the pitching moment showed a significant dependency on $\phi$. The finless body is stable at low $\alpha$ and becomes unstable at higher $\alpha$. The finned body data show that the most stable configuration is the + configuration and the least stable is the × configuration. These data show a significant broadening of the pitching moment data based on the aerodynamic roll angle at the highest angles of attack.

Also shown on Figs. 2 and 3 are data from a theoretical prediction formulated by Jorgensen for finless slender bodies.[6] Comparison of the finless CN data with the theoretical prediction shows good agreement over the entire $\alpha$ range shown. Comparison of the finless CLM data with the prediction shows good agreement for $\alpha \geq 30$ deg. Below 30 deg, however, the prediction and experimental data do not agree. The data show that our configuration is much more stable at low $\alpha$ than the theory predicts. Our present data also show more stable behavior at low $\alpha$ than do other experimental data.[6,7] The reason for this discrepancy is not quite clear but may be caused by a number of factors. Three dynamic considerations that may lead to differences are as follows: 1) The fineness ratio for our model was nearly double that of previous researchers, 2) the Mach number (0.15) was significantly lower than the lowest Mach number for which previous data was found (0.6),[6,7] and 3) the Reynolds number was also lower than for previous work. Because of the repeatability of our measurements and the good comparison with other data and prediction for the normal force coefficient and the pitching moment coefficient above $\alpha = 30$ deg, we are quite confident in our data.

Figures 4–6 show the associated out-of-plane loading for the finned and finless body. The data gathered in the out-of-plane channels were not nearly so repeatable as the in-plane. Other researchers have artificially tripped the flow on one side of the body to establish a repeatable vortex formation, and subsequently, a repeatable out-of-plane loading. Artificially tripping the flow was not done in this study. It was desired to let the body vortices form naturally and examine the magnitude of the loading that results without artificial protuberances. The data presented in Figs. 4–6 are the results of a single representative run. These data show the magnitude of the out-of-plane loading at the various $\alpha$ and $\phi$.

Figure 4 shows the significant variations observed in the side force coefficient CY. For this geometry and conditions, the side force coefficient reaches magnitudes of approximately 20% of that of the normal force coefficient. This is true for both symmetric configurations ($\phi = 0$, 45, and 90 deg) as well as the asymmetric cases ($\phi = 22.5$ and 67.5 deg). In fact, the side force does show a dependence on the aerodynamic roll angle at the lower angle of attack. However, the spread of the side force data is so large at the high angles of attack that the effect of the roll angle is lost. Overall, the data show a quasi-maximum magnitude of the side force at each angle of attack.

## Conclusion

High-$\alpha$ aerodynamics of an AMRAAM body at low speed have been presented. The Reynolds number and Mach numbers for the present study were $8.72 \times 10^4$ and 0.15, respectively, and the data are important for preliminary design and prediction of flight characteristics of slender bodies. Data for the normal and side force coefficients and all three moment coefficients are shown for a slender body with and without wings and tail fins, at five roll angles, and over a range of $\alpha$ from 0 to 70 deg.

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# Utilization of Low-Speed Experiments in Transonic Capsule Stability Research

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## Introduction

A REENTRY capsule is shaped to be blunt so as to survive the intense aerodynamic heating in the hypersonic portion of the flight. However, during the transonic and subsonic phases of the reentry at what might be considered as off-design conditions, the vehicle faces a more pronounced stability and control problem. The dynamic vortex formation typical of the blunt-body wake flow in the aforementioned speed regimes produces unsteady loading on the vehicle and can sometimes, thereby, affect its handling characteristics severely. It is, therefore, important to determine the stability characteristics of the vehicle so as to ensure timely and proper deployment of parachutes prior to the onset of instability, as well as to obtain a thorough description of the flowfield to understand the associated fluid mechanics. The importance of and difficulties in characterizing the unsteady wake of reentry capsules are illustrated and discussed further in Ref. 1.

Using a nonoscillating Apollo capsule as a representative case, this Note provides experimental evidence that the capsule incompressible wake flow is characteristic of the entire subsonic regime (Mach 0–0.7). Therefore, detailed flow diagnostics of the capsule at low speed, where they can be carried out more readily, could be very beneficial in obtaining qualitative information regarding the causes of capsule instability in transonic flow. The experiments focused on the comparison of global aerodynamic quantities and on the flow structures of an Apollo capsule of boilerplate block I configuration in the incompressible, high-subsonic, and transonic regimes.

For a two-dimensional symmetric or three-dimensional axisymmetric body in free flow at zero lift, the associated global time-averaged wake characteristics are dependent on the drag exerted by the body inasmuch as this quantity represents an integral of the wake motion. In the case of a lifting body, it is expected that the lift would play its role and manifest itself ultimately in the wake as well. Some insight into the flow around the body can also be derived from surface pressure measurements, whose values reflect the initial distribution of vorticity shed into the wake. With the aforementioned in mind, the test series was designed to acquire the global aerodynamic quantities, lift, drag, and moment coefficients, about the center of gravity at four different Mach numbers. The investigation included acquisition of surface pressure data as well as visualization around and in the near wake of the capsule. In addition, the temporal characteristic of the flapping wake motion was mapped out. Four

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wind tunnels were used in this endeavor. Information related to the experiments, including precautions taken in minimizing the interference with the wake flows, are found in Ref. 2. Data were acquired at Mach numbers from 0 (incompressible) to 0.9, with the associated Reynolds number based on the heat-shield diameter spanning from $10^4$ to $10^5$. The Reynolds number range attained is narrow and low with respect to in-flight values on the order of $10^7$. However, Reynolds number influence is believed to be secondary, particularly for practical cases in which the heat shield faces the freestream, so that a substantial part of the separation would be essentially fixed by the small radius present at the sphere–cone junction. The findings in this Note are, therefore, considered generic enough to be applicable to most planetary capsules.

## Results and Discussion

The force and moment measurements are summarized in Figs. 1–3. The force data at various Mach numbers exhibit many of the same trends. On the other hand, the pitching-moment data at Mach 0.9 reveal a significant departure from the data obtained at lower Mach numbers. The data, therefore, suggest that the global wake features are similar irrespective of compressibility effect at least up to Mach number of 0.7. For practical situation in which the heat shield is facing forward, the statically stable position, that is, $C_{m_{\mathrm{cg}}} = 0$ with a negative $\partial C_{m_{\mathrm{cg}}}/\partial\alpha$, is seen to decrease from 165 deg at Mach 0 to 153 deg at Mach 0.9. Nevertheless, the general heat-shield forward orientation is maintained, as well as the similar trend of decreasing $C_{m_{\mathrm{cg}}}$.

The surface pressure distribution along the center plane was measured at various angles with the heat shield facing forward. Representative results taken from $\alpha = 155$ deg are shown in Fig. 4. The pressure coefficients have been normalized with that of the theoretical value at the stagnation point $Cp_0$. The data again exhibit similar behavior at different degrees of compressibility.

The flowfields around and in the near wake of the capsule at various angles of attack were mapped in greater detail in the incompressible flow regime. Three-dimensional laser Doppler velocimetry (LDV) surveys were made up to two heat-shield diameters downstream for the model at $\alpha = 147$, 155, and 165 deg. Additional velocity measurements along the plane of symmetry were made with LDV and particle image velocimetry (PIV) at other angles of attack ranging from 0 to 180 deg. The results of the flow mapping, which have been in part documented in Refs. 3 and 4, show an array of complex wake motion including separation and reattachment of the wake flow around the body. Because pressure drag is the predominant component of the total drag in a bluff body and would manifest itself in the size of the circulating zone, the dimension of the wake along the symmetric plane should provide a qualitative indication of the drag. Similarly, the vertical position of the wake rear-stagnation point should be indicative of the downwash or upwash in the wake and, thus, should be associated with the amount of lift experienced

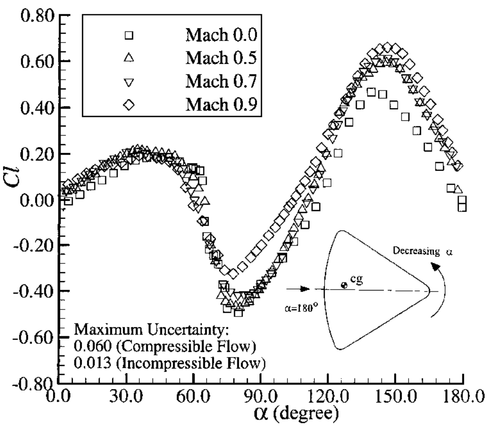


**Fig. 1 Lift coefficient.**

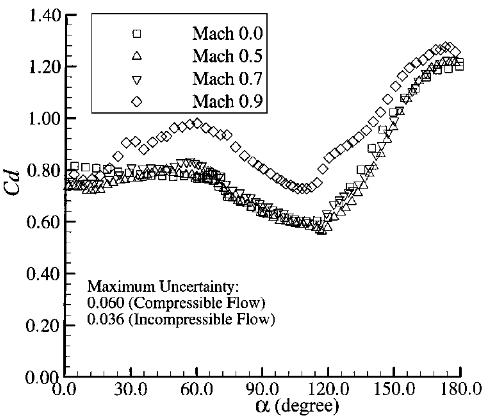


**Fig. 2 Drag coefficient.**

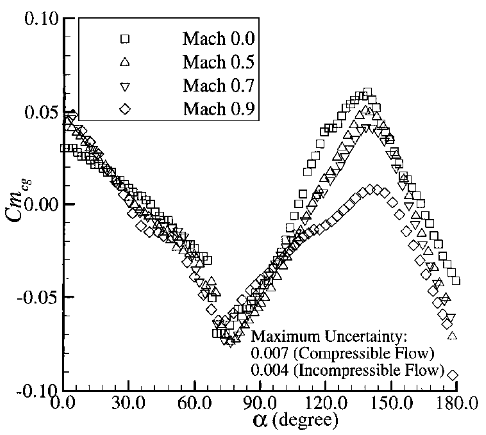


**Fig. 3 Pitching moment coefficient about center of gravity (c.g. located longitudinally at 0.636*D* from the theoretical apex and 0.058*D* above the axis of symmetry).**

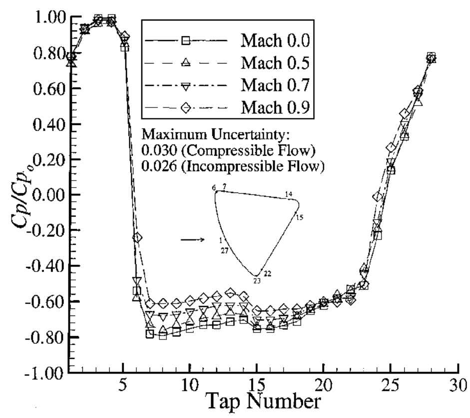


**Fig. 4 Pressure distribution along the model center plane at $\alpha = 155$ deg.**

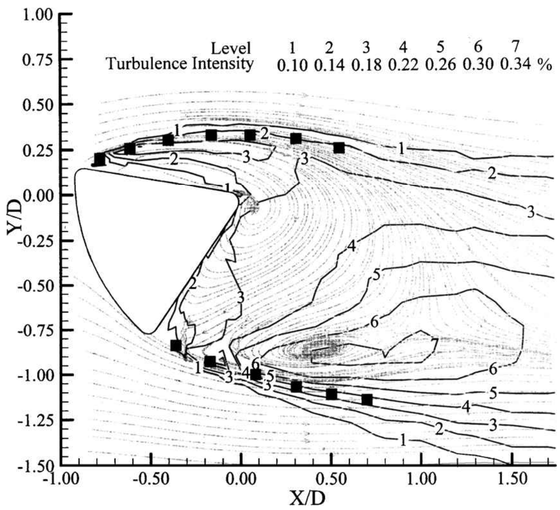


**Fig. 5 Comparison of the mean wake shape at $\alpha = 155$ deg.**

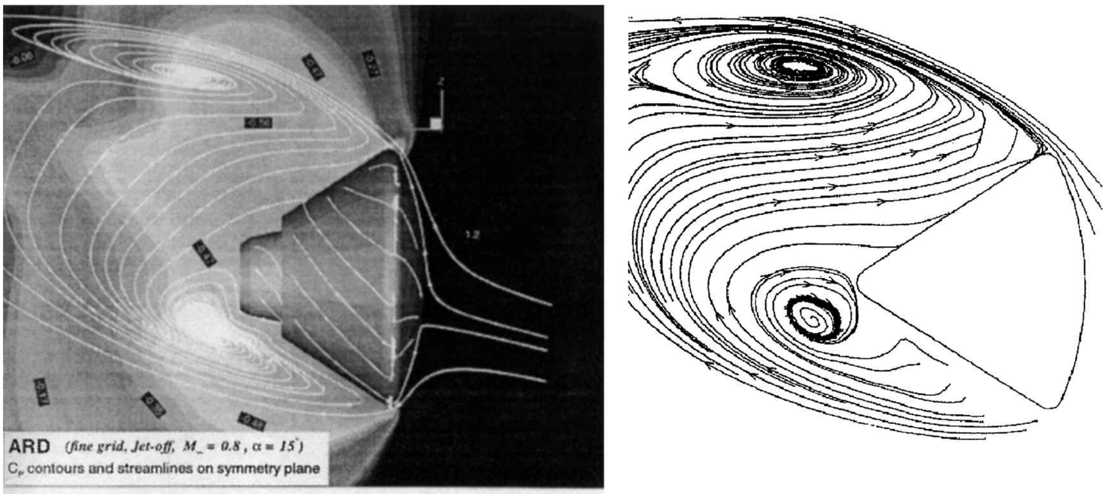


**Fig. 6 Comparison of computational fluid dynamics results at Mach 0.8 (Ref. 5) and incompressible flow LDV data.**

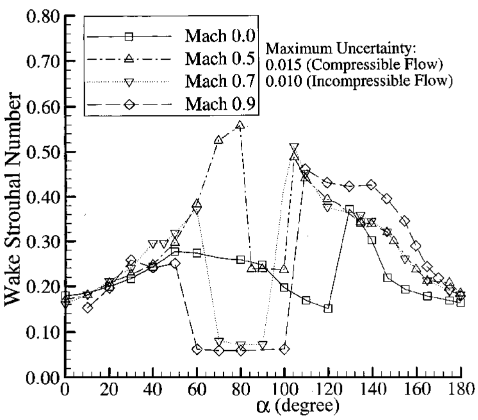


**Fig. 7 Strouhal number detected in the vicinity of the wake closure point.**

by the body. Using this basic premise, the wake dimensions in the plane of symmetry can be correlated with the global force and moment characteristics of the capsule, thereby providing a mean of evaluating the unsteady loading on the capsule by unsteady measurements in the wake.[3,4] In the compressible flow regime, due to hardware constraints, investigation on the wake size has been limited to schlieren visualization for cases in which the heat shield faces the freestream. Within the resolution of determining dimensions from photographs, the shape of the shear layers, which also characterizes the size of the turbulent wake, is seen to be independent of the compressible flow range covered by the current investigation. To illustrate this point, the shapes of the shear layers in the compressible and incompressible regimes are shown in Fig. 5. The squares, representing the centerline of the shear layer as revealed in the schlieren photograph, are superimposed onto the turbulence intensity contour mapped at low speed. The data clearly indicate similar wake sizes in both compressible and incompressible regimes. Because the $Cd$ and $Cl$ trends for the forward-facing heat shield are similar for the various Mach numbers investigated and because the shapes of the shear layers are alike, the locations of the wake rear-stagnation points are construed to be similar. Further circumstantial evidence to support this notion is found in Ref. 5, from which the computed wake flow of an Apollo-style capsule, that is, the Atmospheric Reentry Demonstrator of ESA, at transonic flight condition is taken to compare with the authors' low-speed LDV data. The comparison is shown in Fig. 6, and the flowfield similarity is noted.

Low-speed PIV experiments showed that there exists an oscillatory motion in the wake's rear-stagnation point. Because there would be a coupling between the near wake and the body, as postulated earlier, the oscillatory behavior of wake's rear-stagnation point can then be taken as indicative of the magnitude as well as the frequency of the unsteady loading acting on the vehicle. The characteristic frequency associated with the rear-stagnation point meandering was, thus, investigated. The results are presented in Fig. 7. The general trends in Strouhal number variation vs angle of attack at various Mach numbers are similar, although there are notable differences elaborated in detail in Refs. 2 and 4. With regard to the heat-shield forward attitudes, although the magnitudes of the nondimensional frequencies in the two flow regimes are somewhat different, that is, in general, a higher Strouhal number with increasing Mach number, the variation with $\alpha$ is nevertheless similar, particularly around the trim angles.

## Concluding Remarks

The accumulated data suggest that sufficient similitude exists in the capsule's incompressible and compressible wake flows and that transonic stability characteristics are intimated in low-speed testing. The similarity is particularly favorable for orientations of practical interest when the heat shield is facing the freestream. The dynamics of bluff body wake flow and its influence on the capsule stability in incompressible flow may, thus, reveal qualitative information about stability at higher subsonic Mach numbers. Simulations of this nature, in an environment where visualization and modern optical measurement techniques can be carried out more readily, is also helpful in devising strategies to modify the wake behavior.

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