Turbulence Measurements and Noise Generation in a Transonic Cryogenic Wind Tunnel

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A high-frequency combination probe was used to measure dynamic flow quality in the test section of the NASA Langley 0.3-m Transonic Cryogenic Tunnel. The probe measures fluctuating stagnation (total) temperature and pressure, static pressure, and flow angles in two orthogonal planes. Simultaneous measurements of unsteady total temperature and pressure were also made in the settling chamber of the tunnel. The data show that the stagnation temperature fluctuations remain constant, and the stagnation pressure fluctuations increase by a factor of two, as the flow accelerates from the settling chamber to the test section. In the test section, the maximum rms value of the normalized fluctuating velocity is 0.7%. Correlation coefficients failed to show vorticity, entropy, or sound as the dominant mode of turbulence in the tunnel. At certain tunnel operating conditions, periodic disturbances are seen in the data taken in the test section. A possible cause for the disturbances is found to be acoustic coupling of the test section and plenum chamber via the perforated side walls in the tunnel. The resonance frequencies observed in the experiment agree well with calculations based on acoustic coupling theory.

Nomenclature

M	= Mach number
P_T	= total (stagnation) pressure
P_{WALL}	= wall static pressure
$P_{1,2,3,4}$	= pressure as measured from transducer, 1, 2, 3, or 4
T_T	= total (stagnation) temperature
P_{WALL}	= wall static pressure
u	= freestream velocity
ρ	= density
ρu	= mass flux

I. Introduction

THE requirements to simulate full-scale flight Reynolds numbers in wind tunnels have prompted an effort to develop transonic tunnels with very high unit Reynolds numbers. The recent development and application of cryogenic wind tunnels, such as the U.S. National Transonic Facility (NTF) and the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT), represent a major advance in aerodynamic testing technology. Cryogenic tunnels, because of their extremely low temperatures and high pressures, are able to develop very high unit Reynolds numbers. Because of the expense of cryogenic tunnels, however, experimentation will continue to be done in existing ambient tunnels. To this end, the detailed documentation of dynamic flow quality in a transonic cryogenic wind tunnel becomes a prime research requirement for the cryogenic facilities. In addition, it is necessary to be able to measure the conditions in a given test section to insure that consistent, smooth, uniform flow can be achieved. Of particular interest are the detailed time-resolved measurements of the turbulence intensities for velocity, temperature, and pressure fluctuations. For a number of years, there has been a concerted effort to quantify the disturbance levels in subsonic and transonic wind tunnels. Owen and co-workers[1] summarize the results of a portion of this effort and discuss factors that can improve the flow quality in transonic wind tunnels.

Dynamic flow quality measurements have been made in a transonic cryogenic wind tunnel. Stainback et al.[2] and Johnson et al.[3] used a three-wire hot-wire probe, with each wire operating at a different overheat ratio to measure the velocity, density, and total temperature fluctuations in the test section of the 0.3-m TCT. Aside from the difficulty associated with lengthy calibration and possible wire breakage, the measured turbulence intensities from three-wire probes are usually much higher than measured intensities from other types of probes. In addition, pressure and flow angularity cannot be measured using this method. Ng and Rosson[4] used an aspirating temperature and pressure probe to measure turbulence intensities in the settling chamber and test section of the 0.3-m TCT. Only limited data were obtained, however, and they did not cover the entire operating envelope of the tunnel.

In an effort to determine noise origins in a wind tunnel, possible sources must be identified. Tunnel blockage and shock-wave reflections are known sources of poor flow quality in transonic wind tunnels. As a solution to these problems, many transonic tunnels use porous walls to connect the test section with a plenum chamber. Plenum suction is used to decrease the boundary layer in the test section and thus reduce blockage. The holes in the wall also allow many of the shocks to pass through to the plenum chamber rather than reflect back into the test section. A disadvantage of the porous walls, however, is that they create additional noise in the test section. Most research[5-10] has found that porous walls are the dominant source of noise in the test sections of tunnels. Edge tones, vortices shed by the leading edge of the holes, are thought to be the mechanism by which the noise is generated. Distur-

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bances created by the edge tones are then radiated outward into the test section. The edge-tone disturbances are periodic in nature. Thus, resonance frequencies are created in the wind tunnel by the addition of porous side walls.

Experiments have shown that measurements taken near the tunnel resonance frequency are in considerable error. Research was therefore conducted to predict tunnel resonance frequencies generated by the porous side walls in a test section. Mabey[9] was able to predict the natural frequencies for tunnels with slotted and perforated walls connecting the test section with the plenum chamber. His theory agrees well with experiments in rectangular tunnels. Lee[10] then developed a finite-element method that predicts resonance frequencies for arbitrarily shaped test sections and plenum chambers. For the 0.3-m TCT experiment reported in this paper, perforated side walls were used in the test section of the tunnel, and periodic disturbances were observed under certain tunnel operating conditions. Therefore, in the present work, resonance frequencies generated by the porous walls are examined as a possible source of the periodic disturbances observed in the tunnel.

The purpose of this paper is to present the results of the 0.3-m TCT experiment. Brief descriptions of the combination probe and experimental setup are presented first, followed by a discussion of the results. The turbulence intensities in the settling chamber and test section of the tunnel, in terms of normalized total temperature and pressure fluctuations, are documented for the entire operating envelope of the tunnel. Whenever possible, data are compared with previous measurements in the tunnel for consistency. Next, resonance frequencies generated by the porous side walls in the tunnel are investigated as a possible cause of the periodic disturbances. Correlation coefficients are also calculated to determine the dominant mode of turbulence in the tunnel. A discussion with final conclusions is then given.

II. Experimental Background

The 0.3-m Transonic Cryogenic Tunnel at NASA Langley Research Center is a fan-driven, closed-circuit wind tunnel using nitrogen as the working fluid. The injection of liquid nitrogen into the tunnel circuit, just downstream of the test section, allows cryogenic total temperatures to be obtained. For steady operating conditions, the heat of compression of the fan is removed by the injection of liquid nitrogen. Under equilibrium conditions, the excess mass is removed from the circuit through an exhaust system located just upstream of the settling chamber. The test section is 13 × 13 in., with perforated side walls for boundary-layer removal. In addition, the tunnel has adaptive top and bottom walls for reducing blockage effects due to the presence of test models.

Measurements were taken at the following tunnel conditions, which represent the operating envelope of the tunnel: $0.30 < M < 0.85$, $1.2 < P_T < 6$ atm, and $120 < T_T < 250$ K.

Two types of instruments were used in the experiment. The first probe is a dual hot-wire aspirating temperature and pressure probe. The second instrument is a miniature high-frequency angle probe consisting of surface-mounted silicon pressure sensors.

The high-frequency aspirating probe consists of two coplanar constant-temperature hot wires at different overheat ratios operated in a 1.5-mm-diam channel with a choked exit, so that the flow past the wires is at constant Mach number (Fig. 1). Thus, the mass flux by the wires is a function only of freestream total temperature and pressure and is not otherwise affected by changes in freestream velocity or density. The hot wires are operated in two separate constant-temperature anemometer circuits, thus yielding two independent measurements from which the two unknowns, freestream stagnation temperature and pressure, can be uniquely determined. Further application and performance characteristics of the aspirating probe are given in Ref. 11.

As shown in Fig. 1, the aspirating temperature and pressure probe is piggyback-mounted with a high-frequency angle probe. The angle probe is a four-sensor, 5.2-mm-diam pyramid-type probe capable of simultaneously measuring the time-resolved stagnation and static pressures and two orthogonal flow angles. The probe consists of surface-mounted silicon pressure sensors, yielding a frequency response above 20 kHz.

The two probes combined can give measurements of freestream stagnation pressure and temperature, static pressure, and flow angles in two planes. From these, the Mach number and its components in three directions, fluctuating mass flow, and velocity components can also be deduced. Further details of the combination probe's construction and calibration can be found in Ref. 12.

The combination probe was mounted in a rake in the test section of the tunnel. A high-frequency semiconductor pressure transducer was also mounted flush on the test section side wall to monitor the wall static pressure fluctuation.

A second aspirating temperature and pressure probe was mounted in the settling chamber of the tunnel. The probe was mounted downstream from the damping screens of the settling chamber and was positioned in the freestream of the settling chamber. This provides simultaneous turbulence measurements of total temperature and pressure in both the settling chamber and test section of the tunnel.

All semiconductor pressure transducers used in this experiment were calibrated for variations in both pressure and temperature. Because of excessive zero drift in the transducer resulting from the large temperature range, it is not possible to retrieve the absolute dc level of the data.

All data were digitized on-line at a rate of 100 kHz using a high-speed analog/digital (A/D) system. The data acquisition system is preceded by antialiasing four-pole Bessel filters and amplifiers where appropriate. Further details on the data acquisition system can be found in Ref. 12.

III. Experimental Results

During the 0.3-m TCT experiment, periodic disturbances were observed in the test section of the tunnel at several tunnel operating conditions. The data with periodic disturbances are treated separately from the data with random turbulence, as they are different phenomena. The data exhibiting resonance are therefore not included in the rms summaries of the fluctuations.

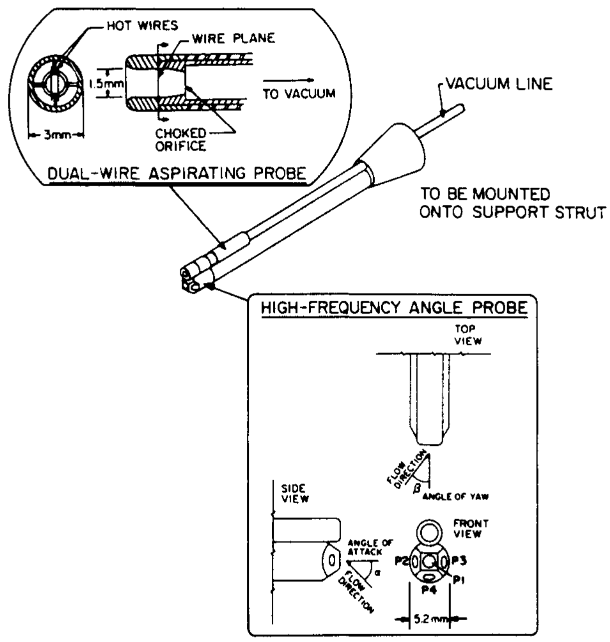

Fig. 1 Scale drawings of combination probe overall, including details of aspirating probe (top) and angle probe (bottom).

Turbulence Data

Figure 2a shows the rms of the fluctuating total temperature in the settling chamber as measured from the aspirating probe. The data are normalized by the mean total temperature in the tunnel. The rms values are all given in percentages. It can be seen that the normalized fluctuating total temperature is not a strong function of Reynolds number or Mach number. For most of the operating envelope of the tunnel, the turbulence intensity is close to 0.2%.

In examining the rms figures, it is important to realize that a particular Reynolds number in the tunnel can be achieved by various combinations of total pressure and temperature. Data that appear to be at the same Reynolds number do not correspond to identical tunnel conditions.

Figure 2b shows the corresponding temperature data measured from the aspirating probe in the test section. Here, a slight Mach number dependency is seen. The normalized rms total temperature fluctuation increases from 0.05% at $M = 0.30$ to approximately 0.2% at $M = 0.70$. The data do not show any Reynolds number dependency.

Comparing Figs. 2a and 2b, a large difference in the number of data is noticed. This is because of hot-wire breakage for the aspirating probe in the test section and to the omission of the data caused by periodic disturbances. Further comparison of Figs. 2a and 2b reveals that the level of turbulence, as measured by the normalized rms total temperature fluctuation, does not change between the settling chamber and the test section. Most of the data fall close to the value of 0.2%.

Figure 2c is the rms of the fluctuating total pressure in the settling chamber, normalized by the mean total pressure in the tunnel. Figure 2c shows that the rms value of the total pressure in the settling chamber is independent of Reynolds number but that it increases with increasing Mach number. At $M = 0.30$, the average rms fluctuation is about 0.02%. This increases by almost an order of magnitude to 0.15% at $M = 0.85$. Nevertheless, the fluctuating total pressure in the settling chamber is still fairly small.

Figure 2d is the corresponding fluctuating total pressure in the test section, as measured by the angle probe. The maximum rms fluctuation of the total pressure in the test section is about 0.3%. The trend is similar to the normalized total pressure fluctuations in the settling chamber in that both are increasing with Mach number. The amplitude of the fluctuation is rather independent of Reynolds number. As the Mach number increases from 0.30 to 0.85, the rms value increases from 0.03% to about 0.3%.

Comparison of Figs. 2c and 2d shows that the maximum normalized pressure fluctuations increase from 0.15% in the settling chamber to 0.3% in the freestream of the test section. In general, the rms value of the total pressure is about two times higher in the test section than it is in the settling chamber. In other experiments, Johnson et al.[13] measured fluctuating pressures in both the settling chamber and the test section, using high-frequency semiconductor transducers mounted flush on the walls. The magnitudes of the fluctuations agree with the magnitudes found in the current experiment. The

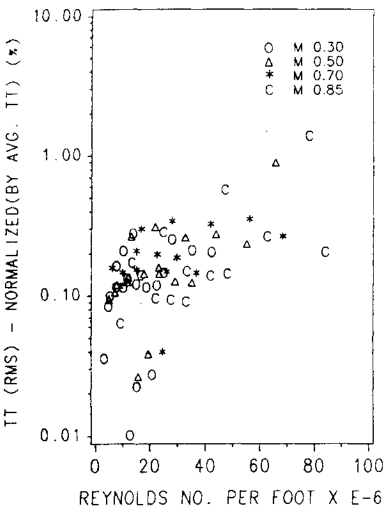

Fig. 2a Total temperature fluctuation measured in the settling chamber.

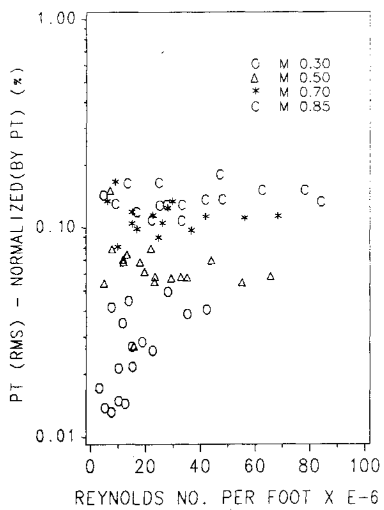

Fig. 2c Total pressure fluctuation measured in the settling chamber.

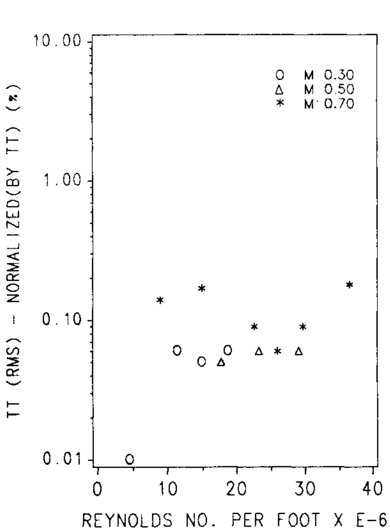

Fig. 2b Total temperature fluctuation measured in the test section.

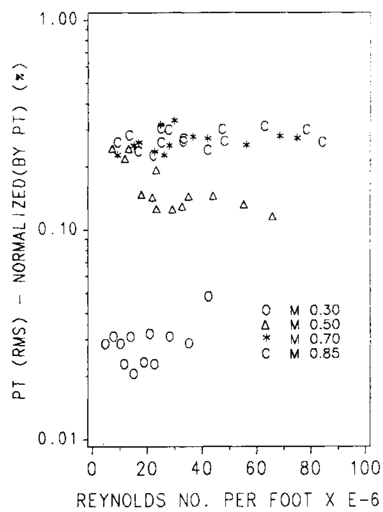

Fig. 2d Total pressure fluctuation measured in the test section.

increase in the rms values of the normalized fluctuating total pressure as the flow accelerates from the settling chamber to the test section is also consistent with the present experiment.

The frequency contents of the pressure fluctuations measured in the settling chamber and in the test section were also examined. In general, from the fast Fourier transform (FFT) of the fluctuating total pressure in the settling chamber, a distinct peak corresponding to the blade passing frequency of the driving fan of the tunnel can be identified. In the test section, the peak seems to be redistributed. Some of the harmonics of the blade passing frequency are, however, still present in the test section but at a smaller amplitude compared to that in the settling chamber.

The results of flow angularity measurements made with the angle probe in the test section show that all of the rms data fall below a level of 0.5 deg. The rms of the Mach number fluctuations, normalized by the local mean Mach number in the test section, is less than 1.0%.

It is well known that velocity fluctuations are of primary and fundamental interest in the determination of disturbance levels in wind tunnels. Figure 3 is the rms of the fluctuating freestream velocity in the test section, normalized by the mean freestream velocity. Once again, the turbulence levels increase with increasing Mach number. With the exception of one data point, the turbulence intensity is less than 0.7%.

Freestream velocity fluctuations in the test section were also measured by Stainback et al.[2] using a three-wire hot-wire probe. The maximum normalized value was found to be 7.5% at $M = 0.70$. In the present experiment, the maximum normalized fluctuation is 0.7% at $M = 0.70$. The value measured in Ref. 2 is an order of magnitude higher than the value in the present case. This might be caused by the use of a three-wire hot-wire probe. Probes of this nature tend to measure turbulence intensities much higher than expected.[14]

The rms of the mass flux (ρu) fluctuations in the test section, normalized by the average mass flux, is presented in Fig. 4. The data show no discernible Reynolds or Mach number dependency. All of the mass flux fluctuations, when normalized by the mean mass flux, fall below a value of about 0.5%.

Periodic Disturbances

As just discussed, several tunnel conditions invoked periodic disturbances in the test section. Figure 5 shows pressure measurements from the angle probe for one of these data points. Only P_1 and P_2 are shown; P_3 and P_4 exhibit similar behavior. The data show a strong periodicity, and all four transducers on the angle probe see the same disturbance. The magnitude of the disturbance is about the same for all four transducers. A fast Fourier transform of the pressure from P_1 is shown in Fig. 6. A distinct peak is seen at 1306 Hz. At this particular tunnel operating condition, the driving fan blade passing frequency was 702 Hz. This can hardly be identified in Fig. 6. The wall static pressure in the test section, as measured from a semiconductor pressure transducer flush-mounted on the tunnel side wall, is plotted in Fig. 7. The corresponding FFT of the signal is shown in Fig. 8. Although the periodicity in the wall static pressure measurement is not as pronounced as the angle probe, the same 1306-Hz disturbance is still easily identified from the FFT shown in Fig. 8. This leads to the conclusion that the periodic disturbance seen by the angle probe is not caused by probe vibration but stems from the tunnel. In addition, the natural frequency characteristics of the probe stem and support rake were examined by using accelerometers. The results also support that the periodic disturbance seen during the experiment was from the tunnel and was not caused by probe vibration.

As mentioned in the Introduction, a source of noise in the test section of a tunnel is the acoustic coupling of the test section and plenum chamber via the perforated side walls. Edge tones are created when vortices are shed by the leading edge of a hole and are reinforced by the sharp trailing edge of the hole. The trailing-edge vortices propagate back upstream

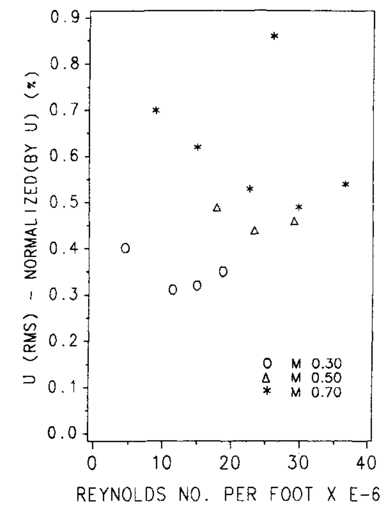

Fig. 3 Velocity fluctuation in the test section as calculated from the measurements of the combination probe.

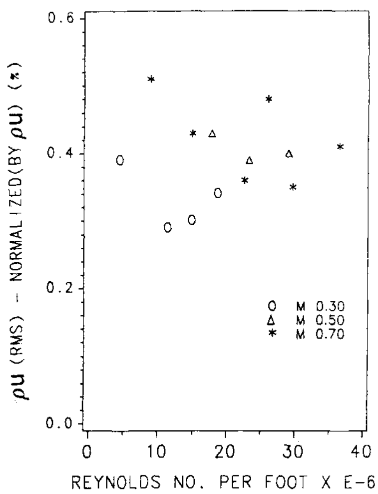

Fig. 4 Mass flux fluctuation in the test section as calculated from the measurements of the combination probe.

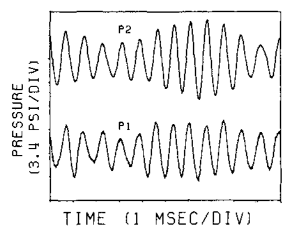

Fig. 5 Pressures measured from the angle probe showing periodic disturbance in the test section of the tunnel.

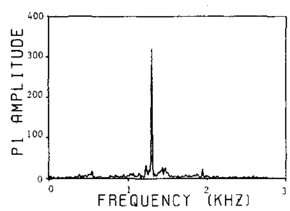

Fig. 6 Spectrum of the data in Fig. 5.

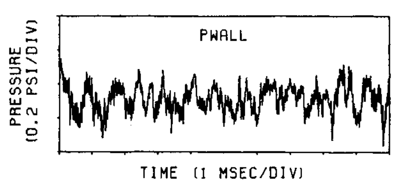

Fig. 7 Pressure measured from the test section side wall showing periodic disturbance.

and systematically generate more vortices at the leading edge.[7] The noise generated by the edge tone is radiated into the test section and, because of the periodic nature of the creation of the tones, can induce resonance in the tunnel.

The resonance frequencies created by porous walls have been successfully predicted for tunnels with rectangular test sections.[9] For the 0.3-m TCT, the porous side walls are 0.18 m (7 in.) high and 0.36 m (14 in.) long and are located upstream of the position where a model would be placed. In Ref. 9, a velocity potential analysis is done on the test section and plenum chamber of a tunnel with perforated side walls. The boundary condition at the perforated wall is that of mass continuity. In addition, an equation for the pressure drop across the perforated wall is developed in terms of the velocity potentials in the test section and plenum chamber. The boundary condition at the outer walls of the plenum chamber is that the normal velocity is zero. With these boundary conditions, the velocity potentials can be solved (see Ref. 9 for details). The resulting eigenvalue equation is

$$\tan p - \left(\frac{\beta^2}{R}\right)\cot(Rdp) + \left(2\beta^2 k\frac{T}{H}\right)p = 0 \qquad (1)$$

where

$$R = \left[(1 - M^2) - \frac{M^2}{(1 - M^2)}\right]^{1/2}$$

$$\beta = (1 - M^2)^{1/2}$$

$$T = 0.85D + Z$$

D = hole diameter

Z = plate thickness

$$k = (1 - \sigma)/\sigma$$

σ = open-area ratio

Equation (1) shows that the eigenvalues p are functions of the Mach number M, the ratio of plenum chamber depth to tunnel depth d, the effective hole diameter of the perforations T, an open-area-ratio function k, and the tunnel depth H. The eigenvalues p are in turn a function of the resonance frequency.

$$p = \frac{\pi f H}{a\beta} \qquad (2)$$

Thus, for a given Mach number, the resonance frequency due to acoustic coupling of the test section and the plenum chamber can be calculated for a given geometry. This was done for a tunnel condition of $T_T = 250$ K (450 R), and the result is presented in Fig. 9.

The modes in Fig. 9 correspond to the first, third, and fifth solutions of the preceding equation for the eigenvalues p. The second and fourth solutions of the equation have no meaning as they are the solutions at points where the eigenvalue equation is undefined. The predicted frequencies from the acoustic coupling theory were calculated, as outlined earlier, by varying the Mach number from 0.0 to 1.0. It can be seen from Fig. 9 that the resonance frequencies observed during the experiment agree relatively well with the theory. This suggests that acoustic coupling of the test section and the plenum chamber via the perforated side walls is indeed a source of resonance in the tunnel.

In addition, Eq. (2) reveals that, for a given Mach number, the resonance frequency f is only a function of the speed of sound a. Thus, the resonance frequency at another temperature should be related to the resonance frequency at one temperature by a direct ratio of the speeds of sound. The experimental data were found to follow this trend.

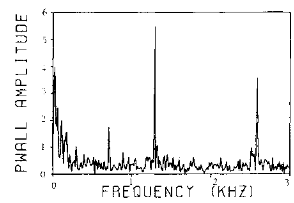

Fig. 8 Spectrum of the data in Fig. 7.

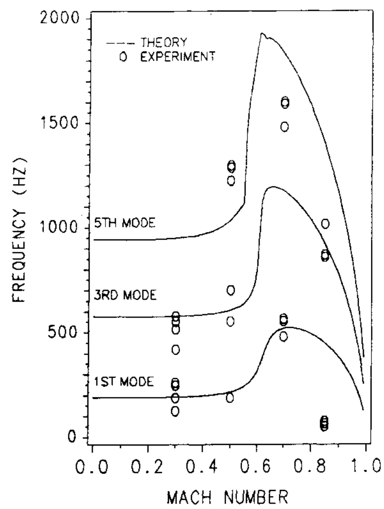

Fig. 9 Comparison between theory and experiment showing resonance frequencies as a function of Mach number.

The periodic disturbance peaks at a tunnel operating temperature of 250 K and at $M = 0.50$. Aerodynamic testing data obtained under these tunnel operating conditions could be questionable. At other temperatures and Mach numbers, the periodic disturbance is of much smaller amplitude. The recommendation is to avoid running the tunnel at conditions that may excite this periodic disturbance and to achieve the same unit Reynolds number by a different combination of temperature and pressure.

IV. Discussion

Correlation coefficients have been used in the past to determine the major source of turbulence in a tunnel.[14-16] The velocity and density correlation coefficient $R_{\rho u}$, the velocity and total temperature correlation coefficient R_{uT_T}, and the density and total temperature correlation coefficient $R_{\rho T_T}$ are defined as follows:

$$R_{\rho u} = \frac{\overline{u'\rho'}}{\tilde{u}\tilde{\rho}}$$

$$R_{uT_T} = \frac{\overline{u'T_T'}}{\tilde{u}\tilde{T}_T}$$

$$R_{\rho T_T} = \frac{\overline{\rho' T_T'}}{\tilde{\rho}\tilde{T}_T}$$

where a primed quantity represents an instantaneous measurement of that quantity, a bar represents the mean of a quantity, and a quantity with a tilde is the rms value of that quantity. In Ref. 15, small-perturbation analysis is applied to the equation of state as well as to the conservation of momentum, energy, and mass. The resulting equations are linearized and used to define three modes of fluctuation: vorticity, entropy, and sound wave. Reference[16] then relates small perturbations in velocity, density, and total temperature to fluctuations due to vorticity, entropy, and sound, as defined in Ref. 15. Thus, if it is assumed that only one mode of turbulence is present, the fluctuations of velocity, density, and total temperature can be described in terms of fluctuations due to vorticity, entropy, or sound. The resulting equations can then be substituted into the definitions of the correlation coefficients. In Ref. 14, this substitution was performed, and it was found that the correlation coefficients have specific values if it is assumed that the turbulence is due to a single mode.

All of the correlation coefficients were calculated for the random turbulence data in the present experiment to see if a major mode of turbulence could be determined. Details of the results are presented in Ref. 17. It was found that these correlation coefficients do not center around any particular values. Therefore, it does not appear that one mode of turbulence dominates in the tunnel. The turbulence in the tunnel seems to be caused by all three fundamental modes: vorticity, entropy, and sound.

Conclusions

A newly developed high-frequency-response combination probe was used to make time-resolved measurements in a high-dynamic-pressure, transonic cryogenic wind tunnel. Turbulence measurements were taken in the settling chamber and test section of the 0.3-m TCT at NASA Langley Research Center. Measurements of fluctuating total temperature, total and static pressures, and flow angularity were made in the experiment. From these measurements, fluctuations of Mach number, velocity, and mass flux were calculated. It was found that, at certain tunnel operating conditions, a large-amplitude periodic disturbance is present in the tunnel that creates unusually high freestream turbulences. For all other tunnel operating envelopes, however, the turbulence intensities are generally small. In the settling chamber, as well as in the test section, the normalized rms total temperature fluctuations are about 0.2%. The maximum normalized total pressure fluctuations in the settling chamber are 0.15%, whereas those in the test section are 0.3%. The normalized rms fluctuations for velocity in the test section are less than 0.7%. Calculated correlation coefficients failed to show vorticity, entropy, or sound as the dominant source of turbulence in the tunnel. It is therefore believed that the three fundamental modes of turbulence coexist in the 0.3-m TCT.

The periodic disturbances in the tunnel at certain tunnel operating conditions are possibly caused by acoustic coupling of the test section and the plenum chamber via the perforated side walls. The resonance frequencies observed agreed well with the frequencies predicted by Mabey's[9] acoustic coupling theory.

Acknowledgments

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References

[1]Owen, F. K., Stainback, P. C., and Harvey, W. D., "An Evaluation of Factors Affecting the Flow Quality in Wind Tunnels and Testing Techniques," Paper 12, AGARD-CP-348, Feb. 1984.

[2]Stainback, P. C., Johnson, C. B., and Basnett, C. B., "Preliminary Measurements of Velocity, Density and Total Temperature Fluctuations in Compressible Subsonic Flow," AIAA Paper 83-0384, Jan. 1983.

[3]Johnson, C. B., Johnson, W. G., Jr., and Stainback, P. C., "Summary of Reynolds Number Effects on Some Recent Tests in the Langley 0.3-Meter Transonic Cryogenic Tunnel," Society of Automotive Engineers, Paper SAE-861765, Oct. 1986.

[4]Ng, W. F., and Rosson, J. C., "Cryogenic Tunnel Measurement of Total Temperature and Pressure," *Journal of Aircraft*, Vol. 23, March 1986, pp. 244–249.

[5]Varner, M. O., "Noise Generation in Transonic Tunnels," *AIAA Journal*, Vol. 13, Nov. 1975, pp. 1417–1418.

[6]Dougherty, N. S., Jr., and Steinle, F. W. Jr., "Transition Reynolds Number Comparisons in Several Major Transonic Tunnels," AIAA Paper 74-627, July 1974.

[7]Schutzenhofer, L. A., and Howard, P. W., "Suppression of Background Noise in a Transonic Wind-Tunnel Test Section," *AIAA Journal*, Vol. 13, Nov. 1975, pp. 1467–1471.

[8]Cox, R. N., and Freestone, M. M., "Design of Ventilated Walls with Special Emphasis on the Aspect of Noise Generation," *Fluid Motion Problems in Wind Tunnel Design*, AGARD Rept. 602, No. 6, Nov. 1972.

[9]Mabey, D. G., "Resonance Frequencies of Ventilated Wind Tunnels," *AIAA Journal*, Vol. 18, Jan. 1980, pp. 7–8.

[10]Lee, I., "Plenum Chamber Effect on Wind-Tunnel Resonance by the Finite-Element Method," *AIAA Journal*, Vol. 26, Sept. 1988, pp. 1087–1093.

[11]Ng, W. F., "Review-Simultaneous Measurements of Stagnation Temperature and Pressure Using an Aspirating Probe," *Proceedings of the ASME Symposium on Pressure and Temperature Measurements*, ASME, New York, Dec. 1986, pp. 97–104.

[12]Ng, W. F., and Popernack, T. G., Jr., "Combination Probe for High-Frequency Unsteady Aerodynamic Measurements," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 24, Jan. 1988, pp. 76–84.

[13]Johnson, C. B., and Stainback, P. C., "A Study of Dynamic Measurements Made in the Settling Chamber of the Langley 0.3-Meter Transonic Cryogenic Tunnel," AIAA Paper 84-0596, March 1984.

[14]Jones, G. S., Stainback, P. C., Harris, C. D., Brooks, C. W., and Clukey, S. J., "Flow Quality Measurements for the Langley 8-Foot Transonic Pressure Tunnel LFC Experiment," AIAA Paper 89-0150, Jan. 1989.

[15]Kovasznay, L. S. G., "Turbulence in Supersonic Flow," *Journal of the Aeronautical Sciences*, Vol. 20, Oct. 1953, pp. 657–674.

[16]Morkovin, M. V., "Fluctuations and Hot-Wire Anemometry in Compressible Flow," AGARDograph 24, Nov. 1956.

[17]Griffith, D. O., Jr., "Turbulence Measurements and Noise Generation in a Transonic Cryogenic Wind Tunnel," M. S. Thesis, Department of Mechanical Engineering, VPI & SU, April 1989.