Engineering Notes

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Drag of a Tubular Projectile with Internal Blockage

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A SERIES of wind-tunnel experiments has been conducted to evaluate the magnitude and distribution of aerodynamic forces acting upon a tubular projectile in flight. The particular configuration of interest, described more fully in Ref. 1, is internally fitted with a bored spherical ball that is free to rotate within the projectile so that the tubular passage is automatically opened as the projectile emerges from the launch tube. This Note describes the method used to deduce the drag on the ball at various degrees of opening and compares the wind-tunnel results with those predicted by simple one-dimensional compressible flow theory.

The model used in the wind-tunnel was a full-scale version of a 20-mm tubular projectile and is illustrated in Fig. 1. For a complete description of the model construction, the mounting and sensing apparatus, the other details of the experiments, the reader is referred to Ref. 2. It is sufficient here to note that the model is equipped with an internally-mounted ball that can be preset at selected fixed orientations, θ, with respect to the model axis. Both the ball and the model are bored-through with holes of the same diameter so that with the ball aligned with the model axis ($\theta = 0°$) there is no obstruction to flow through the model. Depending upon the orientation of the ball, the model presents itself to the oncoming flow in a range of configurations from slender body ($\theta = 0°$) to bluff body ($\theta = 90°$).

The tests were conducted with the model at zero angle of attack and at freestream Mach numbers of 1.94, 2.88 and 4.00. At each Mach number, data were recorded for a series of nine values of θ from zero to 90°. In addition to drag forces, pitching moment was measured (with limited success) and Schlieren photographs were used to illustrate the shock wave and flow patterns at the conditions of each data point.

Of particular interest are the changes in the drag of the projectile. The data are therefore presented in Fig. 2 in the form of:

$$R_D = \frac{C_D - C_{DO}}{C_{DC} - C_{DO}}$$

where C_D = drag coefficient (based upon model frontal area), C_{DO} = drag coefficient without blockage ($\theta = 0°$), and C_{DC} = drag coefficient at $\theta = 90°$. The experimentally determined most probable values of C_{DO} and C_{DC}, together with their difference, are shown in Table 1.

The points recorded in Fig. 2 are averages of repeated measurements after correction for strut drag and interference effects. The method of correction (Ref. 2) is relatively unreliable at large ball angles and low Mach numbers and is thought to be a major source of uncertainty in the projectile drag coefficient under these conditions. (Note, for example, the value of R_D slightly greater than unity at $M_\infty = 1.94$ and $\theta \approx 70°$).

Although the dependency of the drag coefficient upon ball angle is generally in accordance with expectations (rising as the ball closes), it is interesting to note from Fig. 2 that the drag rise is relatively gradual and essentially complete well before the projectile opening is fully blocked. (In the model used in these tests, full blockage occurs at about $\theta = 75°$, or a value of about 0.83 on the abcissa of Fig. 2.) This may be attributed to the combined effects of viscosity and shock wave interaction within the projectile when the ball is in a partially-open position. Thus the internal flow may be effectively blocked even though the ball is partially open (within a range of $50° < \theta < 60°$, say). The Schlieren photographs[2,3] further support these observations in that the emergence of the bow shock wave is seen to begin at relatively low ball angles with a gradual increase in steadiness and stand-off distance as the ball closes. Likewise the Schlieren photographs indicate that shock swallowing is a gradual process as the ball opens (θ decreases) with more opening (a larger critical area) required at the lower Mach numbers. At Mach 1.94, for instance, the experiments showed that the ball hole must be aligned with the projectile axis to within less than 18° for the shock to be swallowed. The corresponding angle at Mach 4.0 is about 40°.

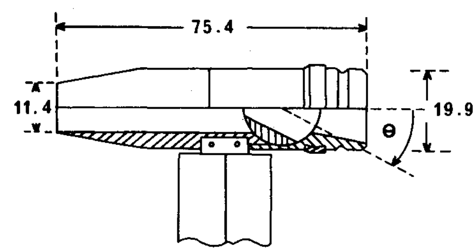

Fig. 1 Wind-tunnel model of tubular projectile. Dimensions in millimeters.

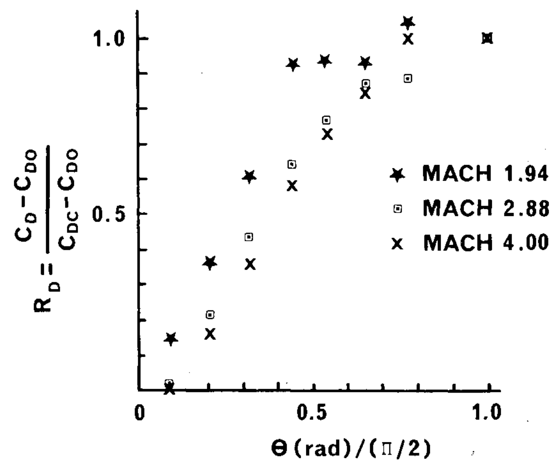

Fig. 2 Non-dimensional projectile drag rise with ball position.

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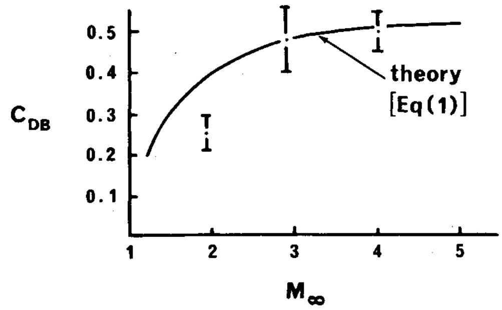

Fig. 3 Ball drag coefficient deduced from experiments. Comparison with simple theory.

Table 1 Ball open ($\theta = 0°$) and ball closed drag coefficients

Ball position	Freestream Mach number, M_∞ 1.94	2.88	4.00
Open, C_{DO}	0.390	0.250	0.210
Closed, C_{DC}	0.645	0.738	0.714
$C_{DB} = C_{DC} - C_{DO}$	0.255	0.488	0.504

The experiments also show that the dependency of drag on Mach number reverses as the projectile passage changes from an open to a blocked condition. Since the projectile configuration changes in this evolution from a relatively slender body to that of a blunt body, the dominant drag mechanism may be expected to become one which is largely blunt body form drag dominated by the pressure rise across the normal bow shock wave. (The ratio of pressures across a normal shock is about 4 times higher at Mach 4 than at Mach 2). This also explains the relatively large benefits in drag reduction at the higher Mach numbers where opening of the passage results in the removal of a relatively strong bow shock.

As the ball moves, the change in the total drag acting upon the projectile is largely attributable to the change in the drag force acting upon the ball itself. There is some validity, therefore, to the approximation that the drag on the ball at a non-zero value of θ is given by the difference between the total projectile drag at that ball position and the projectile drag with unblocked flow ($\theta = 0$). The drag on the ball in the fully closed ($\theta = 90°$) position is especially useful in prediction of the motion of the ball during projectile flight and, with the above approximation, this is given by:

$$C_{DB} = C_{DC} - C_{DO}$$

In Ref. 1 this was approximated using normal-shock static pressure on the face of the ball and negligible base pressure recovery. Under these assumptions, the ball drag coefficient is given as:

$$C_{DB} = 4\bar{r}^2 (1 - 1/M_\infty^2) / (\gamma + 1)$$

where $\bar{r}$ is the ratio of ball hole radius to the projectile radius and γ is the isentropic exponent. Using the parameters pertinent to these experiments ($\bar{r} = 0.573$ and $\gamma = 1.4$) the drag coefficient for the fully-closed ball is given theoretically as:

$$C_{DB} = 0.55 (1 - 1/M_\infty^2) \qquad (1)$$

This expression is compared with the experimental values (Table 1) in Fig. 3.

Drag-coefficient uncertainty bands are also shown in Fig. 3 for reference purposes. These bands are thought to be conservative in that they are based upon estimates of maximum errors in the measurements of drag force and freestream static pressure at the ball angle giving the greatest scatter of data. The initial series of measurements was conducted at Mach 2.88, and the smaller uncertainties at the other Mach numbers reflect improvements in experimental apparatus (particularly in mounting the projectile) and techniques. Given the experimental uncertainties the formula recommended above appears to be well-supported by the data. The departure of theory from experiment at low Mach numbers is not unexpected, since the validity of the theoretical prediction is sensitive to differences between normal-shock downstream static and stagnation pressures. These differences become insignificant at the higher Mach numbers. In addition, at the lower supersonic Mach numbers, it is expected that an improved theory would require considerably more sophistication in modelling the recirculation regions both upstream and downstream of the ball.

References

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Space Shuttle Heating Analysis with Variation in Angle of Attack and Catalycity

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Introduction

THE Shuttle has the aerodynamic capability of re-entering the Earth's atmosphere at steeper or shallower angles of attack for different cross-range requirements of landing. Depending on the angle of attack of the Orbiter, the Shuttle could have different stagnation point locations and, thus, different effective nose radii, since the local radius of curvature changes rapidly on the Shuttle nose. This, in turn, would affect the nonequilibrium/equilibrium characteristics of the flowfield as well as the surface heating. A study to analyze this effect, therefore, is desirable.

For a surface having large catalytic efficiency (or, surface recombination rate, $k_{w,i}^*$), the heating during the re-entry is increased[1-3] by the heat of dissociation released during the recombination of oxygen and nitrogen atoms (mostly the oxygen atoms) at the surface. The thermal protection system

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