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Quiet-Flow Ludwieg Tube for High-Speed Transition Research

Steven P. Schneider* and Christine E. Haven†
Purdue University, West Lafayette, Indiana 47907

Low-noise supersonic wind tunnels are required for unambiguous experimental research into high-speed laminar-flow instability and transition. The experience of the successful NASA Langley quiet-tunnel development program has been used to design and construct a new kind of low-cost, short-duration, quiet-flow tunnel. Measurements of the flow quality in the 9.7 × 10.9 cm Mach 4 test section were obtained using fast response pressure transducers mounted in the tip of a pitot tube. When the rms pitot pressure is approximately 0.05–0.10% of the mean pitot pressure, bursts of noise appear in the pitot-pressure signals. These bursts appear to be the radiated signature of turbulent spots in the boundary layers on the nozzle walls. Their appearance confirms the presence of laminar nozzle-wall boundary layers and quiet flow when the rms pitot pressure is about 0.06% or less. Based on this criterion, quiet flow is achieved to Reynolds numbers based on the axial length of the quiet-flow test region of more than 400,000 at unit Reynolds numbers of approximately 40,000 per cm. This performance is sufficient for research into receptivity, roughness, and instability effects at high speeds.

Nomenclature

L_q	= length of uniform quiet-flow region, see Fig. 2
M_e	= Mach number at the boundary-layer edge
$P_{t2,\mathrm{mean}}$	= mean pitot pressure, total pressure behind the pitot shock
P'_{t2}	= fluctuating part of the pitot pressure
$P'_{t2,\mathrm{rms}}$	= rms of pitot pressure fluctuations
P_0	= stagnation pressure
$P_{\infty,\mathrm{mean}}$	= mean static pressure
$P'_{\infty,\mathrm{rms}}$	= rms of static pressure fluctuations
$Re_{x,\mathrm{crit}}$	= Reynolds number based on distance from leading edge; critical value where instability begins
Re_{δ^*}	= Reynolds number based on displacement thickness
r_{peak}	= peak height of tunnel-wall roughness
x	= spanwise coordinate in two-dimensional nozzle
y	= vertical coordinate
z	= axial or streamwise coordinate; 0 at the contraction entrance
z_s	= location where boundary layer originated

I. Introduction

MOST experiments on supersonic transition have been performed in conventional facilities, which suffer from noisy freestream flows and turbulent test-section-wall boundary layers that radiate sound onto the model (for recent reviews, see Refs. 1–4). However, the supersonic case is similar to the incompressible case, in that the acquisition of conclusive data for the transition process usually requires quiet-flow facilities. Measurements on sharp cones at zero angle of attack have shown that transition Reynolds numbers in quiet facilities are comparable to flight and roughly four times higher than those in conventional facilities (see Fig. 2 in Ref. 1). However, this shift in transition location is only part of the difficulty with measurements in conventional facilities. The contaminating noise sources in conventional facilities can also cause the trends in conventional-tunnel data to differ from those obtained in flight and in quiet facilities.[5] For example, linear stability theory suggested that the transition Reynolds number on a sharp 5-deg half-angle cone should be 0.7 of that on a flat plate, but conventional wind tunnel data showed that the cone transition Reynolds number was actually higher than the flat plate result. Only when quiet-tunnel results were obtained was the theory verified.[6] Thus, quiet environments are required for definitive study of many instability and transition phenomena. Research in high-speed transition is critical to the design of transatmospheric aircraft,[7] the proposed High Speed Civil Transport,[8] high-speed missiles,[9,10] and high-speed reconnaissance aircraft. NASA Langley has demonstrated quiet flow in several facilities to Reynolds numbers based on the length of the quiet-flow test rhombus that are in excess of 10×10^6 (Ref. 11). Quiet flow was also observed in the old Jet Propulsion Laboratory 20-in. supersonic tunnel, when it was operated below unit Reynolds numbers of about 10,000 per cm (Refs. 12 and 13). Recently, NASA Ames,[14] Montana State,[15] and Purdue have initiated efforts toward developing quiet facilities.

Quiet facilities require low levels of noise in the inviscid flow entering the nozzle through the throat, and laminar boundary layers on the nozzle walls. These features make the noise level in quiet facilities an order of magnitude lower than the 0.5–3% pressure fluctuations typical of conventional facilities. To reach these low noise levels, conventional blow-down facilities must be extensively modified. Requirements include a 1-μ particle filter, a highly polished nozzle with bleed slots for the contraction-wall boundary layer, and a large settling chamber with screens and sintered-mesh plates for noise reduction.[1]

How low must the noise level be to make a supersonic wind tunnel quiet? Since data on environmental noise in flight are sparse,[16] a direct comparison of noise levels and characteristics is not currently practical. The best working definition seems to be that transition on a model in a quiet tunnel should occur at a Reynolds number comparable to flight. Data on cones at zero angle of attack are summarized by Beckwith and Miller,[1] who suggest that this criterion corresponds to rms static pressure fluctuations below approximately 0.05% of the mean static pressure ($P'_{\infty,\mathrm{rms}}/P_{\infty,\mathrm{mean}} < 0.0005$, where $P'_{\infty,\mathrm{rms}}$ is the rms of the static pressure fluctuations and $P_{\infty,\mathrm{mean}}$ is the mean static pressure). Previous work[17] has shown that $P'_{\infty,\mathrm{rms}}/P_{\infty,\mathrm{mean}} \simeq 1.08\, P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}}$ under conditions similar to those in our facility. Here, $P'_{t2,\mathrm{rms}}$ is the rms of the pitot-pressure fluctuations and $P_{t2,\mathrm{mean}}$ is the mean pitot pressure. Thus, Beckwith's criterion corresponds to requiring that $P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}}$ be less than about 0.0005 for quiet flow. This criteria is only approximate, since the spectra and character of the facility disturbances are as important as the rms level.

To reach these low noise levels in an affordable way, the Purdue facility has been designed as a Ludwieg tube (see Refs. 18–20 for details). A Ludwieg tube is a long pipe with a converging-diverging nozzle on the end, from which flow exits into the nozzle, test section, and second throat (see, e.g., Fig. 1 and Ref. 21). A diaphragm is placed downstream of the test section. When the diaphragm bursts, a shock wave passes downstream, and an expansion wave travels

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*Assistant Professor of Aerodynamics, School of Aeronautics and Astronautics. Member AIAA.

†Graduate Research Assistant, School of Aeronautics and Astronautics. Student Member AIAA.

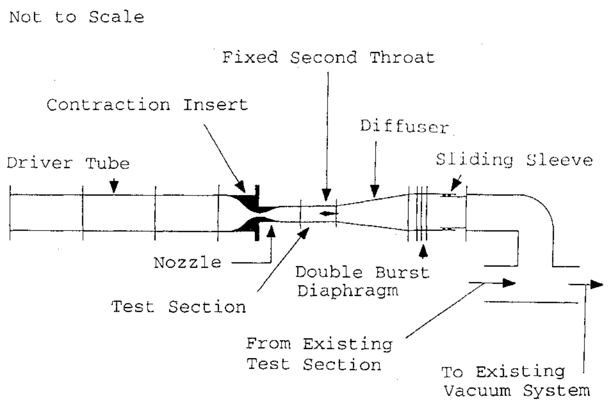

Fig. 1 Schematic of Purdue quiet-flow Ludwieg tube.

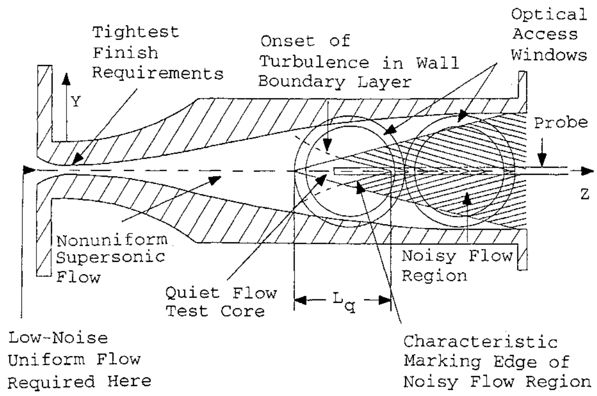

Fig. 2 Schematic of Mach 4 quiet-flow nozzle.

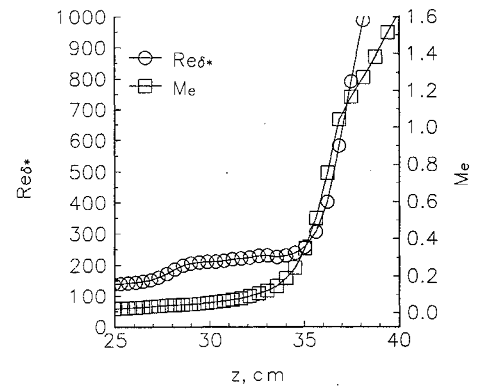

Fig. 3 Boundary-layer Reynolds numbers.

upstream through the test section into the driver tube. The test is initiated some time after the wave has passed through the test section, and ends when the expansion wave has returned to the test section after reflecting off the upstream end of the driver tube.

The Ludwieg tube has several advantages, particularly for quiet-flow research. First, the smooth acceleration from inherently constant stagnation conditions yields naturally low noise flow, so that a flow conditioning and settling chamber is not required. Second, the required 1-μ particle filtering can be carried out during the slow pump-up phase, if the tube is treated as a clean room. Thus, filtering of the flow during the high mass-flow testing phase is not required. Third, the short run times that are possible are two orders of magnitude shorter than the shortest possible in blow-down facilities. Costs for tanks, pumps, and compressors are thus two orders of magnitude less, for the same size test section. Useful measurements are still possible, despite this short (0.1 s) run time, using modern instrumentation. The larger test sections made possible by the short run times generate thicker boundary layers, which ease tunnel-wall polish requirements and also make deployment of instrumentation easier. Fourth, the thermal boundary condition at the model is relatively easy to control, since the deviation from initial equilibrium temperature is small due to the short run time. Fifth, the small total gas volume eases the precise control of gas content required for use of advanced optical instrumentation techniques. Finally, the simple design allows operation by a single researcher. Thus, the operating costs are low.

Although quiet-flow wind tunnels can be treated as transition experiments involving complex geometries and pressure gradients, this paper proposes only to show that a new kind of quiet-flow facility has been successfully developed. The causes and mechanisms involved in the transition of the tunnel-wall boundary layers remain a topic for future research.

II. Purdue Quiet-Flow Ludwieg Tube

The Purdue facility is based on a 30-cm-diam driver tube that is 20.7 m long. Flow is initiated using a double burst-diaphragm assembly located downstream of the test section. A smooth contraction tapers from the driver tube to the first throat, which is followed by the Mach 4 rectangular nozzle. The nozzle is two dimensional, with 9.7-cm-wide curved walls and a height of 10.9 cm at the exit. Figure 2 shows the nozzle, which was fabricated at NASA Langley in the middle 1970s according to a conventional design. Four window openings were added at Purdue, at the locations shown in the figure. The lines drawn upstream from the exit of the nozzle show the approximate beginning of the region of uniform flow, since they are drawn at the Mach angle for Mach 4. Also shown on the figure is a schematic of the region affected by the onset of turbulence in the boundary layers on the tunnel walls. It should be emphasized that the figure is only a schematic; the actual development of turbulence on the four tunnel side walls is intermittent, probably unsymmetrical, and poorly understood. The test rhombus between the beginning of uniform flow and the region affected by turbulence on the tunnel walls is characterized by quiet uniform flow. The axial length of this quiet uniform flow region is labeled L_q in the figure and is used to form the quiet-flow length Reynolds number. The pitot probe sketched in the figure contains a fast pressure transducer in its tip and is used for characterizing the flow.

The throat area of the nozzle is 8.83 cm^2, giving an area ratio of 83 for the 30-cm driver tube. Immediately downstream of the nozzle is a two-dimensional test section, with a 9.7×10.9-cm cross section and optical access on three sides. A double-wedge centerbody forms the second throat of the test section as shown on Fig. 1. The model sting support is incorporated into the centerbody.

The Purdue facility integrates the quiet-flow nozzle design techniques developed by NASA Langley with the naturally low noise Ludwieg tube design developed over the past 30 years. Since the Purdue facility currently does not incorporate boundary-layer suction at the throat, the design of the contraction is more important. The computations presented are based on quasi-one-dimensional area relations for the pressure, and a finite-difference compressible boundary-layer code.[22] The one-dimensional area relations were used after careful comparison to more sophisticated three-dimensional computations of the contraction flow revealed only small deviations from one-dimensional flow. Although these simple computations are not accurate enough to be used for transition estimation, they serve as useful indications of the character of the mean flow. Both the stagnation temperature and the wall temperature were taken as 311 K for the computations. The wall temperature is assumed isothermal, due to the short run time.

Because the Mach number in the driver tube is only 0.0069 due to the large contraction ratio, the driver-tube gas flows only a short distance during the 0.1-s run time. Figure 3 shows the Reynolds number based on the displacement thickness, at midspan on the curved walls, at a total pressure of 103 kPa (1 atm). The figure is a detail for the contraction and also gives the edge Mach number. The axial coordinate z increases streamwise, from $z = 0$ at the beginning of the contraction through $z = 36.695$ cm at the throat. The boundary layer shown in the figure originates at $z_s = 5.1$ cm, a location that corresponds approximately to the middle of the useful test time. The figure shows that the Reynolds number remains below the Blasius instability limit ($Re_{\delta*} = 520$) up to very near the throat. Thus, the boundary layer should be relatively stable in

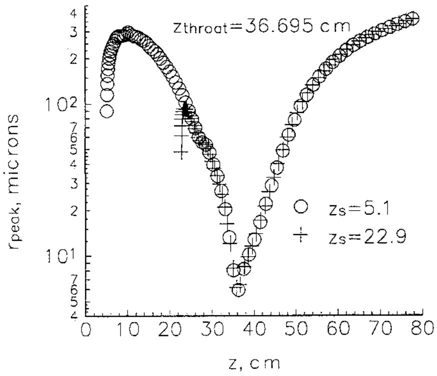

Fig. 4 Allowable peak roughness heights in nozzle.

the contraction. Although three-dimensional effects in the boundary layer and mean flow are a major concern, these are difficult to model and are not considered here.

Roughness is known to be a critical issue in the design of quiet-flow nozzles. Current Langley practice[23] suggests that throat roughness Reynolds numbers below 10 will not cause transition in the nozzle. Here, the roughness Reynolds number is based on velocity, density, and viscosity in the laminar boundary layer at the local peak roughness height. The allowable peak roughness heights based on this criterion are plotted in Fig. 4, for a total pressure of 103 kPa (1 atm). The allowable roughness heights are smallest near the throat, where the boundary layer is thinnest. Although these numbers are large, it should be emphasized that they refer to the peak roughness, which is commonly 15–30 times larger than the rms roughness (I. Beckwith, private communication). Thus, the rms roughness requirement in the throat at 103 kPa is about 5.6 μ divided by 30, or about 0.2 μ (7 μin.). These computations show that very fine polishes are required in the throat to reach the quiet-flow levels desired. The results presented here were obtained only after the nozzle was professionally polished, by a firm that specializes in polishing injection molds. The finish in the throat region of the nozzle was improved to approximately 0.02–0.04-μ rms (according to the polisher's estimates), and all visible scratches were removed. The entire nozzle is now a mirror finish, from $z = 31.2$ to $z = 79.0$ cm, although the work was concentrated in the region a few centimeters upstream and downstream of the throat. Maintenance of the nozzle finish in this clean and highly polished condition has been critical to maintenance of quiet flow.

III. Experimental Results and Discussion

A. Instrumentation

The quality of the flow in the facility was studied using a technique similar to that used by Beckwith and Moore.[17] Pressure fluctuation data were obtained using Kulite pressure transducers mounted in the tip of a 7.62-mm-diam pitot probe. Most of the measurements were obtained using a Kulite XCQ-080-50G transducer. This is a ceramic transducer of strain-gauge type, with an active area 0.71mm in diameter and a natural frequency of 290 kHz. It is rated for 345 kPa (3.4 atm) differential. The second port of the transducer is open to atmospheric pressure. The transducer output is amplified by a factor of 100 using a low noise INA103 instrumentation amplifier. A second channel of output is then high-pass filtered at 800 Hz and fed to a second INA103 which supplies a further gain of 100 to the ac part of the signal. A Tektronix TDS420 digital oscilloscope is used to sample 15,000 12-bit words at 250 kHz for each of the two transducer channels (ac and dc parts of the signal for the single transducer).

A typical pitot-probe record is shown in Fig. 5. The solid line shows the complete dc pressure record as a function of time, and the dotted line trace on the right-hand side of the figure shows the ac part of the record for the steady part of the run, after the initial startup transient. The run was made with a stagnation pressure of about 100 kPa (1 atm), and the pitot probe is mounted on the tunnel centerline, at $z = 65.0$ cm. The dc trace is flat during the first 0.003 s, before the diaphragms burst. A startup transient of about 25 ms follows, during which the flow is highly unsteady. Starting at about 0.03 s

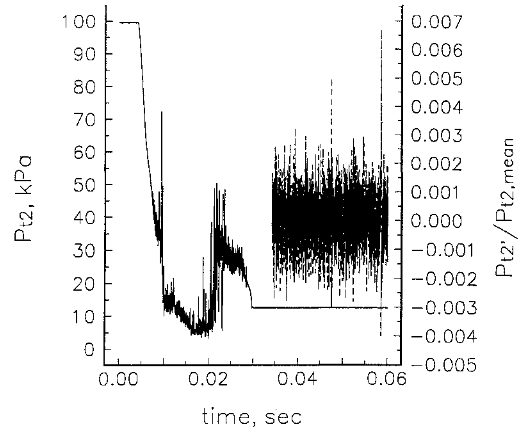

Fig. 5 Typical Kulite pitot-pressure records.

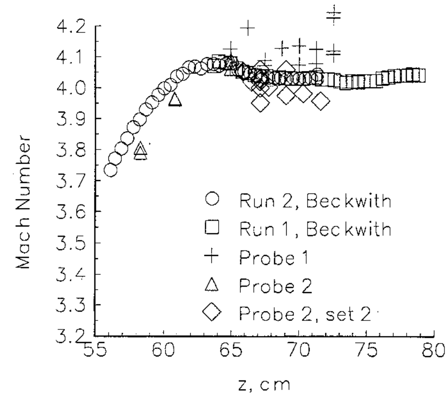

Fig. 6 Mean Mach number on the nozzle centerline.

in Fig. 5, the flow is steady. Although the steady-flow period is generally in excess of 80 ms, only the first 30 ms is shown here, due to the limitations of the oscilloscope record length. The mean Mach number and rms unsteadiness can be obtained from the pitot data for the steady part of the run, after 0.035 s. The amplification of 10,000 used on the ac part of the signal gives good resolution of very small fluctuations, as can be seen from the high-resolution scaling used for $P'_{t2}/P_{t2,\mathrm{mean}}$ in the right-hand axis. Here, P'_{t2} is the ac part of the pressure fluctuations, and it is normalized by the mean pitot pressure during the steady part of the run, $P_{t2,\mathrm{mean}}$. The rms electronic noise in the P'_{t2} signal corresponds to 0.0003 psia.

B. Mean Flow Results

If lines are drawn from the nozzle exit at the Mach angle for the design Mach number of 4.0, they intersect about 19.6 cm upstream, at $z = 59.4$ cm; here, the beginning of uniform flow can be expected. Thus, the first window was located so that the upstream edge is at $z = 58.2$ cm, so that the entire uniform-flow region is optically accessible. Measurements of the mean flow in the nozzle were made in December 1977 by Beckwith, in a blow-down facility at NASA Langley. These pitot probe results, presented in Fig. 6, were obtained at a total pressure of 690 kPa (6.8 atm). They are published here for the first time. The two separate runs agree well where the data overlap and show that the Mach number is nearly 4.0 from the nozzle exit to about 13 cm upstream. The Mach number overshoots to about 4.07 at $z = 65$ cm, about 15 cm upstream of the exit, and then drops off monotonically as the pitot probe is moved farther upstream. Mach 4 is crossed at about $z = 60.2$ cm, which is thus defined as the beginning of the uniform flow region. The data from the Purdue experiments are also presented in Fig. 6. It can be seen that these data, collected at total pressures of 62–145 kPa (0.6–1.4 atm), fall near the earlier data obtained by Beckwith at higher pressures. The probe 1 data was obtained with the gauge-pressure referenced Kulite pressure transducer used for most of the measurements. The accuracy of the probe 1 results is roughly ±5%, based on the observed scatter and the limited accuracy of the barometric equipment used. The probe 2 data was obtained with an XCQ-062-25A Kulite, referenced to absolute pressure. This probe also has an active area 0.71 mm in diameter and a natural frequency of 500 kHz. The results presented here reflect more accurate transducer calibrations performed at Wright Laboratory after the presentation of Ref. 20. Since equipment for in-situ calibrations was not yet available, a slow calibration drift of about ±3% in Mach number could not be eliminated. The probe 2, set 2 data was acquired after a reconstruction of the electronics. A set of eight repeated measurements included in the probe 2, set 2 data, at $z = 67.1$ cm, display a standard deviation of 0.8% of the mean Mach number. The streamwise locations given are accurate to within 0.05 cm.

C. Noise Measurements

Since the pitot tube measures the total pressure behind the shock it creates (P_{t2}), one measure of the noise in the facility is the rms fluctuations in this value ($P'_{t2,\mathrm{rms}}$), normalized by the mean ($P_{t2,\mathrm{mean}}$). Results for other quantities can be inferred from the supersonic pitot formula. The results at various pressures and streamwise stations are shown in Fig. 7. Most of the noise data presented were obtained using probe 1; the set 2 data were obtained using probe 2. At pressures below atmospheric (100 kPa), the noise level is below 0.07% of the mean pitot pressure, at all locations upstream of $z = 71.3$ cm. At $z = 72.6$, the noise level begins to rise for total pressures of about 96–102 kPa, but remains below 0.1% to 102 kPa. The signal-to-noise ratio based on rms is about 2 to 1 for the lowest noise results, since the electronic noise is 0.015% of a typical mean pitot pressure. The results are corrected for this background noise by subtracting the square of the rms noise from the square of the rms signal, as in Ref. 24. A set of eight runs at 101 kPa and $z = 67.1$ cm with probe 2 yielded an average noise level of 0.05% of $P_{t2,\mathrm{mean}}$ and a standard deviation of 0.02% of $P_{t2,\mathrm{mean}}$. Since loss of quiet flow is sometimes observed, due to the appearance of grease streaks on the nozzle walls, a large fraction of the normal run-to-run deviations in noise is probably also due to variation in nozzle and air cleanliness. The accuracy of the noise measurements is limited mainly by the simple correction for the electronic background noise. Recall that the Beckwith criteria for quiet flow suggests that a flow is quiet for $P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}}$ below about 0.0005. Clearly, quiet flow exists in the nozzle at sufficiently low Reynolds numbers.

The Beckwith criterion for the quietness of the flow was confirmed by the presence of the signatures of turbulent spots in data obtained at conditions that are marginally quiet. Consider the boundary layer on the nozzle walls at the acoustic origin for the probe, which is defined by tracing Mach lines upstream from the probe tip to the nozzle walls, and which is the farthest downstream region capable of influencing the signal at the probe location. With the probe at a fixed location, the boundary layers on the wall of the nozzle at the acoustic origin for noise reaching the probe are laminar at sufficiently low total pressures. As the total pressure and Reynolds number is raised, high-frequency pressure pulses corresponding to the passage of turbulent spots can be expected at the probe. These pulses will occur with increasing probability as the Reynolds number is further increased. The progression from low noise to high noise is thus expected to be through an increasing probability of intermittent pulses. Just such a progression was observed in the Mach 6 quiet tunnel at NASA Langley.[11]

This progression was also observed in our facility, as shown by Figs. 8–11. Figure 8 shows a portion of a typical record reflecting truly quiet pressure fluctuation data (in Figs. 8–11, only a portion of the entire record is shown, for clarity). Even the peaks in the fluctuations are rarely above 0.15% of the mean pitot pressure, and the noise as shown by the spectra (presented in Ref. 20) is broadband. The corrected rms noise level for this record is 0.040%, and the signal is above 0.2% for only 0.02% of the time. As the pressure is increased, the signature of turbulent spots in the nozzle-wall boundary layer becomes apparent in the pressure records on the centerline. A weak pulse of this type is present in Fig. 9 at 0.054 s. The rms noise for

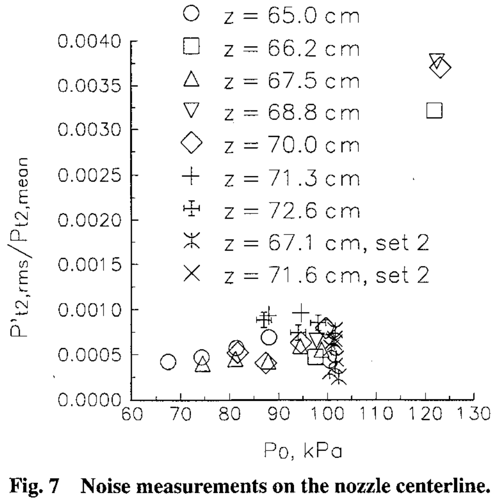

Fig. 7 Noise measurements on the nozzle centerline.

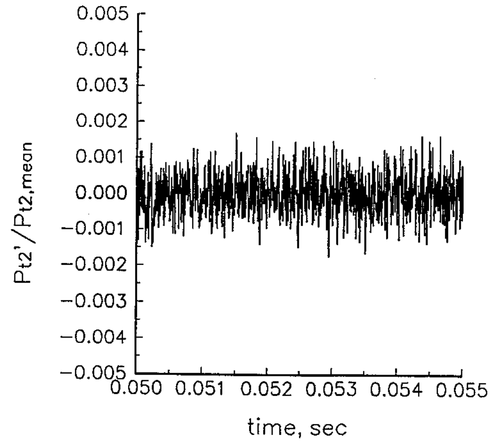

Fig. 8 Pressure fluctuations at z = 67.5 cm, P_0 = 74.5 kPa

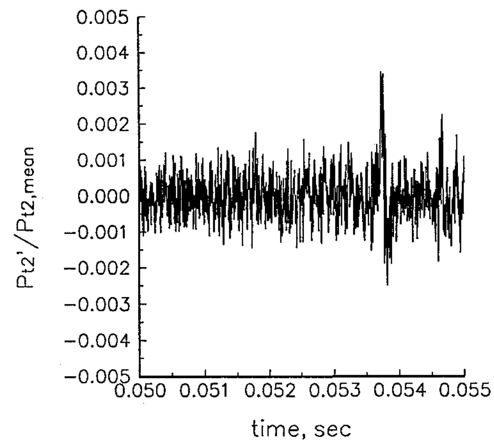

Fig. 9 Pressure fluctuations at z = 67.5 cm, P_0 = 81.2 kPa.

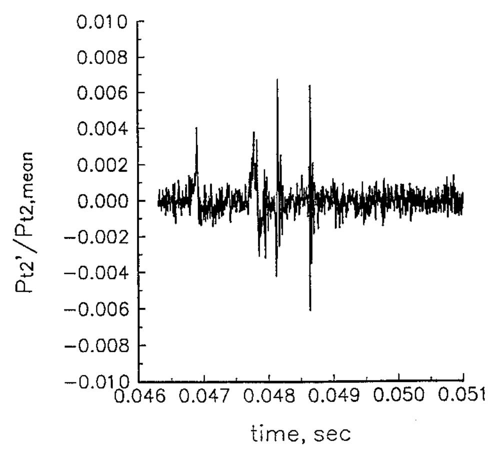

Fig. 10 Pressure fluctuations at z = 67.5 cm, P_0 = 94.3 kPa.

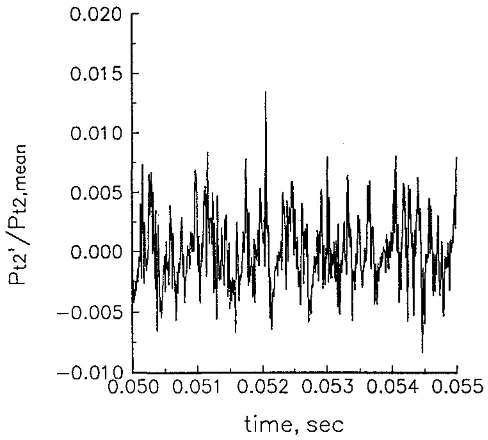

Fig. 11 Pressure fluctuations at z = 68.8 cm, P_0 = 122.4 kPa.

this record has increased to 0.045%, but is still small, since only a single small pulse is present. The signal is above 0.2% for 0.3% of the time. Further increases in pressure produce data like that shown in Fig. 10, which contains several pulses whose peaks are an order of magnitude above the background. The rms noise in this record is still only 0.059%, but the flow is beginning to reflect the occasional presence of turbulence in the boundary layers on the tunnel walls. However, the pressure fluctuations in this trace are above 0.2% of the mean for only 1.2% of the time. Figure 11 typifies the results observed when the total pressure is raised further. The noise level in this record is 0.38%, almost an order of magnitude higher than in Fig. 10, and 56% of the signal is above 0.2% of the mean. The acoustic origin on the nozzle walls is probably now turbulent. Although much remains to be determined and documented regarding this process, this qualitative change in the pressure records as the noise level rises confirms earlier conclusions that the nozzle-wall boundary layer is laminar below rms pressure fluctuation levels of about 0.1% of the mean pitot pressure. Clearly, the pressure fluctuations felt on the nozzle centerline due to the passage of turbulent spots on the nozzle walls must depend on the geometry of the nozzle as well as on the general flow conditions. In our case, it seems conservative to say that the flow is quiet when $P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}}$ is about 0.06% or less. Although the occasional pressure pulse will still pass the measuring station even under these conditions, ensemble averaging or conditional sampling techniques should be able to handle this small proportion of noise in the flow.

Figure 7 can now be reassessed with this criterion in mind. Quiet flow is clearly present to $z = 70.0$ cm when the total pressure is below about 94 kPa (0.9 atms), using the presented criterion. Since uniform flow begins at about $z = 60.2$ cm, a region of quiet flow about 10 cm in length is present at 94 kPa (i.e., L_q in Fig. 2 is about 10 cm at 94 kPa). This pressure corresponds to a unit Reynolds number of 42,000/cm. A conservative estimate of the Reynolds number based on the length of uniform quiet flow is thus about 400,000. These Reynolds numbers are well above the critical Reynolds numbers for onset of instability (for a flat plate at Mach 4.5, $Re_{x,\mathrm{crit}} \approx 40,000$ (Ref. 25, Fig. 10.5). They are thus useful, although they are well below flight Reynolds numbers for the end of transition on cones at zero angle of attack, which are about 10^7 (Ref. 24, Fig. 20).

Quiet-flow operation at these Reynolds numbers makes the facility suitable for measurements of receptivity and instability, if not complete transition to turbulence. The Reynolds number is clearly sufficient for study of receptivity (and roughness) effects, since these are most important in the region of the critical Reynolds number.[3] Instability experiments at similar Reynolds numbers have already been carried out by other investigators. For example, Kosinov et al.[26] studied the instabilities of a Mach 2 flat-plate boundary layer using measurements at length Reynolds numbers of 160,000 to 800,000. Kendall[27] measured the instabilities in flat plate boundary layers at Mach numbers from 3 to 4.5 using measurements at length Reynolds numbers as low as 90,000 and unit Reynolds numbers of 40,000 to 70,000 per cm. Three-dimensional boundary layers that are susceptible to crossflow instability can be expected to become unstable at even lower Reynolds numbers[28] End-of-transition measurements may even be possible for bodies with sufficiently strong instabilities. For example, the transition Reynolds number on a 5-deg sharp cone at Mach 3.5 decreases from 8×10^6 to 2×10^6 when the cone is pitched from zero to a 4-deg angle of attack, under quiet-flow conditions.[29] Controlled perturbations, roughness, or increased three dimensionality could cause large instability waves or even transition to occur at length Reynolds numbers well below 1×10^6, under similar conditions. In addition, previous quiet-tunnel experience has indicated that transition Reynolds numbers remain comparable to flight as long as the sensitive upstream regions of a model are within the quiet-flow region, even if the transition point is not.[6] A 5-deg half-angle sharp cone with a length of 27 cm has been successfully started in the facility.

The results also show that the basic concept for the facility is sound. Operation with quiet flow at higher Reynolds numbers now requires only a larger and higher quality test section.

IV. Summary

A new kind of low-cost, short-duration, quiet-flow wind tunnel has been constructed, for the study of high-speed boundary-layer instability and transition. Although the nozzle does not have the boundary-layer bleed slots used at NASA Langley, quiet flow was still observed to a Reynolds number that exceeded 400,000, based on the axial length of the quiet-flow region. Maintenance of a clean, high-quality mirror finish is essential to achieving this performance. Earlier NASA Langley data indicating that the flow is quiet when $P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}} < 0.001$ are here confirmed by qualitative indications of the signatures of turbulent spots in the nozzle-wall boundary layers at $P'_{t2,\mathrm{rms}}/P_{t2,\mathrm{mean}} \simeq 0.0005$–$0.0010$.

Acknowledgments

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