Engineering Notes

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Viscous Effects on Center-of-Pressure Location for Sharp and Blunted Cones

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Nomenclature

C_∞ = $\mu_\infty T_w / d_w T_\infty$ = Chapman-Rubensin viscosity coefficient
F_N = aerodynamic normal force
ℓ_v = sharp cone length
M_∞ = freestream Mach number
Re_ℓ = freestream Reynolds number scaled to actual model length
$\bar{V}_\infty$ = $M_\infty (C_\infty / Re_\ell)^{1/2}$ = hypersonic viscous parameter
X_{cp_v} = center-of-pressure location measured from sharp cone vertex
α = angle of attack
γ = ratio of specific heats
θ_c = semivertex cone angle
μ_∞, μ_w = viscosity based on freestream static temperature (T_∞), based on model wall temperature (T_w)
ψ = nose radius/base radius = bluntness ratio

Introduction

ADVANCED re-entry vehicle designs now demand knowledge of the center-of-pressure location to within ½% of model length in that static margins of 1% or less are common. In applying wind-tunnel test data to flight conditions, this requirement necessitates a more critical assessment of viscous effects peculiar to high Mach number facilities in which flight Reynolds numbers cannot be simulated. New emphasis has been placed on the development of inviscid and viscous flowfield computational techniques. However, the uncertainty of these techniques is yet to be rigorously established. It is apparent that for high Mach number conditions, experimental results with sufficient resolution to delineate possible viscous effects on center-of-pressure location and to establish parametric trends are needed both to assess these effects and, furthermore, to provide a means of comparative evaluation of the computational results. The purpose of this Note is to present newly acquired experimental results that serve as partial fulfillment of these needs.

Experimental Results

Sharp and spherically blunted cones have been tested in the Naval Surface Weapons Center, White Oak Laboratory, Mach 18 Hypervelocity Research Tunnel[1] at a unit Reynolds number of 0.5×10^6 per ft. An in-house designed, high resolution strain-gage balance, mounted internal to the model, was used to obtain normal force and pitching moment data under steady-state conditions for a continuous variation of angle of attack from -6 to +12 degrees. Center-of-pressure location, as defined in Figs. 1 and 2, was then computed from the measured force and moment values.

Center-of-pressure data for the sharp ($\psi = 0$) seven-degree cone considered are presented in Fig. 1. The center-of-pressure location measured from the cone vertex and normalized with respect to the sharp cone length is shown vs angle of attack. The Mach 18 results correspond to a Reynolds number based on model length of 6×10^5 yielding a value of the hypersonic viscous parameter, $\bar{V}_\infty$, equal to 0.023. The accuracy of these experimental results for the center-of-pressure location is within $\pm 0.2\%$ of model length. The inviscid analytic result for the center-of-pressure location of a sharp cone is easily derived, by use of conicity, as

$$X_{cp_v} / \ell_v = 2/3 \cos^2 \theta_c \tag{1}$$

independent of Mach number, angle of attack, and flow species (γ). Deviation of the present results at low angles of attack from the inviscid prediction for $\theta_c = 7°$ is apparent. The viscous influence has a stabilizing effect with an aft shift of approximately 1% of model length occurring near zero angle of attack for the present conditions ($\theta_c = 7°, \psi = 0, M_\infty = 18, \bar{V}_\infty = 0.023$). As the angle of attack increases, the viscous effect decreases and the center-of-pressure location asymptotically approaches the inviscid prediction within the experimental uncertainty. This viscous effect on the center-of-pressure location of sharp cones is evident in the previously published data of others.[2-5] The more recent results[4,5] especially serve to support the illustrated trend of the viscous influence with angle of attack.

Recent numerical results have been obtained by Lubard[5] for a high Mach number viscous flow about a 7° "sharp cone" at angles of attack of 1, 5 and 10°. A solution to an approximate form of the full Navier-Stokes equations is achieved. Lubard's center-of-pressure results are included in Fig. 1 for comparison to the present data. In addition to the "sharp" cone results for the principal Reynolds number condition of interest in Ref. 2, results for the same Re_ℓ and, alternatively, for the same $\bar{V}_\infty$ as the present case are shown. This

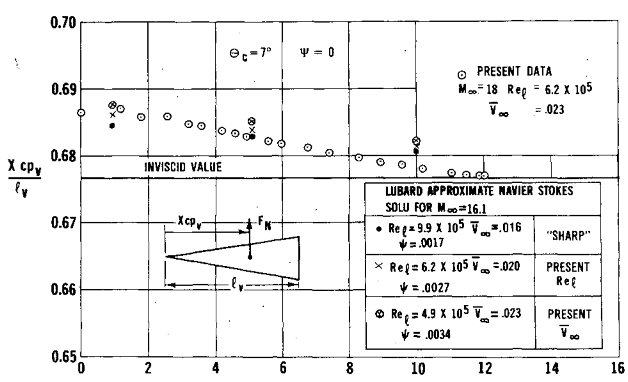

Fig. 1 Mach 18 experimental data for center of pressure of sharp cone.

Received May 8, 1975; revision received Feb. 13, 1976. The author gratefully acknowledges the cooperation of J.M. Solomon in performing the inviscid computations.

Index categories: Jets, Wakes, and Viscid-Inviscid Flow Interactions; Supersonic and Hypersonic Flow; LV/M Aerodynamics.

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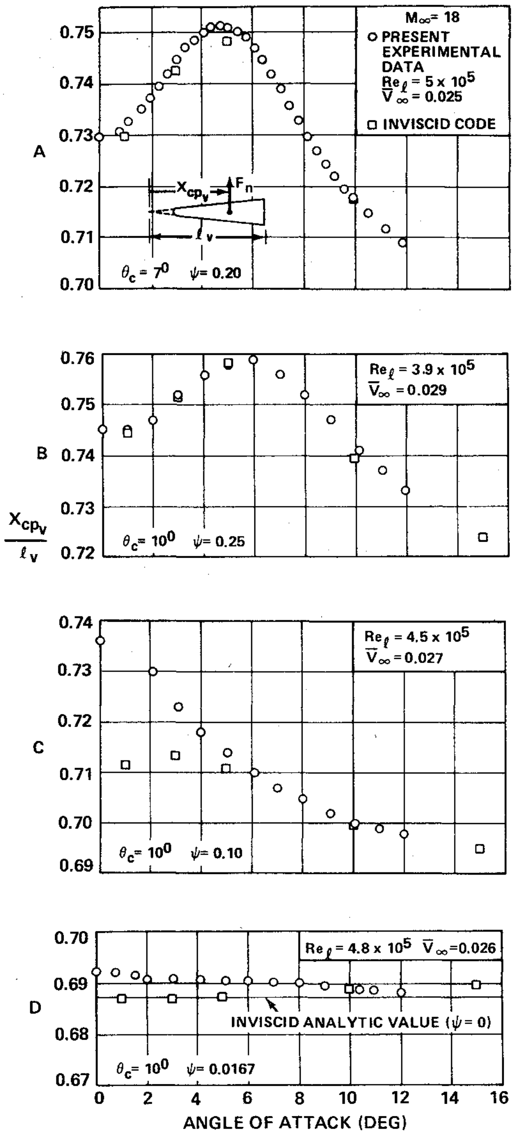

Fig. 2 Mach 18 experimental data for center of pressure of blunt cone.

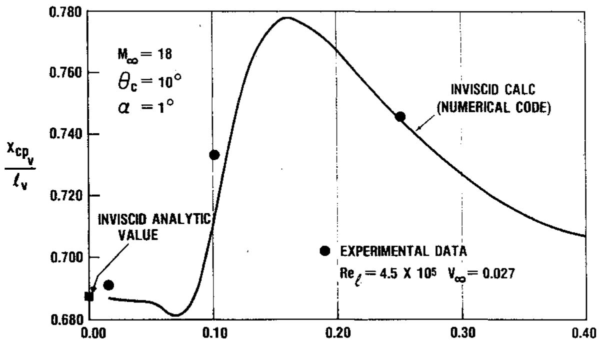

Fig. 3 Center-of-pressure dependence on bluntness.

is possible only at the expense of slightly increased bluntness (ψ) since results are computed as a function of model length for a fixed spherical nose radius. The calculation predicts the same behavior with angle of attack for the viscous influence on center of pressure as that exhibited by the experimental results. The quantitative agreement is within estimates of the combined uncertainties of the numerical and experimental results. More definitive interpretation of the comparison is thus precluded.

The blunt cone, Mach 18 center-of-pressure data are presented in Fig. 2. Results for 10°, spherically blunted cones with bluntness ratios of 0.0167, 0.10, and 0.252 and for a 7° cone with a bluntness of 0.20 are illustrated. For each bluntness, the behavior of the center-of-pressure location with angle of attack is well established by the experimental results. The viscous parameter, $\bar{V}_\infty$, as indicated on the figures, varied slightly due to changing model length. Inviscid computations have been performed for each case at angles of attack of 1, 3, 5, 10, and 15°, using a three-dimensional, finite-difference program. Comparisons are included in Fig. 2. Excellent agreement is seen for the most blunt case for each cone angle. The detailed angle-of-attack dependence established by the experiments is well predicted by the theory. For the less-blunt cases considered for the 10° cone, the experimental results diverge from the inviscid prediction as angle of attack decreases – an apparent viscous effect. Note, however, that for the lower angles of attack this effect on center of pressure is nonmonotonic with bluntness. For example, consider Fig. 3 which compares the present 10° cone results for $\alpha = 1°$ to the inviscid prediction of the variation of center of pressure with bluntness. Agreement is found between the experiment and the calculation for $\psi = 0.25$. For $\psi = 0.10$, the experimental results indicate a center-of-pressure location approximately 2% of model length further aft; whereas, for $\psi = 0.0167$ a shift aft of about 0.5% is indicated. Note additionally that Fig. 3 reveals that the $\psi = 0.10$ bluntness is within the range where the inviscid computation predicts a strong dependence of center of pressure on bluntness, especially in relation to the dependence predicted near $\psi = 0.0167$. Consequently, the larger departure from the inviscid prediction for $\psi = 0.10$ could loosely be ascribed to a much smaller change in "effective" inviscid bluntness.

It should be noted that the experimental results for each bluntness were reproducible to well within the quoted experimental uncertainty. In addition, the interchangeable model noses were determined, through use of precision templates in conjunction with an optical comparator, to be spherically blunted to the specified radius to within the design tolerances of ± 0.0005 in. (corresponding to an uncertainty in ψ of ± 0.00022).

In summary, hypersonic viscous interaction is observed to have a stabilizing influence on the center of pressure of a sharp, slender cone at low angles of attack ($\alpha \lesssim \theta_c$) in that an aft shift relative to the analytic inviscid prediction is observed. As angle of attack increases, the viscous effect decreases and the center of pressure asymptotically approaches the inviscid prediction (within the experimental uncertainty). Analogously, for the less-blunt spherically blunted cones, the experimental results deviate from the numerical inviscid calculations as the angle of attack decreases. This apparent viscous effect is nonmonotonic with bluntness.

References

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