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New Technique for Reducing Test Section Noise in Supersonic Wind Tunnels

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Nomenclature

l	= distance along nozzle centerline from upstream tip of test rhombus
$\dot{m}$	= tunnel mass flow
M_∞	= freestream Mach number
M_w	= inviscid Mach number at nozzle wall
$\tilde{p}_\infty$	= rms value of freestream static pressure
$\bar{p}_\infty$	= mean value of freestream static pressure
R_∞	= freestream unit Reynolds number
r^*	= nozzle throat radius
Δx	= length of low-noise uniform flow test region
y_e	= nozzle exit radius

Abstract

THE major problem in the design of a low-noise supersonic wind tunnel is to reduce the noise radiated from the turbulent, nozzle-wall boundary layer. This broadband noise is generally the dominant disturbance mode in wind tunnels at Mach numbers greater than about 2.5 (Refs 1 and 2). These acoustic disturbances are propagated along Mach lines in supersonic flow; hence, their sources are located far upstream of the test section at so-called "acoustic origins" near the nozzle wall. It is shown that tailoring the nozzle contour to reduce the Mach number and boundary-layer thickness at the acoustic origins significantly reduces the noise levels in the upstream part of the test rhombus.

Contents

The influence of tunnel noise on boundary-layer transition has been clearly demonstrated.[3-5] In certain types of wind tunnel tests, it is important to simulate transition behavior in atmospheric flight, but the freestream disturbance levels and frequency content required have yet to be determined. Further research on this and related problems requires a low-noise facility such as the "quiet" wind tunnel[6,7] under development at the Langley Research Center.

Previous work has concentrated on ways of maintaining laminar, nozzle-wall boundary layers,[8] or on ways of physically shielding the test model from the incoming noise.[7] An entirely new technique is presented herein for producing a relatively low-noise, supersonic test region at high unit Reynolds numbers where the nozzle-wall boundary layer is fully turbulent and where no physical shielding device is required in the flowfield.

A constant-current, hot-wire probe was used to measure freestream disturbances in two axisymmetric, contoured Mach 5 nozzles over a range of freestream unit Reynolds numbers from 10×10^6/m to 50×10^6/m. Figure 1 shows the contours of both nozzles. The "rapid expansion" nozzle[8] was designed with a large maximum wall angle to reduce the overall nozzle length and was equipped with a suction slot to remove the incoming turbulent boundary layer. For the present tests, no slot suction was used, since a fully turbulent, nozzle-wall boundary layer was desired. A typical probe location is shown in the conventional nozzle of Fig. 1 illustrating the acoustic origin of the radiated noise reaching the probe tip.

Typical disturbance measurements along the centerline of both nozzles are presented in Fig. 1. (The rms pressures are obtained from the hot-wire data for the conditions of these tests by well-known procedures.[1]) The noise levels for both nozzles decrease by approximately an order of magnitude from the nozzle exit to the beginning of the uniform test rhombus, with the rapid-expansion design exhibiting a significantly lower level over most of this region. One reason for these results is the fact that eddy Mach wave radiation from the turbulent boundary layer decreases with decreasing Mach number.[9] Laufer[1] found an M_∞^4 variation in his tests in the Jet Propulsion Laboratory's 18×20 in. supersonic tunnel. Thus, as the probe is moved upstream along the nozzle centerline, the acoustic origin associated with that probe position moves upstream along the nozzle-wall contour (Fig. 1), where the M_w values "seen" by a probe in the rapid-expansion nozzle are generally much lower than those "seen" in the conventional design. In fact, at the acoustic origin corresponding to the centerline probe station $l=0$, M_w is approximately 36% smaller in the rapid-expansion nozzle than in the conventional nozzle. Phillips[10] showed that Laufer's[1] data also contained a boundary-layer thickness effect; that is, the intensity of the radiated noise is directly related to the radiating volume[9] which depends on the local

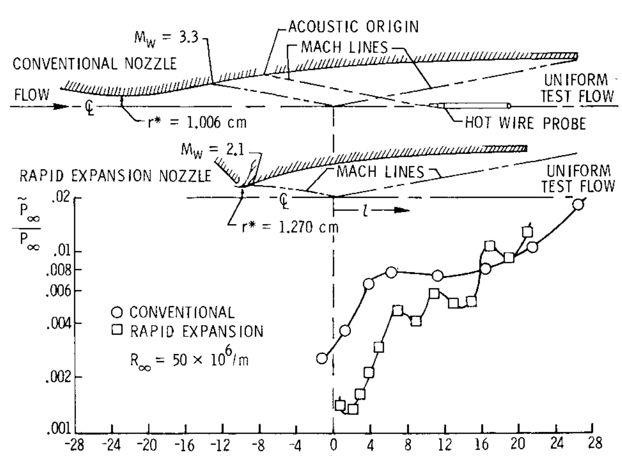

Fig. 1 Normalized rms static pressure fluctuations along centerlines of two $M_\infty = 5$ axisymmetric nozzles.

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Index categories: Testing, Flight and Ground; Nozzle and Channel Flow; Supersonic and Hypersonic Flow.

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nozzle radius and boundary-layer thickness at the acoustic origin. Based on computed boundary-layer thicknesses, the rapid-expansion design provides a radiating volume that is only about 5% of that for the conventional nozzle at the acoustic origins corresponding to the centerline probe station $l=0$. Thus, with favorable effects in both Mach number and radiating volume, the rapid-expansion design produces a lower noise level in the upstream part of the test rhombus.

Another interesting phenomenon observed in the present work accounts for the "lumpy" distribution in noise level along the centerline of the rapid expansion nozzle (Fig. 1). Several mean flow disturbances (see Ref. 11) focused on the centerline of this nozzle and were traced to extremely small axisymmetric machining errors of ± 0.0013 cm (± 0.0005 in.) on the nozzle wall. These mean flow disturbances were "shivered" by the nozzle wall boundary layer and thus produced the several localized peaks in the rms pressure distributions for the rapid expansion nozzle.

Because of the axial noise gradient, the size of a "quiet" test core within the uniform mean flow test region will obviously depend upon the maximum noise level that is acceptable. For example, choosing a rather arbitrary maximum disturbance level of 0.3% in the rapid-expansion nozzle yields a test core $5r^*$ long with a maximum diameter of approximately $2r^*$. This small test core would not be useful for practical-sized wind-tunnel models; however, two alternatives are available to increase this size. Obviously, the nozzle throat size can be increased to achieve a corresponding increase in length of the quiet test core. However, the accompanying increase in mass flow may prove to be prohibitive. The other alternative is to reduce the exit Mach number. The effect of exit Mach number on the length of the quiet test core is shown in Fig. 2, where the variation of Reynolds number based on test core length Δx with unit Reynolds number is illustrated for axisymmetric nozzles with fixed $y_e = 0.25$ m. The quiet test length Δx is defined for this figure as the distance from the upstream tip of the uniform test rhombus to the point where the $M_w = 2.7$ Mach line crosses the nozzle centerline. For the rapid-expansion nozzle, this results in $\tilde{p}_\infty / \bar{p}_\infty \leq 0.003$. Also shown are the approximate flight transition limits on sharp cones[6] at two Mach numbers in terms of local flow conditions. Presumably, to achieve transition on models in "quiet" flow, one would have to operate above these limits. It is immediately apparent from Fig. 2 that large mass flows are required to operate above the flight transition limits for freestream Mach numbers greater than 4. At reduced Mach numbers, however, the mass flow requirements become more modest, even at length Reynolds numbers well beyond those required by the flight limits. For example, at $M_\infty = 3.5$, a mass flow of 91 kg/s (200 lbm/s) would be required to produce a quiet ($\tilde{p}_\infty / \bar{p}_\infty \leq 0.003$) flow Reynolds number of 35×10^6. Detailed calculations have shown that two-dimensional nozzles, which do not have the axisymmetric focusing problems, will provide approximately the same range of quiet test conditions as axisymmetric nozzles, but with some penalty in larger mass flows for $M_\infty < 3.5$.

One advantage of the new technique is that the nozzle wall boundary layer is always fully turbulent, avoiding the troublesome transition problem. Another advantage is that both the level and spectral content (see Ref. 11) of the noise can be varied by locating the model in different parts of the test rhombus.

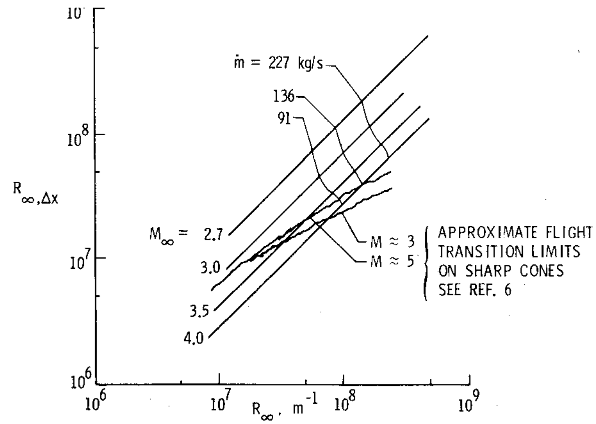

Fig. 2 Variation of quiet test length Reynolds number with unit Reynolds number in axisymmetric nozzles, $M_w = 2.7, y_e = 0.25$ m.

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