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Asymmetric Shock-Wave Oscillations on Spiked Bodies of Revolution

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Nomenclature

D	= overall model diameter
F	= frequency
p_1, p_2	= pressure sensed by transducers 1 and 2
p_{ns}	= pressure downstream of normal shock
p_∞	= stream static pressure
S	= Strouhal number
T_o	= wind-tunnel supply temperature
u_∞	= freestream flow speed
x	= coordinate in stream direction
y	= coordinate normal to x
$(\bar{\ })$	= time-averaged quantities
< >	= root-mean-square quantities

IT is well known that the shock-wave configuration in front of "spiked" axisymmetric bodies in supersonic flow can be unstable.[1,2] This instability arises primarily in cases where the forebody geometry has a forward-facing step such as those found in supersonic inlet diffusers with conical centerbodies, or on blunt bodies with drag-reducing spikes. For certain ranges of forebody geometry and flow parameters[3-5] these configurations do not allow a steady-state shock shape capable of satisfying the momentum and continuity equations. As a result, the shock structure oscillates harmonically with a Strouhal number based on body diameter and stream speed which, characteristically, is of order 0.2. This oscillation has been termed a "catastrophic" or "E-oscillation." Until recently, the shock motion was thought limited to one degree of freedom in the radial direction; that is, the shock has been observed to move in an expanding-collapsing fashion symmetrically about the body axis. In this Note, we report observations which imply a more complex motion such as would result from two or more degrees of freedom. Time-averaged and instantaneous surface pressure data presented should be of some interest also since they control the time-averaged drag, and since their prediction by theory is difficult at this juncture.

Experiments were performed in the Aeronutronic Ford Supersonic Wind Tunnel with a model, sketched in Fig. 1, which consisted of a sphere-cone-cone cylinder. In units of the cylinder afterbody diameter D, the hemisphere at the model tip had a 0.05 D diam. The cone following it had a half-angle of 20° and the second cone a half-angle of 80°. The model was positioned at zero incidence in continuous flow at Mach 3.02 ± 0.02 and supply temperature T_0 of 100°F. The Reynolds number based on D and freestream properties varied from 40,000 to 150,000 and the model wall temperature was nearly equal to T_0.

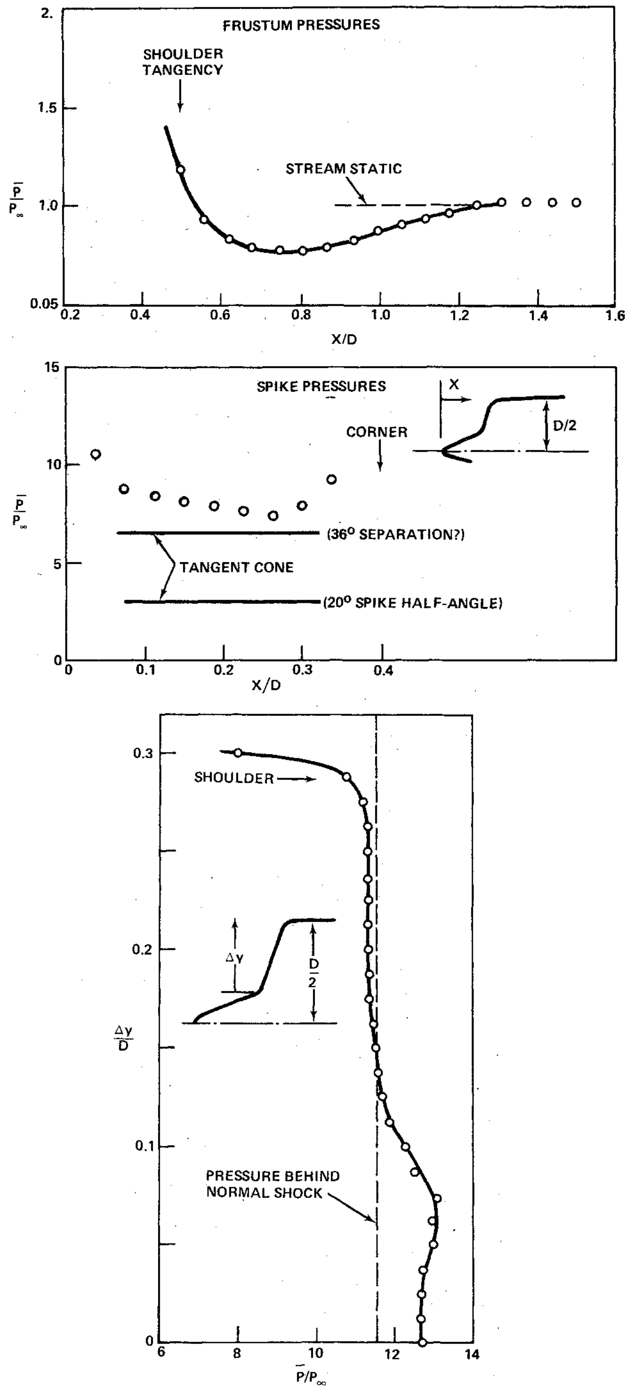

Fig. 1 Time-averaged surface pressure distribution over the spike, front "face" and frustum of the model.

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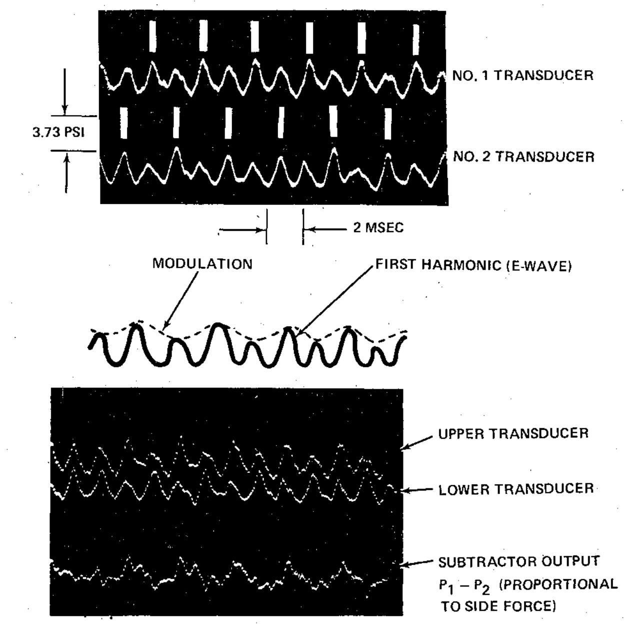

Fig. 2 Typical waveforms of the pressure transducer outputs on opposite sides of the model spike. Markers show maxima of modulation.

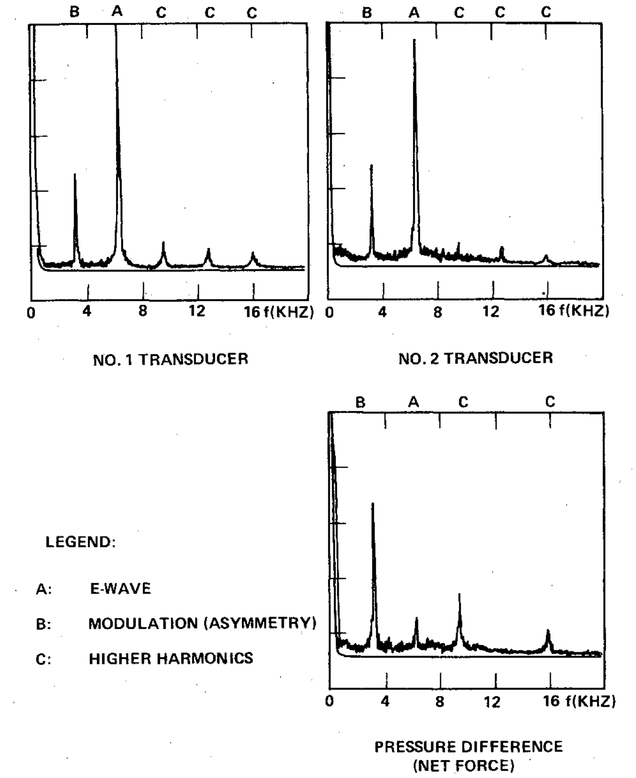

Fig. 3 Spectra of the output of the two transducers on the model spike and of their algebraic difference.

As anticipated from the model geometry, the strong "E-oscillation" of the shock structure was observed clearly. The oscillation frequency f was 7140 Hz giving a Strouhal number $S=fD/u_\infty$ of 0.225. Mean (time-averaged) surface pressure measurements taken along the entire forebody contour during the oscillation are shown on Fig. 1. It is seen that over most of the forebody "face" (the 80° half-angle cone) the surface pressure is close to the normal shock pressure at this Mach number. The only truly surprising feature is the surface pressure on the conical "spike" (the 20° half-angle cone) which fits much better a 36° cone surface than the actual spike cone angle. Schlieren and probe surveys confirmed that a quasi-steady conical separation zone sheaths the spike and is coaxial with it during the shock oscillation.

The most important finding, however, concerned the mode of shock oscillation. To examine the unsteady surface pressures, two pressure transducers were placed at two diametrically opposite points on the circle defining the base of the spike. Their simultaneous pressure-time signals are shown on Fig. 2. Both signals are nearly sinusoidal and seemingly correlated (in phase), i.e., the pressure rise or decrease at a point on the spike base coincides with a similar rise or decrease at a point 180° away at the spike's other side. Closer inspection of Fig. 2, however, shows that each oscillation is modulated with another wave of half the frequency and, further, that the two modulations are out of phase (anti-correlated) by 180°. This phenomenon was confirmed by the spectra shown on Fig. 3. The first two spectra are of the two individual transducers and show prominently the E oscillation (with weak higher harmonics present characteristic of imperfections of the sine waves shown on Fig. 2). The modulation also appears on the spectra, but with an intensity lower than that of the E-wave. The third spectrum shown is of the instantaneous difference of the two signals as obtained with an electronic subtractor circuit. There the E-oscillation nearly vanishes, implying that the E-wave mode is fairly uniform over most of the forebody. The modulation, however, is very priminent here. To the extent that each transducer signal is representative of the local force, this third spectrum is that of the net side force on the spike.

Quantitative measurements were also made of the time-dependent pressures $p_1(t)$ and $p_2(t)$ at the two transducer locations. In terms of the static pressure p_{ns} behind a normal shock at the test Mach number $M_\infty = 3$, the time averaged pressures were $\bar{p}_1 = \bar{p}_2 = 1.12\ p_{ns}$. For the unsteady pressures (e.g., the oscillograms of Fig. 2) the rms pressures $\langle p_1 \rangle$ and $\langle p_2 \rangle$ were 0.213 p_{ns}, while typical peak-to-peak values were of order 0.8 p_{ns}. The rms pressure difference $\langle p_2 - p_2 \rangle = 0.188\ p_{ns}$; typical peak-to-peak pressure differences were also of order 0.8 p_{ns}. The side forces on the spike thus were of considerable magnitude. Specifically, on the basis of the aforementioned findings the total rms side force was found approximately equal to the axial rms side force was found approximately to the axial rms force on the spike, and about 1/4 the total time-averaged axial force on the spike.

The instantaneous asymmetric pressures imply a corresponding asymmetry in the shock structure. Photographic evidence exists that the bow shock "bulges" to one side of the spike during those portions of the E-oscillations which bring the shock to its most forward-outward position. One might infer that such a protruding bulge rotates about the spike, completing one revolution for every two cycles of the E-oscillation. According to this inference, an additional (rotational) degree of freedom exists in the E-oscillation. The evidence is far from conclusive, however, and besides, this explanation raises additional questions about the origin and sense of the rotary motion. Therefore, although the possibility of an additional degree of freedom in the E-oscillation appears likely, its effects appear important enough to warrant further study of its origin.

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