are generated by the MSBS. The new equipment allowed us to measure the effectiveness of the electromagnet array in influencing a model, whereas to this point we had relied only on estimates. The results were used to improve the ability of the controller to generate decoupled forces and moments.

At the beginning of this research program no practical method had existed for using the high angle of attack capability of our MSBS. The unique potential of this facility to investigate high alpha aerodynamics free from support interference remained unrealised. Having improved the quality of control it was possible to apply the new balance capabilities to such an aerodynamic investigation. The low speed high alpha behaviour of an ogive cylinder model was studied. This work is of interest because the advent of digital flight control systems coupled with developments in aerodynamics has allowed controlled flight at incidences beyond the stall. This in turn has led to a resurgence of interest in the aerodynamic behaviour of a cylinder-nose combination at high angles of attack.
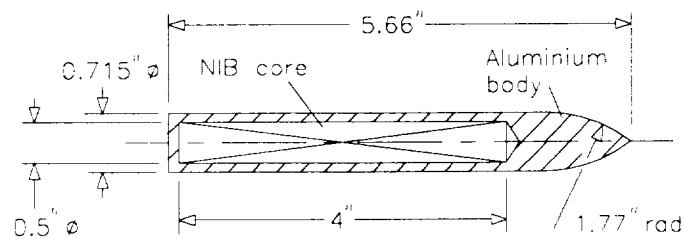

Figure 12. Ogive-cylinder model

The model's outline is shown on figure 12. This simple axi-symmetric shape contains a permanent magnet and was controlled in all degrees of freedom except roll. Tests were conducted over the incidence range -5 to +95 degrees. The DFM rig was used to reduce the wind tunnel test data yielding lift, drag and pitching moment coefficients. Examples for the complete angle of attack range are shown on figure 13.

Unsteady loads sometimes were experienced during high alpha tests with this model, the loads appearing to be periodic and predominately in the lateral direction. The model is likely to have been subject to periodic vortex shedding and the result was pronounced lateral motions, sometimes coupling

into roll due to asymmetries, which points to a need for an overall improvement in the tightness of control. Airspeed was restricted in these circumstances to avoid losing the model.
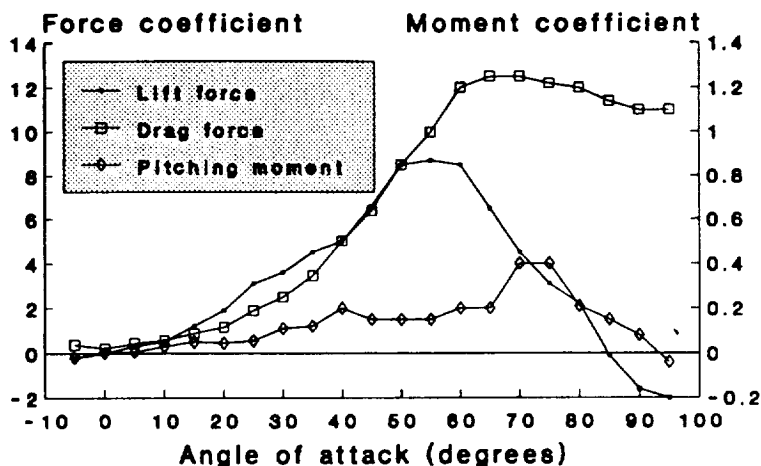

Figure 13. Variation of force and moment coefficients with incidence.
Ogive-cylinder model at Mach 0.1, atmospheric tunnel.
Coefficients are based on frontal area.

CONCLUSIONS

In relation to the simulation of an exhaust jet from a magnetically levitated wind tunnel model:

• Propulsion exhaust simulation experiments are feasible in an MSBS wind tunnel.
• Simple software algorithms can achieve satisfactory control.
• A peak thrust greater than the maximum restraint is rarely acceptable.
• A steady thrust period should exist to permit satisfactory model control and data acquisition.
• The thrust profile must be compatible with the MSBS hardware limitations.
• Pressure telemetry might be desirable to monitor thrust variations.
• Improvements are possible from the use of a higher specific impulse grain and other refinements.
• No separation of jet effects on base flow proved possible.
• Stored CO_2 is an inappropriate gas source unless, perhaps, the flow is regulated and controlled in temperature.

And in relation to Direct Force Measurement:

• The rapid assessment of aerodynamic loads is possible using a DFM rig post-test.
• The equipment may be used to improve the generation of force components by the control system.
• Pre-calibration of model cores could be simplified by this technique.
• Interference-free, high α wind tunnel tests may be performed.

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