pp. 190–195.
[9]Ecer, A. and Akay, H. U., "Finite-Element Analysis of Transonic Flows in Cascades – Importance of Computational Grids in Improving Accuracy and Convergence," NASA CR-3446, July 1981.
[10]Deconinck, H. and Hirsch, Ch., "Transonic Flow Calculations with Finite Elements," *GAMM Workshop on Transonic Flow Calculations with Shocks*, Vieweg, 1979.
[11]Hafez, M., South, J., and, Murman, E., "Artificial Compressibility Methods for Numerical Solutions of Transonic Full Potential Equations," *AIAA Journal*, Vol. 17, Aug. 1979, pp. 838–844.
[12]Akay, H. U. and Ecer, A., "Finite-Element Analysis of Transonic Flows in Highly Staggered Cascades," AIAA Paper 81-0210, Jan. 1981.
[13]Whitehead, D. S. and Newton, S. G., "Finite-Element Method for the Solution of Two-Dimensional Transonic Flows in Cascades," *International Journal of Numerical Methods in Fluids*, Vol. 5, Feb. 1985, pp. 115–132.
[14]Prasad, J. K., Varambally, B. S., Pillai, N. M., and Srivaram Krishnan, A. E., "Aerodynamic Load on Heat Shield in Mach Number Range of 0.8 to 1.1," Vikram Sarakhai Space Centre, Trivandrum, India, EWTT:02:84, June 1984.
[15]Ahmed, S., "Pressure Measurements in the Heat Shield Region at Transonic Speeds, " National Aeronautical Laboratory, India, TWT, 1-32-84, July 1984.

Transonic Flow Modes of an Axisymmetric Blunt Body

Keith Koenig*
Mississippi State University, Starkville, Mississippi

David H. Bridges†
California Institute of Technology
Pasadena, California
and
Gary T. Chapman‡
NASA Ames Research Center
Moffett Field, California

Introduction

THE use of induced flow separation devices for blunt-body drag reduction has proved effective in several practical applications. Notable examples are the spike used on the Trident ballistic missile[1] and the various cab-mounted shields found on large tractor-trailer trucks.[2] Little has been done to exploit this concept at transonic speeds, however. The present work is intended partly to provide information on the aerodynamic properties of flow separation devices at transonic speeds in order to assess their potential in this flow regime.

This work has a broader and more fundamental purpose, however, and that is to examine the fluid mechanic properties of a cavitylike flowfield in the transonic regime. The geometry in question is sketched in the inset of Fig. 1. It is composed of a simple, flat-faced, circular cylinder (diameter d_2) aligned with the flow and in front of which is coaxially extended a smaller-diameter flat-faced cylinder, known as the probe. The probe diameter d_1 and length l can be varied. For relatively short probes, there is a single separated zone between the probe face and the cylinder face, whereas longer probes produce two separated zones in this region.[3] These two situations correspond to the open and closed modes, respectively, of a cavity or cutout in a wall[4] (see the inset of Fig. 3). The probe length, which distinguishes the open from the closed mode, is designated as the critical length l_{cr}. Cavitylike flows are encountered in a wide variety of situations, and this study is intended to explore one such situation found in drag reduction schemes.

Presented as Paper 88-3536 at the AIAA 1st National Fluid Dynamics Conference, Cincinnati, OH, July 25-28, 1988; received Aug. 15, 1988; revision received Nov. 11, 1988.

*Associate Professor, Aerospace Engineering. Member AIAA
†Graduate Student, Aeronautics. Student Member AIAA.
‡Senior Staff Scientist, Thermosciences Division. Associate Fellow AIAA.

Experimental Details

In this presentation, measurements of drag coefficient C_D as a function of probe length, probe diameter, and freestream Mach number will be used to calculate the flowfield characteristics. The drag coefficient is based on the drag force acting on the entire probe and cylinder minus the cylinder base drag. The reference area is the cylinder cross-sectional area. No corrections for blockage were made to the drag coefficient, and its estimated accuracy is ± 0.02.

These measurements were obtained in the (now nonexistent) 1.83-m × 1.83-m supersonic wind tunnel at the NASA Ames Research Center. The Mach number M ranged from 0.8 to 1.5, and the stagnation temperature and pressure were nominally atmospheric for the majority of the tests. The cylinder had a diameter of 127 mm and was 889 mm long. Three probe diameters were used giving diameter ratios d_1/d_2 of 0.248, 0.368, and 0.45. The smallest probe had a length ratio l/d_2 up to 3; the two larger probes had maximum l/d_2 of 2. The results to follow are representative examples for the smallest probe diameter; a complete presentation for all diameters can be found in Ref. 5.

Results and Discussion

Figure 1 demonstrates how C_D varies with length ratio for fixed Mach number. The trends for subsonic and supersonic flow have qualitative similarities. The value of C_D at very short lengths is large and roughly proportional to the freestream stagnation pressure coefficient. Increasing length brings about a rapid decrease in C_D to a minimum value. The subsonic minimum is broad and is followed by a gradual increase to a plateau. The supersonic flow abruptly changes to a higher drag level; the probe is too short to show the asymptotic behavior. Hysteresis (not unique to this experiment[6]) appears in the supersonic drag as the probe is subsequently shortened; no subsonic hysteresis occurs. The magnitude of the drag reduction due to the probe, as much as two-thirds of the zero length drag, is significant enough to perhaps be of practical value.

Insight into the fluid mechanic properties of this flow system is provided by the alternate presentation of C_D as a

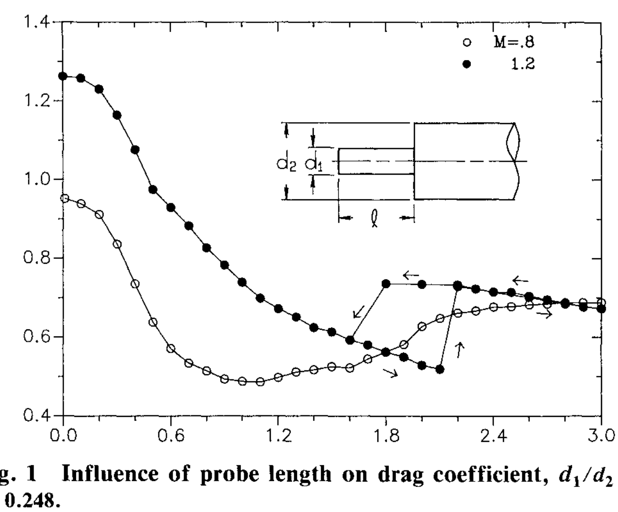

Fig. 1 Influence of probe length on drag coefficient, d_1/d_2 = 0.248.

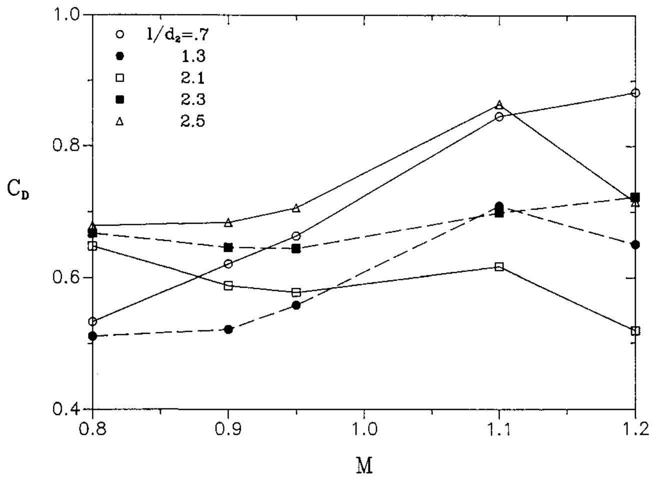

Fig. 2 Influence of Mach number on drag coefficient, d_1/d_2 = 0.248.

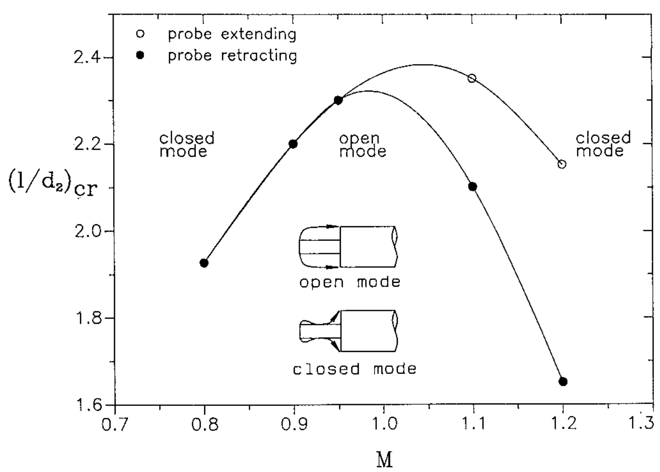

Fig. 3 Critical probe length, d_1/d_2 = 0.248.

function of M for fixed l/d_2 in Fig. 2. Each curve shown in this figure has been chosen to highlight a particular flow phenomenon.

For $l/d_2 = 0.7$, a monotonic increase in C_D is observed through the entire test range of M. This is characteristic of relatively blunt bodies. Lengthening the probe to $l/d_2 = 1.3$ produces a drop in C_D beyond $M = 1.1$. The differences in these two cases are probably related to the shock detachment distance as follows. Each of these probe lengths produces open-mode flow, and at supersonic speeds this mode has a single bow shock ahead of the main cylinder.[5] For a flat-faced cylinder, the shock detachment distance is on the order of 2–1.5 cylinder diameters for M varying from 1.1 to 1.2.[7] In the $l/d_2 = 0.7$ case, the probe is apparently too short to have much influence on the bow shock, and the probe and cylinder faces are thus subjected to the high pressure produced by a nearly normal shock. For $l/d_2 = 1.3$, the probe length is approximately the same as the detachment distance, particularly at $M = 1.2$. It is likely that now the probe distorts the shock into a more oblique shape and thereby reduces the pressure drag.

A most remarkable behavior appears with $l/d_2 = 2.1$ and 2.3: as M approaches 1 from below, the drag coefficient actually decreases. Furthermore, above $M = 1$, the case $l/d_2 = 2.3$ shows an increasing drag coefficient whereas, for lengths on each side ($l/d_2 = 2.1$ and 2.5), C_D decreases. A plausible explanation for these behaviors can be made with the aid of Fig. 3, which has been prepared using the entire set of measurements from Ref. 5. Previous studies of qualitatively similar flows have suggested that C_D reaches a minimum value at a probe length slightly less than critical.[3] Guided by this, the critical length for the probe/cylinder might be approximated by the probe length midway between the minimum and plateau for subsonic flow and by the probe length at which the drag suddenly increases for supersonic flow. The length so determined appears in Fig. 3.

In Fig. 3, the length $l/d_2 = 2.1$ starts out at $M = 0.8$ in the closed mode and progresses into the open mode as M increases toward 1. Correspondingly, the drag coefficient decreases (Fig. 2) as this mode change occurs. Apparently, the multiple compression processes upstream of the main cylinder face in the closed mode exact a greater drag penalty than the single compression process of the open mode.[5] Similarly, at $l/d_2 = 2.3$, there is a mode change from closed to open as M increases toward 1 and a second mode change back to closed as M progresses on to 1.2. Hence, C_D decreases subsonically and increases supersonically. In contrast, $l/d_2 = 2.5$ is greater than critical at all Mach numbers and does not experience any mode changes. The variations of C_D with M for this longest length are thus typical of more slender bodies.

Conclusions

The probe/cylinder geometry experiences significant variations in drag coefficient as Mach number and probe length are changed. These variations appear to be closely linked to changes in the fundamental character of the flow, in particular, the transitions between the cavitylike open and closed modes. The critical length, which distinguishes open from closed flow, is a strong function of Mach number, and this leads to surprising changes in the drag coefficient as Mach number varies for fixed geometry. In addition, an apparent subdivision of the flow character in the supersonic open mode distinguishes probe lengths that do or do not significantly alter the bow shock structure. Although confirmation of these flow descriptions must wait for detailed measurements, the view of the flow as presented here is a reasonable first approximation to this complex and interesting problem.

Acknowledgments

This study was supported by the U.S. Air Force Armament Laboratory, Eglin AFB, and by NASA Ames Research Center Interchange No. NCA2-52. D.H. Bridges was supported by an Office of Naval Research graduate fellowship.

References

[1]French, N. J. and Jecmen, D. M., "Transonic/Supersonic Wind Tunnel Investigation of Effects of Parametric Variations in Nose Fairing and Aerospike Geometry on Trident 1 C4 Missile Body Static Stability and Drag," Lockheed Missiles and Space Co., Sunnyvale, CA LMSC-D 366908, Sept. 1974.

[2]Mason, W. T., Jr. and Beebe, P. S., "The Drag Related Flow Field Characteristics of Trucks and Buses," *Proceedings of the Symposium on Aerodynamic Drag Mechanisms of Bluff Bodies and Road Vehicles,* edited by E. G. Sovran, T. Morel, and W. T. Mason Jr., Plenum, New York, 1978, pp. 45–93.

[3]Haupt, B. F. and Koenig, K., "Aerodynamic Effects of Probe-Induced Flow Separation on Bluff Bodies at Transonic Mach Numbers," *Journal of Spacecraft and Rockets,* Vol. 24, July-Aug. 1987, pp. 327–333.

[4]Charwat, A. F., Roos, J. N., Dewey, F. C., Jr., and Hitz, J. A., "An Investigation of Separated Flows – Part I: The Pressure Field," *Journal of the Aerospace Sciences,* Vol. 28, June 1961, pp. 450–470.

[5]Koenig, K., Bridges, D. H., and Chapman, G. T., "Transonic Flow Modes of an Axisymmetric Blunt Body," AIAA Paper 88-3536, July 1988.

[6]Beastall, D. and Turner, J., "The Effect of a Spike Protruding in Front of a Bluff Body at Supersonic Speeds," British Aeronautical Research Council, London, ARC R&M 3007, 1957.

[7]Liepmann, H. W. and Roshko, A., *Elements of Gas Dynamics,* Wiley, New York, 1967, p. 105.