Lateral Oscillations of Sting-Mounted Models at High Alpha

L. E. Ericsson*
Lockheed Missiles & Space Company, Inc., Sunnyvale, California 94089

It is shown that in a static test of a model of a high-performance aircraft or missile, lateral oscillations can occur, resulting in static, time-average measurements of the asymmetric loads that are close to zero. In contrast, the loads needed for analysis of full-scale aircraft or missile maneuvers are the instantaneous asymmetric loads, which because of the coupling between vehicle motion and flow separation will approach their maximum magnitude. Results applicable to full-scale free flight could be obtained by use of an apparatus such as the rotary rig, which permits coning and/or spinning motions of the model, provided that the measurements are corrected for support and wall interference effects. Until such capability is in hand, the best approach appears to be to use the asymmetric load extremes, e.g., such as determined in a static test where the model has been rolled through the full 360-deg range.

Nomenclature

c = reference length, $c = D$
C_N = $N/(\rho_\infty U_\infty{}^2/2)S$
C_{nr} = $\partial C_n/\partial(rD/2U_\infty)$
$C_{n\beta}$ = $\partial C_n/\partial(\beta D/2U_\infty)$
C_Y = $Y/(\rho_\infty U_\infty{}^2/2)S$
c_y = $\mathrm{d}C_Y/\mathrm{d}(x/c)$
D = maximum body diameter
M = Mach number
N = normal force
n = yawing moment
Re = Reynolds number, $Re = U_\infty D/\nu_\infty$
r = yawing rate
S = reference area, $S = \pi D^2/4$
t = time
U = velocity
x = axial body-fixed coordinate
Y = side force
y = lateral space-fixed coordinate
$\dot{y}$ = $\partial y/\partial t$
α = angle of attack
β = angle of sideslip
ν = kinematic viscosity of air
ρ = density of air

Subscript
∞ = freestream condition

Introduction

CURRENT high-performance missiles and aircraft have long slender forebodies, which for subsonic crossflow conditions generate asymmetric aerodynamic loads at high angles of attack, even in the case of zero sideslip.[1] In a static test of such a geometry, lateral oscillations can occur, resulting in static, time-average measurements of the asymmetric loads that are close to zero. In contrast, the experimental results really needed for analysis of full-scale vehicle maneuvers at high alpha are the maximum possible, instantaneous, asymmetric loads, resulting from the coupling between vehicle motion and flow separation through so-called moving wall effects.[2]

Presented as Paper 89-0047 at the AIAA 27th Aerospace Sciences Meeting, Jan. 12, 1989; received May 24, 1989; revision received March 8, 1990.

*Senior Consulting Engineer. Fellow AIAA.

A sting-supported model at high angles of attack experiences an asymmetric aerodynamic load on its slender forebody that is unaffected by a downstream sting support[3] (Fig. 1). Thus, one has only to consider the coupling between a lateral oscillatory motion and the asymmetric loads on the slender forebody itself.

Discussion

The experimental results for an ogive-cylinder[4] (Fig. 2) show that the side force measured at $\alpha = 50$ deg is extremely sensitive to Reynolds number and can reach a magnitude exceeding that of the normal force. Figure 3 shows how the direction of this large side force is determined by body-fixed nose microasymmetries and can be directed by rolling the ogive-cylinder.[5]

As is discussed in Ref. 2, even a slow spinning or coning motion of the forebody can overpower this microasymmetry effect and determine the direction of the side force. This is demonstrated by the test results for a cone-cylinder.[6] The authors describe how only a slight push was needed to establish the coning motion in one direction or the other (Fig. 4), regardless of how the measured static yawing moment was biased by rolling the body-fixed nose microasymmetries.[1] The cone-cylinder body reached very nearly equal steady-state coning rates in positive and negative rotation directions, i.e., the motion dominated over the static asymmetry, locking-in the separation asymmetry in the direction of the body motion and driving it.

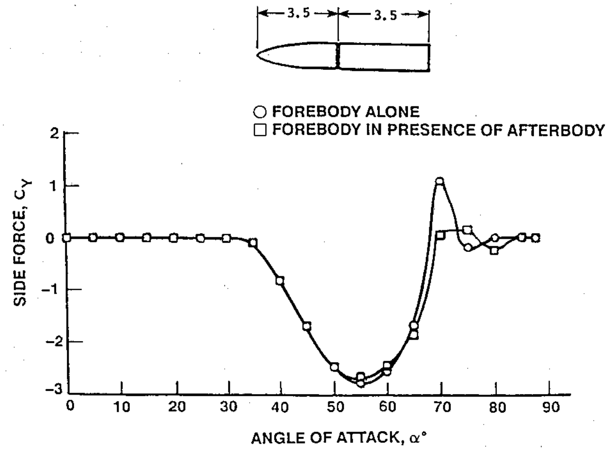

Fig. 1 Effect of cylindrical aft body on asymmetric loads on an ogive-cylinder (Ref. 3).

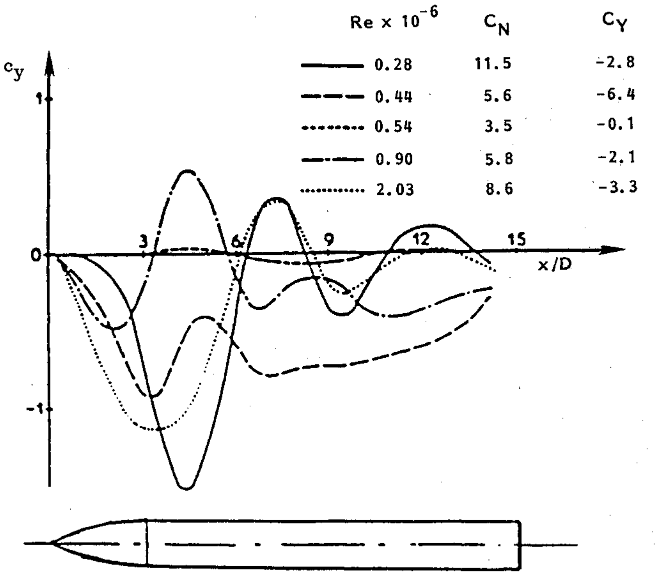

Fig. 2 Side-force distribution at α = 50 deg on an ogive-cylinder through the critical Reynolds number range (Ref. 4).

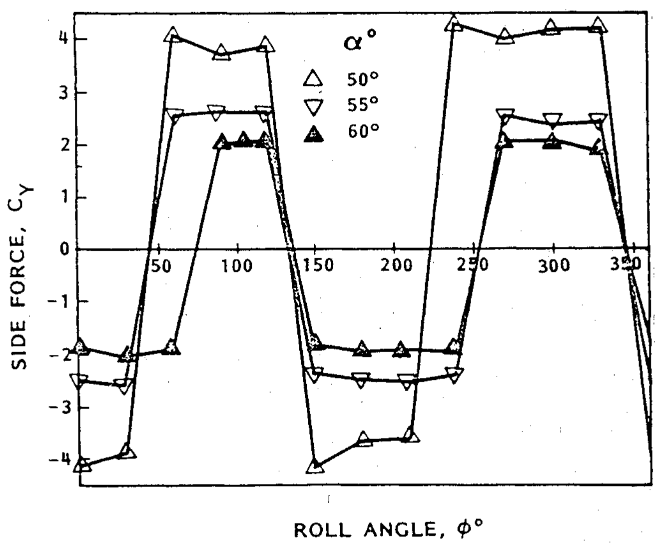

Fig. 3 Side-force characteristics of a 3.5-deg ogive (Ref. 5).

In the case of the coning motion, the moving wall effects act as follows on the translating cross section[2] (Fig. 5). The lateral motion of the circular cross section causes the flow separation to be delayed on the advancing side and promoted on the retreating side, the important moving-wall effects being those close to the flow stagnation point. Thus, the motion produces a force that drives it until an equilibrium coning rate is reached, where the separation-induced driving moment is balanced by the drag-generated damping moment.[7]

In the present case, the body motion considered is the lateral bending oscillation rather than the coning motion just discussed. However, the flow mechanism described by Fig. 5 applies also to the translatory, oscillatory motion. The lateral bending degree-of-freedom of a sting-mounted model (Fig. 6) is analyzed in Ref. 8, showing that a limit-cycle-type oscillation will result unless the support is very rigid. The potential for such lateral oscillations is large at the beginning and end of the angle-of-attack region for stationary asymmetric flow separation and vortex shedding. In the case of the incipient asymmetric flow separation, it can be driven by the lateral oscillation behavior between its symmetric and asymmetric states. Such a flow change has even been observed to occur intermittently in a static test[9] (Fig. 7), indicating that a potential for truly self-excited lateral oscillations exists at incipient asymmetric flow conditions.

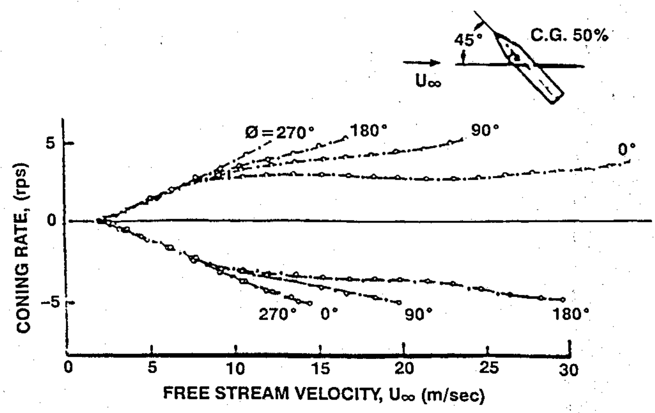

Fig. 4 Coning characteristics of a cone-cylinder at α = 45 deg (Ref. 6).

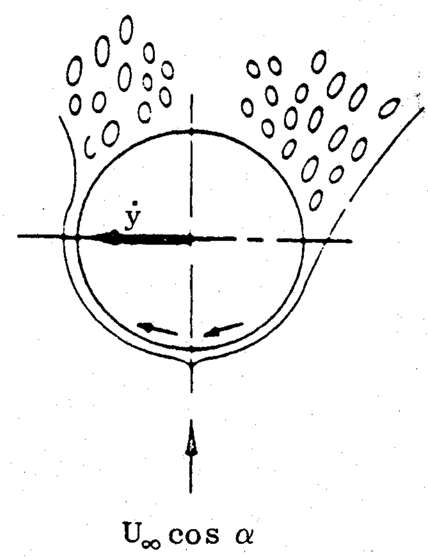

Fig. 5 Conceptual crossflow characteristics for a coning body.

Recent results, obtained on an ogive-cylinder describing lateral oscillations,[10] illustrate the problem the test engineer faces in a "static" test at incipient asymmetric flow conditions (Fig. 8). At $\alpha \approx 30$ deg, the time-average value of the yawing moment, $\tilde{C}_n$, which corresponds to the moment measured in a static test, is practically zero. This contrasts to the dynamic measurement $C_{nr} - C_{n\dot{\beta}}\cos\alpha$, which shows a maximum undamped value of a magnitude twice as large as the damped value at $\alpha < 25$ deg.

As has been discussed before,[11,12] the potential for self-induced lateral oscillations at the high-alpha end of the α range for steady asymmetric flow separation and vortex shedding is probably twice as large, although a lateral perturbation of a magnitude of 1 or 2% of the cylinder diameter may be needed to start the oscillations.[8] Of course, at these high angles of attack, above α = 50 deg, the unsteady Karman-type vortex shedding occurring on the cylindrical aft body is likely to provide the needed perturbation to flip the asymmetric flow separation between its two extreme positions, as was described in Ref. 11.

An example of the resulting model vibrations is provided by the experimental results[13] in Fig. 9. The side force and yawing moment are likely to have exhibited zero time averages, if measured, in agreement with the characteristics shown in Fig. 8. This was observed in wind-tunnel tests of the Vertical

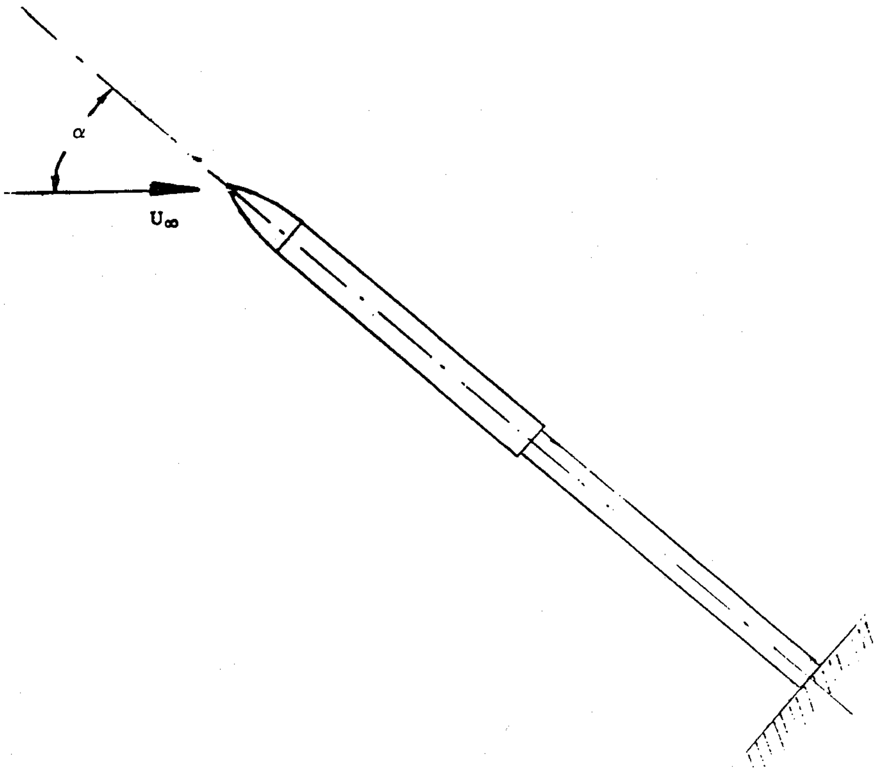

Fig. 6 Definition of model-support geometry.

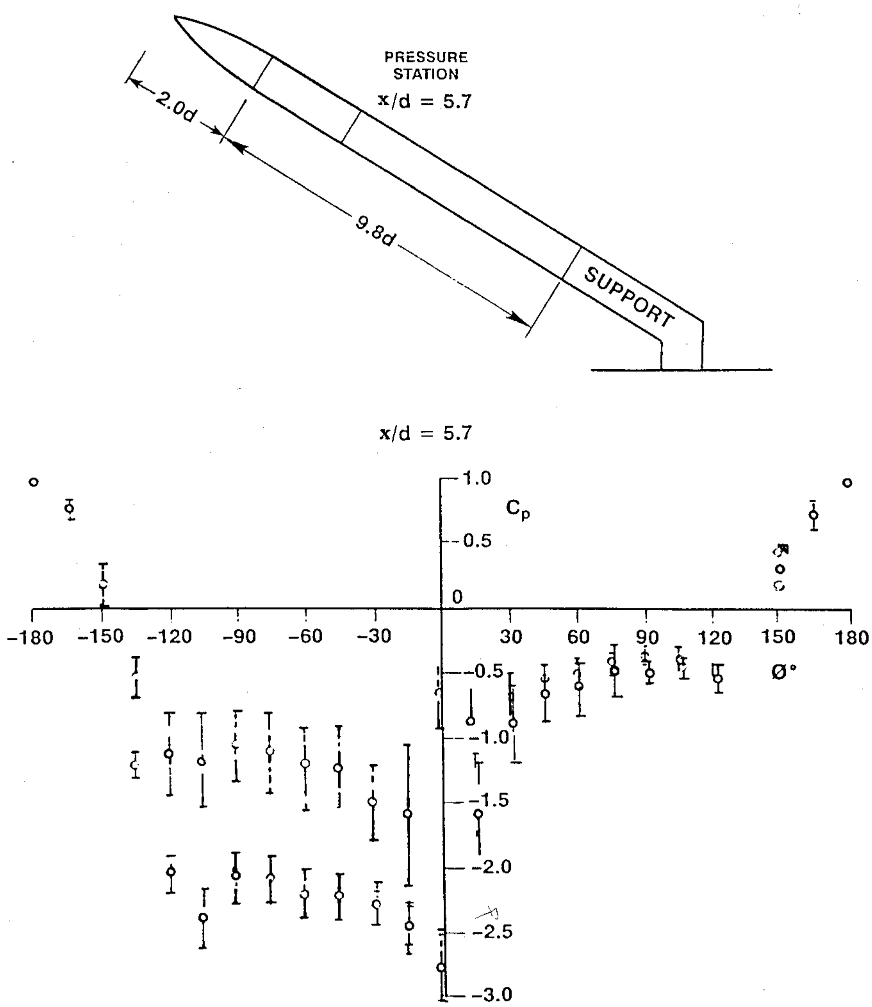

Fig. 7 Pressure distributions on an ogive-cylinder at $\alpha = 45$ deg and $Re = 0.11 \times 10^6$ (Ref. 9).

Launch ASROC (VLA) missile[14] (Fig. 10) to investigate the effect of a tilted nose cap. The results shown in Fig. 11 were obtained at $\alpha = 50$ deg. At a roll angle of $\phi \approx 60$ deg, the yawing moment went to zero. The authors observed this zero time-average to be associated with large model vibrations. This was observed also in other test cases, leading the authors to the following observation: "On several occasions, configurations which, because of an increased asymmetry, were expected to produce larger yawing moments, in fact, did not. However, those smaller moments were usually accompanied by a more violent shaking of the model." This statement supports the message of the present paper and can be interpreted as follows: when the potential for asymmetric flow separation is large, and the coupling with the vehicle motion would result in the most serious asymmetric load condition in free flight, the static wind-tunnel test may show the asymmetric loading to be negligibly small.

The present author, when visiting the NASA Langley Spin Tunnel in November 1988, in the company of M. Beyers, National Research Council, Canada, was reminded very powerfully of this problem of using static test data to describe the asymmetric loads on a vehicle in free flight. We both observed how, before the start-up of the rotary test at $\alpha = 60$ deg, an aircraft model with pointed nose, similar to the one shown in Fig. 12, described significant lateral oscillations of the nose. However, as soon as the coning rate had become significant, possibly 10–20% of the final rate, the lateral oscillations stopped, because now the one-sided moving-wall effect due to the coning motion dominated over the oscillatory one caused by the lateral vibration.

Thus, lateral support oscillations can give misleading, zero time-average, measurements in a static test. As a consequence, data applicable to free flight cannot be obtained in static tests. Such data can be measured by a support that allows coning or

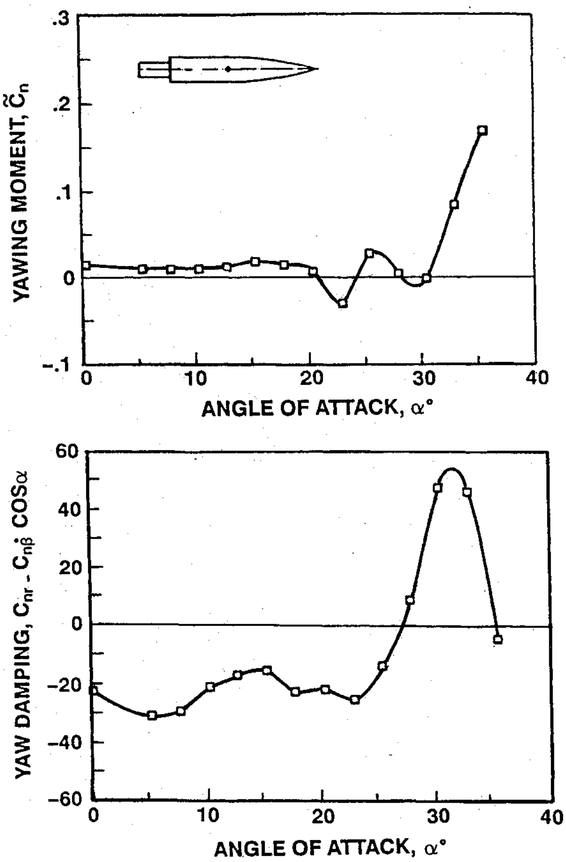

Fig. 8 Time-averaged c_n and associated yaw damping measured in forced oscillations of 1.5-deg amplitude at $M_\infty = 0.7$ of an ogive-cylinder body (Ref. 10).

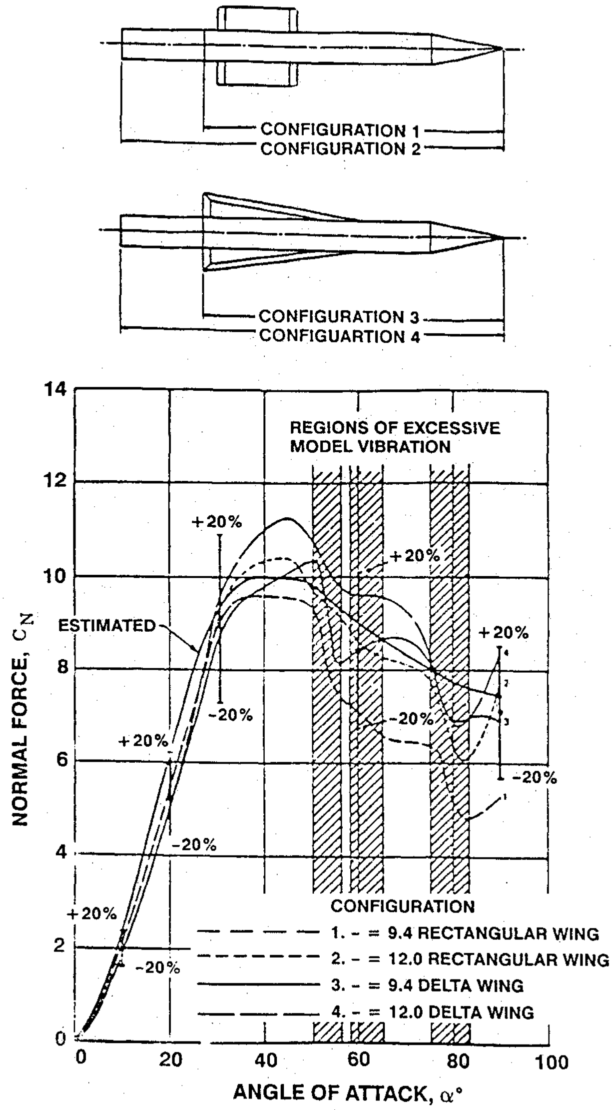

Fig. 9 Normal-force measurements of wing-body combinations at $0 \le \alpha \le 90$ deg (Ref. 13).

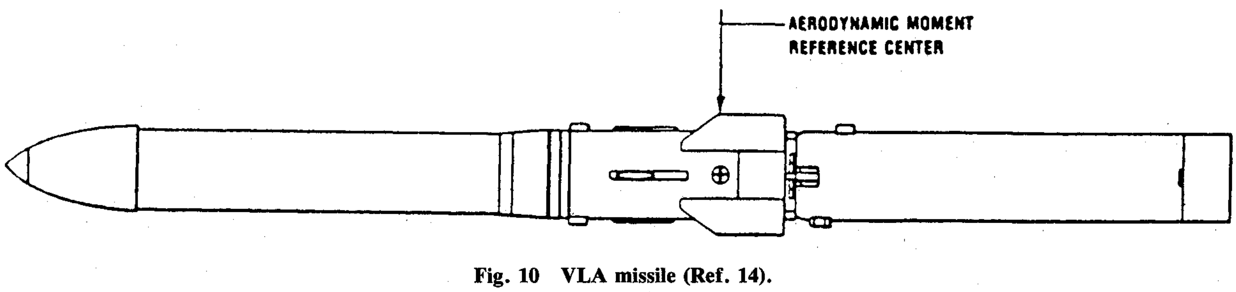

Fig. 10 VLA missile (Ref. 14).

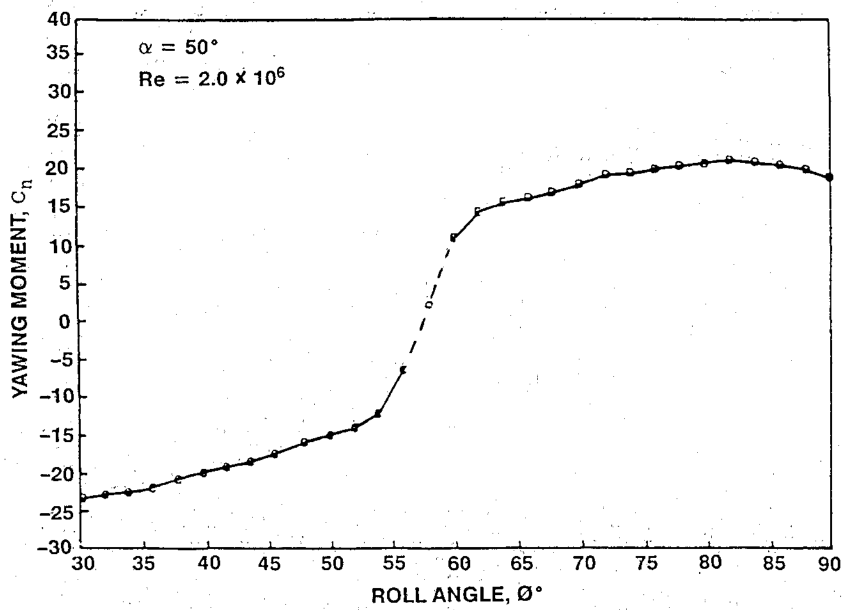

Fig. 11 Yawing-moment variation with roll angle for VLA missile model with canted nose tip, $\alpha = 50$ deg and $Re = 2 \times 10^6$ (Ref. 14).

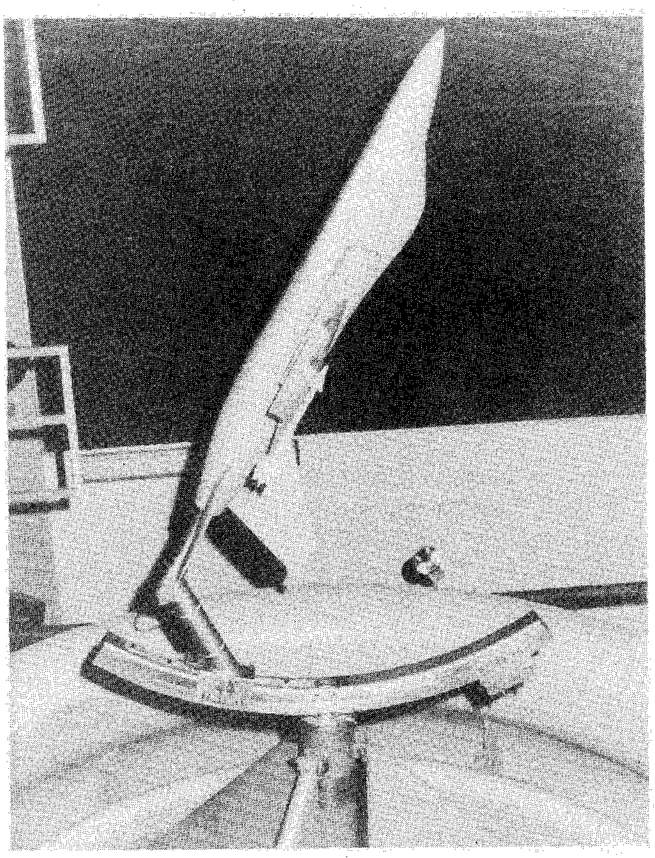

Fig. 12 Typical advanced aircraft model used in rotary rig tests.

rolling motions, such as the rotary rig.[15,16] However, in this case the measurements often have to be corrected for support and wall interference,[17-19] a capability that only will be in hand after completion of the test program outlined in Ref. 20. At the present, the best approach appears to be to obtain a conservative estimate by using the extremes of asymmetric load levels, measured in a static test in which the forebody has been rolled through the full 360-deg range to determine the load extremes,[21] e.g., as shown in Fig. 3. These load extremes can be determined by measurements in the middle of the alpha range for stationary asymmetric flow, e.g., $\alpha = 50$ deg in Fig. 3, where the problem of lateral oscillations does not put extreme demands on the rigidity of the support.

Conclusions

An analysis of the lateral stability of missile and aircraft models in wind-tunnel tests at high angles of attack has shown the following:

1) The asymmetric flow separation on a slender forebody is strongly coupled to the model motion, potentially resulting in large-amplitude lateral oscillations of the model and support, especially at the low- and high-angle-of-attack extremes of the steady asymmetric flow region.

2) As a consequence, the time-averaged values of side force and yawing moment measured in a static test can be close to zero, whereas the values experienced by the maneuvering full-scale vehicle often will be of maximum magnitude because of the moving-wall effects generated by the vehicle maneuver.

3) Subscale test results applicable to full-scale free flight could be obtained by use of an apparatus such as the rotary rig, which permits coning and/or spinning motions of the model, provided that the measurements are corrected for support and wall-interference effects. Until such capability is in hand, the best approach appears to be to use the asymmetric load extremes, e.g., such as determined in a static test where the model has been rolled through the full 360-deg range.

References

[1]Ericsson, L. E., and Reding, J. P., "Asymmetric Vortex Shedding from Bodies of Revolution," *Progress in Astronautics and Aeronautics: Tactical Missile Aerodynamics,* Vol. 104, edited by M. J. Hemsch and H. N. Nielsen, 1986, pp. 243–296.

[2]Ericsson, L. E., "Moving-Wall Effects in Unsteady Flow," *Journal of Aircraft,* Vol. 25, No. 6, 1988, pp. 997–990.

[3]Keener, E. R., Chapman, G. T., and Kruse, R. L., "Effects of Mach Number and Afterbody Length on Onset of Asymmetric Forces on Bodies at Zero Sideslip and High Angles of Attack," AIAA Paper 76-0066, Jan. 1976.

[4]Champigny, P., "Reynolds-Number Effect on the Aerodynamic Characteristics of an Ogive-Cylinder at High Angles of Attack," AIAA Paper 84-2176, Aug. 1984.

[5]Lamont, P. J., "The Complex Asymmetric Flow Over a 3.5 D Ogive Nose and Cylindrical Afterbody at High Angles of Attack," AIAA Paper 82-0053, Jan. 1982.

[6]Yoshinaga, T., Tate, A., and Inoue, K., "Coning Motion of Slender Bodies at High Angles of Attack in Low-Speed Flow," AIAA Paper 81-1899, Aug. 1981.

[7]Ericsson, L. E., "Prediction of Slender Body Coning Characteristics," AIAA Paper 89-2223, July 1989.
[8]Ericsson, L. E., "Lateral Oscillations of Sting-Mounted Models at High Alpha," AIAA Paper 89-0047, Jan. 1989.
[9]Yanta, W., and Wardlaw, A., "Multistable Vortex Patterns on Slender, Circular Bodies at High Incidence," AIAA Paper 81-0006, Jan. 1981.
[10]Beyers, M., "Unsteady Wall Interference in Rotary Tests," AIAA Paper 89-0046, Jan. 1989.
[11]Ericsson, L. E., "Vortex Unsteadiness on Slender Bodies at High Incidence," *Journal of Spacecraft and Rockets*, Vol. 24, No. 4, 1987, pp. 319–326.
[12]Ericsson, L. E., "Flow Unsteadiness Considerations in High Alpha Tests," *Journal of Aircraft*, Vol. 25, No. 6, 1988, pp. 1033–1037.
[13]Thomson, K. D., "Subsonic Wing-Body Interference for Missile Configurations at Large Angles of Attack," *Aeronautical Quarterly*, Vol. 28, Aug. 1977, pp. 163–175.
[14]Dunne, A. L., Black, S., Schmidt, G. S., and Lewis, T. L., "VLA Missile Development and High Angle-of-Attack Behavior," Paper 11, Missile Aerodynamics Conference in Honor of Dr. J. N. Nielsen, Nielsen Engineering & Research, Inc., Monterey, CA, Oct. 31-Nov. 2, 1988.
[15]Schiff, L. E., and Tobak, M., "Results from a New Wind-Tunnel Apparatus for Studying Coning and Spinning Motions of Bodies of Revolution," *AIAA Journal*, Vol. 7, No. 11, 1970, pp. 1953–1957.
[16]Malcolm, G. N., "New Rotation-Balance Apparatus for Measuring Airplane Spin Aerodynamics in the Wind Tunnel," *Journal of Aircraft*, Vol. 16, No. 2, 1979, pp. 264–268.
[17]Ericsson, L. E., and Reding, J. P., "Dynamic Support Interference in High-Alpha Testing," *Journal of Aircraft*, Vol. 23, No. 6, 1986, pp. 889–896.
[18]Ericsson, L. E., "Another Look at High-Alpha Support Interference," AIAA Paper 90-0188, Jan. 1990.
[19]Beyers, M. E., "Unsteady Wall Interference in Rotary Tests," AIAA Paper 89 – 0046, Jan. 1989.
[20]Orlik-Rückemann, K. J., *Rotary Balance Testing for Aircraft Dynamics*, AGARD AR 265 (to be published).
[21]Ericsson, L. E., "The Fickle Effect of Nose Microasymmetry on the High-Alpha Aerodynamics," AIAA Paper 90-0067, Jan. 1990.

Clark H. Lewis
Associate Editor