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Effect of a Spike on the Drag and on the Aerodynamic Stability of Blunt Bodies in Supersonic Flow

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Nomenclature

a = spike's diameter (= $d/16$ in present study)
C_D, C_L = drag and lift coefficients D/qS and L/qS
C_m = moment coefficient $\bar{M}/q\,Sd$
d = body diameter (= hemispherical nose diameter)
D, L = drag and lift forces, respectively
l = spike length
M_∞ = Mach number of undisturbed freestream
$\bar{M}$ = pitching moment
$p, \Delta p$ = pressure and pressure rise respectively
q = dynamic pressure, $\rho V^2/2$
Re_d = Reynolds number based on diameter
Re_f = Reynolds number based on the length from the spike's tip apex to the tip shoulder
S = reference area
V = velocity
$x_{a.c.}$ = position of the aerodynamic center (measured from the base)
α = angle of attack
θ_c = equivalent cone half-angle of the separated flow on the spike
ρ = air density

Subscripts

b, F, n = base, forebody, and nose, respectively
crit = critical
max = maximum

Introduction

SPIKES have been used to reduce the wave drag of a blunt nose by converting the flow from a blunt-body pattern to an essentially conical flow pattern.[1–12] The spike establishes a conical separated flow zone when it is of a proper length. When a certain critical spike length is exceeded, the separation moves from the spike tip to some position on its length, and the effectiveness of the spike is greatly reduced. A method for estimating this critical spike length is presented in this Note. Some studies[5,8–10] have shown that the effect of the spike on the nose drag is diminished as the angle of attack α increases. The effect of the spike on the static stability is very small.[11] In the present investigation these effects are studied at Mach numbers 1.5 and 2.25 at various Reynolds numbers and spike lengths. The results provide a better understanding of these effects.

The experiments were done in the 30 cm × 30 cm supersonic blow down wind tunnel at the Aerodynamic Laboratory of the Department of Aeronautical Engineering. The models are cylindrical bodies 28 mm in diameter by 180 mm long, hemispheric and ogive with a hemispherical nose of 11 mm radius. The spike is installed in the nose center. Its diameter (a = 1.75 mm) is $\frac{1}{16}$ of the model's body diameter (d = 28 mm) and its tip is conical with half-angle of 10°. The spike length l is varied to give l/d values of 0, 0.5, 1.0, 1.5, and 2.0. The aerodynamic forces and moments are measured by a 3-component, strain-gage balance. The flow is photographed by a Schlieren or a shadow optical system using movie photography (24 to 80 frames/sec) and by a Polaroid camera.

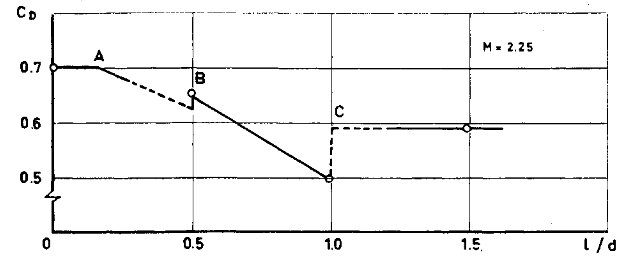

Fig. 1 Variation of the forebody drag coefficient with spike length.

Critical Spike Length

At low supersonic Mach numbers (i.e. $M_\infty < 1.5$) the conical wave drag coefficient is higher than the corresponding blunt-body wave drag coefficient. At higher M_∞, the blunt-body drag becomes the much larger, and the drag coefficient varies with spike length as shown in Fig. 1 for M_∞ = 2.25. (The circles represent measured values.) The initial drag level, extending up to Point A, corresponds to the conditions where the spike is shorter than the detached shock-wave stand-off distance for the blunt nose. As the spike length is increased further, from A to B and to C, the over-all wave drag is reduced as the conical flow becomes shallower. A small local increase in drag is expected at point B where the separation shock moves from the spike's tip to the tip shoulder as shown

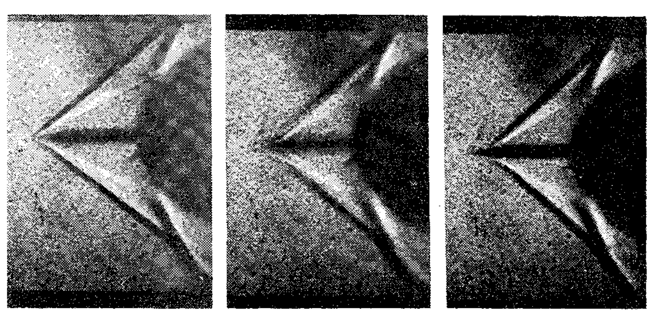
Fig. 2 Shadowgraph of the flow on the model with a spike. M = 2.25, l/d = 0.5, Re_f = 2 × 10[5].

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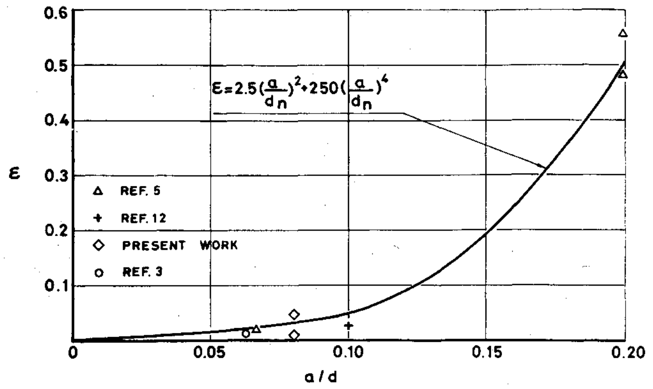

Fig. 3 The correction function ϵ, due to the effect of spike diameter.

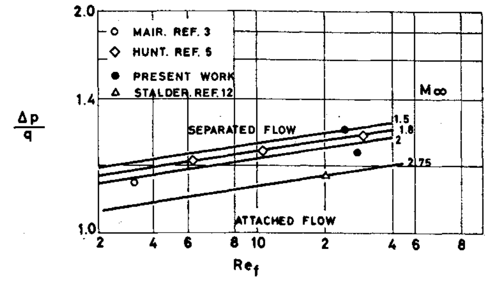

Fig. 4 The pressure jump required for separation at the shoulder of a 10° half-angle cone.

in Fig. 2. At point C the critical length is reached (at $l/d_n = 1.27$ in this particular case). As the spike length is increased further the separation cone becomes shallower; therefore, the pressure rise is not sufficient to separate the boundary layer at the tip or at the tip shoulder. In this case the flow beyond the spike's tip remains attached. Now, the local Reynolds number for the attached flow on the spike is increased, since the attached boundary layer extends further on the spike; therefore, the boundary layer may become turbulent, and then a much higher pressure rise is required for its separation. This turbulent boundary layer remains attached to a distance where the pressure rise caused by the blunt nose exceeds the allowable pressure rise. As this separation position corresponds to a large apex angle the drag rise is much larger in this case. This is indicated in the expected drag rise beyond the critical length shown in Fig. 1.

According to the previous discussion, the critical spike length occurs when the longest and shallowest separated region is still attached to the tip of the spike. The pressure rise that causes the separation of the boundary layer on the tip is assumed to be equal to the pressure jump across the conical shock wave; i.e., the separated region affects the flow as if it is a solid cone of half-angle θ_c whose apex is at the spike's tip and its envelop is tangent to the body's nose. Fig. 2 supports this assumption. Thus, for $1.5 < M_\infty < 3$[16]

$$\Delta p/q = [0.705/(M_\infty^2 - 1)][2(M_\infty^2 - 1)^{1/2} \tan\theta_c]^{1.69} \quad (1)$$

For a very thin spike ($a/d = 0$)

$$\sin\theta_c = d/2(l + d/2) \quad (2)$$

Now, for a spike of a small diameter

$$l/d = [(1 - \sin\theta_c)/2 \sin\theta_c] \cdot \epsilon(a/d) \quad (3)$$

where the function $\epsilon(a/d)$ is evaluated from the experimental data ($1.5 < M_\infty < 3$) of Refs. 3, 5, 12, and the present tests, and is shown in Fig. 3. This correlation function which is independent of M_∞, yields, for the critical spike length,

$$(l/d)_{\text{crit}} = [(1 - \sin\theta_c)/2 \sin\theta_c]_{\text{crit}} \times [1 + 2.5(a/d)^2 + 250(a/d)^4] \quad (4)$$

The $\Delta p/q$ values required to separate the spike's boundary layer have been determined from measured critical length presented in Refs. 3, 5, and 12, and from the present test results, all for a conical tip of half-angle of 10°, and are plotted in Fig. 4 as a function of the Reynolds number based on the length from the conical tip's shoulder [$a/2 \sin(10°)$]. The results are correlated by

$$(\Delta p/q)_{\text{crit length}} = 0.059(1 - 0.203M_\infty)Re_f^{3/19} \quad (5)$$

By equating the right-hand sides of Eqs. (1) and (3) and solving for $(\theta_c)_{\text{crit}}$, we obtain

$$(\theta_c)_{\text{crit}} = \tan^{-1}[0.115(M^2 - 1)^{0.09}(1 - 0.203M)^{0.59}Re_f^{0.0935}] \quad (6)$$

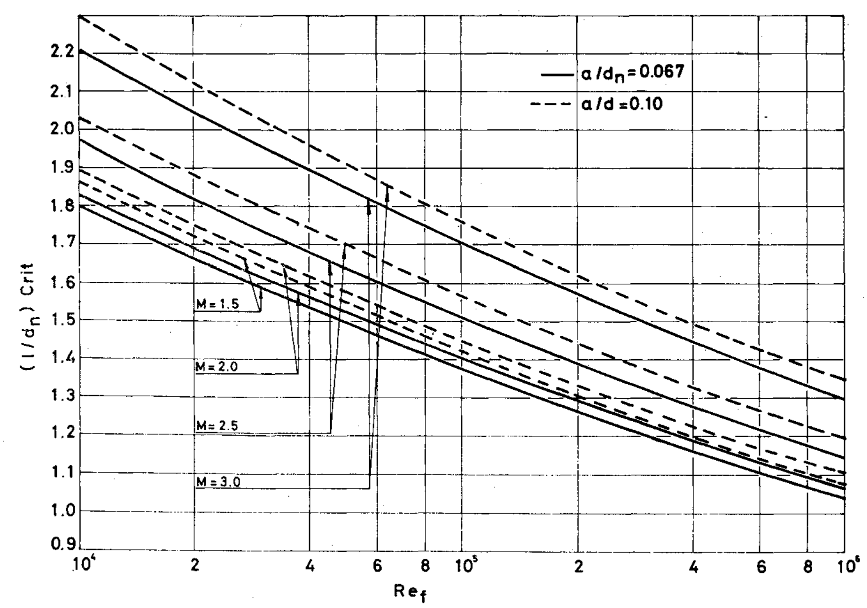

Fig. 5 The critical spike length vs Re_f for $1.5 \leq M_\infty \leq 3$ and $a/d = 0.067$ and 0.1.

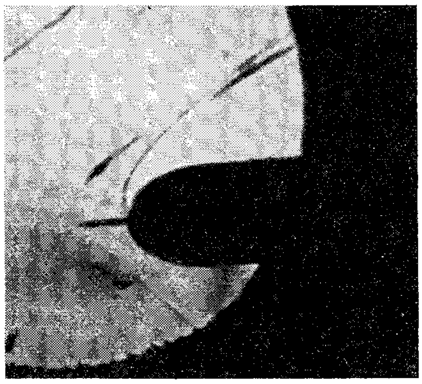

Fig. 6 The flow pattern on the ogive-cylinder model with a spike at angles of attack. $M = 2.25$, $\alpha = -8.5°$.

Substituting this θ_c into Eq. (4) yields $(l/d)_{crit}$, which is presented as a function of Re_f at M_∞'s from 1.5 to 3.0 for two values of a/d, in Fig. 5.

Some indication of the validity of this method can be obtained from the comparison of calculated critical spike length with actual measurements reported in Ref. 13. It should be noted that the results of Ref. 13 were not used in the estimation of the semiempirical coefficients of Eq. (6). Critical spike lengths determined from the measurements of Ref. 13 vary from 1.9 to 1.75 for $M_\infty = 1.75$ to 2.3, at $Re_f = 2.45 \times 10^5$; the corresponding values estimated by the present method varying from 1.6 to 1.72. The variation due to Re_f variation at a constant M_∞ of 2.5 is predicted even better; the measurements in Ref. 13 for $0.97 \times 10^5 < Re_f < 2.45 \times 10^5$ show 1.88 to 1.75, whereas the present method predicts values of 1.92 to 1.72.

When the body with a spike is held at an angle of attack, the flow pattern, shown in Fig. 6, behaves as if the conical separated region is swept in the flow direction with its apex held at the spike's tip. A large portion of the blunt nose is exposed to the supersonic flow, resulting in a strong shock

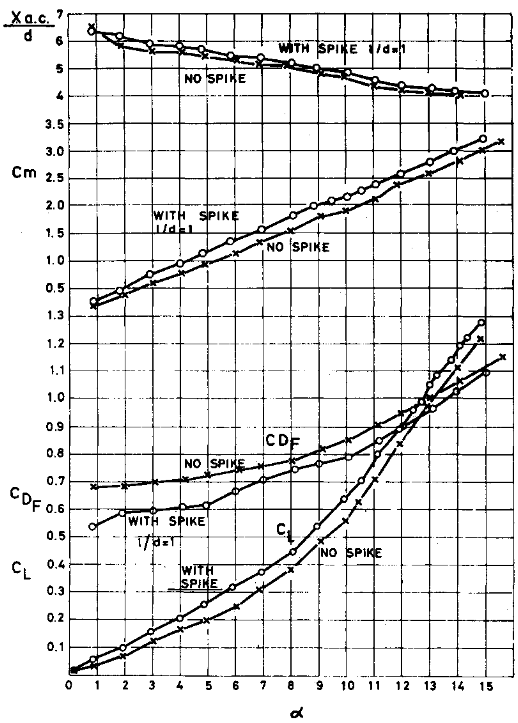

Fig. 7 Variations of C_D, C_L, C_M, and x_{ac}/d with α for the ogive-cylinder model with and without a spike at $M = 2.25$.

wave which appears on the exposed part of the nose. This strong shock wave causes an increase in the forebody drag, and thus the beneficial effect of the spike is diminished, as seen in Fig. 7. The forebody drag reduction due to the spike falls from 30% at $\alpha = 0$, to zero when α is increased to $\sim 15°$.

The variations of the lift and the moment coefficients and the aero-dynamic center with α for the blunt body with and without the spike are shown in Fig. 7; both C_L and C_m are slightly larger for the body with the spike, but x_{ac}/d does not vary with the addition of the spike. In all of these cases the spike is of a critical length, which for the present experimental conditions is $l/d = 1$. These conclusions are in good agreement with the results presented in Refs. 8, 9, 10, 14, and 15.

Conclusions

1) There exists an optimum spike length for drag reduction at zero angle of attack, defined here as the critical length [see Eqs. (4) and (6) and Fig. 5].

2) The drag reduction caused by the spike diminishes as the angle of attack α is increased and becomes negligible for $\alpha \simeq 15°$.

3) The static stability of the blunt configuration is unaffected by the addition of the spike.

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