Engineering Notes

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The Drag Balance: An Apparatus for Studying Atmosphere-Satellite Surface Interactions

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THE interaction between upper atmosphere molecules and satellite surfaces is poorly understood. Because of this, accurate theoretical determination of drag coefficients is not currently possible. Since the drag force on a surface is dependent on the product of drag coefficient and atmospheric density, this inaccuracy in drag coefficient prediction also limits the accuracy with which atmospheric density can be deduced from measurements of satellite drag.[1]

Study of this interaction has produced a large volume of literature, but the difficulty of duplicating orbital conditions in the laboratory has hampered the acquisition of high-quality experimental data. Theoretical studies have yielded models that are rather general, and depend upon a number of parameters, such as that due to Schamberg,[2] but it has proven difficult to determine values of these parameters due to the lack of relevant experimental data.

The models of Schamberg and others show that the drag coefficient on a flat plate as a function of incident angle has a shape dependent on the values of the parameters. Hence, a precise measurement of the relative drag coefficients at varying incident angles on a flat plate of given material would enable the values of these coefficients to be determined for this material.

This observation has led to the concept of the experiment described below. It employs a sensitive torsional balance to measure the relative variation of drag coefficient on a flat plate with incident angle, and the configuration is such that the measurement is not dependent upon knowledge of atmospheric density. Torsional balances have been used before in molecule-surface interaction studies,[3] but not with incident particle energies as great as those in orbit, nor in the configuration proposed here.

Consider a flat plate of area A whose surface normal makes an angle θ to the incoming atmospheric beam. The atmosphere has density ρ and speed V. The drag force on the plate will be given by

$$F_D = \tfrac{1}{2}\rho V^2 A\cos\theta C_D(\theta,i) \qquad (1)$$

where $C_D(\theta,i)$ is the drag coefficient for a plate of material i at incident angle θ. Equation (1) is actually the definition of the drag coefficient.

To infer C_D from measurements of F_D it is necessary to know ρ and V. The latter quantity is readily available, but the atmospheric density is highly variable. Hence, the following approach is taken.

A torsional balance is constructed as shown in Fig. 1. Two plates, whose surfaces are coated with materials i and j, are mounted on the balance. One is fixed at normal incidence to the incoming atmospheric beam, and the other is free to rotate so that its incident angle can be changed. The rotation axis is along the arm of the balance so that any lift forces generated by the rotatable plate will not torque the balance in the direction in which it is free to move. Movable shutters attached to the spacecraft frame are positioned in front of the fixed plate to adjust the area of it exposed to the atmospheric beam.

To perform the experiment, the movable plate is first rotated to a selected incident angle θ. Then, the shutters are adjusted until the balance arm comes to the initial "zero" position, where the forces on the two plates are equal. The equation representing this condition is

$$\tfrac{1}{2}\rho V^2 A\cos\theta C_D(\theta,i) = \tfrac{1}{2}\rho V^2 a(\theta) C_D(0,j) \qquad (2)$$

where $a(\theta)$ is the area exposed by the shutters when the balance is nulled with the movable plate at angle θ. From Eq. (2),

$$C_D(\theta,i)/C_D(0,j) = a(\theta)/A\cos\theta \qquad (3)$$

The quantities on the right are known, so the ratio on the left, which is the relative variation of drag coefficient with incident angle, can be determined with no knowledge of atmospheric density.

By choosing both plates of the same material, the functions $C_D(\theta,i)$ can be determined to within a multiplicative constant. By interchanging plates of different materials, the various $C_D(0,i)/C_D(0,j)$ ratios can be measured. Other balance configurations can be chosen to compare the lift forces on two plates, or even the lift force on one plate with the drag force on another.

Thus the drag balance concept shows promise of significantly improving understanding of molecule-surface interactions. It is next necessary to demonstrate its feasibility.

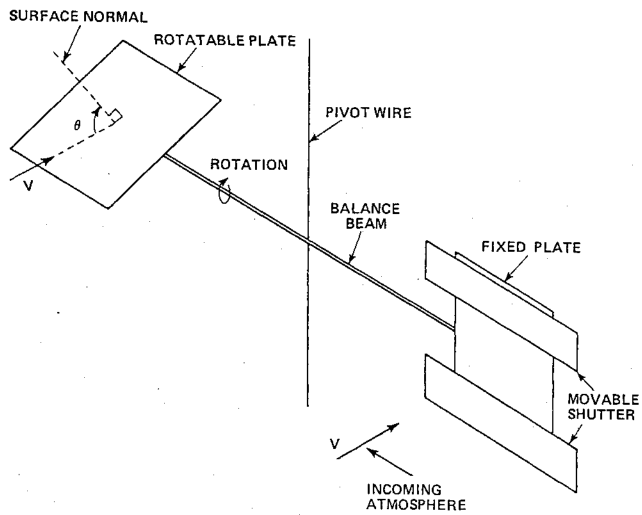

Fig. 1 Drag balance concept.

Received March 24, 1980; revision received Aug. 18, 1980.

Index categories: Rarefied Flows; Atmospheric and Space Sciences.
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Assume each drag plate has an area A and mass/area density σ. If the balance beam is of length $2D$ and its mass is negligible, the moment of inertia is

$$I = 2\sigma A D^2 \tag{4}$$

Lt P_D be the drag pressure (force per unit area) on each plate. The torque due to the full area of the fixed plate will be

$$\tau_0 = A P_D D \tag{5}$$

To be able to measure the drag force to a fractional precision ϵ, the system should be capable of sensing a net torque of

$$\delta\tau = \epsilon\tau_0 = \epsilon A P_D D \tag{6}$$

Let the torsional constant of the pivot wire be K. The balance must be adjustable to the null position to within an angle

$$\delta\phi = \delta\tau / K = \epsilon A P_D D / K \tag{7}$$

To maximize sensitivity, $\delta\phi$ should be as large as possible.

The actual nulling of the balance, by adjustment of the shutter aperture a, is done by a control loop. This loop must have the capability of steering the balance to the null position with zero steady-state error in a time short enough to allow measurements to be completed quickly. One such loop has been designed that settles the balance to the null position to within 0.1% of the input step magnitude in a time equal to

$$T_{0.1\%} = 27.6\sqrt{I/K} \tag{8}$$

Based upon these computations, a study has demonstrated the feasibility of the experiment. It has shown that a balance can be designed that is sensitive enough to distinguish between the molecule surface interaction mechanisms of interest, yet is responsive enough to allow measurements to be made in a relatively short time.

Four interaction mechanisms were considered. Of these, the hardest to distinguish were the thermal re-emission and the total-absorption models. It was determined that measurement of the relative drag force with an accuracy of 0.1% would allow these interaction mechanisms to be distinguished, hence

$$\epsilon = 10^{-3} \tag{9}$$

was chosen as the required fractional measurement precision of the apparatus.

The study showed that this precision is possible in a balance capable of performing measurements at 5-min. intervals if the drag plates are made of aluminum foil with a surface mass density of $\sigma = 0.01$ gm/cm^2, and the balance arms are $D = 5$ cm long. A zero-gravity taut band suspension system would be used with a torsional constant of $K = 0.035$ dyne cm/rad.

A number of technical concerns remain. These include the following.

1) To prevent inteference from the cloud of emitted and scattered molecules surrounding the spacecraft, the experiment must be deployed at the end of a boom. This cloud of molecules must be studied and modeled to determine the required boom length and the seriousness of the interference.

2) The shutter will have to be mounted so that "fringing" of the atmospheric beam due to thermal motion does not change the effective area. The trapping of molecules between the shutter and drag plate will also have to be eliminated. If this is impractical, an alternative approach is to dispense with the shutters altogether and allow the area of the fixed plate to vary by other means, such as using two movable overlapping plates.

3) Sun and albedo shields must be designed to remove the effects of radiation pressure.

4) Means must be provided to prevent forces due to charge buildup. At the least, the entire balance system will have to be grounded.

5) A more optimal control loop must be designed.

6) The possibility of resonance between the balance beam and spacecraft attitude excursions must be eliminated.

7) Active temperature control may be necessary.

Acknowledgments

This work was supported by the Department of the Navy under Contact N00024-78-C-5384 with the Applied Physics Laboratory of The Johns Hopkins University.

References

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Effect of HMX on the Combustion Response Function

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Introduction

NITRAMINE propellants are of interest for rocket applications because of their potential for improved energy and smokeless combustion products, and recent studies have been devoted to understanding and improving their steady-state combustion characteristics.[1-4]

Rocket motors are, in general, principally concerned with steady-state performance, although anomalous combustion behavior can be brought about by unsteady processes occurring in combustion chambers. The most prevalent anomalous behavior is combustion instability. It is of particular concern in smokeless propellants because the absence of particulate combustion products deprives the combustion chamber of significant stabilization. There is extensive literature on the stability characteristics of homogeneous, nitrocellulose (NC) based solid propellants and inert binder propellants utilizing ammonium perchlorate (AP) as the oxidizer (e.g., Refs. 5 and 6). But little or no systematic information is available on the influence of nitramine oxidizers such as HMX (cyclotetramethylenetetranitramine) on driving propellant combustion instability. A series of T-burner combustion instability experiments were, therefore, carried out, the purpose of which was to determine the effect of replacing AP with HMX on the response function of inert binder (hydroxyterminated polybutadiene—HTPB) propellants, and of HMX addition on the response function of NC propellants.

Received June 12, 1980.

Index categories: Combustion Stability, Ignition, and Detonation; Fuels and Propellants, Properties of.

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