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# Evaluation of Flow Quality in Two NASA Transonic Wind Tunnels

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**Recognizing the importance of aircraft fuel efficiency, the NASA Langley Research Center and Industry are currently trying to define and demonstrate a practical boundary-layer suction system for viscous drag reduction. During wind tunnel testing of such a system, it will be particularly important that facility generated disturbances do not influence boundary-layer behavior unrealistically. To obtain a better understanding of the characteristics of the disturbances and identification of their sources for possible facility modification, detailed flow quality measurements were made in two potential test facilities. This paper will present experimental results of an extensive and systematic flow quality study of the settling chamber, test section, and diffuser of the Langley 8-ft transonic pressure tunnel and the Ames 12-ft pressure wind tunnel.**

## Nomenclature

| | |
|---|---|
| $a$ | = acoustic velocity |
| $C$ | = model chord |
| $D$ | = diameter |
| $f$ | = frequency |
| $L$ | = test section length |
| $M$ | = Mach number |
| $p$ | = pressure |
| $q$ | = $\frac{1}{2}\rho u^2$ |
| $Re$ | = unit Reynolds number |
| $Re_c$ | = Reynolds number based on wing chord |
| $R_{xy}$ | = correlation value |
| $t$ | = time |
| $u$ | = velocity |
| $x$ | = axial distance or distance from wall slot origin |
| $\gamma$ | = ratio of specific heats |
| $\rho$ | = density |

*Superscripts*

| | |
|---|---|
| $(\bar{\ })$ | = mean value |
| $(\tilde{\ })$ | = rms value |

*Subscripts*

| | |
|---|---|
| $\infty$ | = freestream |
| $t$ | = total conditions |

## Introduction

ONE of the largest economic problems facing the airlines industry today is the rapid rise in fuel cost. Recognizing the importance of fuel efficiency, the NASA Langley Research Center and Industry are currently trying to define and demonstrate a practical, reliable, and maintainable boundary-layer suction system for viscous drag reduction. This concept has resulted in the design of advanced laminar flow control (LFC) wings and the necessity to confirm experimentally their performance in wind tunnels to establish a technology data base for future long range commercial transports of the 1990's. Aside from other considerations, it is particularly important, when measurements are obtained on low-drag airfoils whose boundary layers remain laminar over long lengths, not to adversely influence the laminar boundary layer by facility disturbances.

Although wind-tunnel wall effects on experimental data have long been recognized, presently little is known about the influence of freestream turbulence on steady and dynamic measurements in wind tunnels at transonic speeds. Indeed, few measurements have been made of the characteristics of freestream unsteadiness in transonic wind tunnels. The result is that information on velocity and pressure fluctuations, their amplitude and spectra is lacking. This information is required to accurately assess the relationship between wind tunnel and flight transition behavior. Furthermore, characteristic source disturbances must be identified for proper facility modification and anticipated improved flow quality.

Perhaps the major open question is the influence of freestream disturbances on model boundary-layer transition. Earlier results at subsonic speeds have shown the effects of freestream disturbance on transition.[1-4] Recent developments in boundary-layer transition research,[5] particularly those of the NASA transition study group, have stressed the dominant role that freestream fluctuations have on model boundary-layer stability at transonic and supersonic speeds. Not only do the external fluctuation amplitudes influence transition but their energy spectra are particularly significant. More recently, a significant quantity of available data have been compiled which shows that the beginning of transition on simple models is influenced both by freestream disturbances and local conditions; and the data collapse along a single curve for a wide range of test conditions and wind tunnels.[6]

Previous LFC experiments[7] have shown that the characteristics of such airfoils can be successfully measured only in low turbulence tunnels. Figure 1 illustrates the effect of environmental disturbance level on maintaining laminar flow on low drag wings and bodies of revolution with suction in several wind tunnels and flight.[8] Tunnels whose level of turbulence is very small ($\tilde{u}/\bar{u} \simeq 0.05\%$) are required to achieve laminar flow on wings for large chord Reynolds numbers approaching flight conditions. This objective increasingly becomes difficult at transonic speeds and cannot always be

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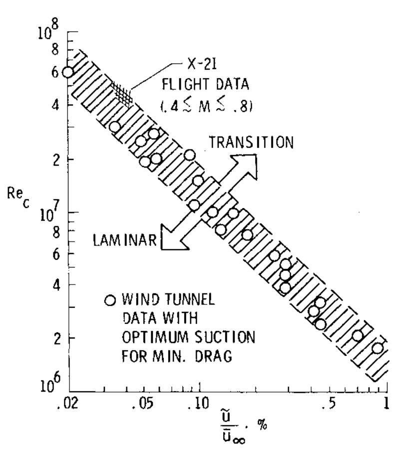


**Fig. 1 Effect of turbulence level on transition Reynolds number for transition at the trailing edge for wings and bodies of revolution with suction (data from Pfenninger).**

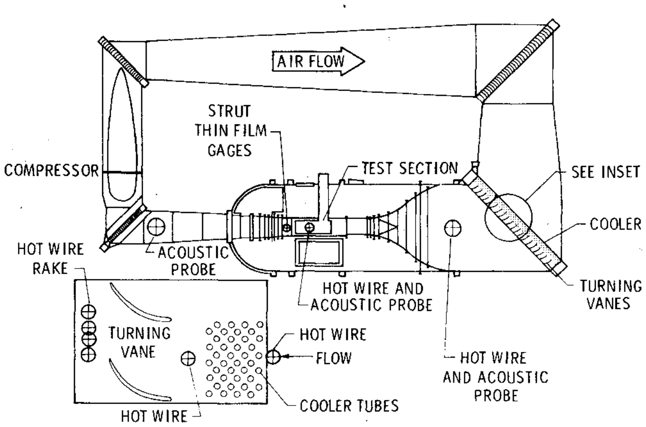


**Fig. 2 Sketch of Langley Research Center 8-ft transonic pressure tunnel and measuring stations.**

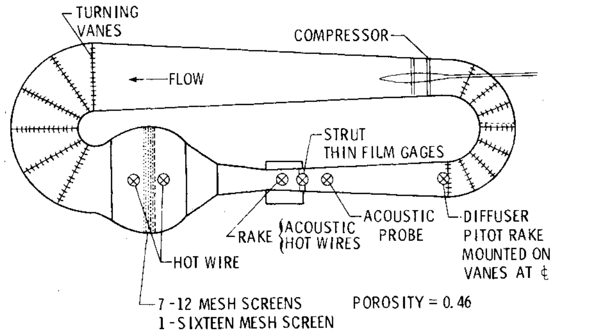


**Fig. 3 Sketch of Ames Research Center 12-ft pressure wind tunnel and measuring stations.**

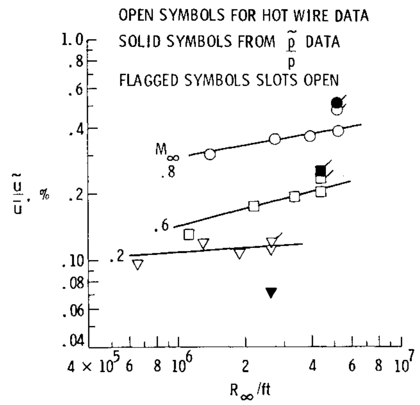


**Fig. 4 Velocity fluctuations levels in the test section of the Langley 8-ft tunnel.**

attained since there are disturbances present generated by the fan, turning vanes, diffuser, strut, and wind tunnel walls. The need for transonic wind tunnels with low disturbance levels also has been recognized and work is being done to develop such tunnels.[9,10] However, based on very limited information indicating good flow quality in both facilities, the NASA Langley 8-ft transonic pressure and Ames 12-ft pressure wind tunnels were selected for flow quality evaluation for possible future LFC research. In order to obtain a better understanding of the characteristics of the disturbances and identification of their sources[11,12] for possible modification, detailed flow quality measurements were made in both facilities. This paper presents experimental results of an extensive and systematic flow quality study made in the settling chamber, test sections, and in the diffuser of the Langley 8-ft and Ames 12-ft tunnels over a range of operating conditions.

## Facilities and Instrumentation

Sketches of the Langley 8-ft and Ames 12-ft tunnel circuits are shown in Figs. 2 and 3, respectively, along with an indication of the stations where measurements were made (crossed circles). The Langley 8-ft tunnel has slotted top and bottom test section walls and is similar to most transonic tunnels except for the presence of a cooler, consisting of eight staggered rows of finned tubes, located in the corner just upstream of the turning vanes at the entrance of the 36-ft diam settling chamber. The cooler turns the flow 45 deg and turning vanes downstream of the cooler turns the flow an additional 45 deg. There are no turbulence suppression screens in the settling chamber, and the nozzle has a contraction ratio of 20:1. Features of the Ames 12-ft tunnel (Fig. 3) include a rapid expansion (area ratio = 2) ahead of the 60-ft diam settling chamber which has eight screens. The contraction ratio of the nozzle is 25:1. Most of the present tests were conducted with cover plates mounted flush to the existing surface slots in the Ames tunnel support strut. This facility has solid test section walls. For comparison purposes, the Langley 8-ft tunnel wall slots were covered during the present tests.

The same types of measuring probes and instrumentation were maintained as nearly identical as possible in each tunnel for consistency. Hot-wire anemometry techniques and Kulite gages, cavity mounted within ogive-cylinder probes, were used to measure dynamic data. The probes were either individually or raked mounted (Figs. 2 and 3) as required for measuring spatial variations. Surface thin-film gages (operated at constant overheat) were used to determine the chordwise flow character over the struts in each tunnel. In the Ames 12-ft tunnel, individual hot-wire measurements were made in the settling chamber, at a point downstream of the rapid expansion ahead of the screens, and at a point several hundred mesh diameters downstream of the last screen. A rake of hot-wire and acoustic probes was sting mounted in the test section ahead of the strut, and in the diffuser an acoustic probe was mounted from the wall. Two thin-film gages were used to monitor the flow over the strut at $x/c$ values of $\approx 0.25$ and 0.75.

In the Langley 8-ft tunnel, hot-wire probes were mounted ahead and immediately downstream of the cooler. Two rakes were used in the settling chamber; one having four hot wires was mounted immediately downstream of the turning vanes and another with hot-wire and acoustic probes was mounted in the settling chamber ahead of the contraction. Hot-wire probes were both sting and wall mounted in the test section. Again, two thin-film probes were used to monitor the flow over the strut at $x/c \approx 0.25$ and 0.75.

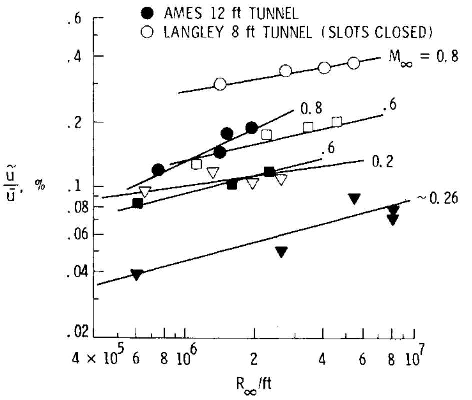


Fig. 5 Comparison of velocity fluctuations in the test section of the Ames 12-ft and Langley 8-ft tunnels.

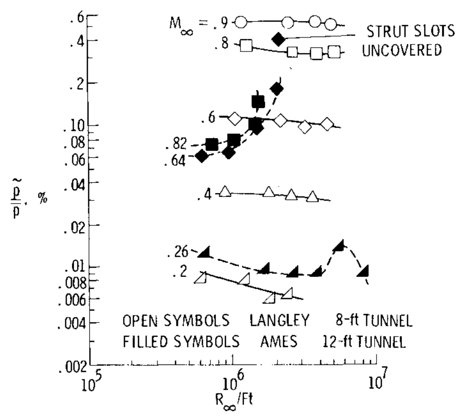


Fig. 6 Comparison of pressure fluctuations in the test section of the Ames 12-ft and Langley 8-ft tunnels.

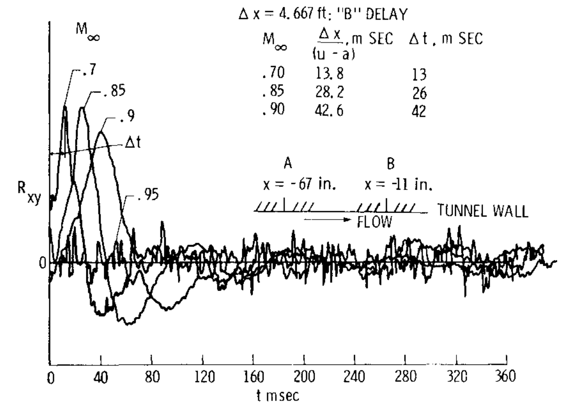


Fig. 7 Cross correlation of pressure fluctuations measured at the test section wall of the Langley 8-ft tunnel.

## Results and Discussion

Since the proposed laminar flow wing experiments will be performed with solid test section walls contoured to simulate free flight conditions, attention was primarily focused on data obtained with solid walls, i.e., with the slots covered. Hot-wire measurements in the Langley 8-ft tunnel are shown in Fig. 4 for a range of test section Mach and unit Reynolds numbers. The hot-wire data show increasing turbulence levels with increases in both parameters. Velocity fluctuations obtained over a Mach number range at maximum unit Reynolds numbers with the wall slots open show increased turbulence levels above the solid wall condition at the higher Mach number. Spectra (not shown) indicate that these increases, generated primarily by shear between the moving air in the test section and the air in the surrounding plenum chamber, are broadband with no edgetones being present. Velocity fluctuations obtained from pressure fluctuation measurements using the relationship $\tilde{u}/\bar{u} = \tilde{p}/\gamma \bar{p} M$, for the case with the Langley 8-ft tunnel slots open, are shown in Fig. 4 for comparison with the hot-wire data. At the higher Mach numbers, the velocity fluctuations calculated from pressure fluctuations agree with those obtained from the measured hot-wire data. At $M_\infty = 0.2$ the velocity fluctuations calculated from the fluctuating pressures are lower than those obtained from the hot wire. This is probably due to the fact that the pressure contribution from vorticity fluctuations are proportional to $M^2$ and at low Mach numbers the pressure contributions from vorticity would be very small, thereby reducing the indicated fluctuating pressure and the calculated fluctuating velocity.

Freestream velocity fluctuations obtained from hot-wire measurements made in the Ames 12-ft tunnel are compared with those of the Langley 8-ft tunnel in Fig. 5. At low subsonic speeds ($M_\infty \approx 0.2$) the freestream turbulence levels in the Ames 12-ft tunnel are low, less than 0.1% at the highest unit Reynolds number. At $M_\infty = 0.6$ the turbulence levels are still low ($\approx 0.1\%$). Therefore, at the lower subsonic Mach numbers the Ames 12-ft tunnel has significantly lower turbulence levels than the Langley 8-ft tunnel.

In the Ames 12-ft tunnel, there appears to be a marked increase in the slope of the freestream turbulence data with increasing unit Reynolds number (Fig. 5) at $M_\infty = 0.8$. This is probably due to adverse strut-diffuser flow interactions which will be discussed subsequently. The disturbance levels at $M_\infty = 0.8$ in the Ames 12-ft tunnel are significantly lower than those in the Langley 8-ft tunnel at the lower unit Reynolds number, however, if the Ames data were extrapolated to higher unit Reynolds number, which can be achieved in the Langley tunnel and are required for LFC testing, the turbulence levels in the Ames tunnel would approach the levels in the Langley 8-ft tunnel.

The static pressure fluctuations measured in the test section of both tunnels are shown in Fig. 6. At $M_\infty \approx 0.2$, the fluctuating pressures in both tunnels are very low ($\tilde{p}/\bar{p} \approx 0.01\%$) with the Langley 8-ft tunnel having a somewhat lower level. At $M_\infty \approx 0.6$-$0.8$ and low unit Reynolds number, the levels in the Ames tunnel data are lower than those in the Langley tunnel; however, there is a significant increase in the fluctuating pressure levels in the Ames tunnel at the higher unit Reynolds number. At $M_\infty \approx 0.6$, the levels in the Ames tunnel exceed those in the Langley tunnel. It appears that the most intense sound waves at the higher Mach numbers are those moving in the upstream direction. This has been confirmed by cross-correlation measurements in both tunnels. Probe separation in the Ames 12-ft tunnel was sufficient to make the correlations of the turbulence negligibly small; thus correlations of the acoustic modes can be measured directly. At Mach numbers below 0.8, with the diffuser probe output delayed, it was apparent that there were coherent acoustic modes that propagated upstream into the test section from the diffuser. The propagation speed determined from the spatial separation and time delay for optimum correlation was determined to be approximately equal to the speed of sound minus the wind tunnel freestream velocity. When sonic flow exists over the area of the test section, all correlation disappeared since upstream moving pressure waves cannot propagate forward in sonic or supersonic flow. Thus the only response of the freestream transducer, under these conditions, is to pressure waves moving downstream and to noise radiated from the turbulent boundary layers on the walls ahead of the probe. The presently observed strut-diffuser flow interaction for the Ames facility indicates that the tunnel choked at $M_\infty \approx 0.8$ and this is in contrast to earlier results with the old strut[3] that apparently choked at $M_\infty \cong 0.9$.

Cross correlations of data measured with two pressure transducers located at the test section wall in the Langley 8-ft

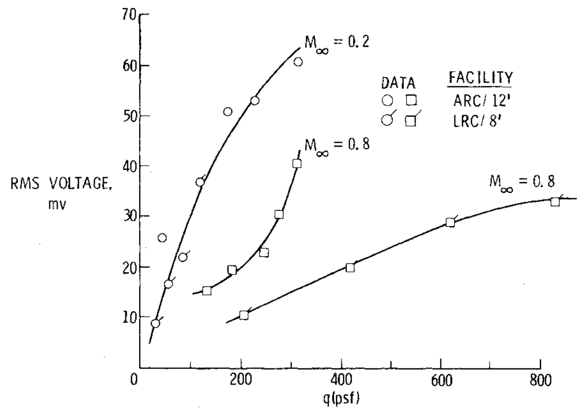


**Fig. 8 Comparison of flow fluctuations on the struts of the Ames 12-ft and Langley 8-ft tunnels, $x/c \approx 0.75$.**

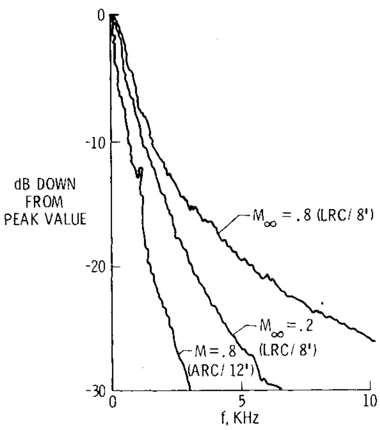


**Fig. 9 Comparison of the spectra measured with a thin film on the struts of the Ames 12-ft and Langley 8-ft tunnels, $x/c \approx 0.75$.**

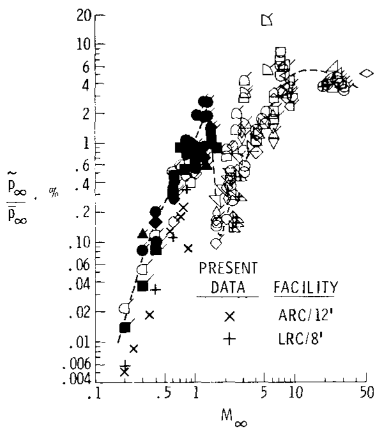


**Fig. 10 Comparison of present results with test section pressure fluctuation in several wind tunnels; see Table 1 of Ref. 6 for data source and test conditions.**

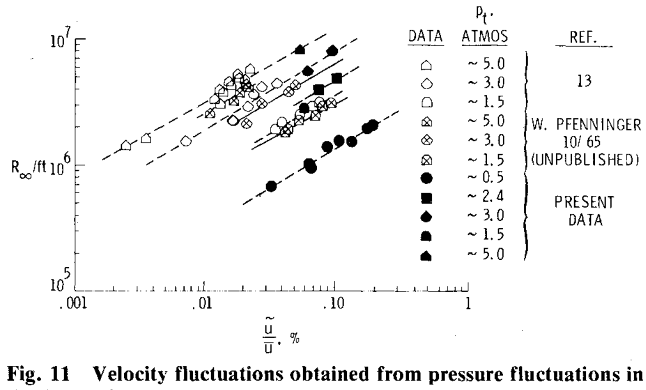


**Fig. 11 Velocity fluctuations obtained from pressure fluctuations in the Ames 12-ft tunnel.**

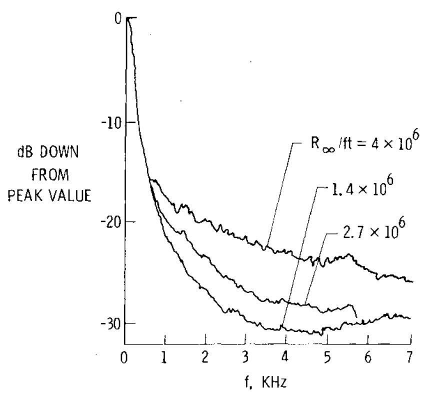


**Fig. 12 Spectra from hot-wire measurements in the test section of the Langley 8-ft tunnel at $M_\infty = 0.8$.**

tunnel are shown in Fig. 7. These results show that upstream propagating acoustic waves exist in the test section at the lower Mach numbers, and that when the flow is choked at $M_\infty = 0.95$ there is no peak in the correlation and its level is reduced significantly.

The thin-film surface gage rms fluctuation levels and spectra at $x/c \approx 0.75$ indicate flow separation on the Ames strut (Figs. 8 and 9). It can be seen that, although there is good agreement between the data for the two tunnels at $M_\infty = 0.2$, higher rms values and associated larger scale fluctuations are indicative of flow separation on the Ames strut at $M_\infty = 0.8$. This leads to degraded diffuser flow quality at transonic speeds.

Disturbance levels in both tunnels are compared with results[6] from other facilities in Fig. 10. The present data (slots closed in Langley 8 ft) agree in trend with previous data,[6] and are considerably lower than those from porous or slotted-wall transonic tunnels. However, based on the results presented in Fig. 1, the Langley 8-ft and the Ames 12-ft tunnels have disturbance levels in the test section that are too high to conduct meaningful LFC research at high subsonic Mach numbers.

Again assuming that the pressure fluctuations are plane waves and unidirectional, the velocity fluctuation levels have been calculated for a range of tunnel total pressures for the Ames 12-ft tunnel. These results (Fig. 11) agree quite well with unpublished data by W. Pfenninger and previous data[13] and again suggest that the measured pressure fluctuations can account for a large part of the turbulent velocity fluctuations in this facility over the speed range tested.

As previously mentioned, not only do fluctuation amplitudes affect wind-tunnel performance but spectral characteristics are particularly important. This is one significant item missing in the interpretation of Fig. 1, for example.

Representative variations of the freestream broadband energy spectra from the hot-wire measurements at $M_\infty = 0.8$ in the Langley 8-ft tunnel are shown in Fig. 12. Although there is an increased high frequency (small scale) contribution with increasing Reynolds number, the energy contribution is several orders of magnitude down for $f \approx 6$ kHz and there are no significant energy peaks for $0 < f < 6$ kHz. The rapid decay in energy with frequency is typical of most low-speed tunnels. Freestream pressure spectra (Fig. 13) again show, apart from a probe cavity resonance ($f \approx 1.4$ kHz), similar trends; i.e., rapid decay of energy with increasing frequency. The hot-wire autocorrelations in Fig. 14 show an increase in the small time scale of turbulence as the Mach number is increased, i.e., more rapid decay of the correlation near the origin. The turbulent integral scales increase from approximately 1.2 in. at $M_\infty = 0.2$ to 3.94 in. at $M_\infty = 0.8$.

Representative energy spectra obtained in the Ames 12-ft test section with hot-wire and pressure probes are shown in Figs. 15 and 16 for several test conditions. Integrated fluctuation levels are included to illustrate the increased levels with Mach number. Once again, the hot-wire broadband

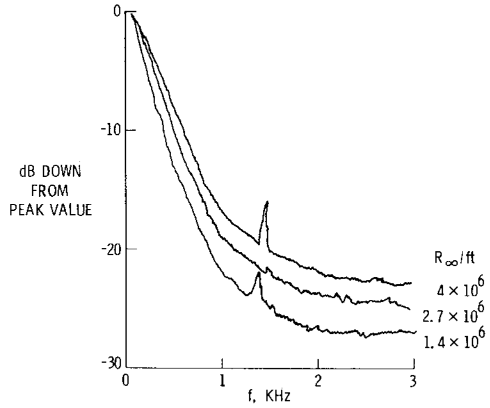


**Fig. 13 Spectra from pressure measurements in the test section of the Langley 8-ft tunnel at $M_\infty = 0.8$.**

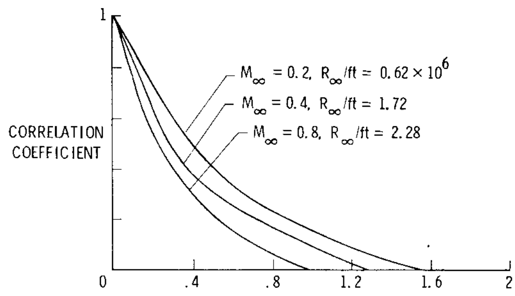


**Fig. 14 Autocorrelations from hot-wire measurements in the test section of the Langley 8-ft tunnel.**

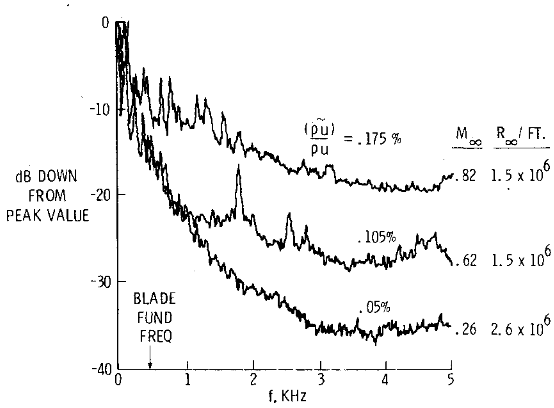


**Fig. 15 Spectra from hot-wire measurements in the test section of the Ames 12-ft tunnel.**

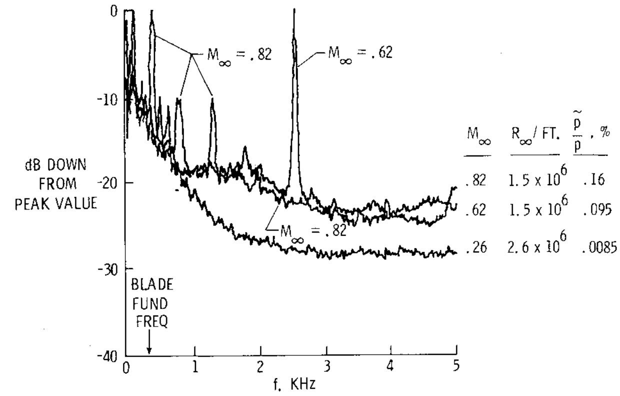


**Fig. 16 Spectra from pressure measurements in the test section of the Ames 12-ft tunnel.**

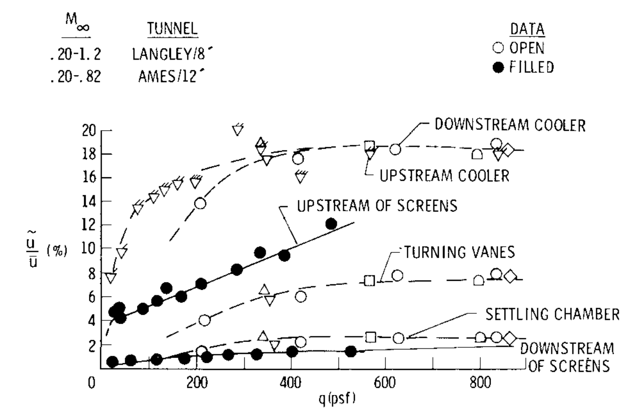


**Fig. 17 Comparison of the settling chamber turbulence levels in the Ames 12-ft and Langley 8-ft tunnels.**

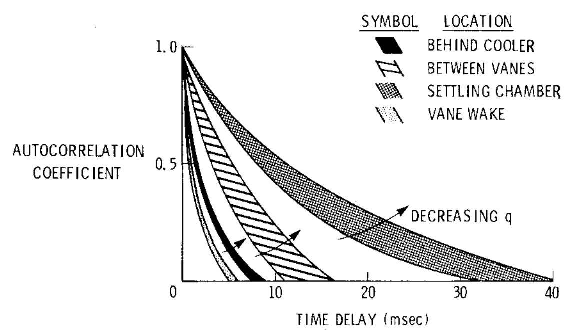


**Fig. 18 Autocorrelations from hot-wire measurements in the settling chamber of the Langley 8-ft tunnel.**

spectra indicate a significant decrease in relative energy at higher frequencies. However, there are several discrete frequencies present in the spectra due primarily to the greatly reduced signal to noise ratio at these lower turbulence levels. The spectra shown in Fig. 12 for the Langley 8-ft tunnel and in Fig. 15 for the Ames 12-ft tunnel indicate that there is less relative energy at the higher frequencies in the Langley tunnel than the Ames tunnel. The reason for this difference is not known at the present time.

The spectra obtained with the pressure probe in the Ames 12-ft tunnel for the two higher Mach numbers indicate the existence of several discrete frequencies below about 2.5 kHz. Other than pressure probe cavity resonance and compressor blade energy peaks, these discrete frequencies at the high Mach numbers are probably due to acoustic disturbances from the strut and diffuser propagating upstream into the test section as discussed earlier.

It is apparent from the present measurements (Fig. 7) that choking the flow, intentionally or unintentionally, blocks the propagation of sound from the diffuser into the test section. Thus, it is likely that the introduction of a sonic choke device downstream of the test section but ahead of the strut and diffuser would significantly improve the flow quality characteristics of both facilities. With a choke device implemented, further flow quality improvement can come only from alterations of the tunnels ahead of the contraction. Thus, it is required to determine the turbulence characteristics in the settling chambers of both facilities.

Figures 17-19 show a comparison of the turbulence levels and autocorrelations measured at several locations in the settling chamber of the Langley 8-ft tunnel and across the screens in the Ames 12-ft tunnel for a range of dynamic pressures. The Langley 8-ft tunnel results were obtained upstream of the cooler, on the centerline downstream of the cooler and vanes, and near the middle of the settling chamber. Similar results were obtained for the Ames 12-ft tunnel several hundred wire mesh diameters up and downstream of the screens. The cooler in the Langley 8-ft tunnel produces

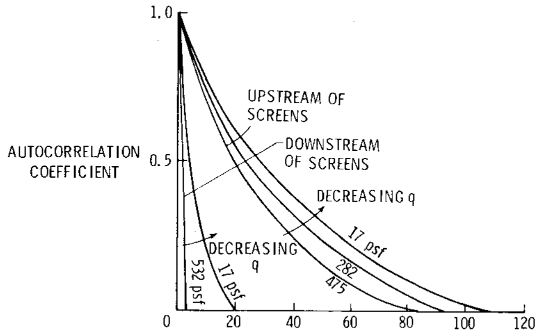


**Fig. 19 Autocorrelations from hot-wire measurements in the settling chamber of the Ames 12-ft tunnel.**

very high turbulence levels of about 20% (Fig. 17) that are about equal to values measured upstream of the cooler. However, due to the closely spaced fins on the tubes of the cooler, integral scales of the turbulence behind the cooler are small ($\approx 0.1$ ft) compared to upstream scales that are about 2 ft. Evidently, the cooler tends to manage incoming turbulence similar to a honeycomb-screen combination. Downstream of the turning vanes, the turbulence levels have decreased by a factor of about 3 (Fig. 17) with an increase in the scale of turbulence ($\simeq 0.25$ ft). Further downstream in the settling chamber, the level of disturbances is about 2% and the scale size increased to about 1.1 ft. This increase in scale size (Fig. 18) is due to the addition of large scale turbulence by the vanes and the decay of small scale turbulence.

The screens in the settling chamber of the Ames 12-ft tunnel (Fig. 17) reduced the high incoming turbulence levels by a factor of about 10 over the dynamic pressure range shown. Since the test section Mach number was constant, the integral scales of turbulence both upstream and downstream of the screens (Fig. 19) decrease with increasing $q_\infty$. These results clearly demonstrate the importance of screens for turbulence suppression prior to the contraction.[14,15] The absence of screens in the LRC 8-ft tunnel is partly responsible for the higher freestream turbulence levels shown in Fig. 17.

Although the turbulence reduction across the screens in the Ames 12-ft tunnel well exceeds that calculated[16] for a single screen producing the same pressure drop, it falls well short of that predicted for the same total pressure drop across eight screens in series. An important aspect of turbulence reduction is the uniformity of the mean flow velocity ahead of the screens.[16] If the mean velocity has nonuniformities of only a few percent some regeneration of turbulence can occur through a screen and the screen efficiency is reduced. Such small nonuniformities could possibly be produced in the Ames 12-ft tunnel by unsteady flow separations downstream of the sudden expansion which were evident from the hot-wire data ahead of the screens, particularly at high dynamic pressures. It would be more efficient to manage existing large scale unsteady motions ahead of the screens. This would lead to improved screen efficiency, lower settling chamber turbulence levels, and, consequently, even lower test section turbulence. Analysis, based on results from earlier experience with turbulence suppression devices, suggests that the Ames 12-ft tunnel screens may have a solidity that is too high.[14-16] Decreasing the solidity could also reduce the test section turbulence.

## Concluding Remarks

Tests have been conducted in the Langley Research Center 8-ft transonic pressure tunnel and the Ames Research Center 12-ft pressure wind tunnel to measure characteristic disturbance levels and energy spectra in their respective settling chambers, test sections, and diffusers and to determine the sources of these disturbances. The primary conclusions are as follows.

At low Mach numbers the Ames facility has superior flow quality. However, at higher Mach numbers disturbances from flow separation at the strut are propagated upstream into the test section degrading its flow quality. The present Ames tunnel model support system appears to choke the flow for $M_\infty \approx 0.8$ and flow separation that occurs on the strut at $M_\infty \simeq 0.6$ is one of the primary causes of the more rapid increase of fluctuation levels with Reynolds number at high freestream Mach numbers.

Although the freestream velocity and pressure fluctuation levels in both facilities are considerably lower than those in porous or slotted-wall transonic tunnels, the disturbance levels at high Mach numbers are still too high to conduct meaningful supercritical LFC research.

Other than a few discrete peaks in the Ames hot-wire and pressure fluctuation spectra at the higher Mach numbers, that are principally caused by upstream propagation of sound due to strut-diffuser flow interactions, no other significant energy peaks were observed in either facility. Rapid, smooth decays of energy with frequency, typical of most low speed tunnels, were observed. This is considered favorable for LFC testing.

Pressure fluctuation levels in both facilities appeared to account for most of the flow disturbances in the test section. These fluctuations are believed to be primarily the result of strut-diffuser flow interactions in the Ames tunnel and diffuser unsteadiness in the Langley 8-ft facility which are propagated upstream into the test section. The disturbances are somewhat more severe in the Ames facility at high Mach numbers due to flow separation on the strut.

## Recommendations

1) Significant reduction of the disturbance levels in both facilities could be effected by introducing a variable sonic choke device downstream of the test section but upstream of the strut and diffuser. This choke device would prevent strut-diffuser fluctuations from propagating upstream into the test section. Thus the only remaining test section disturbances would be relatively low level pressure fluctuations propagating from the settling chamber and turbulent wall boundary layers and vorticity fluctuations convected from the settling chamber.

2) Although the Langley tunnel cooler does perform somewhat like a honeycomb-screen combination, further reduction of the test-section disturbance levels can be expected by the installation of properly selected honeycomb and screens in the settling chamber as the present turbulence levels ahead of the contraction are about twice those in the Ames facility. On the other hand, the eight screens presently in the Ames facility do not perform particularly well for the pressure losses incurred at the higher Mach numbers. This lack of screen efficiency is probably due to large scale unsteady flows associated with recirculation at the sudden expansion, which could produce mean gradients in the flow ahead of the screens, and also due to high screen solidity. Screen efficiency could be greatly improved by reducing the extent of separation in this region and by using lower solidity screens assuming further unsteadiness does not occur due to power limitations. The installation of screens would be more efficient in the Langley 8-ft tunnel since there are no area expansion problems downstream of the cooler.

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