Transonic Flow Quality Improvements in a Blowdown Wind Tunnel

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The development and evaluation of a new type of flow conditioning system between the control valve and stilling chamber of the Vought Systems Division 4 × 4-ft transonic-supersonic wind tunnel are reported. The new system results in a series of normal shocks created by four perforated plates to dissipate total pressure differences between the reservoir and stilling chamber. Data are presented which demonstrate flow quality improvements obtained by using the new design, including a significant reduction in test section flow unsteadiness and elimination of flow angularity induced by the control valve at transonic Mach numbers. Design methods are developed which insure no loss in run time at transonic Mach numbers and minimum run time losses at higher supersonic Mach numbers.

Nomenclature

A = area
ΔC_p = root-mean-square pressure fluctuation coefficient, $\Delta P_s/q$, wide band unless otherwise noted
f = center frequency, Hz
Δf = analyzer bandwidth, Hz
i = order number of perforated plate, numbered from stilling chamber
M = test section Mach number
n = total number of perforated plates
P = pressure, psia
ΔP = root-mean-square pressure fluctuation, psia; wide band (20 Hz − 25 kHz) unless otherwise noted
q = dynamic pressure, psi
R = pressure ratio across shock
$\Delta\alpha$ = valve-induced flow angularity in the pitch direction, deg
ϵ = frequency ratio, $\Delta f/f$
Θ_v = valve position, deg
$\Delta\Psi$ = valve-induced flow angularity in the yaw direction, deg

Subscripts

0 = stilling chamber
0′ = wide-angle diffuser entrance, upstream of all grids and screens
r = reservoir
s = static pressure in test section
v = valve

Superscript

$*$ = sonic conditions

Introduction

THE Vought Systems Division (VSD) 4 × 4-ft High Speed Wind Tunnel is a transonic and supersonic facility with an interchangeable transonic test section and supersonic diffuser. This facility was one of several large blowdown tunnels constructed between 1958 and 1962 with similar circuit arrangements and performance. A feature common to almost all of these high Reynolds number facilities was a Mach number range from subsonic to about Mach 5.0. These facilities were unique in that they were the first large blowdown transonic wind tunnels to be constructed.

In the operational use of these facilities at transonic speeds, certain common flow characteristics were observed. These characteristics included flow angularity measurements which were not repeatable within the desired accuracy. The flow angle variations were most pronounced at low subsonic Mach numbers ($M \leq 0.6$) and diminished or vanished at higher subsonic and transonic speeds. Supersonic flow quality was excellent. It was found that the transonic effects could be minimized and data of satisfactory quality obtained in the VSD facility by data smoothing, by using four fine-mesh screens in the stilling chamber, and by limiting the maximum control valve opening to about 70%. Nevertheless, in common with almost all transonic wind tunnels, the need for more accurate and consistent transonic aerodynamic data was fully recognized.

In 1968 an extensive cooperative effort among several of these wind tunnels, including the VSD facility, was begun to improve the accuracy and consistency of transonic wind-tunnel data. The control valve was isolated as the cause of flow angle variations in the test section as reported by Whitfield.[1] Results of another flow improvement investigation were reported by Lowe and Cumming.[2] All of the facilities conducting such evaluations found valve-induced flow angularities of significant magnitude, greatly exceeding ±0.02° which is considered a reasonable accuracy goal for time-dependent flow angularity.

Concurrent with these flow angularity investigations, other studies of pressure fluctuation levels in the test section and stilling chamber were also conducted at VSD. It was determined that the level of pressure fluctuations was higher than desirable, particularly at low subsonic Mach numbers. The flow unsteadiness was not severe enough to cause model or balance fatigue problems or seriously interfere with conventional force testing although the static force data smoothing problem was made more difficult. Pressure fluctuations were sufficiently high to interfere with unsteady pressure measurements and buffet onset and intensity measurements using the wing-root-bending testing technique. The pressure fluctuation criterion for light buffet measurements on thin swept wings established by Mabey[3] states that the unsteadiness parameters, $\Delta P_s/q\epsilon^{1/2}$, should not be greater than about 0.003 at the natural frequency of the model wing. The initial level was approximately two to three times this value.

The initial concept of multiple-shock entrance diffuser as a simple and effective solution to the flow problems discussed above was initially developed in 1969 and evalu-

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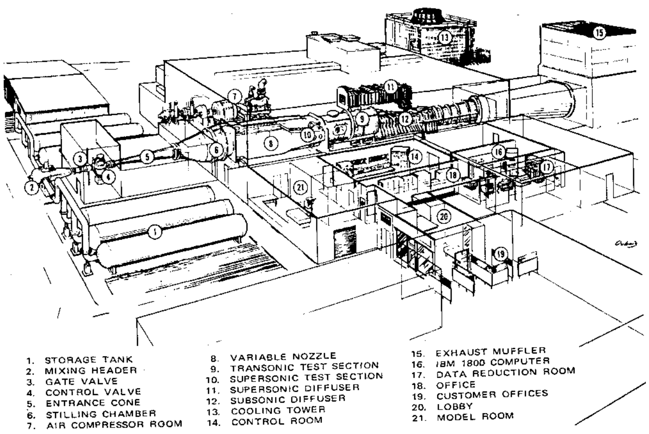

Fig. 1 Vought Systems Division high speed wind tunnel.

ated in 1970 and 1971 in a simplified, 1/12-scale model of the facility. Results of these studies were used to optimize the design of the full scale entrance diffuser. The modified diffuser was installed and evaluated early in 1972. Results of these evaluations are presented in this paper.

Description of Facility

A brief description of the VSD 4 × 4-ft High Speed Wind Tunnel is necessary to understand the source of the aforementioned transonic flow characteristics and the design approach chosen for correction.

The general arrangement of the facility is shown in Fig. 1. An 8000-hp electric motor drives a centrifugal compressor system which supplies 18 lb/sec of dry air at 600 psia to six high pressure storage tanks with a total volume of 28,000 ft^3. During a run the stored air is released through a 24-in. diameter rotating-plug valve which is servo controlled to maintain a preset stilling chamber pressure. During a maximum-length transonic run the control valve area can vary from less than 50 to 100% of full open as the tank pressure is reduced during the blowdown process. Maximum usable run times vary from 40 to 100 sec depending on Mach number. Typical test runs are accomplished in about 20 sec.

The control valve and entrance diffuser dissipate the high storage pressure (600 psia maximum) to maintain the desired stilling chamber pressure (20 psia minimum). The process whereby this energy is dissipated will be discussed in detail later. Flow conditioning devices in the wide-angle diffuser section of the stilling chamber consist of seven screens to prevent separation. Four additional fine screens are located in the maximum diameter section of the stilling chamber for turbulence reduction. Details of the original entrance diffuser are shown in Fig. 2.

A contraction section downstream of the stilling chamber provides transition to a 38-ft long flexible plate nozzle. The contraction ratio at Mach 1.0 is 10. The nozzle terminates in a 4 × 4-ft test section for supersonic Mach numbers. For transonic testing, a separate test section is installed downstream of the flexible plate nozzle. This test section, also 4 × 4-ft, has 22% normal-hole perforated walls surrounded by a plenum chamber. A detailed description of this facility may be found in Ref. 4.

Development of New Entrance Diffuser Concept

The purpose of the throttling process in a blowdown wind tunnel is to maintain a constant stagnation pressure while the storage reservoir pressure decreases during air withdrawal. For a blowdown wind tunnel which operates over a wide Mach number range the selection of the storage pressure, control valve size, and entrance diffuser de-

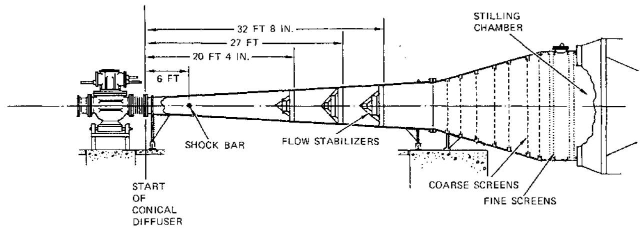

Fig. 2 Original entrance diffuser.

sign becomes a challenging problem. Tradeoffs are necessary because of the wide range of mass flows and pressures required for operation from subsonic to high supersonic Mach numbers. The configuration selected will obviously depend upon the Mach number for which the system is optimized.

The dissipation of energy by a compressible throttling process can be demonstrated by considering a simple valve and entrance diffuser, such as depicted in Fig. 3. The function of the valve is to control the mass flow into the system by means of a variable area, choked throat. The dissipation of total pressure, normally attributed directly to the valve, is primarily accomplished by a shock system in the entrance diffuser. When the total pressure to be dissipated is high, as at the beginning of a run, the shock Mach number must also be high. The flow must be accelerated from the partially-open valve throat to a sufficiently high supersonic Mach number to provide the shock losses necessary to match the downstream stagnation pressure in the stilling chamber.

A simple conical diffuser has several inherent disadvantages for transonic wind-tunnel applications involving high ratios of storage reservoir to stilling chamber pressures. The strong normal shock preceded by relatively turbulent supersonic flow can generate a very high level of acoustic noise as discussed by Ribner.[5] In addition, the interaction of the shock system and the duct wall boundary layer can generate an unsteady separation process which also contributes to downstream flow unsteadiness. Finally, flow asymmetries caused by the partially open rotating-plug control valve can be carried downstream into the test section, causing flow angularity effects which vary with valve position and therefore with time. In developing the original facility design it was found that the shock bar and flow stabilizers, as shown in Fig. 2, reduced pressure fluctuations somewhat. However, their addition did not significantly change the basic single-shock throttling mechanism of a simple diffuser. Repeated fatigue failures of the flow stabilizing devices within the diffuser also occurred due to the unsteady, very high dynamic pressure, supersonic flow within the diffuser at transonic test section Mach numbers.

Consideration of the various factors discussed above leads to the concept of a diffuser system downstream of the valve with the following characteristics. 1) The flow

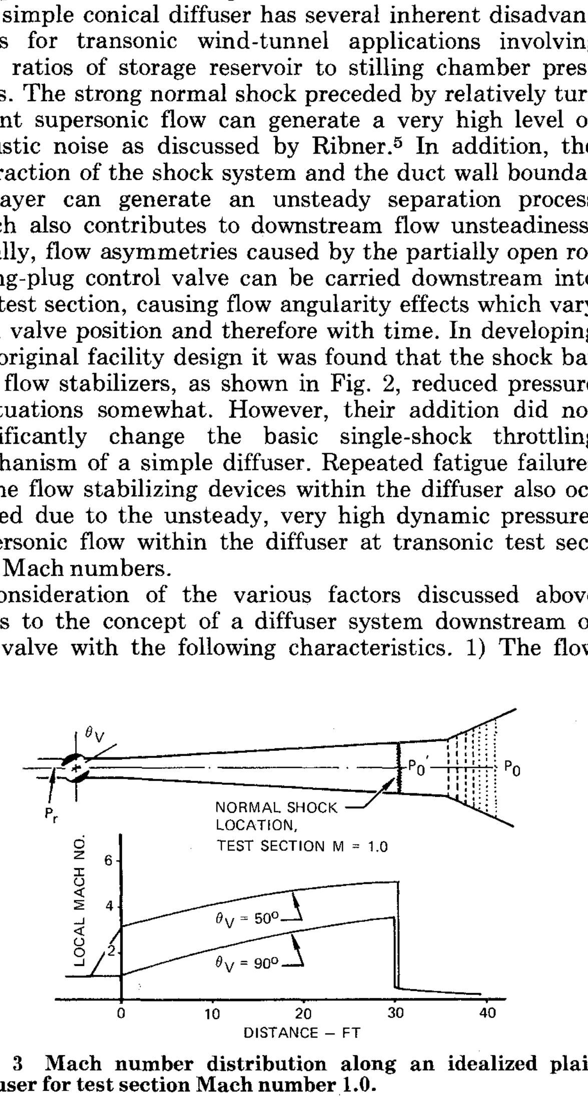

Fig. 3 Mach number distribution along an idealized plain diffuser for test section Mach number 1.0.

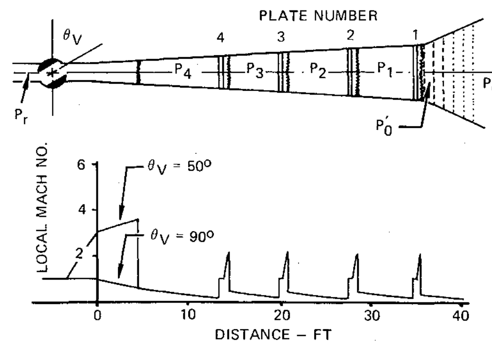

Fig. 4 Mach number distribution for a four-plate diffuser at test section Mach number 1.0.

through the system must be primarily subsonic to prevent shock-induced boundary-layer separation and to reduce fatigue failures of the internal structures. 2) Sufficient flow resistance must be provided to insure a flat velocity profile at the diffuser exit at all valve openings. 3) Run time must not be decreased due to additional losses in the diffuser.

The concept of a series of perforated plates to accomplish the above objectives was developed using simple one-dimensional flow analysis. Whereas the original diffuser utilized essentially a single terminal shock system, properly designed perforated plates could force multiple normal shocks of lesser strength to obtain the same final pressure ratio. Use of these plates would avoid extensive regions of supersonic flow, as shown by Fig. 4, prevent shock-induced boundary-layer separation, and provide the necessary resistance for a flat velocity profile. All of the above effects tend to minimize the generation of flow unsteadiness and acoustic noise.

Development of the simplified design equations may be obtained by equating mass flow through the choked full-open valve and the choked $M = 1.0$ test section to obtain the end-of-run total pressure ratio.

$$(P_r/P_o)_{\substack{\min \\ M=1.0}} = A^*_{o,M=1.0}/A^*_{v,\max} \tag{1}$$

where A^*_0 is the effective nozzle throat area, and $A^*_{v,\max}$ is the maximum effective valve flow area. The maximum available run length at the design Mach number of 1.0 will not be reduced if the pressure ratio in Eq. (1) is not increased.

The use of n choked perforated plates in series could achieve this end-of-run pressure ratio in n equal steps such that

$$(P_o/P_{o'})(P_r/P_o)_{\substack{\min \\ M=1.0}} = R^n \tag{2}$$

where $P_{0'}$ is measured upstream of the stilling chamber screens. Both pressure ratios on the left side of Eq. (2) can be obtained experimentally. The term R is the pressure ratio across each shock.

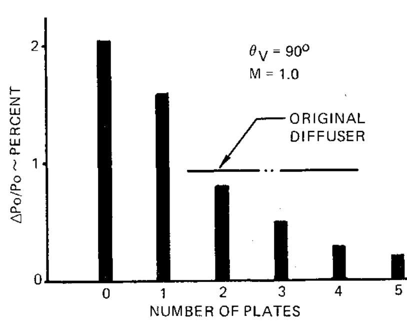

Fig. 5 Stilling chamber pressure unsteadiness as a function of number of plates, model tunnel data.

The effective open area of each plate required to produce n equal-strength shocks can be determined by equating the mass flow through the plate to that through the nozzle. For plate no. i ($i = 1$ is the most downstream plate),

$$A^*_i = (P_o/P_{o'})R^{-i}\ A^*_{o,M=1.0} \tag{3}$$

It can be shown from Eq. (3) that for the plate just downstream of the valve ($i = n$) the open area, A^*_n, is equal to the effective full-open valve area.

At Mach numbers higher (or lower) than $M = 1.0$ the plates successively unchoke, beginning at the most downstream plate, as the throat area becomes equal to the plate area. Above about $M = 3.2$ all plates are unchoked and low subsonic, high density flow exists downstream of the valve shock. At higher supersonic Mach numbers the duct flow density and velocity are such that the losses due to flow through the perforated plates are small and the maximum available run length is unchanged.

Design of Full Scale Diffuser

A 1/12-scale model representing the full scale facility from the control valve to the nozzle exit was constructed to evaluate various plate configurations designed according to the foregoing equations. Principal parameters evaluated were stilling chamber pressure fluctuations and velocity distribution at the diffuser exit. The over-all pressure fluctuations measured in the stilling chamber of the model tunnel agreed closely with similar measurements in the full-scale tunnel, both as to level and to variation with value pressure ratio. For adequate reduced frequency matching, the over-all rms fluctuation measurements in the model facility were essentially flat to 50 kHz. It was found that two to three plates were sufficient to eliminate valve-induced flow angularity, but more plates of the proper porosity achieved a significant reduction in stilling chamber pressure fluctuations.

Model tunnel results which show effectiveness of the number of plates in reducing stilling chamber pressure unsteadiness are shown in Fig. 5. Final results of the model tunnel program can be found in Ref. 6.

Following analysis of the model tunnel data, a four-plate 43% porosity configuration was selected based on both cost and performance considerations. The downstream plate (no. 1) was located at the exit of the 6° diffuser.

Pressure and strain measurements, including dynamic strain measurements, on the plates in the model facility were used to confirm the structural design of the full scale diffuser. The method of Gardner[7] was used for structural analysis of the perforated plates. The plate thickness was fixed at 4⅝ in. for plates 1, 2 and 3 and 5¾ in. for plate 4. Hole diameters were 1⅞ in. for plate no. 4 and 2.0 in. for all others. Internal dimensions of the diffuser shell remained the same as the original but the shell thickness of the upstream half was increased to accommodate higher transient pressures generated by the perforated plates during supersonic start and valve failure-mode conditions. The modified diffuser configuration is shown in Fig. 6.

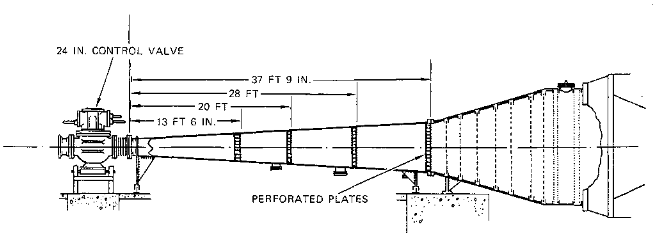

Fig. 6 Modified entrance diffuser.

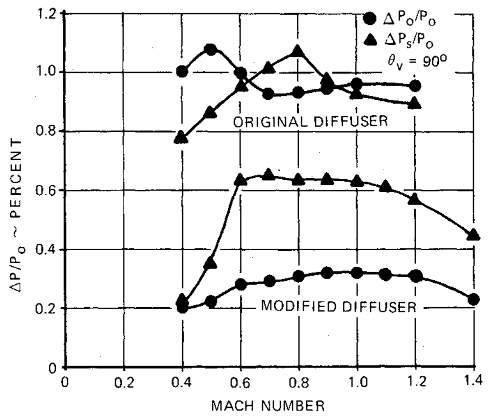

Fig. 7 Variation of stilling chamber and test section static pressure fluctuation levels with Mach number.

Evaluations of Flow Quality Improvements

Valve Induced Flow Angularity

Flow angle measurements with both the original and modified diffuser were obtained with a wing-body model held at zero degrees angle of attack and constant flow conditions until the control valve reached full open. Changes in lift coefficient were converted to changes in flow angle from a separate evaluation of lift coefficient vs angle of attack at several Mach numbers. Corrections for sting and balance deflections were included.

These data showed that, with the original diffuser configuration, the most significant flow angularity variations occurred at $M = 0.6$ between valve positions $\theta_v = 60°$ and $70°$. At these conditions $\Delta\Psi$ varied $\pm 0.4°$ and $\Delta\alpha$ varied $\pm 0.15°$. At other Mach numbers the $\Delta\Psi$ and $\Delta\alpha$ variations were less, although $\Delta\Psi$ was always greater than $\Delta\alpha$. At $M = 1.0$ $\Delta\Psi$ varied $\pm 0.15°$ with negligible $\Delta\alpha$ variation.

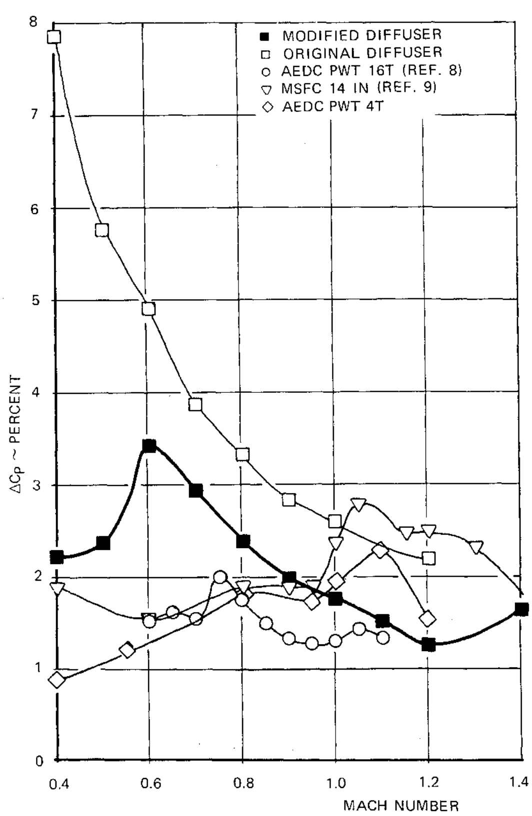

Fig. 8 Variation of test section centerline static pressure fluctuation level with Mach number.

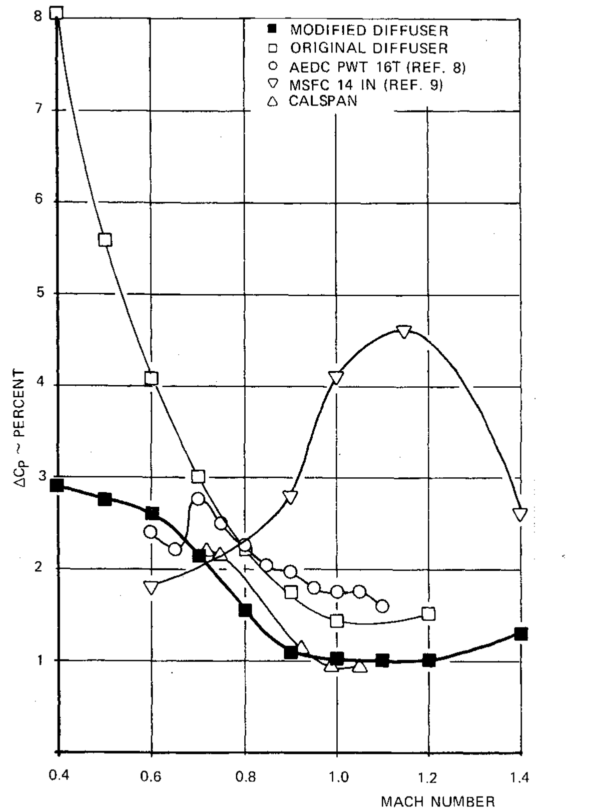

Fig. 9 Variation of test section wall pressure fluctuation level with Mach number.

After modification the $\Delta\Psi$ and $\Delta\alpha$ variations were eliminated at all valve positions and all Mach numbers within the measurement accuracy, estimated to be $\pm 0.02°$.

Pressure Fluctuations

The reduction in stilling chamber and test section pressure fluctuations was evaluated by measurements made before and after the diffuser modification. These comparisons are shown in Figs. 7–9 as measurements of over-all rms pressure fluctuation levels in the 20 Hz to 25 kHz range, and as pressure fluctuation spectra in the 80 Hz to 10 kHz range in Figs. 10 and 11. Test section pressure fluctuation levels were measured both at the wall and on the centerline at the same streamwise tunnel station. The centerline measurements were made on a 5° half-angle

Fig. 10 Spectra of stilling chamber pressure fluctuations, referred to 1 Hz bandwidth.

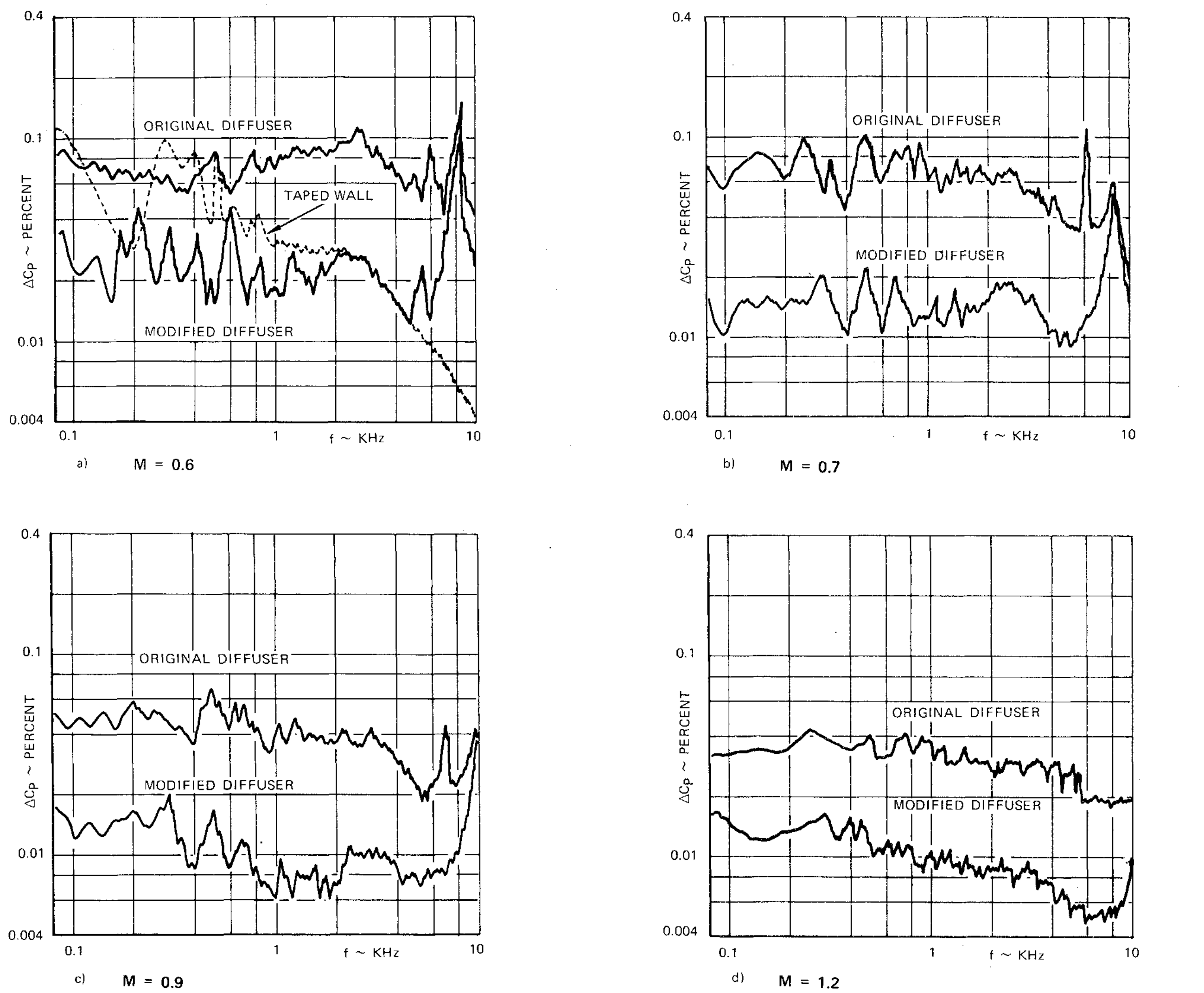

Fig. 11 Spectra of test section centerline pressure fluctuations, referred to 1 Hz bandwidth.

cone model and wall measurements were made on a small flat plate mounted normal to the wall. Small, high frequency response pressure transducers were used at both test section locations and in the stilling chamber.

Comparisons of stilling chamber and test section pressure fluctuation levels, Fig. 7, show stilling chamber pressure fluctuations were reduced by a factor of 3 which is in close agreement with the reduction predicted on the basis of model tunnel results. Test section static pressure fluctuations were reduced by a factor of 1.6. The probable explanation for the smaller reduction in test section pressure fluctuations is that with the original diffuser the upstream flow unsteadiness largely masked the test section generated unsteadiness in the over-all pressure fluctuation measurements. Although the upstream-induced fluctuations were diminished by the modifications, the test section generated unsteadiness was unaltered.

The static pressure fluctuation level in the test section at a constant total pressure was highest between $M = 0.6$ and 1.0 as shown in Fig. 7. However, when related to dynamic pressure as in Fig. 8, the unsteady pressure coefficient was a maximum at $M = 0.6$ and minimum at about $M = 1.1$.

Figure 8 presents centerline static pressure fluctuation data compared with similar data from other facilities.[8,9] All data presented in Fig. 8 were obtained on the same 5° half-angle conical model. Both continuous and intermittent wind tunnels are represented. Wall pressure fluctuation measurements from various facilities are compared in Fig. 9. Techniques and instrumentation for measurement of the wall pressure unsteadiness levels were identical for only the Calspan and VSD data. In general, the VSD wall unsteadiness levels were found to be somewhat lower than the centerline levels, whereas the other tunnel measurements indicated wall unsteadiness levels higher than the centerline levels.

Narrow-band spectra in the 80–10,000 Hz range are shown in Figs. 10 and 11 for both the stilling chamber and test section centerline locations. The data in these figures were obtained using a narrow-band frequency analyzer with a constant 20 Hz bandwidth averaged from 256 samples using the relation:

$$\Delta P(\text{per Hz}) = \Delta P(\text{per } \Delta f)(1/\Delta f)^{1/2} \tag{4}$$

where $\Delta f = 20$ Hz analyzer bandwidth.

The stilling chamber pressure fluctuation spectra, as percent of stagnation pressure, are shown in Fig. 10. These data were found to be essentially uninfluenced by Mach number but increased in level at smaller valve openings. Significant reductions due to the diffuser modification were observed in the frequency range from 20 Hz to 4 kHz.

Test section centerline spectra at several Mach numbers are shown in Fig. 11 as percent of dynamic pressure. These data show reductions at all frequencies except in the vicinity of 8 to 10 kHz, depending upon Mach number, where test section noise generation is observed as prominent peaks. Data obtained with the test section walls covered with vinyl tape, Fig. 11a, show a dramatic reduction of this high frequency energy. Similar results were obtained with covered perforations at $M = 0.7$, 0.9, and 1.2. These results indicate that the high level peaks are probably edge tones generated by flow over the 13/32-in. diameter normal holes in the perforated wall. These peaks do not exist below $M = 0.4$ or above $M = 1.4$ (at least below 10 kHz). The generally higher level and variation of level with frequencies below 1000 Hz with the walls covered with tape may indicate that the perforated test section walls are selectively absorbing energy in this frequency range.

The test section spectra shown in Fig. 11 were found to be independent of valve position, although the stilling chamber pressure fluctuations increased at lower valve openings. It was inferred from these results that reducing the stilling chamber fluctuation below 0.3 to 0.4% may result in negligible improvements in over-all test section pressure fluctuations, at least at Mach 0.6 and higher, since test section generated unsteadiness will dominate.

Model Dynamics and Buffet Measurements

Reductions in test section flow unsteadiness below 1000 Hz are of particular interest since model and balance natural frequencies are within this range and can receive considerable excitation from flow unsteadiness. As an example, normal force fluctuation measurements were made on a wing-body configuration before and after the modification. At low angles of attack the wide-band rms fluctuations of normal force were reduced by a factor of two by the modification. This improvement is reflected in improvements in the accuracy and repeatability of static force data.

An evaluation of flow unsteadiness improvement was made by employing the tunnel unsteadiness criteria for light buffeting given by Mabey.[3] Figure 12 presents the unsteadiness parameter $\Delta P_s/q\epsilon^{1/2}$ on the tunnel centerline at four center frequencies as a function of Mach number. These data were averaged over a ½-octave range with center frequencies of 100, 150, 200, and 300 Hz. The test section unsteadiness parameter at the natural frequency of a wing should be less than about 0.003 to obtain meaningful buffet onset and intensity data. Figure 12 shows a very significant improvement of the buffet testing capability.

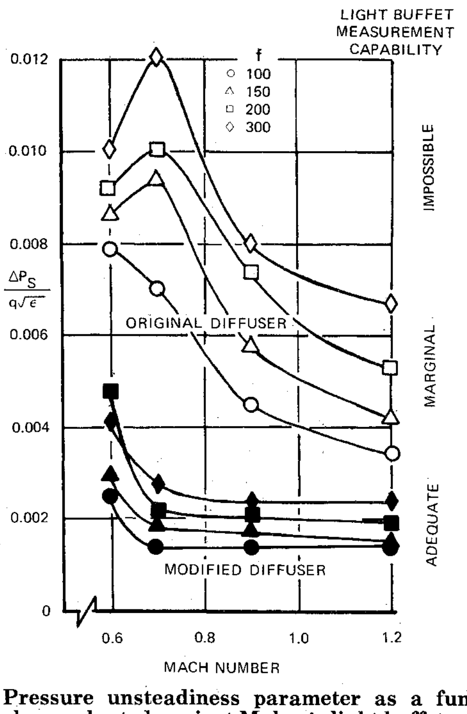

Fig. 12 Pressure unsteadiness parameter as a function of Mach number evaluated against Mabey's light buffet criteria.

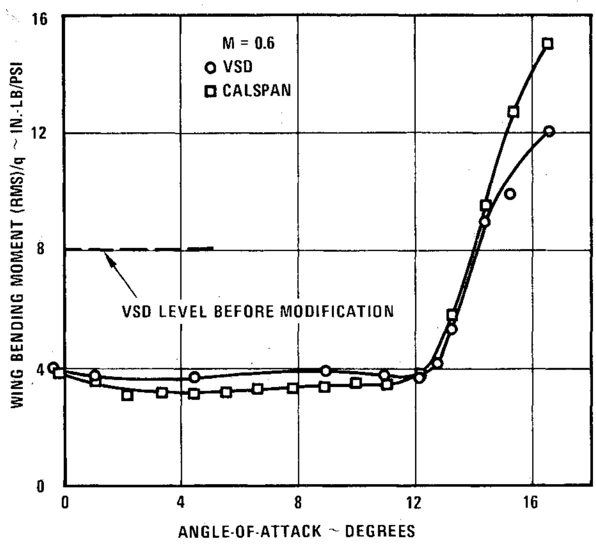

Fig. 13 Wing-root-bending moment buffet data comparison.

A more direct evaluation of the effects of the unsteadiness reduction on typical wing-root-bending buffet data is shown in Fig. 13, comparing data obtained from tests on the same wing-body model in the VSD and Calspan facilities. Note the agreement in level at low angles of attack and the reduction in level by a factor of two in the VSD facility resulting from the modification. Approximately 5 sec of run time per point produced repeatable and consistent results in the modified VSD facility. Previously, ten to twenty seconds had been required. These wing-root-bending data include frequencies from approximately 20 Hz to 1 kHz. The balance and model sting were the same in both facilities, but the over-all Calspan support system was probably somewhat more flexible than the VSD system due to a longer total sting length. This factor may account for the differences above about 14° angle of attack.

Conclusions

An evaluation of the multiple-shock entrance diffuser has shown significant improvements in transonic flow quality. Among the more important improvements are: 1) elimination of control valve-induced flow angularity in the test section; 2) a significant reduction in the flow unsteadiness level in the test section at all frequencies up to about 9 kHz; 3) a decrease in model force measurement fluctuations by a factor of two; and 4) an improvement of the flow quality for unsteady pressure and buffet tests to satisfactory levels. These flow quality improvements were gained from a new type of flow conditioning system which controls the dissipation of the high storage pressure in a transonic wind tunnel with essentially no penalties in run time. This flow conditioning technique can be applied to any high pressure ratio throttling requirement where a loss in total pressure is desired without creating high levels of noise and flow unsteadiness downstream. The method is applicable to any system in which the downstream choke area is larger than the full-open control valve area.

The results of this modification and evaluation program demonstrate that careful flow conditioning is required for a high Reynolds number blowdown, transonic wind tunnel, but that transonic flow quality essentially equal to that in a continuous facility can be achieved.

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