Fig. 3c. The position of the tail of each arrow on the ordinate corresponds to the measurement location. The arrow is drawn in the indicated flow direction, with a length proportional to the speed. This figure is representative of the type of detailed flowfield information that the probe was designed to provide. The maximum gradient in flow angularity, i.e., the maximum convergence of streamlines, is seen to occur where the speed is the lowest. This is the case in the vicinity of a free stagnation (wake closure) point, which must exist slightly upstream, nearer the finite thickness (1% chord) trailing edge.

Conclusions

A probe for the measurement of flow direction in one plane, as well as of stagnation pressure, has been constructed, calibrated, and used in a study of flow about a transonic airfoil. The tip dimensions are comparable to those of the smallest boundary-layer pitot probes in current use, while the resulting data contain an extra dimension of information.

References

[1] Bryer, D. W. and Pankhurst, R. C., *Pressure-Probe Methods for Determining Wind Speed and Flow Direction*, Her Majesty's Stationery Office, London, 1971.

[2] Dudzinski, T. J. and Krause, L. N., "Flow-Direction Measurement with Fixed-Position Probes," TM-X-1904, Oct. 1969, NASA.

[3] Hurley, F. X., Spaid, F. W., Roos, F. W., Stivers, L. S., Jr., and Bandettini, A., "Supercritical Airfoil Flowfield Measurements," submitted for publication to the *Journal of Aircraft*.

Test Time Determination by End Wall Pressure Measurement in an Arc-Driven Shock Tube

A. J. MULAC* J. L. MARK,† AND J. A. GUZMAN‡
Sandia Laboratories, Albuquerque, N. Mex.

SUCCESSFUL shock tube experimentation depends critically on the separation of the shock front and contact surface. Separation is achieved readily in the classical diaphragm shock tube. However, in high-energy devices such as the Sandia arc-driven shock tube facility, separation may not always occur and is not readily predicted.

This Note presents shock-wave-contact surface separation measurements by means of a fast rise time, long-dwell, end-wall pressure gage. The end-wall pressure is a sensitive indicator of the interactions between the reflected shock wave and the contact surface, and provides a measure of the density profile behind the incident shock. The measurement of end-wall pressure has been developed into a very powerful shock tube diagnostic technique by Baganoff and Hanson.[1-4]

The application of the end-wall technique to test-time determination is based on the density or more specifically, acoustic impedance discontinuity at the contact surface. There are three possible interactions between the reflected shock and the contact surface. If the driver gas impedance is larger than the test gas impedance, a compression wave will reflect and produce a pressure rise on the shock tube end wall. If the driver gas impedance is less than the test gas impedance, a rarefaction wave will reflect and produce a pressure drop on the shock tube end wall. When the impedance is matched across the contact surface, the reflected shock will be transmitted and no signal will be received on the end wall.

The end-wall pressure gage used in this study is of the type described by Hanson and Baganoff.[5] The gage is a 10.16 cm diam pressure bar with a dual capacitive element in the center to detect normal stress. The gages used in this study were calibrated with a separate pressure-driven shock tube. The calibration shots were chosen to provide a pressure step with no real gas effects. The calibrations confirmed the linearity of the end-wall gages and provided a gage factor for data reduction. Because of the severity of the arc-driven shots, the calibration of the pressure gages was checked after each shot. Gage lifetime ranged from 4–20 shots; a total of 9 gages were used in this study. The end-wall pressure gages were used in a differential mode. One capacitive element was charged to $+2$ kV and the other to -2 kV. Noise due to ionization in the test gas and precursors is independent of the charge polarity; however, the pressure signal is sensitive to charge polarity. Thus, the signals from the two elements were subtracted to eliminate the noise and double the gage sensitivity.

The Sandia arc-driven shock tube and its performance have been described previously.[6,7] For these experiments a 76-cm-long arc driver and a 12-cm-diam driven tube was used. The driven tube was evacuated to 10^{-2} torr or less before each shot. The combined leak/outgas rate was $\leq 2\times10^{-3}$ torr/min. Since the dwell time of the end-wall pressure gage was limited to 25 μs, very low initial pressures were necessary to see the contact surface wave interaction on the end wall. P_1 values of 0.1 torr and 0.5 torr were used and measured with a capacitive manometer (Baratron gage). The uncertainty in the initial pressure was $\Delta P_1/P_1 \leq 10\%$. This large uncertainty was due primarily to the leak/outgas rate and the time between filling and arc initiation.

The shock speed in these experiments was determined from time of arrival data at several shock detectors (impedance probes and piezoelectric pressure gages). Shock attenuation was negligibly small over the approximately 1 m measurement span. Shock speed uncertainty was $\Delta u/u \leq 5\%$.

Figure 1 presents end-wall pressure histories for three shock speeds from 7.8 to 10.4 km/sec in 0.1 torr nitrogen. The monotonic pressure rises are terminated by slight decreases in pressure followed by strong rises and subsequent oscillations. The measurement time (gage dwell time) for each of these shots was 25 μs. The slight fall in pressures is interpreted as a reduced impedance mixing region in front of the contact surface which is indicated by the sharp pressure rise. The end of the test time

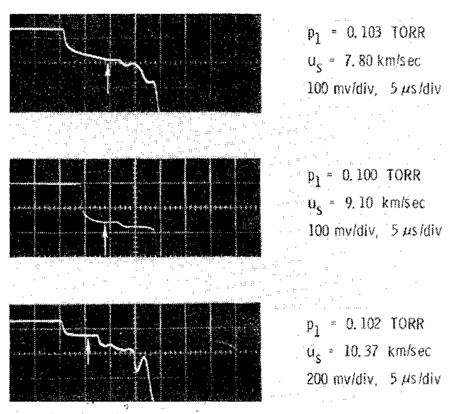

Fig. 1 End-wall pressure records for 0.1 torr nitrogen experiments. The departure of the trace represents shock front arrival at the end wall. The arrows indicate the arrival of the disturbance from the mixing region in front of the contact surface.

Received August 27, 1974. This work was supported by the United States Atomic Energy Commission.

Index category: Nonsteady Aerodynamics.

* Member of Technical Staff, Project Leader. Member AIAA.

† Member of Technical Staff; presently at Boeing Airplane Company, Seattle, Wash.

‡ Engineering and Science Assistant.

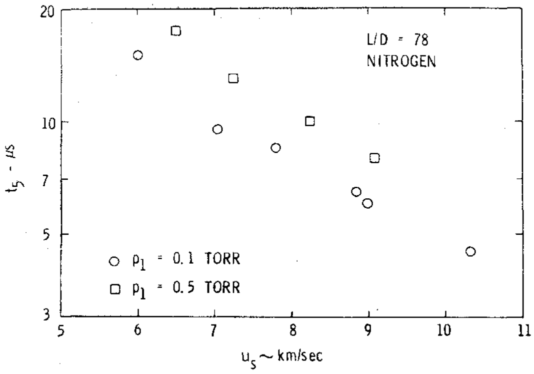

Fig. 2 End-wall test time vs shock speed.

is taken as the first deviation from the smooth pressure profile; these times are plotted in Fig. 2 as the end-wall test time. A mapping technique[2,3] was used to convert the end-wall test times to the incident shock-contact surface separation as a function of shock speed. Figure 3 shows the resulting incident shock test time. These data are compared to summary data presented by Warren and Harris.[8] The cross-hatched area represents reported maximum experimental test time for seven shock tube facilities. The present data falls on the lower bound

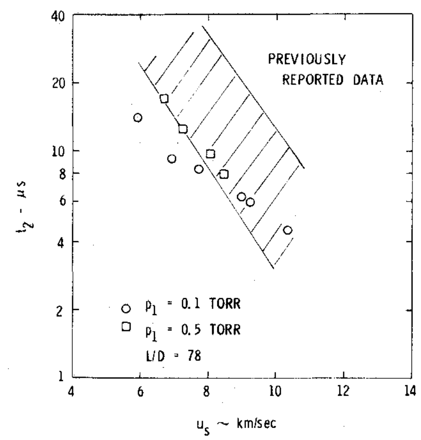

Fig. 3 Incident shock test time vs shock speed. The cross-hatched region indicates test time data from other facilities summarized in Ref. 8.

of this comparison because the first indication of driver gas, test gas mixing is taken as the end of the test time. This is a very conservative determination of test time.

These measurements also present the opportunity to compare the calculated[9] equilibrium pressure with the measured pressure; a $\pm 15\%$ deviation from theory was observed which compares with that found by Bengtson.[10]

The fact that test time exists for energetic shock waves produced in the Sandia arc-driven shock tube has been demonstrated. The usefulness of fast rise time, long-dwell time pressure measurements for test-time determination has also been demonstrated. The major limitations of this technique are 1) an a priori knowledge of the relaxing gas pressure history and 2) test times short enough to detect with the available dwell time of the gage. Theoretically the dwell time can be increased by enlarging the pressure bar diameter. However, in practice the bonding of very thin sheets of dielectric and metal foils becomes very difficult to achieve over large diameters.

References

[1] Baganoff, D., "Experiments on the Wall-Pressure History in Shock Reflexion Processes," *Journal of Fluid Mechanics*, Vol. 23, Pt. 2, Oct. 1965, pp. 209–228.

[2] Hanson, R. K. and Baganoff, D., "Shock-tube Study of Nitrogen Dissociation Rates using Pressure Measurements," *AIAA Journal*, Vol. 10, No. 2, Feb. 1972, pp. 211–215.

[3] Hanson, R. K., "Shock-tube Study of Vibrational Relaxation in Carbon Monoxide using Pressure Measurements," *AIAA Journal*, Vol. 9, No. 9, Sept. 1971, pp. 1811–1819.

[4] Hanson, R. K. and Flower, W., "Verification of a Simple Relationship for Shock-Wave Reflection in a Relaxing Gas," *AIAA Journal*, Vol. 11, No. 12, Dec. 1973, pp. 1777–1778.

[5] Hanson, R. K. and Baganoff, D., "Improved Fast Response Pressure Gauge for Shock-Reflection Studies in Ionized Gases," *Review of Scientific Instruments*, Vol. 43, No. 3, March 1972, pp. 394–399.

[6] Mulac, A. J., Mark, J. L., and Guzman, J. A., "Sandia 500-Kilojoule Arc-Driven Shock Tube Facility, SC-DR-70-217, June 1970, Sandia Labs., Albuquerque, N. Mex.

[7] Mark, J. L., "Performance Calibration of the Sandia Arc-Driven Shock Tube," SC-DR-72-0709, Dec. 1972, Sandia Labs., Albuquerque, N. Mex.

[8] Warren, W. R. and Harris, C. J., "A Critique of High Performance Shock Tube Driving Techniques," in *Shock Tubes—Proceedings of the Seventh International Shock Tube Symposium*, edited by I. I. Glass, University of Toronto Press, Toronto, Canada, 1970, pp. 143–176.

[9] Shipley, K. L. and Kaestner, P. C., "The Calculation of Equilibrium Composition and Thermodynamic Properties of High-Temperature Gases Produced in Shock Tubes," SC-DR-72-0033, Feb. 1972, Sandia Labs., Albuquerque, N. Mex.

[10] Bengtson, R. D., Miller, M. H., Koopman, D. W., and Wilkerson, T. D., "Comparison of Measured and Predicted Conditions Behind a Reflected Shock," *Physics of Fluids*, Vol. 13, No. 2, Feb. 1970, pp. 372–377.