[5]Oswatitsch, K. and Keune, F., "Flow Around Bodies of Revolution at Mach Number One," *Proceedings of the Conference on High Speed Aerodynamics*, Polytech. Inst. of Brooklyn, 1955, pp. 113-131.

[6]Hosokawa, I., "A Refinement of the Linearized Transonic Flow Theory," *Journal of the Physical Society of Japan*, Vol. 15, No. 11, 1960, pp. 149-157.

[7]Cole, J. D., "Drag of the Finite Wedge at High Subsonic Speeds," *Journal of Mathematics and Physics*, Vol. 30, No. 2, July 1951, pp. 79-93.

[8]Ferrai, C. and Tricomi, F., *Transonic Aerodynamics*, Academic Press, New York, 1968, pp. 231-260.

Shock-Wave Profiles about Hemispherical Noses at Low Supersonic Mach Numbers

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IN a recent Synoptic, Hsieh[1] presented the results of a systematic theoretical and experimental study of a hemisphere-cylinder at zero incidence for Mach numbers ranging from 0.7 to 2. In the computational segment of the analysis, a direct method of a time-dependent finite difference solution to the unsteady Euler's equation is employed. As a result, Hsieh was able to present comparisons of theoretical shock positions about a hemispherical nose with existing and obtained experimental data.

It is interesting to note that a correlation concept of the bow shock profile for spheres utilizing the density ratio across a normal shock was employed by Gregorek and Korkan[2] in a study of hypersonic blunt body similitude. In this study,[2] the general form of the equation for the spherical shock as obtained from the blast wave analogy was employed, i.e.

$$r_s/d_N = A\ [x/d_N]^n \qquad (1)$$

where the coordinate system is taken at the origin of shock apex. As reported in Ref. 3, shock wave profile experimental data were obtained in the 4-in. continuous, free-jet, hypersonic wind tunnel of the Ohio State University. Values of the shock wave radial coordinate r_s and the axial coordinate x were thus determined. When these values were nondimensionalized by the sphere diameter d_N and displayed on a logarithmic scale, the profiles were observed to be approximately linear and therefore could be expressed in the form of Eq. (1). However, the correlations presented earlier[2,3] were based upon $M_\infty \geq 2$ data. With the data exhibited by Hsieh,[1] these correlations may now be extended to the low supersonic Mach numbers.

Employing the shock wave constants obtained for spheres,[2] in addition to Hsieh,[1] Seiff,[4] Baer,[5] and Love,[6] values for A and n were plotted against Mach number as shown in Fig. 1 for $\gamma = 1.4$. From these results, the empirical correlation for A and n based on a density ratio presented earlier[2] has been modified to fit the experimental data and takes the form

$$A = 1.52\ k^{-0.20} + [0.823/(M_\infty^2 - 1)] \qquad (2)$$

$$n = 0.61\, M_\infty^{\ -0.11} \qquad (3)$$

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and therefore Eq. (1) becomes

$$\frac{r_s}{d_N} = \left[1.52\ k^{-0.20} + \frac{0.823}{(M_\infty^2 - 1)}\right]\left(\frac{x}{d_N}\right)^{0.61 M_\infty^{\ -0.11}} \qquad (4)$$

The experimental values of A are well represented by their empirical expression, with the maximum deviation being less than 2%. Values of the exponent n show more scatter, due to the greater measurement difficulty in obtaining the slope of the shock wave profile from the experimental data.

Application of the present empirical correlation expressed in Eq. (4) to the experimental results shown by Hsieh[1] and Gregorek and Korkan[2] is presented in Fig. 2. As can be seen, the agreement between prediction and experiment is acceptable over a wide range of Mach numbers which now encompass the low supersonic regime, e.g., $12.00 \geq M_\infty \geq 1.10$. It may also be noted that the results of Figs. 1 and 2 may be plotted in terms of density ratio across a normal shock k as had been done earlier[2] with good agreement with experimental data for $k \leq 15$.

Since the empirical correlation given by Eq. (4) has a coordinate system located at the apex of the shock wave profile, the shock detachment distance has also been investigated. Using the data presented by Hsieh[1,7-10] and those given by Gregorek and Korkan,[2,5,11] a comparison has been made with the shock detachment distance prediction utilizing the Ambrosio and Wortman[11] expression based on k, i.e.

$$\Delta/r_N = 0.52\ \ (k-1)^{-0.861} \qquad (5)$$

The results are shown in Fig. 3 and indicate good agreement between Eq. (5) and experiment over a wide range of Mach numbers including the low supersonic regime, i.e., $15.00 \geq M_\infty \geq 1.10$.

Therefore, with the aid of the data presented by Hsieh[1] and other investigators, the empirical correlation[2,3] based on k and M_∞ to predict the shock wave profile about a hemispherical nose has been extended to include Mach numbers ≥ 1.10 while still being valid up to $M_\infty \simeq 15$. It has also been shown that the shock detachment distance for a hemispherical nose can also be predicted up to $M_\infty \simeq 15$ including the low supersonic range by an empirical expression originally formed by Ambrosio and Wortman.[11] The expressions presented by Eqs. (4) and (5) provide a rapid method to predict the shock wave profile and detachment distance about a hemispherical nose for $15.00 \geq M_\infty \geq 1.10$. However, the need for computational methods still exists to satisfy such requirements as obtaining the details of the

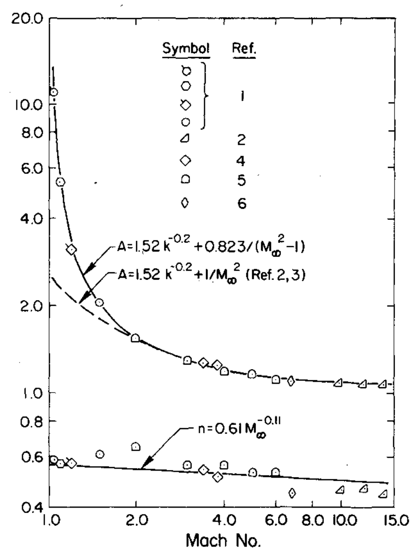

Fig. 1 Dependence of shock wave constants on freestream Mach number.

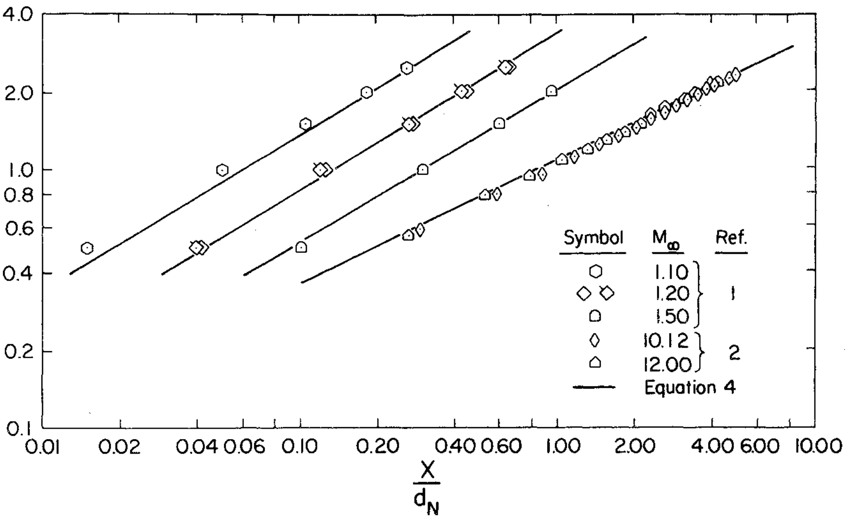

Fig. 2 Comparison of experimental bow shock profiles and results of present empirical correlation.

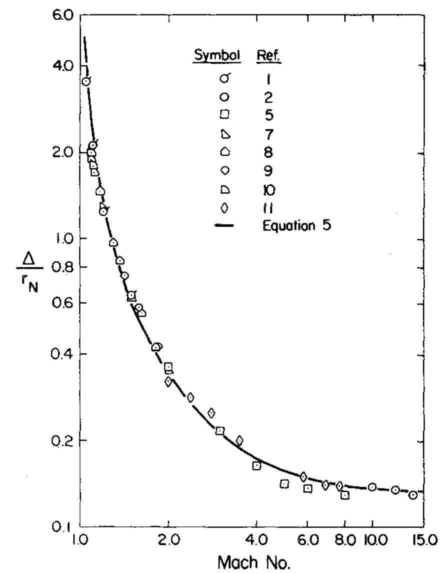

Fig. 3 Comparison of experimental shock detachment distance and existing empirical correlation as a function of freestream Mach number.

flowfield or to provide/verify the results of existing numerical approaches.

References

[1]Hsieh, T., "Hemisphere-Cylinder in Low Supersonic Flow," *AIAA Journal*, Vol. 13, Dec. 1975, pp. 1551-1552.

[2]Gregorek, G. M. and Korkan, K. D., "Hypersonic Blunt Body Similitude in a Perfect Gas," FDL-TDR-64-92, June 1964.

[3]Korkan, K. D., "Comments on 'Bow Shock Shape About a Spherical Nose,'" *AIAA Journal*, Vol. 4, Feb. 1966, pp. 381-382.

[4]Seiff, A. and Whiting, E. E., "A Correlation Study of the Bow Wave Profiles of Blunt Bodies," NASA TN D-1148, Feb. 1962.

[5]Baer, A. L., "Pressure Distributions ona Hemisphere Cylinder at Supersonic and Hypersonic Mach Numbers," AEDC-TN-61-96, Aug. 1961.

[6]Love, E. S., "A Re-examination of the Use of Simple Concepts for Predicting the Shape and Location of Detached Shock Waves," NACA TN-4170, Dec. 1957.

[7]Gilinskii, S. M. and Lebedev, M. G., "Investigation of a Flow at Low Supersonic Speeds—Past Plane and Axisymmetric Bodies with a Separated Shock Wave," Akademiia Nauk SSSR, *Izvestiia Mekhanika*, Jan.-Feb. 1965.

[8]Herberle, J. W., Wood, G. P., and Gooderum, P. B., "Data on Shape and Location of Detached Shock Waves on Cones and Spheres," NACA TN 2000, Jan. 1950.

[9]Holder, D. W. and Chinneck, A., "The Flow Past Elliptic-nosed Cylinders and Bodies of Revolution in Supersonic Air Streams," *The Aeronautical Quarterly*, Vol. IV, No. 2, Feb. 1954.

[10]Stlip, A., "Stromungsuntersuchungen an Kugeln mit transonischen und supersonischen Geschwindigkeiten in Luft and Frigen-Luftgemischen," Bericht Nr. 10/65, Ernst-Mach-Institut, Freiburg, Germany, 1965.

[11]Ambrosio, A. and Wortman, A., "Stagnation Point Shock Detachment Distance for Flow Around Spheres and Cylinders in Air," *Journal of the Aerospace Sciences*, Vol. 29, No. 7, July 1962.

Study of the Turbulent Near Wake of a Flat Plate

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Introduction and Analysis

ONE of the important aspects of fluid flow past submerged bodies is the study of flow characteristics at the trailing edge. While a number of such studies have been made for bodies of different shapes in laminar flow,[1-3] information for the case of turbulent flows is rather scanty. A number of investigators have studied the far wake of a submerged body and the results are well documented.[2,4-6] The studies available on the near wake are, however, limited.[6,8,10,14,15] For the case of flow past a flat plate at zero incidence, writing the momentum balance for a control volume as shown in Fig. 1, and combining it with Reichardt's momentum transfer law one gets Reichardt's fundamental equation for free turbulence[16]

$$\frac{\partial \overline{u^2}}{\partial x} - \beta \frac{\partial^2 \overline{u^2}}{\partial y^2} = 0 \tag{1}$$

in which u is the instantaneous velocity in the x-direction and β the momentum transfer length. Substituting

$$\bar{u} = u + u' \tag{2}$$

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