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Viscous Effects on Missile Aerodynamics at Low Angles of Attack

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Analytic results obtained through a recently developed preliminary design code are compared with experimental results. It is found that, especially at transonic speeds, viscous flow effects can severely distort the inviscid unsteady aerodynamic characteristics of typical tactical missile geometries. The different sources for these "anomalous" viscous effects are described, and the potential danger of using subscale experimental data as the basis for a design code is illustrated by a few well-documented examples.

Nomenclature

c = reference length, usually $c=d_N$
d = diameter of cylindric aft body
d_N = base diameter of nosetip
l = total body length
M = Mach number
M_p = pitching moment, coefficient $C_m = M_p/(\rho_\infty U_\infty^2/2)S$
p = static pressure, coefficient $C_p = (p-p_\infty)/(\rho_\infty U_\infty^2/2)$
q = body pitch rate
Re = Reynolds number, $Re_l = U_\infty l/\nu_\infty$
S = reference area, $S=c^2/4$
t = time
U = axial velocity
x = axial distance from nosetip
α = angle of attack
$\Delta\alpha$ = pitch amplitude
Δ = increment
θ_c = cone half-angle
ν = kinematic viscosity of air
ρ = density of air

Subscripts

c = cone
CG = center of gravity
N = nose
TR = transition
∞ = freestream conditions

Derivative symbols

$$\dot{\alpha} = \frac{\partial\alpha}{\partial t}$$

$$C_{mq} = \frac{\partial C_m}{\partial(cq/U_\infty)} : C_{m\dot{\alpha}} = \frac{\partial C_m}{\partial(c\dot{\alpha}/U_\infty)}$$

Introduction

THE dominating viscous flow effects on missile aerodynamics at high angles of attack are well known.[1-5] Less well known is the fact that they, in many cases, can be equally dominating at low angles of attack. The flow separation induced by a blunt nose at transonic speeds often causes dynamic instability of cylinder-flare bodies at low angles of attack and amplitudes.[6,7] Adding a bulbous, dome-shaped base to a slender vehicle can also result in a complete loss of pitch damping at transonic speeds.[7,8] Somewhat more subtle than these effects of separated flow is the observed large effect of boundary layer transition on the low-α vehicle aerodynamics of a slender cone.[9-11]

The present paper illustrates how viscous flow phenomena, such as the ones mentioned above, can influence the low-α aerodynamic characteristics of typical missile geometries. As the viscous effects are largest in regards to the unsteady aerodynamics, only the dynamic stability characteristics will be discussed. The potential danger posed by these viscous flow phenomena when using subscale experimental data for missile design is illustrated by a few well-documented examples.

Discussion

Figures 1a and 1b demonstrate that a recently developed preliminary design code[12,13] can predict the pitch damping derivative measured experimentally[14,15] on ogive-cylinder bodies of varying slenderness. The predicted damping by the inviscid design code[12,13] is the same for both the regular and the boattailed $l/d=3$ ogive-cylinder shown in Fig. 2. The figure shows that the effect of Reynolds number is small for the regular ogive but very large for the boattailed body. This adverse effect of a boattail or a bulbous base on dynamic stability has been described in detail.[7,8] When the Reynolds number is increased so that the boundary layer becomes turbulent before the base, the adverse boattail effect is minimized. This explains why a compilation of experimental data for an $l/d=5$ ogive-cylinder[15] does not show any distinctive boattail effects (Fig. 3). What can be the reason, then, for the poor prediction by inviscid theory[12,13] of the experimental results in Fig. 3? Figure 4 gives the answer. The experimental results[16] show that boundary layer transition effects could have caused the increased damping.

It is shown in Ref. 9 that transition aft of the center of gravity (CG) on a slender cone will increase the dynamic stability substantially and decrease the static stability slightly. It is also shown that the transition effect for the cone is inversely proportional to the cone angle. Thus, one would expect the transition effect to become large for such a slender body as the ogive-cylinder in Fig. 4 (and Fig. 3). That it really is a case of low-α viscous effects is confirmed by the good agreement between inviscid prediction and the measured damping levels before transition in Fig. 4 (denoted by X in Fig. 3).

Figure 5 shows the inviscid theory[12,13] to agree with experiment for a cone-cylinder,[17] at least at transonic speeds where the viscous flow effects are minimized. At the large amplitudes used in the test,[17] 3 deg $\le \Delta\alpha \le$ 6 deg, large viscous cross flow effects, which will increase in magnitude with increasing slenderness and decreasing Mach number,[13] are expected. This is exactly the trend for the deviation between experiment and inviscid theory in Fig. 5. In contrast to the good agreement between predicted and measured damping at transonic speed in Fig. 5, one finds the experimental data for the same geometry[18] shown in Fig. 6 to disagree with the

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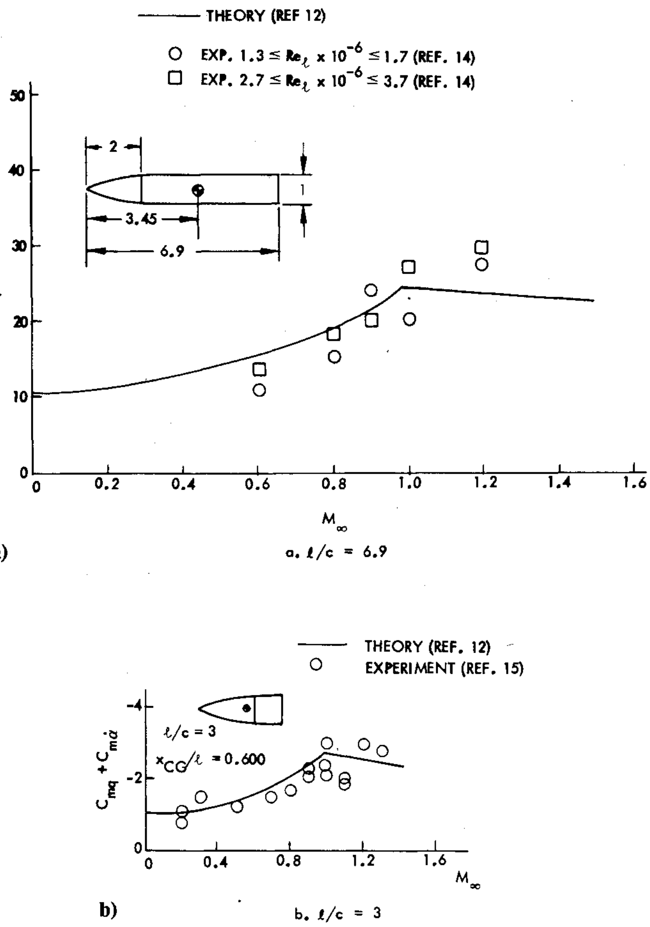

Fig. 1 Comparison between theoretical and experimenal pitch damping results for ogive-cylinder bodies.

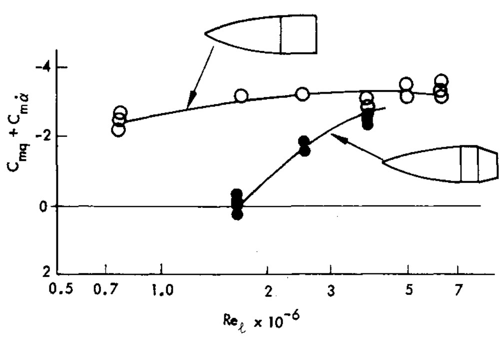

Fig. 2 Measured effect of Reynolds number on $l/d=3$ ogive-cylinder bodies at $M=1.0$ (Ref. 15).

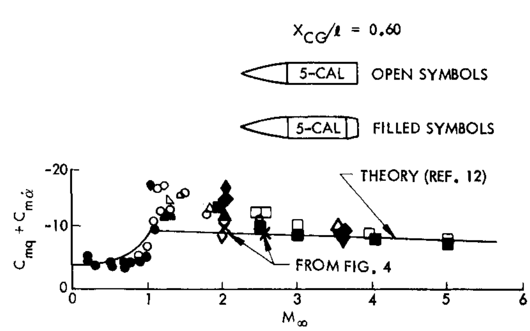

Fig. 3 Comparison between theoretical and experimental damping for an $l/d=5$ ogive-cylinder.

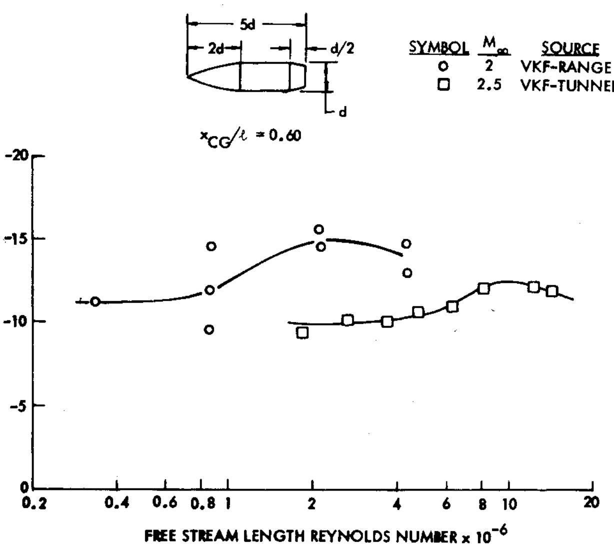

Fig. 4 Effect of Reynolds number on an $l/d=5$ ogive-cylinder body (Ref. 16).

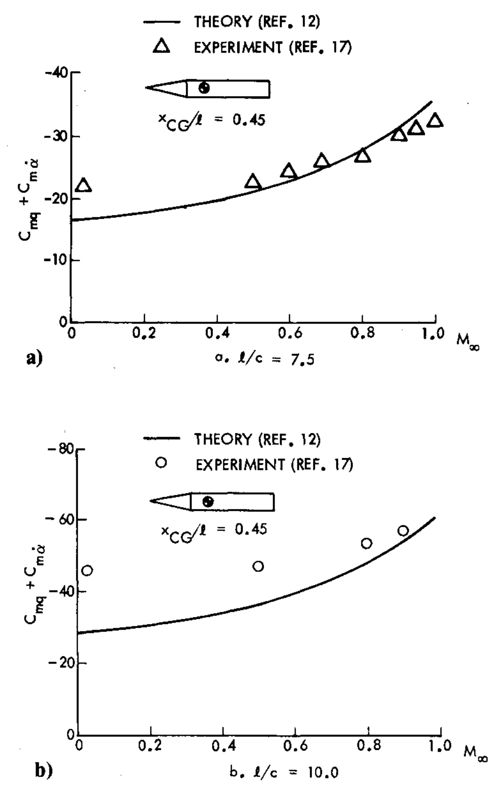

Fig. 5 Comparison between theoretical and experimental damping for cone-cylinder bodies.

inviscid prediction.[12,13] There are two low-α viscous flow phenomena that can cause the loss of damping exhibited by the experimental data in Fig. 6. One is the transition effect just discussed, in this case occurring forward of CG, when the effect is reversed[11] (Fig. 7)† and the damping will be decreased rather than increased. Another flow mechanism is nose-induced flow separation, which has been shown to cause greatly reduced damping at high subsonic speed, often leading to dynamic instability, as is exemplified by the data for a hemisphere-cylinder[19,20] (Fig. 8). For a slender conic nose the separated flow effect is less drastic,[21] but could still lead to

†Note that $x_{TR}/l>1$ in the figure means that transition moves to the leeside of the body at $\alpha>0$.

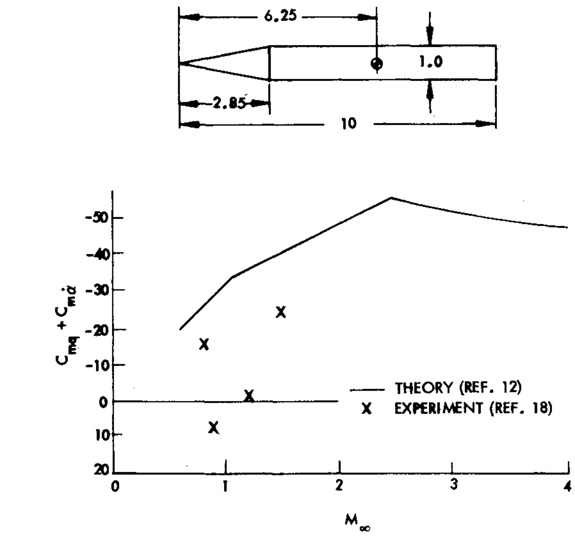

Fig. 6 Comparison between inviscid theory and experiment for an $l/d = 10$ cone-cylinder.

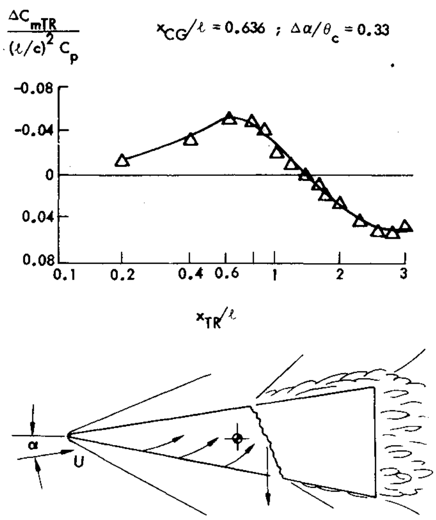

Fig. 7 Effect of transition location at $\alpha = 0$ on the transition-induced moment amplitude on a slender blunted cone at large flow inclination, $\alpha/\theta_c = 0.33$ (Ref. 11).

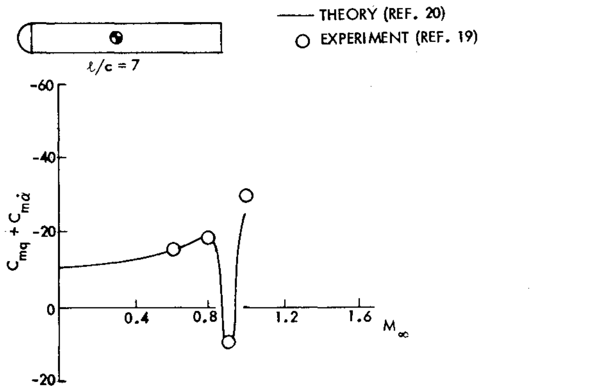

Fig. 8 Damping characteristics of a hemisphere-cylinder body.

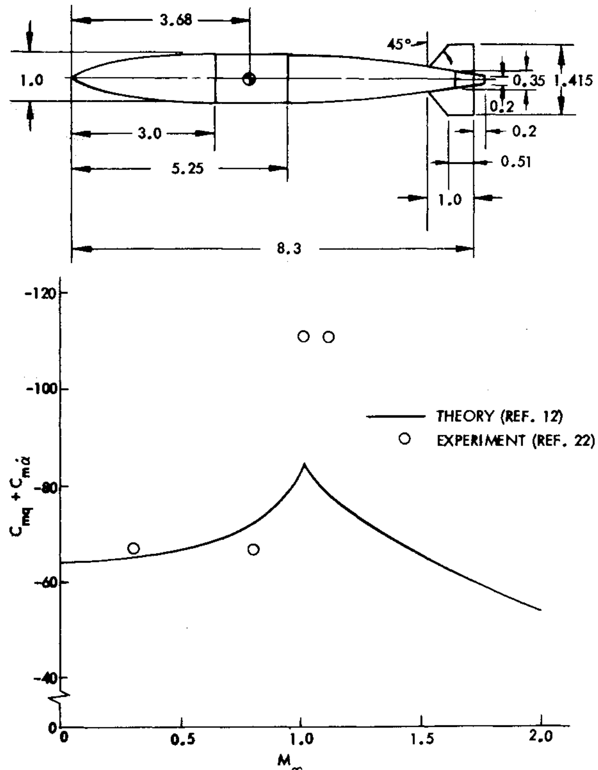

Fig. 9 Comparison between inviscid theory and experiment for a finned body.

the measured total loss of damping considering the leverage given to the undamping forebody loads[21] by the CG location far aft of the nose (Fig. 6).

Figure 9 shows that the inviscid prediction[12] of the pitch damping for a finned body agrees well with experimental results[22] at subsonic speeds but grossly underpredicts the damping measured at transonic speeds. The likely reason for this disagreement at transonic speeds is flow separation caused on the boattail by the fin shocks. In low-density flow such interaction can cause separation even on a cylindrical aft body. Only when the Mach number becomes so large that the fin shocks intersect each other aft of the base does this interaction effect disappear.[23] The flow separation decreases the tail lift, causing decreased static stability. Because of the time lag associated with the finite convection velocity in the fuselage boundary layer, the effect on the dynamic stability is of the opposite sign.[21] Consequently, the flow separation will increase the measured pitch damping in agreement with the experimental data trend in Fig. 9.

Scaling Problems

Following good engineering practice, the experimental data base existing at one time for ogive-cylinder bodies was used to formulate computational means by which the aerodynamics of future missile designs could be predicted.[24] This so-called Spinner code gives predictions that are in better agreement with the existing experimental results for the five-caliber ogive-cylinder shown in Fig. 3 than the predictions by the inviscid theory[12,13] (see Fig. 10a). The likely reason for this is that the data base used for the Spinner code was for long ogive-cylinder bodies where boundary layer transition is likely to occur on the cylindrical aft body. This is confirmed by the poor prediction through the Spinner code for the $l/d = 3$ ogive-cylinder, where the short aft body probably never experienced any boundary layer transition effects (Fig. 10b).

Applying the Spinner code to the cone-cylinder geometry in Fig. 5 gives the results shown in Fig. 11. The experimental results were apparently not influenced significantly by boundary layer transition effects. The large oscillation am-

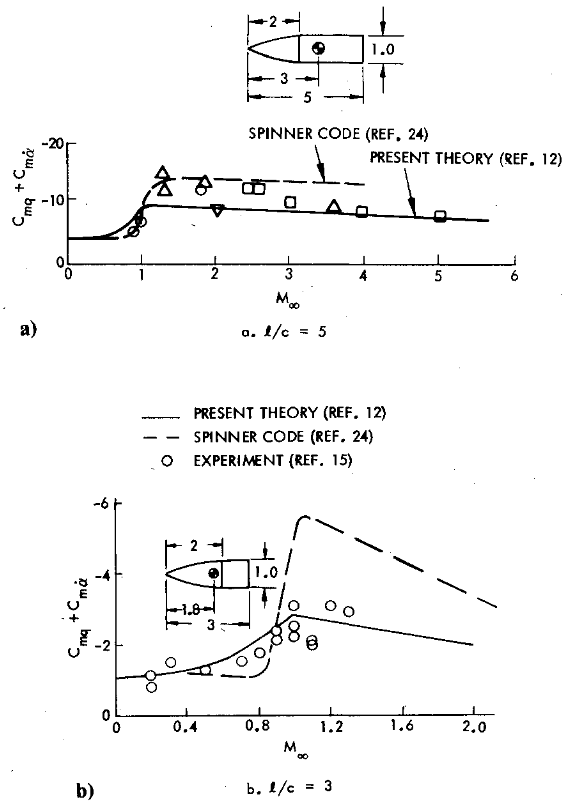

Fig. 10 Comparison between two theoretical predictions and experiment for an $l/d = 5$ ogive-cylinder body.

plitude, $3\ \mathrm{deg} \leq \Delta\alpha \leq 6\ \mathrm{deg}$, used in the test[17] makes it difficult for the transition to influence the measured pitch damping to any large degree. The transition effects for these very slender bodies are probably limited to the α-region below 1 or 2 deg.[25] Figure 12 shows that one cannot apply the Spinner code[24] to geometries outside the nose-cylinder category, such as a slender cone. Whereas the experimental results[26] agree well with present[13] and other[27] inviscid theories, once the effect of support interference has been accounted for,[28] the Spinner code overpredicts the measured damping by several hundred percent at transonic and low supersonic speeds.

The examples just given illustrate the danger of applying subscale experimental data to full-scale design. It is shown in Refs. 29 and 30 that the strong coupling existing between boundary layer transition and vehicle motion makes it impossible to simulate full-scale unsteady aerodynamics in a subscale wind tunnel test. This would seem to make it mandatory to perform all dynamic tests at full-scale Reynolds numbers. However, this is not true in many cases, as is illustrated by the comparison between experiment and inviscid theory in Figs. 1, 5, and 12. The results in Fig. 4 show that as long as the boundary layer transition does not enter into the picture the effect of Reynolds number is negligibly small, barring near wake effects, as in the case of the boattailed body in Fig. 2, and separated flow effects in general.[6-8]

However, when the experimental results are affected by viscous effects one has to be aware of it, as is demonstrated by the results in Figs. 3, 6, 8 and 9. In this case one needs dynamic tests at full-scale Reynolds numbers or systematic tests at subscale Reynolds numbers to support analytic extrapolation to full scale, as is described in Ref. 31. That is, static and dynamic tests are performed over a range of subscale Reynolds numbers, and the results are used to formulate analytic means by which the dynamic effects of transition can be determined, as was done in Refs. 10 and 11 for slender cones. Static tests at full-scale Reynolds number will then supply the input needed to determine the full-scale

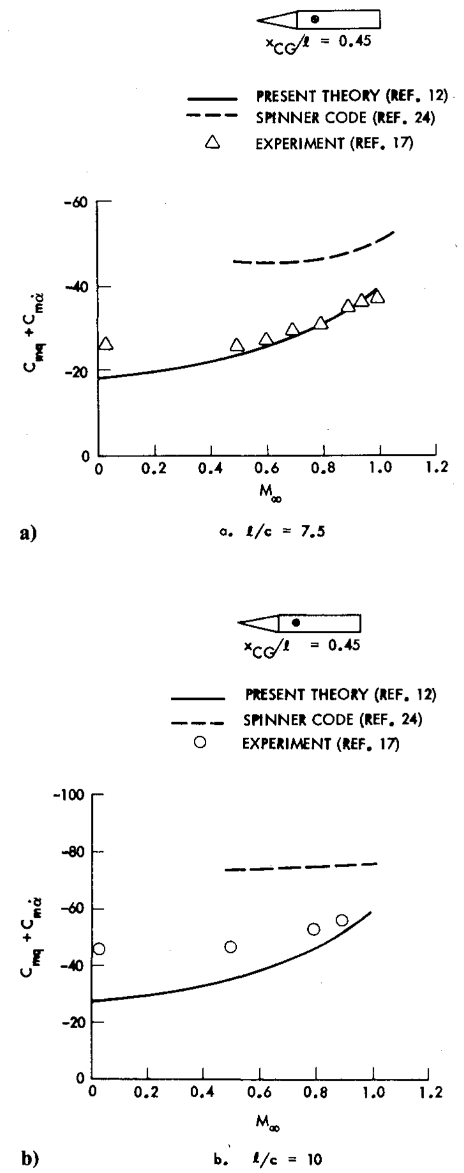

Fig. 11 Comparison between two theoretical predictions and experiment for cone-cylinder bodies.

vehicle dynamics including transition effects. It should be emphasized that it is not a simple matter to obtain the correct subscale dynamic test data. These low-α viscous flow phenomena are highly nonlinear, limited to a small α range around $\alpha = 0$, and are, therefore, usually very difficult to measure. In the case of ballistic range and other free-flight tests one faces the problems of data resolution and data nonuniqueness. In the case of wind tunnel tests one is faced with the problem of model support interference,[32] which can become especially bothersome in the presence of aft body transition.[28] In spite of these difficulties the technical community is forced to use experimental data not only for documentation purposes but also for preliminary design.‡ The results presented here demonstrate that great caution has to be exercised when using subscale experimental data to predict full-scale aerodynamics, especially in the case of dynamic characteristics.

‡At least until some time in the distant future when computational fluid dynamics (CFD) may be able to include the coupling between boundary layer transition and vehicle motion.

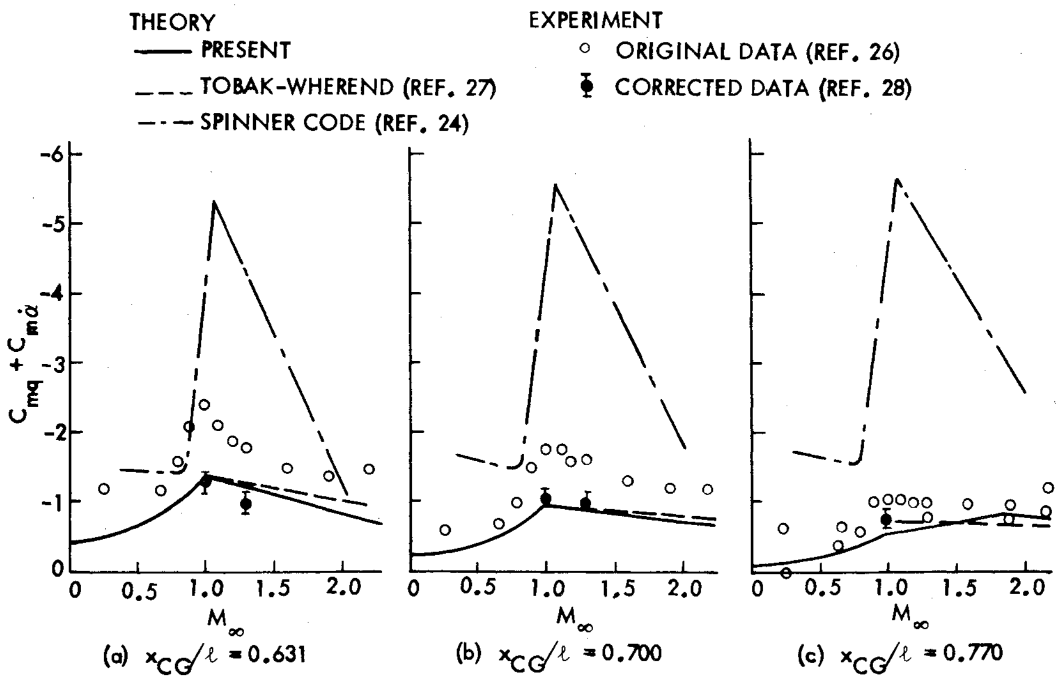

Fig. 12 Comparison between three theoretical predictions and experiment for a 12.5 deg sharp cone.

Conclusions

A review of the existing experimental data base for slender vehicle geometries, typical of tactical and ballistic weapons, has revealed that viscous flow effects often dominate the vehicle aerodynamics even at low angles of attack. Because of viscous flow time lag the unsteady aerodynamics are affected to a larger degree than the static characteristics. It is undoubtedly true that for some time to come the various viscous effects on vehicle dynamics will have to be treated separately for each case. That is, it is not possible at present to include the viscous effects in a push-button type of preliminary design code. Instead one will have to rely on "engineering know-how," based upon past experience.

References

[1] Nielsen, J.N., "Nonlinearities in Missile Aerodynamics," AIAA Paper 78-20, Jan. 1978.

[2] Wardlaw, A.B. Jr., "High Angle of Attack Missile Aerodynamics," Paper 5, AGARD LS-98, March 1978.

[3] Jorgensen, L.H., "Prediction of Aerodynamics Characteristics for Slender Bodies Alone and With Lifting Surfaces to High Angles of Attack," Paper 28, AGARD CP-247, Sept. 1978.

[4] Chapman, G.T. and Keener, E.R., "The Aerodynamics of Bodies of Revolution at Angles of Attack to 90°," AIAA Paper 79-0023, Jan. 1979.

[5] Ericsson, L.E. and Reding, J.P., "Vortex-Induced Asymmetric Loads in 2-D and 3-D Flows," AIAA Paper 80-0181, Jan. 1980.

[6] Ericsson, L.E., "Unsteady Aerodynamics of Separating and Reattaching Flow on Bodies of Revolution," *Recent Research on Unsteady Boundary Layers,* IUTAM Symposium, 1971, Vol. 1, pp. 481-512.

[7] Ericsson, L.E. and Reding, J.P., "Reentry Capsule Dynamics," *Journal of Spacecraft and Rockets,* Vol. 8, June 1971, pp. 575-586.

[8] Ericsson, L.E. and Reding, J.P., "Aerodynamic Effects of Bulbous Bases," NASA CR-1339, Aug. 1969.

[9] Ward, L.K., "Influence of Boundary Layer Transition on Dynamic Stability at Hypersonic Speeds," *Transactions of the Second Technical Workshop on Dynamic Stability Testing,* Paper 6, Vol. II, AEDC, 1965.

[10] Ericsson, L.E., "Effects of Boundary Layer Transition on Vehicle Dynamics," *Journal of Spacecraft and Rockets,* Vol. 6, Dec. 1969, pp. 1404-1409.

[11] Ericsson, L.E., "Transition Effects on Slender Vehicle Stability and Trim Characteristics," *Journal of Spacecraft and Rockets,* Vol. 11, Jan. 1974, pp. 3-11.

[12] Ericsson, L.E., "Modification of Aerodynamic Prediction of the Longitudinal Dynamics of Tactical Weapons," LMSC-D646354 and Addendum LMSC-D646354A, Contract N60921-77C-A294, Lockheed Missiles & Space Company, Aug. 1979.

[13] Ericsson, L.E., "Effect of Mach Number on Slender Vehicle Dynamics," *Journal of Spacecraft and Rockets,* Vol. 18, Jan.-Feb. 1981, pp. 18-23.

[14] Shadow, T.O., "An Investigation of the Half-Model Reflection-Plane Technique for Dynamic Stability Testing at Transonic Mach Numbers," AEDC-TR-76-165, Jan. 1977.

[15] Uselton, B.L. and Shadow, T.O., "Dynamic Stability Characteristics of 3- and 5-Cal Army Navy Spinner Projectiles at Mach Numbers 0.2 through 1.3," AEDC-TR-70-115, July 1970.

[16] Ward L.K., private communication, Feb. 1972.

[17] Bykov, V.S., "Calculation of the Characteristics of Aerodynamic Damping of Bodies of Revolution," FTD-HT-23-1363-74, June 1974.

[18] Murphy, C.H., "Free Flight Motion of Symmetric Missiles," BRL Report 1216, July 1963.

[19] Shadow, T.O. and Paulk, R.A., "Dynamic Stability Characteristics of Bluff Bodies of Revolution at Transonic Mach Numbers," AEDC-TR-72-110, Aug. 1972.

[20] Ericsson, L.E. and Reding, J.P., "Approximate Slender Vehicle Dynamics at all Speeds," *Proceedings 11th Navy Symposium on Aeroballistics,* 1978, Vol. 1, pp. 87-114.

[21] Ericsson, L.E., "Aeroelastic Instability Caused by Slender Payloads," *Journal of Spacecraft and Rockets,* Vol. 4, 1967, pp. 65-73.

[22] Boyle, W. and Mantler, M., "The Effects of Configuration Sensitivity on Ballistics of Bombs, Final Report, Part I, Aerodynamic Math Model and Tolerances," Northrop Services, Inc., Contract N60921-C-A076, Nov. 1978.

[23] Hoekstra, P.W., private communication, Aug. 1974.

[24] Whyte, R.H., "'Spinner'—A Computer Program for Predicting the Aerodynamic Coefficients of Spin-Stabilized Projectiles," G.E. Technical Information Service, Class 2, 69APB3, Aug. 1969.

[25] Ericsson, L.E., "Correlation of Attitude Effects on Slender Vehicle Transition," *AIAA Journal,* Vol. 12, April 1974, pp. 523-529.

[26] Wehrend, W.R. Jr., "An Experimental Evaluation of Aerodynamic Damping Moments on Cones with Different Centers of Rotation," NASA TN D-1768, March 1963.

[27] Tobak, M. and Wehrend, W.R., "Stability Derivatives of Cones at Supersonic Speeds," NACA TN 3788, Sept. 1956.

[28] Ericsson, L.E. and Reding, J.P., "Transonic Sting Interference," *Journal of Spacecraft and Rockets,* Vol. 17, March-April 1980, pp. 140-144.

[29] Ericsson, L.E. and Reding, J.P., "Scaling Problems in Dynamic Tests of Aircraft-Like Configurations," Paper 25, AGARD-CP-227, Feb. 1978.

[30] Ericsson, L.E. and Reding, J.P., "Reynolds Number Criticality in Dynamic Tests," AIAA Paper 78-166, Jan. 1978.

[31] Ericsson, L.E. and Reding, J.P., "Dynamic Simulation Through Analytic Extrapolation," AIAA Paper 81-0399, Jan. 1981.

[32] Reding, J.P. and Ericsson, L.E., "Dynamic Support Interference," *Journal of Spacecraft and Rockets,* Vol. 9, July 1972, pp. 547-553.