

Fluctuating Disturbances in a Mach 5 Wind Tunnel

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An experimental investigation has been conducted to determine the source and nature of disturbances in the settling chamber and test section of a Mach 5 wind tunnel. Various changes in the air supply piping to the wind tunnel are shown to influence the disturbance levels in the settling chamber. These levels were reduced by the use of an acoustic muffler section in the settling chamber. Three nozzles were tested with the same settling chamber, and hot-wire measurements indicated that the test section disturbances were entirely acoustic. Significant reductions in the test section noise levels were obtained with an electroplated nozzle, utilizing boundary-layer removal upstream of the throat. The source of test section noise is shown to be different for laminar and turbulent nozzle-wall boundary layers.

Nomenclature

Δe	= fluctuating voltage from hot wire
Δe_m	= mass flow sensitivity coefficient
Δe_T	= total temperature sensitivity coefficient
L	= nozzle length
M	= Mach number
p	= pressure
r	= radius of nozzle
Δr	= difference between design and measured nozzle radius
Re	= unit Reynolds number per meter in settling chamber or test section
u	= velocity in axial direction
V	= mean voltage across hot wire
x	= axial distance along nozzle from throat

Superscripts

() *	= condition where $M = 1$
() ~	= rms value
() ¯	= mean value

Subscripts

a	= acoustic origin
$t, 2$	= stagnation condition downstream of normal shock
w	= value at wall
∞	= freestream in nozzle or settling chamber
o	= stagnation value

Introduction

It is widely recognized that wind-tunnel noise is an important parameter in high-speed boundary-layer transition studies.¹⁻⁶ Also, some evidence indicates that the background noise in high-speed wind tunnels dominates the fluctuating pressures measured under a turbulent boundary layer⁷⁻⁹ and could modify the structure of free shear layers.¹⁰ For these

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types of tests, control and reduction of wind-tunnel noise obviously is necessary.

The Fluid Mechanics Branch of the Langley Research Center is developing a "quiet" Mach 5 wind tunnel with the objective of reducing test section noise to very low levels.⁹ Since the prime contributor to the test section noise is radiation from the turbulent boundary layer on the wind-tunnel nozzle wall,² efforts have been concentrated on ways of maintaining a laminar nozzle-wall boundary layer,¹¹ or on ways of shielding the test region from the radiated noise.¹² The present paper reports on research concerning the first of these two approaches.

Disturbance measurements were made in the test section of a small, hypersonic wind tunnel while varying a number of factors affecting nozzle-wall boundary-layer transition. These factors included wall roughness, wall temperature, upstream suction through a transverse slot, and settling chamber disturbance levels. The effects on settling chamber disturbances of an acoustic muffler, of changes in upstream piping and valves, and of various entrance baffles also were investigated. Detailed measurements were made of the nature, magnitude, and source of the residual noise in the test section when the nozzle-wall boundary layer was laminar.

Apparatus and Tests

The present tests were conducted in the pilot model "quiet" tunnel (Fig. 1) at the Langley Research Center.⁹ The first type

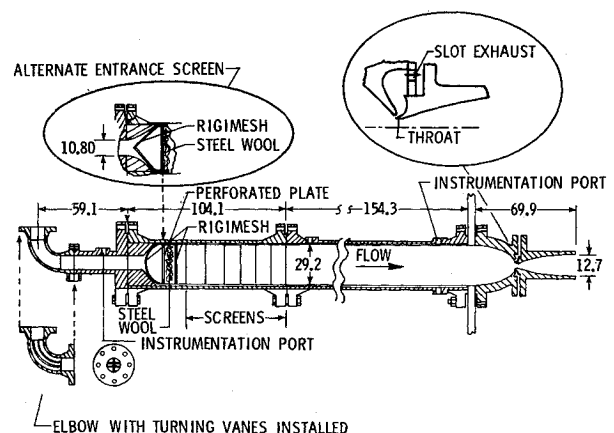


Fig. 1 Schematic scale drawing of settling chamber and slotted nozzle (dimensions in cm).

of nozzle tested was of conventional design and was used primarily to investigate the effect of throat roughness on transition. The second type of nozzle was equipped with an annular slot upstream of the throat for boundary-layer suction. The function of the slot is to remove the turbulent boundary layer that develops along the settling chamber wall. The new, laminar boundary layer that develops downstream of the slot lip is immediately subjected to a large, favorable pressure gradient. This technique would be expected to delay transition to higher Reynolds numbers. Two nozzles of this type were tested. The internal contour for the first nozzle was machined in the conventional way, using a long boring bar to support the tool. Inaccuracies in this technique led to a second slotted nozzle, which was formed by electroplating on a mandrel. Detailed measurements of flow disturbances in all three nozzles are presented in this paper. The disturbance measurements were made with a hot-wire anemometer and a quartz piezoelectric pressure transducer.

Hot-Wire Anemometer

The hot-wire anemometer was the constant current type with a maximum frequency response of 500 kHz. The sensing element of the probe was a 5- μ m-diam platinum wire, with a length-to-diameter ratio of approximately 150. The details of probe construction for the subsonic (settling chamber) and the supersonic (test section) measurements are given in Ref. 13. The supersonic probes required a large amount of wire slack to eliminate strain-gage signals. All probes were individually temperature and flow calibrated. Reference 13 gives a full description of the wire calibrations.

Pressure Transducer

The quartz piezoelectric pressure transducers were converted to operate in the piezotron mode (i.e., converted to a low output impedance device). A typical transducer calibration is given in Ref. 13. Two different size transducers were used in the present tests. For the settling chamber measurements, a 1.08-cm-diam transducer was flush-mounted in the wall of the settling chamber entrance pipe. This transducer had a resonant frequency of 130 kHz. The test section measurements with the conventional and slotted nozzles were made with a 0.318-cm-diam transducer, mounted flush with the front surface of a 0.635-cm-diam pitot probe. The resonant frequency of this transducer was 300 kHz.

Results and Discussion

Settling Chamber Measurements

Fluctuations originating in, or transmitted through, the settling chamber can affect test section disturbance levels by passing directly through the nozzle throat into the test section (temperature spottiness, vorticity, or acoustic waves¹⁴) or by affecting transition of the nozzle wall boundary layer. The

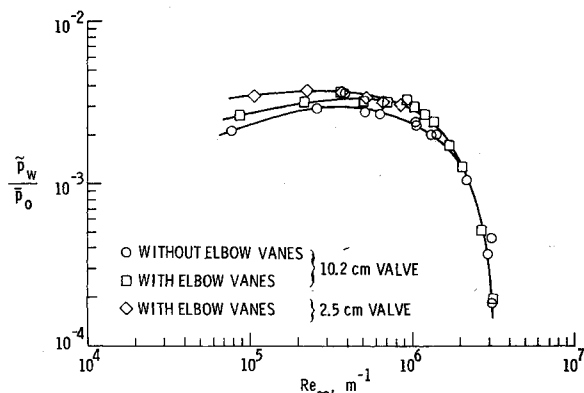


Fig. 2 Normalized wall pressure fluctuations at settling chamber entrance.

nozzle wall boundary layer is formed from the remnants of the settling chamber wall boundary layer and, at least in the subsonic approach of a conventional nozzle, is exposed directly to any fluctuations in the settling chamber freestream. Large settling chamber disturbances may, therefore, cause early transition of the nozzle wall boundary layer with an accompanying increase in the test section noise level.

Because the hot-wire responds to anything that changes the heat-transfer process between the wire and the gas, it is difficult to decompose the signal when vorticity, noise, and temperature fluctuations are all present. Similarly, the wall-mounted pressure transducer responds to turbulence-induced pressure fluctuations as well as acoustic waves, and its signal is not always unambiguous. Considerable effort was made in the following tests to characterize the major contributor to the settling chamber disturbance level. Only noise and vorticity were considered, since previous measurements have shown that temperature spottiness in this facility is negligible.¹³ All settling chamber measurements were made with the slotted nozzle installed in the facility.

Figure 1 shows the arrangement of the various settling chamber components. The initial screen encountered by the incoming flow is a shaped (hemisphere or cone), woven, sintered metal plate, 0.32 cm thick (Rigimesh). This material was designed to provide a pressure drop of 17 N/cm² at 350 N/cm² upstream pressure. The Rigimesh screen is followed by a 57% open perforated plate, a section of loosely packed steel wool, chemical filter paper (Eaton-Dikeman No. 615), a second, flat Rigimesh screen of the same density as the shaped screen, and six conventional woven wire screens of decreasing mesh size (8 \times 8 mesh/cm to 20 \times 20 mesh/cm).

Effect of Control Valves

The stagnation pressure of the tunnel is controlled by two valves. A 2.5-cm valve is used for stagnation pressures up to

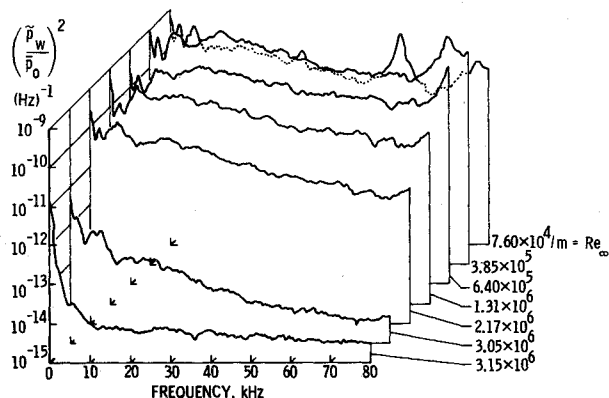


Fig. 3 Spectra of wall pressure fluctuations at settling chamber entrance, 10.2-cm control valve, no elbow turning vanes.

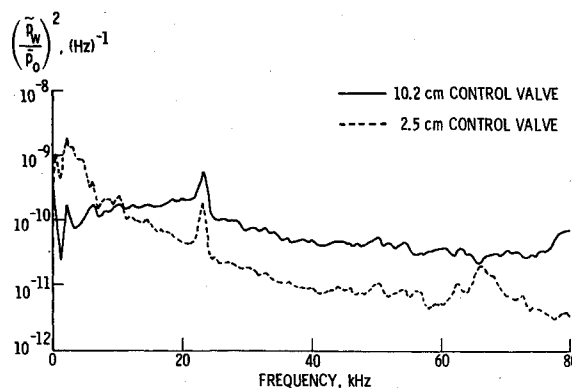


Fig. 4 Wall pressure spectra at settling chamber entrance for two air supply control valves, $Re_\infty = 6.7 \times 10^5$ /m, elbow turning vanes installed.

100 N/cm², and a 10.2-cm valve is used for pressures up to 350 N/cm². During normal tunnel operation, both valves are used for pressures above 100 N/cm², with the smaller valve providing a fine adjustment.

In order to measure the incoming disturbances to the settling chamber, a fluctuating pressure transducer was flush-mounted on the wall of the air supply pipe at the settling chamber entrance (upstream instrumentation port in Fig. 1). Considerable care was exercised in mounting the transducer flush with the surface.¹⁵ The variation of the normalized rms wall pressure fluctuations with Reynolds number is shown in Fig. 2 for operation with the two control valves. The 2.5-cm valve produced slightly higher disturbances at the lower Reynolds numbers, but no appreciable differences were measured above $Re_\infty \approx 7 \times 10^5/m$. Since pressure fluctuations for normal, subsonic turbulent pipe flow¹⁶ at the present conditions would be more than two orders of magnitude lower than the measurements shown in Fig. 2, ordinary pipe turbulence is probably not responsible for the large disturbances shown in Fig. 2.

Turning vanes were added (Fig. 1) to the elbow just upstream of the measurement station to determine if elbow-induced turbulence (due to separation and secondary flow) was at least partially responsible for the high levels shown in Fig. 2. The turning vanes were designed to divide the cross section of the 90° elbow into six compartments, approximately 4.5 × 3.5 cm each. The results with the vanes installed (Fig. 2) show slight increases in the rms levels for $Re_\infty < 2 \times 10^6/m$. Above this Reynolds number, no effect was noted. Any vorticity induced by the elbow would have scales roughly on the order of the pipe diameter (10.2 cm), and the addition of the vanes certainly would be expected to modify this vorticity significantly. The small influence of the turning vanes shown in Fig. 2 indicates that the elbow-induced turbulence contribution to the pressure fluctuations is small.

Spectra for the wall pressure fluctuations with the 10.2-cm control valve are shown in Fig. 3. For Reynolds numbers up to $2.17 \times 10^6/m$, considerable energy is present at frequencies

as high as 80 kHz. In contrast, typical turbulent pipe flow¹⁶ at these conditions has little energy beyond 10 kHz. The most likely mechanism for producing the high-frequency energy shown in Fig. 3 is jet noise¹⁷ from the upstream mass flow control valves. The valves are choked for settling chamber pressures up to about 200 N/cm² ($Re_\infty \approx 2 \times 10^6/m$), and the rather abrupt drop in the rms levels shown in Fig. 2 and the sudden decrease in the high-frequency energy shown in Fig. 3 both occur at about this Reynolds number. It can be shown that the normalized pressure fluctuations for the present case should increase approximately as the square root of the open valve area, as long as the valve remains choked. This corresponds to the gradual increase in the rms values shown in Fig. 2 for low Reynolds numbers (small valve opening). However, when the control valve unchokes, the valve jet velocity drops rapidly with further increases in Reynolds number corresponding to the dramatic decrease in noise level shown in Fig. 2.

Even though the overall rms wall pressure fluctuations at the settling chamber entrance for the two control valves are essentially the same (Fig. 2), the spectral content is quite different, as shown in Fig. 4. This difference was more pronounced at the lowest Reynolds numbers, resulting in a slightly higher overall rms level for the 2.5-cm valve in this region. Obviously, the smaller valve had to be opened more of its total travel to produce the same mass flow as the larger valve, and its characteristic jet dimension therefore was larger. Hence, the 2.5-cm valve produced more low-frequency energy than the 10.2-cm valve.

The disturbance levels measured by a hot wire on the centerline near the settling chamber exit (downstream instrumentation port in Fig. 1) are shown in Fig. 5 for the two control valves. The smaller valve definitely produced a higher overall disturbance level at this station, and the spectra shown in Fig. 6 indicate how this energy was distributed with frequency. Unlike the spectra at the settling chamber entrance, the exit spectra above 10 kHz are almost the same for the two valves. Apparently the increased high-frequency energy for the 10.2-cm valve measured at the settling chamber entrance (see Fig. 4) has been eliminated by the intervening

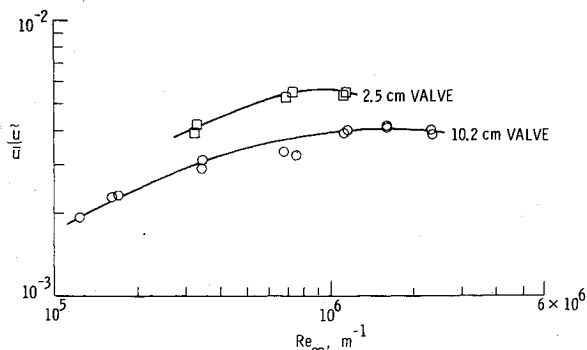


Fig. 5 Effect of control valve size on disturbance level in settling chamber, hot-wire data on settling chamber centerline at nozzle entrance, Rigimesh hemisphere entrance screen.

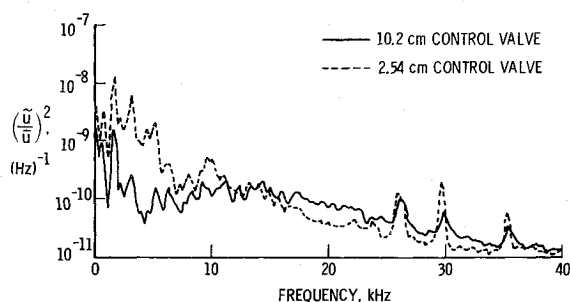
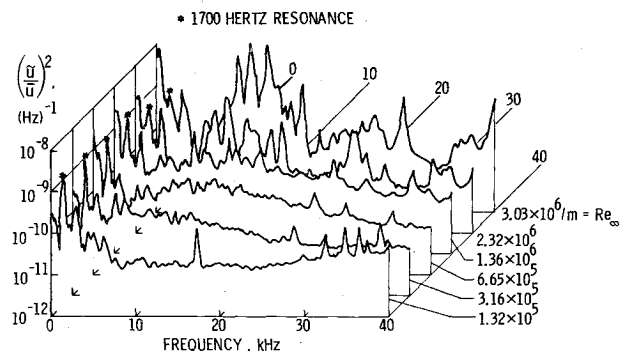
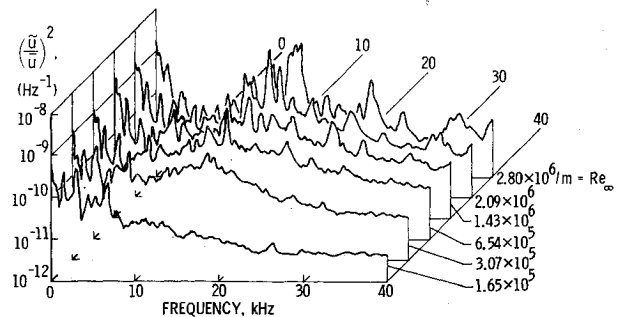


Fig. 6 Hot-wire spectra on settling chamber centerline at nozzle entrance for two air supply control valves, $Re_\infty = 6.7 \times 10^5/m$, Rigimesh hemisphere entrance screen.



a) Rigimesh hemisphere entrance screen.



b) Rigimesh cone entrance screen.

Fig. 7 Hot-wire spectra on settling chamber centerline at nozzle entrance, 10.2-cm control valve.

screens and baffles. More discussion of this high-frequency attenuation is contained in the section on the steel wool muffler. The low-frequency (< 10 kHz) end of the exit spectra shows the same effect of control valve size as the entrance spectra.

In summary, the primary disturbance mechanism upstream of the settling chamber appears to be valve-generated noise. This noise persists through the settling chamber and dominates the disturbance levels at the nozzle entrance. These results are similar to those reported in Ref. 14.

Effect of Settling Chamber Entrance Screen

Two entrance screen (Rigimesh) arrangements are shown in Fig. 1. The resulting rms disturbance levels (measured by a hot wire at the settling chamber exit) for the two configurations, as well as for a third, hybrid configuration, did not show appreciable differences. Although the overall disturbance levels did not change greatly, the spectral content of the signal did show some differences, as shown in Fig. 7. At low Reynolds numbers, the hot-wire signal for the hemispherical screen was dominated by a 1700-Hz component (see Fig. 7a). This dominant frequency was discovered previously in the correlation measurements of Ref. 13, and was attributed to a propagating duct mode in the settling chamber. However, it appears much more likely that this discrete frequency is the result of a standing wave pattern in the settling chamber.¹⁸ The conical entrance screen greatly reduced the 1700-Hz component, and also generally reduced the energy at higher frequencies (Fig. 7b). Apparently, the geometry change to the conical screen modified the end conditions sufficiently to decrease the resonance effect at 1700-Hz. The hybrid screen arrangement, where the diffuser block for the conical screen was used with the hemispherical screen, produced spectra almost identical with that for the normal hemisphere configuration. This result indicates that the differences in the spectra of Figs. 7a and 7b probably are not due to any fluid mechanical phenomenon such as separation in the sharply diverging approach section of the hemisphere screen.

Effect of Steel Wool

The steel-wool-filled section of the settling chamber (Fig. 1) was designed to attenuate upstream valve and pipe flow noise. In order to measure the effectiveness of the steel wool, several tests were performed with the steel wool removed. The results shown in Fig. 8 indicate that the overall disturbance level at the nozzle entrance was significantly reduced by the steel wool. However, this reduction is somewhat less at the higher Reynolds numbers, which agrees qualitatively with theory for sound attenuation through porous media.¹⁹

Figure 9 shows the spectral content of the hot-wire signal with the steel wool removed. Comparison with Fig. 7b shows that the steel wool generally is more effective in attenuating

the higher frequencies than the lower frequencies, again in agreement with theory.¹⁹

The rms levels at the nozzle entrance (Fig. 8), with or without the steel wool, are much lower than the rms levels (Fig. 2) at the settling chamber entrance. (See Ref. 13 for an equation to convert the velocity fluctuations of Fig. 8 to pressure fluctuations, assuming purely acoustic disturbances. An approximate relation for the present tests is $\bar{p}/\bar{p} \approx 0.007 \bar{u}/\bar{u}$.) Therefore, the data without the steel wool indicate that the screens are providing significant attenuation of the entrance noise. Since the open, fine-mesh screens could hardly be expected to attenuate acoustic disturbances appreciably, the two Rigimesh screens (Fig. 1) must be providing most of the sound reduction.

Effect of Slot Suction

Although detailed measurements with varying suction mass flow are not available, measurements were made with the slot suction valves closed and open. The suction slot/plenum with the valves closed produced a resonance effect resulting in an intense tone at 2560 Hz. The overall noise level in the settling chamber was approximately 15 times larger with no suction mass flow than with maximum suction flow. Therefore, it is possible that the suction slot lip is responsible for at least some of the settling chamber noise even when suction is applied to the slot. At present, no assessment of this contribution has been made since no settling chamber noise tests have been conducted with the conventional (no suction) nozzle. Test section disturbance measurements with zero slot suction did not reveal any dominant energy at 2560 Hz.

Test Section Measurements

Previous tests¹³ have shown that the test section disturbances in this facility at Reynolds numbers above the onset of transition are the result of acoustic waves radiated from the transitional/turbulent nozzle-wall boundary layer. The waves generally are propagated along Mach lines, which means that a probe situated on the tunnel centerline senses signals originating at some point upstream where the Mach cone from the probe intersects the wall (an acoustic origin).¹¹ For example, a probe at the exit of the slotted nozzle (39.3 cm from throat) senses signals originating in the nozzle-wall boundary layer approximately 13.2 cm from the throat. This acoustic origin effect is important for the proper assessment and interpretation of the results presented in this section.

Conventional Nozzle

The conventional nozzle was used primarily to investigate the effects of wall roughness upstream of the nozzle throat on nozzle-wall boundary-layer transition. A strong effect of wall roughness in the throat region was noted in Ref. 11, and the present tests were conducted to define the finish required to reduce or eliminate the effect of wall roughness on the transition process. Figure 10 shows data from both the hot-

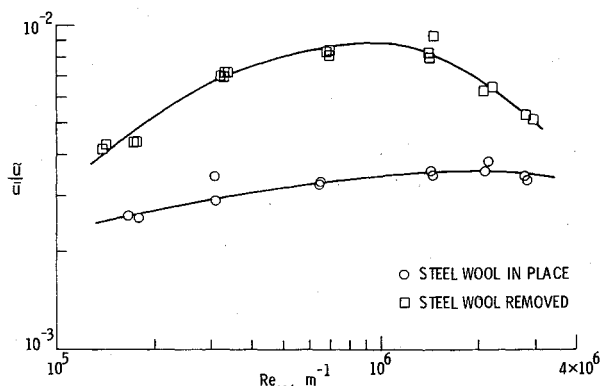


Fig. 8 Effect of steel wool in settling chamber, hot-wire data on settling chamber centerline at nozzle entrance, Rigimesh cone entrance screen, 10.2-cm control valve.

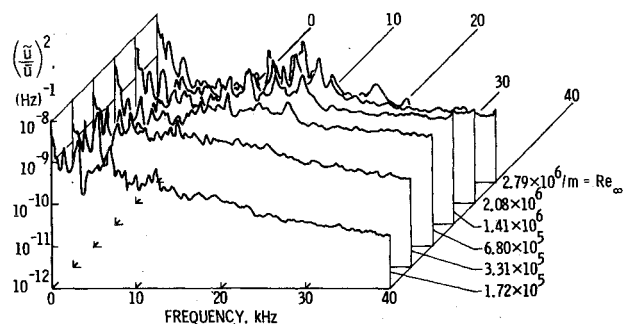


Fig. 9 Hot-wire spectra on settling chamber centerline at nozzle entrance, steel wool removed, Rigimesh cone entrance screen, 10.2-cm control valve.

wire and the fluctuating pitot pressure probe for three surface finishes. The hot-wire data are presented in terms of rms pitot pressure fluctuations (equation given in Ref. 13) to facilitate comparison with the pitot probe data. The "unpolished" condition was just as received from the manufacturer, with a quoted finish of 16 μin . The "roughened" wall condition was generated by many hours of tunnel operation, where small particles impacted the converging nozzle entrance causing a pitted surface. A filter system was installed to remedy this condition, and the nozzle entrance region was laboriously hand-polished to a mirror-like finish. Although no measure of the final finish was obtained, it was a substantial improvement over the original "factory" finish. The changes in transition with surface finish were dramatic (transition is defined as the first appearance of moving sound sources or turbulent "spots" in the boundary layer¹³). Polishing the nozzle entrance increased the transition Reynolds number nearly 150% over the roughened wall case, and more than 30% over the nominal, unpolished wall case. The boundary-layer displacement thickness at the nozzle throat was computed to be approximately 0.025 cm when turbulent spots first appeared at the acoustic origin ($x_a/L=0.536$) of the probe. The results presented in Fig. 10 for the polished wall case represent the best that could be obtained with the conventional nozzle. Cleaning and repolishing after every few runs was necessary to maintain this performance.

Reference 11 noted a large increase (20%) in the transition Reynolds number when the nozzle wall was heated. This increase was attributed primarily to an increase in the boundary-layer thickness and a corresponding decrease in the sensitivity of the boundary layer to wall roughness. The same phenomenon also was observed by Amick.²⁰ Although no measure of nozzle wall temperature was available for the present tests, a strong "apparent" wall temperature effect was noted, even for the highly polished wall case. Figure 10 shows a large drop in the radiated noise level starting from a cold wall condition (room temperature) to near adiabatic wall condition ($T_w \approx 600^\circ\text{R}$) reached after a 1/2-hr run at constant stagnation conditions ($T_0 \approx 660^\circ\text{R}$). The data imply that wall roughness is still influencing the transition process. However, the region just downstream of the throat is extremely difficult to polish, and it is possible that roughness in this area is still contributing significantly to the transition process.

The hot-wire results presented in Fig. 10 were obtained by plotting the hot-wire output in terms of the "mode" variables.²¹ These mode diagrams can provide additional information about the nature and source of the disturbances sensed by the hot wire.²² Figure 11 shows typical mode diagrams obtained with the present data. The linear nature of the curves is consistent with the assumption that the signal is composed entirely of pressure fluctuations.²² Further, the curves at low Reynolds number (for the polished wall) pass

through, or nearly through the origin, which indicates that the source of the sound is fixed (or slowly moving) with respect to the tunnel. These fixed-source disturbances may be the "shivering" Mach waves noted by Morkovin.^{23,24} A detailed discussion of this phenomenon is contained in Ref. 2, 23, and 24. The first appearance of turbulent bursts in the nozzle-wall boundary-layer signals the beginning of transition and produces a signal with a nonzero source velocity with a corresponding nonzero intercept on the mode diagram.¹³ The roughened wall case in Fig. 11 shows transition even at the lowest Reynolds number.

Spectra of the freestream disturbances in this nozzle have been reported previously,¹¹ and showed that at low Reynolds numbers the fluctuation energy is concentrated below approximately 10 kHz. The onset of transition of the nozzle wall boundary layer causes a definite shift of energy to higher frequencies, and for fully turbulent flow, energy is present to 100 kHz.

Slotted Nozzle

The slotted nozzle was designed to remove the turbulent boundary layer that develops along the settling chamber wall, allowing the expansion through the throat to begin with a new, laminar boundary layer and thus delay transition. The highest Reynolds number for operation with a laminar boundary layer (at the probe acoustic origin $x_a/L=0.335$) was obtained with the slot lip 0.12 cm downstream of the original design position.²⁵ The overall characteristics of this nozzle were similar to those of the polished wall, conventional nozzle (Fig. 10), except that the slotted nozzle exhibited higher noise levels at low Reynolds numbers ($Re_\infty < 1 \times 10^7/\text{m}$). It should be emphasized that this nozzle was not polished to the degree that the conventional nozzle was polished, and yet the boundary-layer suction slot delayed transition to about the same Reynolds number. Also, extensive repolishing was not required to maintain this performance.

Hot-wire mode diagrams presented previously in Ref. 13 identified the pretransition disturbances in this nozzle as fixed-source acoustic waves. The reason for the much higher levels with the slotted nozzle was evident upon close examination of the nozzle contour under controlled lighting conditions. A distinct pattern of waviness was noted, especially near the throat. Figure 12 shows the deviation of the measured nozzle coordinates from the design coordinates. The variations near the throat evidently produced a strong Mach wave field, which generated large pressure fluctuations when "shivered" by the nozzle-wall boundary layer or by freestream disturbances. An attempt was made to remachine the nozzle, but the resulting contour was not improved (see Fig. 12) and the laminar noise levels actually increased.¹³ For this reason, a second slotted nozzle was built and tested. The results are presented in the next section.

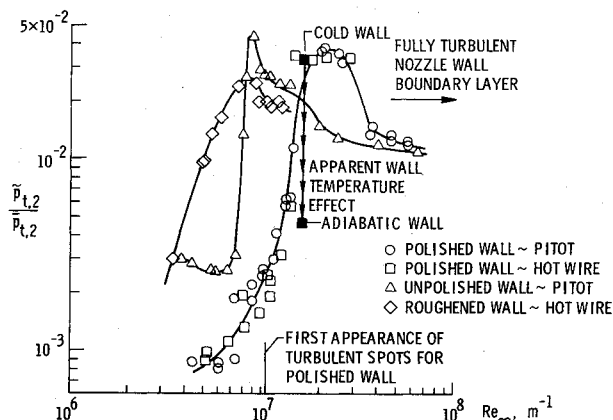


Fig. 10 Freestream rms pressure fluctuations in conventional nozzle, probes at nozzle exit on centerline, $x_a/L=0.536$, nozzle length $L=50$ cm, $M_\infty=5$.

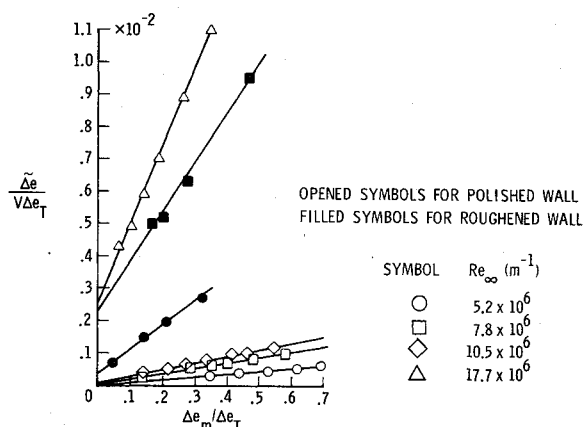


Fig. 11 Hot-wire mode diagrams for conventional nozzle.

Electroformed Slotted Nozzle

The new slotted nozzle contour was formed by electroplating nickel on a highly polished stainless-steel mandrel. Machining accuracies were much easier to maintain on the outside contour of the mandrel (see Fig. 12), and the surface polishing in the critical throat region was much easier to accomplish. Almost 200 man-hours were spent polishing the mandrel, but the resulting finish was only slightly better than that obtained with the conventional (no suction) nozzle. The accuracy of the contour was much improved, however.

Hot-wire data obtained in the electroformed slotted nozzle (with the optimum slot lip position) are shown in Fig. 13, which includes, for comparison, the corresponding data from the original and remachined slotted nozzle (note that the remachined nozzle had extremely high laminar noise levels, and that turbulent spots first appeared at the probe acoustic origin at a low Reynolds number). The transition Reynolds number for the electroformed nozzle increased more than 40% over the original slotted nozzle result, and the noise levels with a laminar wall boundary layer ($Re_\infty m < 13.4 \times 10^6$) were reduced dramatically. Spectra for the slotted nozzle data were similar to those of the conventional nozzle (reported in Ref. 11).

Also shown in Fig. 13 are data obtained with the steel wool removed from the settling chamber. As shown in Fig. 8, removal of the steel wool increased the settling chamber noise levels by more than 100%. This increase, however, had very little influence on the beginning of transition (Fig. 12), and did not change the laminar or turbulent noise levels an appreciable amount. These results agree with those of Ref. 14, where the effect of settling chamber noise on test section disturbances was investigated for freestream Mach numbers from 1.2 to 4. Above $M=3$, Ref. 14 showed that the test section noise appeared to be essentially independent of the

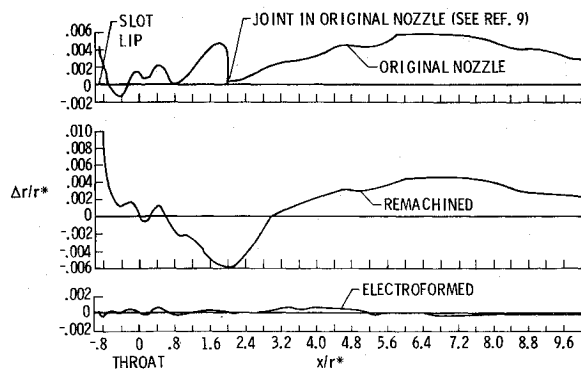


Fig. 12 Computed radius minus measured radius for slotted nozzles, $r^* = 1.270$ cm.

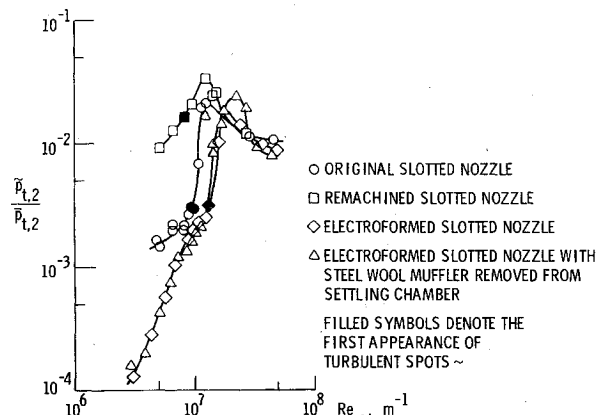


Fig. 13 Effect of contour imperfections and settling chamber noise on transition in the slotted nozzles, hot-wire probe on centerline at nozzle exit, $x_a/L = 0.335$, nozzle length $L = 39.3$ cm, $M_\infty = 5$.

settling chamber noise. The nozzle-wall boundary layers in Ref. 14 probably were always turbulent, whereas the present results show that even with the low, background levels associated with the laminar nozzle-wall boundary layer, no measurable settling chamber noise was transmitted through the nozzle. However, a complete investigation of the levels and frequency composition of settling chamber noise that may affect nozzle-wall boundary-layer transition has yet to be conducted.

Similar to the conventional nozzle data (Fig. 10), a strong, apparent wall temperature effect also was noted in the slotted nozzle data. That is, transition moved downstream with increasing nozzle wall temperature. This temperature effect indicates that, despite the extraordinary effort to achieve a "smooth" surface, some residual roughness still may be influencing transition. However, it is also possible that the performance of the boundary-layer suction slot changed with increasing wall temperature, causing transition to move downstream in the nozzle. Whatever the mechanism, consistent transition behavior was never obtained until the nozzle-wall temperature was stabilized.

Hot-wire mode diagrams for the electroformed nozzle data of Fig. 13 showed that the low Reynolds number disturbances probably were "shivering" Mach waves, but that the level of the pressure fluctuations produced was much lower than in the original, slotted nozzle. This improved performance probably was due to the improved machining accuracy for the electroformed nozzle. That is, the relative machining accuracy of the three nozzles is consistent with their relative performance. Thus, the remachined nozzle showed the poorest performance (Fig. 13) and had the largest machining errors, particularly in the leading-edge region of the slot lip.

Figure 14 illustrates the movement of transition in the electroformed nozzle. The forward movement of transition with increasing Reynolds number is similar to that found in the two previous nozzles, even to the slight decrease in noise just prior to the beginning of transition for the upstream probe positions ($x/L = 0.677, 0.839$).

It is clear from Fig. 14 that a model in the test section of this nozzle would experience a varying noise level over its entire length which would increase with increasing tunnel unit Reynolds number. The magnitude of this radiated noise is quite low when the nozzle-wall boundary layer is laminar, and may be negligible for many types of tests. In fact, Ref. 9 indicates that static pressure fluctuations of 0.1 to 0.5% may be adequate to simulate flight conditions. In the present case, a long, slender model with its leading edge placed at the upstream end of the electroformed nozzle test rhombus would experience pressure fluctuations ($\bar{p}_\infty/\bar{p}_\infty$) below 0.1%, over about the first 30 cm of its length, up to a unit Reynolds number of about $15 \times 10^6/m$ (the nozzle exit diameter is 12.9 cm, so that the tip of the uniform flow test rhombus extends

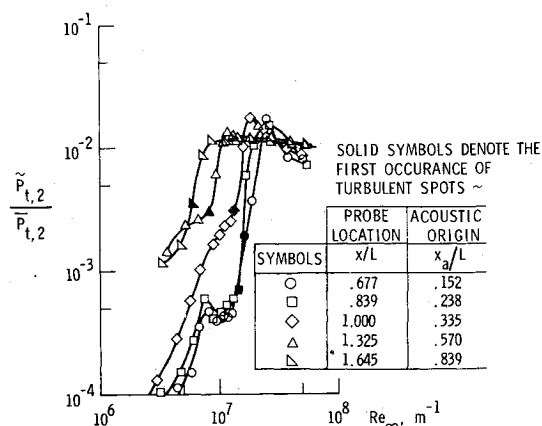


Fig. 14 Movement of transition location in electroformed slotted nozzle, hot-wire probe on nozzle centerline, $M_\infty = 5$.

about 31.6 cm forward of the nozzle exit). Hence, the maximum test Reynolds number based on the length of this "quiet" region would be about 4.5×10^6 , and, according to the analysis of Ref. 9, would be too small to achieve natural transition at this unit Reynolds number. However, the $\frac{1}{2}$ -m Mach 5 quiet tunnel should achieve this same length Reynolds number at $\frac{1}{4}$ the unit Reynolds number (4 times larger tunnel). At this lower unit Reynolds number, transition on the model may be observed, according to Ref. 9.

Fully turbulent flow on models under "quiet" conditions still is not possible, and will likely require some innovative ideas²⁶ applied to high-speed wind-tunnel design.

Conclusions

The major conclusions of this study are listed as follows.

1. Noise from upstream control valves comprised a significant portion of the settling chamber disturbance levels.
2. A strong acoustic resonance effect occurred in the settling chamber, and this effect was altered by changing the settling chamber entrance geometry.
3. Steel wool and porous metal plates significantly reduced the level of acoustic disturbances in the settling chamber.
4. Transition of the nozzle-wall boundary layer was extremely sensitive to roughness in the throat region of the nozzle.
5. Boundary-layer removal upstream of the nozzle throat by a suction slot was more effective than a highly polished wall in increasing the transition Reynolds number of the nozzle-wall boundary layer.
6. Small imperfections in the nozzle contour resulted in large test section disturbances when the nozzle-wall boundary layer was laminar.
7. Large increases in the settling chamber noise level had virtually no effect on transition of the boundary layer on the electroformed nozzle wall.

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