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SOME REMARKS ON THE DESIGN OF TRANSONIC TUNNELS WITH LOW LEVELS OF FLOW UNSTEADINESS

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16. Abstract
Flow unsteadiness in wind tunnels is defined and its importance for aerodynamic measurements outlined. The principal sources of flow unsteadiness in the circuit of a transonic wind tunnel are enumerated. Care must be taken to avoid flow separations, acoustic resonances and large scale turbulence. Some problems discussed are the elimination of diffuser separations, the aerodynamic design of coolers and the unsteadiness generated in ventilated working sections (both slotted and perforated).

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SOME REMARKS ON THE DESIGN OF TRANSONIC TUNNELS WITH LOW LEVELS OF FLOW UNSTEADINESS*

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SUMMARY

Flow unsteadiness in wind tunnels is defined and its importance for aerodynamic measurements outlined. The principal sources of flow unsteadiness in the circuit of a transonic wind tunnel are enumerated. Care must be taken to avoid flow separations, acoustic resonances and large scale turbulence. Some problems discussed are the elimination of diffuser separations, the aerodynamic design of coolers and the unsteadiness generated in ventilated working sections (both slotted and perforated).

1. INTRODUCTION

It is a great personal pleasure for me to be invited to give this lecture at NASA Langley Research Center when the 2.5m x 2.5m National Transonic Facility is being designed. This lecture cannot provide all of the answers to your problems because successful transonic tunnel design involves finding the correct solution of many conflicting requirements. However, the lecture may serve to focus attention on some of the main problem areas.

2. DEFINITIONS AND MEASUREMENTS OF FLOW UNSTEADINESS

Tunnel unsteadiness is really a generic term covering velocity, pressure and temperature fluctuations (fig. 1), but the temperature fluctuations may, in general, be neglected at transonic speeds.

The turbulent velocity components

$$u', v', w'$$

are extremely difficult to measure at subsonic and transonic speeds, even in continuous facilities. Hot wires tend to fatigue rapidly at transonic speeds because of aerodynamic buffeting (the critical Mach number of a circular cylinder is about $M = 0.5$). In addition, there is aerodynamic interference at transonic speeds from the prongs which support the hot wire and the interpretation of the hot-wire signal is difficult.

A few measurements of the lateral components of turbulence v', w' have been derived from differential-pressure yawmeters. Thus Igoe measured rms incidence fluctuations varying from about 0.25 to 0.50° in the Langley 16 ft. transonic tunnel[1], and rms incidence fluctuations of 0.3° have been measured in the NAE 5 ft transonic tunnel[2]. However, it is difficult in yawmeter measurements to isolate the contribution of the static pressure fluctuations.

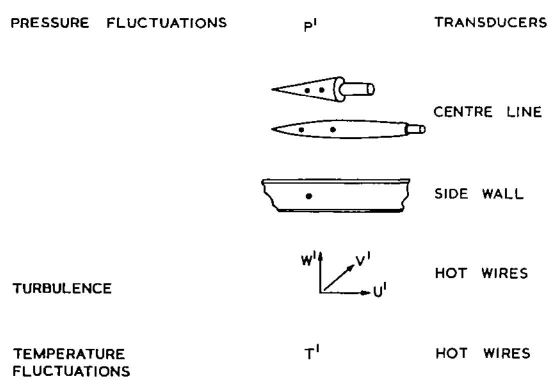

Figure 1. Flow Unsteadiness

In view of these difficulties, the flow unsteadiness is normally assessed by measuring the static pressure fluctuations on a body of revolution on the tunnel centre line or on the sidewall of the tunnel. Centre line and sidewall pressure fluctuations seem to be comparable for many transonic facilities[3] but McCanless suggests that, for several large American tunnels, the centre line pressure fluctuations may vary from 70 percent to 100 percent of those on the sidewall[4]. Siddon has shown how difficult it is to isolate the true static pressure fluctuations from those associated with the velocity fluctuations[5]. (There is also some unpublished evidence that the presence of a body of revolution on the centre line of a windtunnel may itself alter the pressure fluctuations on the sidewall , although this effect was small in other tests[6]).

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*A lecture given at the NASA Langley Research Center on September 15, 1975. The views expressed by the author do not necessarily represent the views of RAE.

Owen has described the basic technique used for pressure fluctuation measurements in RAE windtunnels[7]. The results are presented in nondimensional form (fig. 2) by dividing the rms intensity of pressure fluctuations, $\bar{p}$, by the windtunnel kinetic pressure q. A nondimensional frequency parameter n = fw/V is used (referred to as a Strouhal number when one particular frequency parameter predominates in the pressure fluctuation spectra), where f = frequency Hz (c/s), w = width of tunnel m (ft) and V = velocity in m/s (ft/s) and a nondimensional spectrum function F(n) is defined such that

$$\frac{\overline{p^2}}{q^2} = \int_{n=0}^{n=\infty} F(n)dn = \int_{\log n = -\infty}^{\log n = \infty} nF(n)d(\log n).$$

In buffeting investigations, the presentation of excitation spectra in terms of $\sqrt{nF(n)}$ against log n is useful and this form is adopted here. The pressure transducer receives additional excitation from the fully-established turbulent boundary layer on the sidewall or body of revolution, but this represents a small, nearly constant correction at high frequency, which is often approximated by $\bar{p}/q = 0.006$. For a turbulent boundary layer, the rms pressure fluctuations are given more precisely by $\bar{p}/q = 2.5$ x the skin-friction coefficient C_f, and C_f is estimated to be about 0.002 to 0.003 for these tunnel boundary layers[8]. No corrections are generally made to the spectra for the pressure fluctuations in the turbulent boundary layer or for the size of the transducer relative to the boundary layer, because these corrections are normally of low amplitude and high frequency relative to the spectrum of flow unsteadiness.

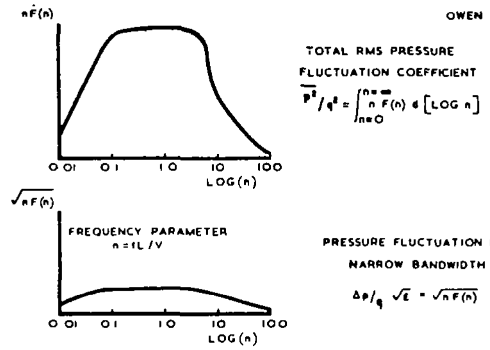


Figure 2. Dimensionless representation of *excitation spectra.*

FLUID MECHANICS

INVISCID FLOW

BOUNDARY LAYER TRANSITION

TURBULENT BOUNDARY LAYER DEVELOPMENT

SHOCK WAVE / BOUNDARY LAYER INTERACTION (WINGS AND INTAKES)

BUBBLE AND VORTEX FLOWS

TRAILING EDGE SEPARATIONS AND WAKES

WIND TUNNEL PROBLEMS

STEADY MEASUREMENTS

RUNNING TIME FOR ACCURATE DATA

DRAG-IN PRESENCE OF AXIAL FORCE VIBRATIONS, FATIGUE FAILURES

UNSTEADY MEASUREMENTS

DYNAMIC DERIVATIVES

FLUTTER

BUFFETING

MORAL

SPECIFY FLOW UNSTEADINESS AS WELL AS REYNOLDS NUMBER

Figure 3. Flow unsteadiness and windtunnel measurements.

3. INFLUENCE OF TUNNEL UNSTEADINESS ON THE FLOW OVER MODELS

Tunnel unsteadiness can influence the flow on models in several different ways that are, however, closely interrelated. In this section, a number *of aspects are discussed, which are important in* model tests, especially in tests of swept wings (fig. 3).

3.1 INVISCID FLOW

The velocity fluctuations *v', w' produce fluc*tuations in the angles of incidence and sideslip (α , β) whereas the u' fluctuation produces a fluctuation in kinetic pressure q and local Mach number M. These fluctuations would collectively produce fluctuating inviscid forces on the model. The fluctuation in kinetic pressure *will* produce fluctuating forces without any first-order change in the shape of the pressure distribution on the wing. However, the shape of the pressure distribution can be altered by the fluctuations in attitude and Mach number and quite small fluctuations may produce *significant* changes in the shape of the pressure distribution at transonic speeds. These effects will probably be most apparent in the low-frequency part of the spectrum of flow unsteadiness.

3.2 BOUNDARY-LAYER TRANSITION

All tests made with free transition at transonic speeds are likely to be sensitive to the level of flow unsteadiness, as Lloyd Jones suggested[9].

Drag measurements with free transition are probably sensitive to flow unsteadiness, which would alter the transition position. Thus, Cumming and Lowe[10] suggest how the drag measured with free transition on a model of the F-111 aircraft was influenced by unsteadiness generated by the walls of the working *section. The model was tested at identical conditions in a windtunnel which could be fitted with either* porous or slotted walls. The minimum drag of the model was much higher with porous walls than with slotted walls, probably because transition was further forward on the model at the higher noise levels which were believed to exist with the porous walls.

Great care may be needed in assessing apparent Reynolds number variations from measurements made "*transition free.*" *Apparent variations in aerodynamic performance (e.g., buffet onset boundaries) with* Reynolds number may be caused by changes in the state of the boundary layer derived from the variation of both the Reynolds number and the level of tunnel unsteadiness.

The prediction of natural transition on swept wings is extremely difficult. Treadgold and Beasley[11] have attempted to calculate transition Reynolds numbers on a series of swept wings in incompressible flow according to four different criteria, namely:

growth of Tollmien-Schlichting waves;
sweep instability;
transverse contamination from the leading-edge; and
relaminarization.

It is planned to extend these calculations to transonic speeds, but it is likely that all these criteria will be influenced by the level of unsteadiness in the flow.

When tests are made with fixed transition, Lloyd Jones suggested[9] that the boundary-layer development is not significantly influenced by variations in the level of tunnel unsteadiness. Despite this suggestion, there is some unpublished evidence from comparative tests on the same model at the same unit Reynolds numbers in both the ARA 9ft x 8ft and RAE 3ft x 3ft tunnels that appreciably different roughness heights are required to fix transition in these facilities. It is possible that these differences in critical roughness height may be caused by differences in the level of unsteadiness at high frequencies in the two facilities, but extensive research would be required to confirm this hypothesis. It is recommended that roughness criteria on models should always be checked when unsteadiness levels are changed in any part of the frequency spectrum, or when the same model is tested in several different facilities with different spectra of unsteadiness.

3.3 TURBULENT BOUNDARY-LAYER DEVELOPMENT

Variations in flow unsteadiness can also influence the development and structure of the turbulent boundary layer. Charney, et. al, have shown[12] that at low speeds variations in turbulence level from $u'/u = 0.3$ percent to 4.7 percent can increase the rate of growth of the boundary layer on a flat plate in a zero pressure gradient, distort the velocity profiles and increase the shear stress at the walls. Green has analyzed these measurements to show how the strength of the wake component of the velocity profile decreases as the free stream turbulence level increases[13]. The analysis suggests that a turbulence level as low as 0.1 percent will increase the local skin friction coefficient, C_f, by about 0.5 percent compared to a quiescent stream; this increase is probably within the limits of experimental accuracy for most skin friction measurements. However, the form parameter, H, will also be 0.003 lower than in a quiescent stream; this corresponds with an equivalent Reynolds number based on momentum thickness about 6 percent higher. Green suggests that similar, or even more pronounced trends would be found in adverse pressure gradients, so that at low speeds a turbulent boundary layer should separate later in a turbulent stream than in a quiescent stream. If this hypothesis is verified, it might justify the practice, once common in some small low-speed windtunnels, of attempting to increase the effective Reynolds number by increasing the free stream turbulence level.

Similar effects are likely to persist at transonic speeds because there is no change in the basic structure of the turbulent boundary layer[14] until high-supersonic speeds. However, at transonic speeds most of the unsteadiness is associated with pressure fluctuations radiated from the slotted or perforated walls, rather than vorticity fluctuations convected from the settling chamber[3], and we do not yet know how the turbulent boundary layer will react to imposed pressure fluctuations.

On lifting wings at transonic speeds, boundary layers are subject to steep pressure gradients, and the turbulence structure in model tests must be representative of full-scale flows to give correct answers for boundary layer thicknesses, profile shape, skin friction and tendency to separation.

3.4 SHOCK WAVE/BOUNDARY-LAYER INTERACTION

The character of the interference caused by flow unsteadiness on shock wave/boundary-layer interactions will probably be different according to whether or not the shock is sufficiently strong to separate the boundary layer. There is evidence that the pressure fluctuations caused by the oscillation of a shock strong enough to separate the boundary layer are strongly influenced by flow unsteadiness[15]. This can also be seen by examination of schlieren photographs taken on an aerofoil (See fig. 5.4 of reference 16) at transonic speeds.

3.5 BUBBLE AND VORTEX FLOWS

Flow unsteadiness is likely to have a strong influence on the pressure fluctuations developed by separated bubble flows, as the author suggested previously[17]. If the tunnel unsteadiness or turbulence is excessively high at a particular frequency, this could alter any feedback process between conditions at separation and reattachment, as a Karman vortex street or an acoustic resonance does. Alternatively, the strength of the wake component of the boundary layer, and hence the low-frequency pressure fluctuations, may be altered. This effect might be important when the wake component is large, close to flow separation or reattachment.

Wills has shown[18] how the first diffuser may introduce spurious low-frequency pressure fluctuations into the working section of a low-speed windtunnel. However, the level of these spurious pressure fluctuations required to alter the spectra generated by separated flows has not yet been established.

Flow unsteadiness may also affect the strength of leading-edge vortex sheets on slender wings and the small pressure fluctuations caused by these vortices, by modifying the structure of the shear layer and the strength and position of secondary vortex sheets. On swept wings, the spanwise origin of part-span vortex sheets may be affected by flow unsteadiness.

3.6 LEADING-EDGE SEPARATIONS AND SHOCKLESS RECOMPRESSIONS

The flow around the leading edge of wings and, in particular, the development of separation or shockless recompressions can be expected to be influenced by flow unsteadiness because both phenomena are strongly dependent upon the state of the boundary layer and the local flow conditions[19].

3.7 TRAILING-EDGE SEPARATIONS AND WAKES

Flow unsteadiness can be expected to have some influence on the development and the structure of the viscous region near the trailing-edge and in the wake of wings and hence on the occurrence of flow separations. This concerns the important type B flow of Pearcey[20], and it is vital that this can be investigated without distortion due to unsteadiness.

3.8 INTAKE MEASUREMENTS

The AGARD Ad Hoc Committee on engine-airplane interference and wall corrections in transonic wind tunnel tests[21] found that very little data are available on either the magnitude of the flow unsteadiness effects on intake performance or of the levels of unsteadiness in windtunnels commonly used for intake tests.

However, paper 2 of ref. 21 includes a brief discussion by Jaarsma on the effect of unsteadiness on the surge characteristics and mean pressure recovery of an intake. The turbulence is generated primarily in the shock region. This region is likely to be subject to strong interference with the unsteadiness, if Robertson's results[15] for missiles are relevant to intakes, which have similar pressure distributions and shock wave/boundary-layer interactions in the vicinity of the shock. Stewart and Fisher[22] showed that the "buzz" boundary of a supersonic inlet could be masked by a high level of tunnel turbulence (which was not measured) just as buffet onset on a wing can be masked by a high level of unsteadiness.

4. POSSIBLE CRITERIA FOR ACCEPTABLE LEVELS AND FLOW UNSTEADINESS

The review above indicated qualitatively the broad range of measurements which can be influenced by flow unsteadiness. However, it is extremely difficult to quantify the magnitude of these effects.

The onset of light buffeting can be detected[3] in a continuous tunnel (fig. 4) if

$$\sqrt{nF(n)} \leq 0.002$$

at all the frequencies of interest, and this makes a severe requirement which may cover most other transonic tests. This criterion corresponds roughly with total rms pressure fluctuations in the free stream of about

$$\bar{p}/q = 0.5 \text{ percent}$$

i.e., of the same order as those generated by an attached turbulent boundary layer. Although a few well designed transonic tunnels achieve this low level at some speeds, most have levels ranging from about

$$\bar{p}/q = 1.0 \text{ percent to } 2.5 \text{ percent}$$

Pugh has recently suggested that for intermittent tunnels an even more severe requirement must be applied to make precise determinations of buffet onset within a comparatively few cycles of buffeting. Perhaps the only safe solution is to aim for the lowest possible level of flow unsteadiness over the complete frequency range.

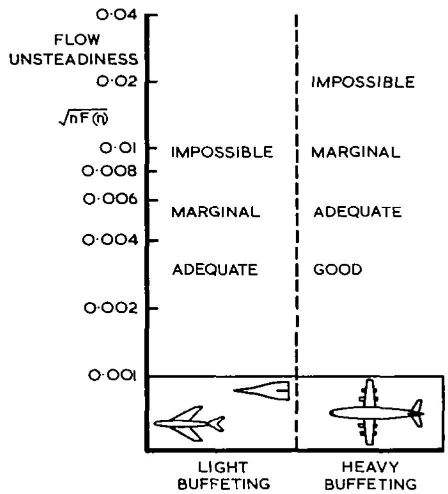


Figure 4. Flow unsteadiness criteria for tunnel buffeting tests.

5. SOURCES OF FLOW UNSTEADINESS IN TRANSONIC TUNNELS

Figure 5 shows most of the sources of flow unsteadiness which may occur in a continuous transonic tunnel driven by a compressor or fan; all of these should be carefully considered in the design of the cryogenic NTF. We shall only have time to consider flow unsteadiness generated in the diffuser upstream of the maximum section, in the cooler, in the first diffuser, and in the ventilated working section.

The golden rules to ensure low levels of flow unsteadiness are shown in fig. 6. These criteria are arranged in ascending orders of magnitude of cost. It is comparatively cheap to ensure no large scale turbulence by using the design criteria given by Bradshaw[23] for low speed wind tunnels. It may be more expensive to eliminate resonances because flow baffles or sound absorbing treatment may be required. It is expensive to eliminate separations because this means careful design and small diffuser angles, which means much greater cost.

It is worth remarking that cryogenic facilities should have no additional intrinsic aerodynamic problems compared with conventional wind tunnels. Thus, the rms pressure fluctuations generated by the attached turbulent wall boundary layers should be smaller because of the higher Reynolds numbers, and because these boundary layers will be thinner the energy in the spectra should be displaced to higher frequencies than in a conventional wind tunnel. Similarly, if flow separations can be avoided for operation with air at atmospheric pressure and temperature, they should also be avoided at the higher Reynolds numbers associated with cryogenic operation because higher Reynolds numbers almost invariably increase the resistance of turbulent boundary layers to flow separation. One possible problem area may be in the selection of the optimum point in the tunnel circuit for the injection of liquid nitrogen.

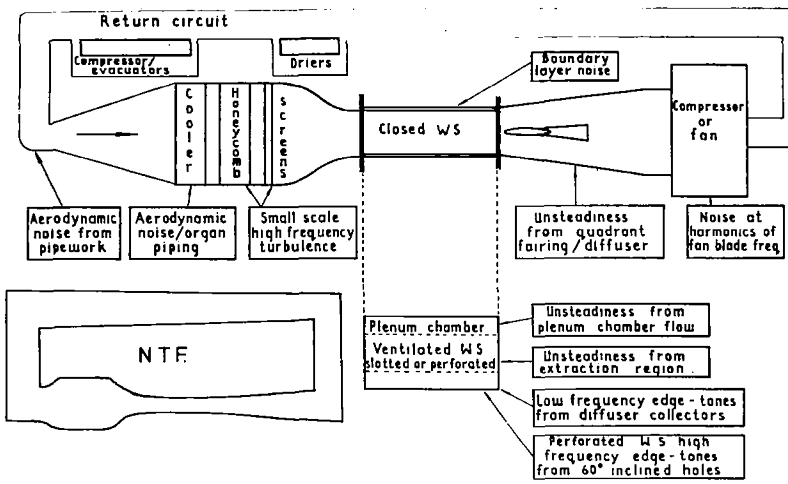


Figure 5. Sources of unsteadiness in transonic tunnels.

Model tests of tunnel designs should give clear guidance for the avoidance of resonances and large scale separations. However, phenomena which occur at small scale, such as edge-tones generated by perforations or organ piping in the plenum chamber excited by the diffuser, may be much more difficult to represent accurately; these problems are sensitive to the boundary layer thickness. The edge-tone problem is being closely investigated both by the AEDC and ONERA using partial models of ventilated walls, and results of these tests should be reported shortly.

GOLDEN RULES	COST
NO LARGE SCALE TURBULENCE	1
NO RESONANCES	10
NO SEPARATIONS	100

Figure 6. Golden rules

5.1 SETTLING CHAMBER DESIGN

The importance of a good aerodynamic design upstream of the working section cannot be too highly stressed, because disturbances from the settling chamber are convected downstream into the working section. One interesting example occurred[24] in the RAE 3 ft x 4 ft supersonic tunnel, which was designed without much attention to the steadiness of the flow. The maximum velocity in the settling chamber was about 13 m/s (at M = 2.5) and this value is fairly typical of a transonic tunnel design.

Figure 7 shows the initial, low frequency, flow fluctuations in the working section, which prevented the accurate calibration of the tunnel. On evidence to be presented later (fig. 10), it was decided that the problem would have to be investigated at full-scale, and that model tests would not be particularly helpful. This was an important decision which was vindicated by the subsequent measurements.

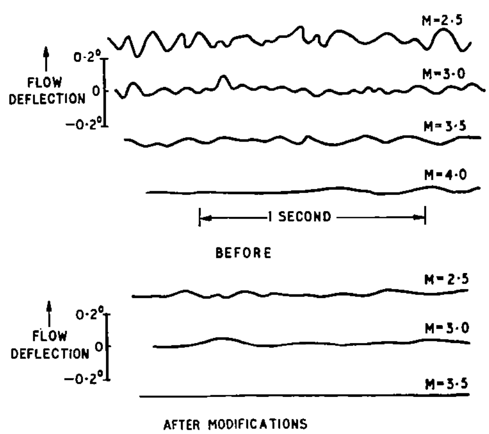


Figure 7. Indicated flow fluctuations in working section.

Figure 8 shows how the flow fluctuations in the working section were generated by a separation on one side of the 13° diffuser upstream of the settling chamber. [This separation was shown in a cine-film which followed this lecture]. A pair of vortex generators was added to eliminate this diffuser separation. Subsequently, a honeycomb was inserted at the end of the diffuser to destroy the large scale turbulence provided by the vortex generators. Following Bradshaw's suggestion[25], to ensure a small turbulence scale in the final flow through the working section, the 4th high drag screen was removed and replaced with another of lower drag (higher open area ratio). An additional low drag screen was added to ensure that the final level of the rms turbulence was lower with the final configuration than with the original configuration. The method of construction adopted for the tunnel [also shown in the cine-film] made it relatively easy to insert the honeycomb and to alter the screen configuration. Turbulence measurements were made in the settling chamber downstream of the last screen to assess the improvement in flow quality.

Figure 9 shows the turbulence reduction achieved with the vortex generators. The first pair adopted achieved a stable diffuser flow with the good inlet distribution provided by parallel operation of the compressors, but a bi-stable condition existed with the poor inlet distribution provided by series operation of the compressors (manifestly these differing inlet distributions would have been difficult to represent in model tests). The addition of a small tip extension to the vortex generators to increase the mixing sufficed to ensure stable diffuser flow for both parallel and series operation of the compressors.

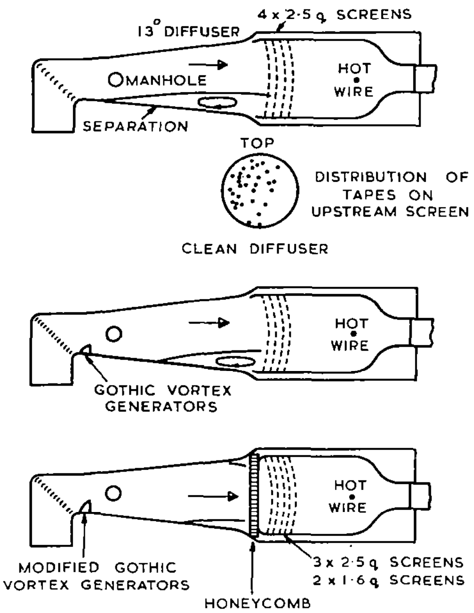


Figure 8. Effect of tunnel changes on mean diffuser flow, M = 2.5.

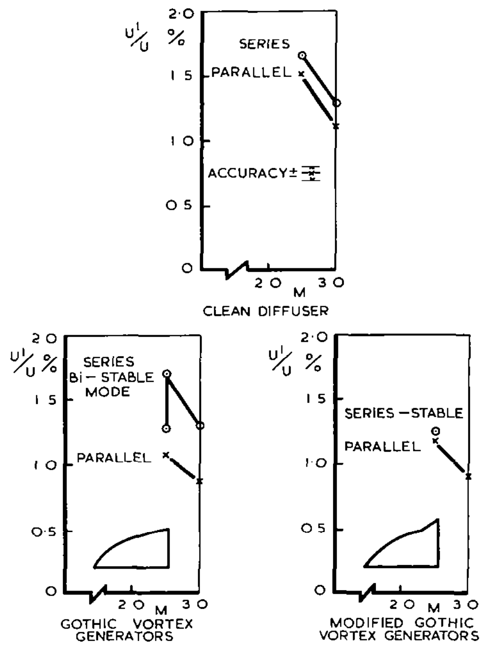


Figure 9. Turbulence reduction with vortex generators.

The next set of curves shows the corresponding improvements in turbulence level in the settling chamber. With the unmodified "clean diffuser" (fig. 10) the flow was anything but clean, with a high turbulence level and large Reynolds number effects, quite different at M = 2.5 and at M = 4.0. This evidence precludes the investigation of the problem in a scale model.

In a transonic tunnel, if similar separations occurred at the same velocities, the Reynolds number effects on the flow in the working section would be large. With the vortex generators the turbulence level is much lower (fig. 11), but there is still a marked difference between the results for M = 2.5 and 4.0, reflecting a flow sensitive to diffuser inlet conditions. Note the large Reynolds number effect at the lower diffuser velocity (curve for M = 4.0). With the addition of the honeycomb we have an ideal flow in the settling chamber (fig. 12) with a low turbulence level u'/U = 0.5 percent invariant with Reynolds number which is almost, but not completely independent of the compressor operation. This is the sort of target we should aim for in the settling chamber of a fan driven transonic tunnel.

The measured reduction in working section flow fluctuations corresponds remarkably well with that predicted by Ribner's theory[26] under the assumption of isotropic turbulence in the settling chamber. Ribner's theory has already been verified at low speeds and fig. 13 suggests that tentatively it may be assumed to be valid at transonic speeds. Thus, this theory could be used to help select an acceptable turbulence level in the settling chamber for a given contraction ratio.

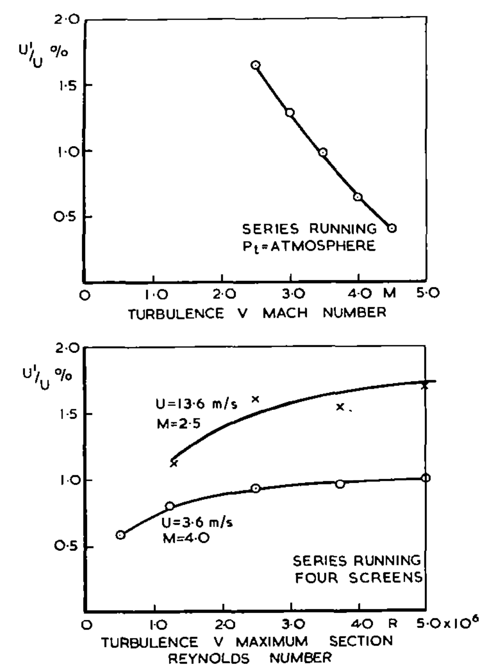


Figure 10. Turbulence with clean diffuser.

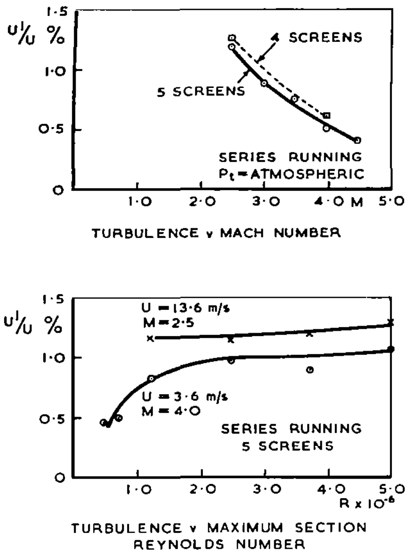


Figure 11. Turbulence with vortex generators.

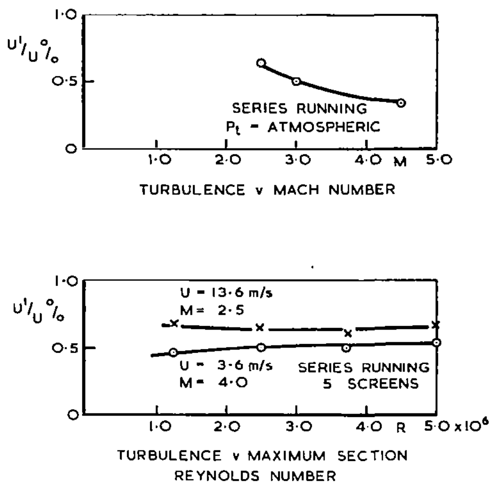


Figure 12. Turbulence with vortex generators plus honeycomb.

5.2 COOLER DESIGN

Most continuous transonic tunnels incorporate a cooler close to the maximum section. The NTF is also to function with air and so a cooler will be provided. If this cooler incorporates circular tubes, there is the possibility of vortex shedding over a wide range of Reynolds numbers. If the vortex shedding frequency (which depends strongly on the details of the cooler configuration) coincides with a standing wave frequency, resonant conditions may be encountered[27-30]. It is preferable to design coolers so that resonant conditions can be avoided, but if by mischance they are encountered in a particular cooler the single vortex shedding frequency may be suppressed by fitting inclined splitter plates into the coolers. These splitter plates also "detune" the coolers by raising the resonant frequencies.

Splitter plates of this type were used to eliminate severe noise and structural vibration in a cooler for the RAE 3 ft wind tunnel.

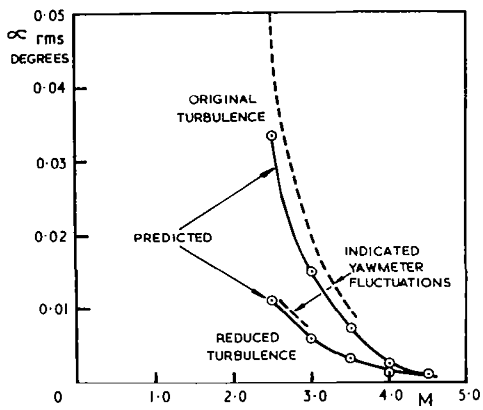


Figure 13. Predicted and indicated fluctuations versus Mach number.

The Karman vortex shedding frequency f_1, Hz for circular tubes is

$$f_1 = kV/d \qquad \text{Eq. 1}$$

where V = velocity between the tubes in m/sec and d = tube diameter in m (ignoring fins). k is the Strouhal number which varies with cooler geometry. For staggered tube arrangements values of k of about 0.2 have been reported[29]. The value of k = 0.46 quoted in ref. 28 is based on the approach velocity, rather than the velocity between the tubes and probably corresponds to k = 0.2 on the present definition. k is also about 0.2 for isolated circular cylinders.

For in-line tubes the experiments of Grotz and Arnold[30] suggest that f_1 should depend on s, the streamwise pitch between the rows, rather than the tube diameter d, k should then be about 0.5. The standing wave resonance frequency f_2, Hz is

$$f_2 = nc/2h \qquad \text{Eq. 2}$$

where n = an integer

c = velocity of sound in m/sec

and h = duct height in m normal to the flow direction and the tube axis. Standing waves can form when

$$f_1 = f_2$$

and the necessary energy is provided by an increase in pressure drop across the coolers[28].

Figure 14 shows features of the 3 ft tunnel coolers relevant to this discussion. There are two cooler banks separated by a duct. The cooler tubes are staggered and their diameter is 19 mm.

Figure 15 shows the variation of vortex shedding frequency with the velocity between the tubes; the values estimated with k = 0.2 compare quite well with audio-frequency measurements, as in an American cooler which experienced comparable noise and vibration[29]. It will be noted that the cooler operates in the subcritical range of Reynolds numbers. At the first resonance, when the noise and structural vibration were severe, the estimated vortex shedding frequency coincides with the frequency of the standing wave measured with a pressure transducer just upstream of the cooler. This frequency, 122 Hz, is the calculated fundamental frequency, equation (2). The wave form of the motion was determined by traversing the pressure transducer from the top to the bottom of the cooler face. There were pressure anti-nodes at the top and bottom of the cooler face and a node on the centre line (fig. 16), corresponding to velocity nodes at the walls and velocity anti-nodes on the centre line. The maximum amplitude of the pressure fluctuations was enormous, about $\bar{p}/q = 28$ and this was sufficient to excite many parts of the tunnel structure although the cooler tubes did not move significantly.

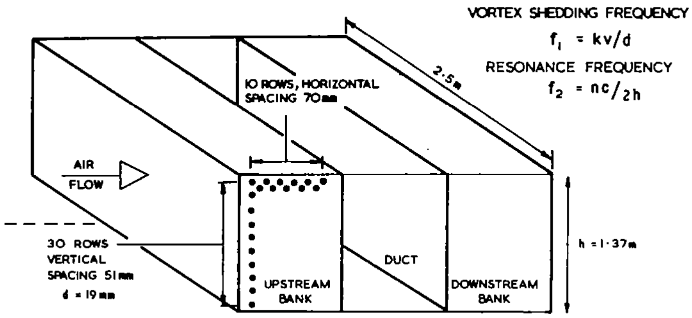


Figure 14. Coolers for 3 ft tunnel.

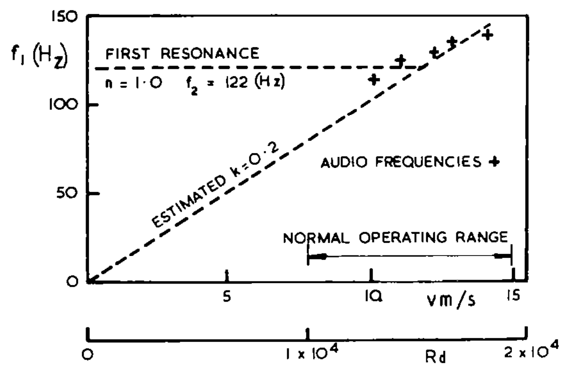


Figure 15. Variation of vortex shedding frequency with velocity.

The noise and vibration in the American cooler[29] were eliminated by raising f_2 by dividing the cooler with splitter plates and a similar modification was applied to the 3 ft tunnel coolers. Two pairs of alternately inclined splitter plates were inserted in the upstream coolers from the upstream end; the inclination of the splitters was determined by the tube spacing (fig. 17). These splitters detuned the upstream bank, raising f_2 to about 360 Hz, but did not directly detune either the intermediate duct or the downstream coolers. However, the noise, structural vibration and the pressure fluctuations at the upstream cooler face were almost completely eliminated by this simple modification.

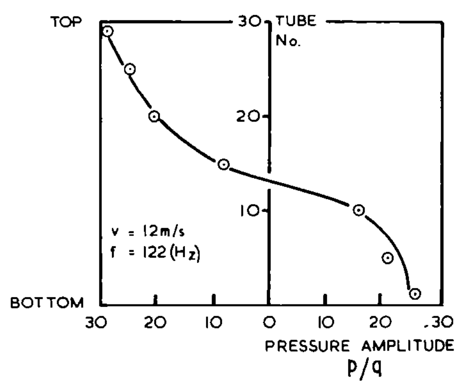


Figure 16. Wave form of pressure fluctuations.

Since these alternately inclined splitters impose a three dimensional non-uniform velocity field on the upstream coolers they must suppress the single vortex shedding frequency which excites the resonance. Thus, the principal effect of the inclined splitters in the upstream coolers is to change the discrete excitation at a particular frequency (given by equation (1)) to an excitation covering a much wider range of frequencies.

The flow at the downstream cooler was probably sufficiently non-uniform to completely suppress vortex shedding at a particular frequency, but to make quite certain of this, splitters were subsequently inserted into the downstream coolers from the downstream end. A honeycomb was also added to eliminate large scale eddies before the flow passed through the tunnel screens into the contraction.

In earlier coolers in the 3 ft tunnel, the tubes were vertical and the critical organ pipe frequencies were then at different levels, namely $f_2 = n \times 67$. Hence, the fundamental frequency was never excited within the normal cooler operating range (from about 8 to 14 m/sec). However, a reappraisal of some pressure fluctuation measurements in the working section suggests that the second harmonic at $f_2 = 134$ Hz may in fact have been excited, although no noise or structural vibration was ever noticed. (The vibration of sting-mounted models in the working section is certainly less with the new cooler configuration.) The large aerodynamically induced vibration was thus encountered only because the tubes in the new coolers were arranged horizontally to facilitate their maintenance.

The wide temperature range of a cryogenic wind tunnel implies a wide variation in the velocity of sound so that it may prove more difficult to avoid acoustic resonances than in a conventional tunnel.

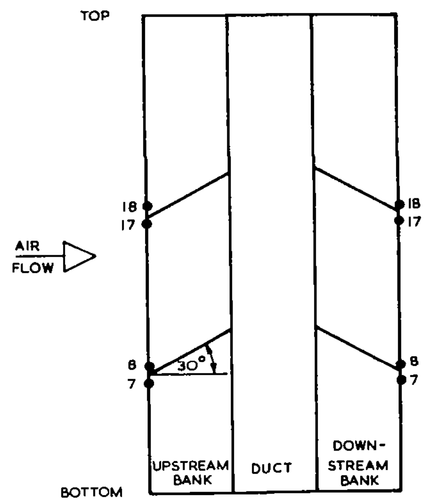


Figure 17. Splitter plates for coolers.

5.3 DIFFUSER DESIGN

Many transonic wind tunnels are equipped with a second throat to prevent pressure fluctuations from the diffuser entering the working section, but this normally requires a significantly higher tunnel pressure ratio, particularly at the lower Mach numbers from say M = 0.30 to 0.60. Hence, it is advisable to design the tunnel so that diffuser separations do not occur at any speed and a second throat is not obligatory. It may be difficult to avoid separations when the first diffuser incorporates a "quadrant" to support the model under test and where short wide angle diffusers are essential to reduce costs.

The RAE 3 ft x 3 ft tunnel was originally designed and operated only at supersonic speeds. Downstream of the quadrant was a central fairing, which formed a constant area duct (to improve supersonic pressure recovery). This fairing was terminated by a bluff end. When the tunnel was subsequently operated at subsonic speeds, the large pressure fluctuations generated by the separation at this bluff end apparently excited the first and second transverse organ pipe resonances and thus produced large pressure fluctuations in the working section both in the RAE 3 ft x 3 ft tunnel [these waves were shown in the cine-film] and in the model 4 in x 4 in tunnel (see fig. 18 for M = 0.80). (This is an interesting example of what is probably a general result: when the length of the separations are of the same order as the working section dimensions the differences between model and full scale performance are small.) The same effect was found at other Mach numbers with some variation of the relative intensity of the modes caused by variations in the predominant frequency of the excitation from the separation. (The base flow on the centre body was not two-dimensional because its aspect ratio was only 3 and there were thick boundary layers on the walls. However, the predominant frequency at n = 0.38 corresponds with a Strouhal number based on the width of the centre body of 0.16, a typical value for bluff bodies.)

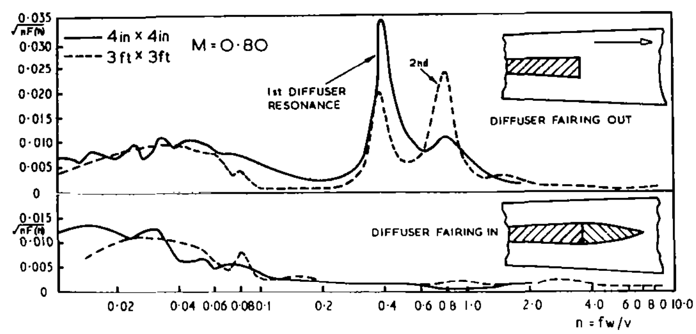


Figure 18. Pressure fluctuations in closed working sections.

A removable fairing to eliminate this separation was developed in the model tunnel and a similar fairing subsequently manufactured for the 3 ft x 3 ft tunnel. This fairing reduced the working section pressure fluctuations (fig. 18) and the axial force balance stress.

At subsonic speeds, even with the diffuser fairing, there is a large low frequency component in the range from n = 0.02 to 0.08 which disappears when the tunnel chokes. A similar low frequency component was found in the model and was higher with the centre body and diffuser fairing than with the unfaired centre body (fig. 18). One hypothesis to explain the origin of this low frequency unsteadiness was that the potential flow did not divide steadily on either side of the long centre body, but oscillated from side to side. (Low frequency unsteadiness of this type has been observed in bifurcated intake ducts[31].) If this hypothesis was correct, it seemed possible that a very short centre body would reduce the low frequency unsteadiness. Hence, the long centre body and diffuser fairing were removed from the model tunnel and replaced by a revised balance section without a centre body which incorporated nearly the same area distribution. This revised balance section reduced the low frequency excitation in the model tunnel (fig. 19) and hence was subsequently incorporated in the 3 ft x 3 ft tunnel.

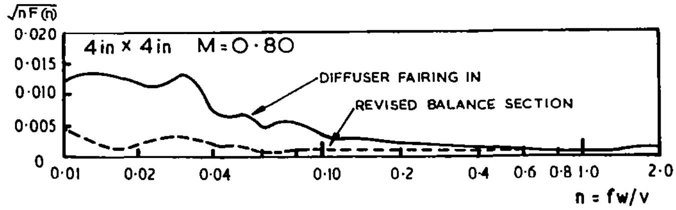


Figure 19. Original and revised balance sections.

Useful reduction in the small scale turbulence generated by the wakes of honeycomb or cooler fairings, turning vanes or struts may be obtained by relatively simple modifications to the trailing-edge region. Although these small scale refinements are often unwisely not incorporated in wind tunnels, they can be essential in the design and operation of water turbines. Thus, Heskestad[32] showed how simple modifications to the trailing-edges of turbine blades reduced the level of vibration, directly reflecting a reduction in the hydrodynamic excitation. Similar Reynolds number ranges occur in transonic wind tunnels so Heskestads results (fig. 20) are of interest.

5.4 WORKING SECTION DESIGN

The ventilated working section inevitably determines the level of flow unsteadiness at the model position if careful design ensures that the sources discussed above are small or non-existent.

Many ventilated working sections operate with diffuser suction (to avoid the complication and capital costs of auxiliary suction) and diffuser suction can cause large pressure fluctuations. Much more work is required to understand and modify the mixing process in this region. [Also illustrated in the cine-film.]

It is convenient to discuss slotted and perforated working section designs separately, although they have much in common. In the author's view[3], low levels of unsteadiness are currently easier to obtain in slotted, working sections, rather than perforated working sections. However, many wind tunnel operators would restrict the use of slotted working sections to Mach numbers below M = 0.95. They would prefer to use perforated working sections (with 60° inclined holes) from M = 0.95 to 1.30 because of their superior shock and expansion wave cancellation properties. These are controversial questions upon which it is unwise to be dogmatic. The working section of the NTF should be designed so that different slotted and perforated walls can be readily fitted and provision made for continuously varying the wall geometry (e.g., the position of perforated screens under the slots or the open area ratio of the 60° perforated wall). Thus, the tunnel could ultimately be made fully "self-correcting" as currently proposed in smaller pilot facilities[33].

5.4.1 SLOTTED WORKING SECTIONS WITH DIFFUSER SUCTION

Figure 21a illustrates the large pressure fluctuations generated in the extraction region at the end of the slotted working section of the 4 in x 4 in tunnel, which reach a peak of $\sqrt{nF(n)}$ = 0.036 at a value of about n = 0.8. When the slots are closed, the pressure fluctuations are reduced dramatically to a uniform level of about $\sqrt{nF(n)}$ = 0.005. Closing the slots will fix the separation line at the end of the working section. In contrast, with the slots open we can imagine the dividing streamline for the slot flow oscillating upstream and downstream and thus generating additional pressure fluctuations, as in a typical bubble flow[34]. Figure 21b shows that the pressure fluctuation spectra in the working section are roughly comparable in shape with those in the extraction region. However, with the slots open the peak is much lower, $\sqrt{nF(n)}$ = 0.01 at n = 0.6. When the slots are closed there is a large reduction in the pressure fluctuations in the working section.

There was no evidence of organ piping across the extraction region, but it was found by experiment that the characteristic excitation frequency of the peak in the working sections in both the 4 in x 4 in and 3 ft x 3 ft tunnels was

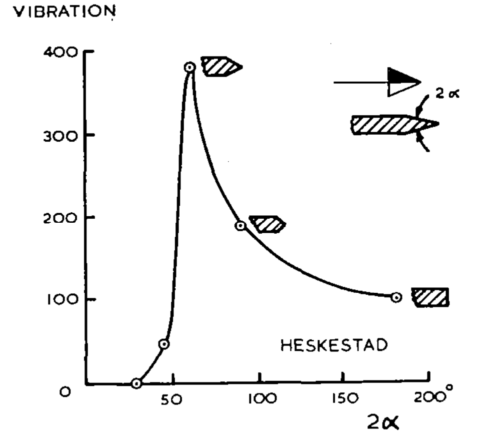


Figure 20. Influence of trailing-edge angle.

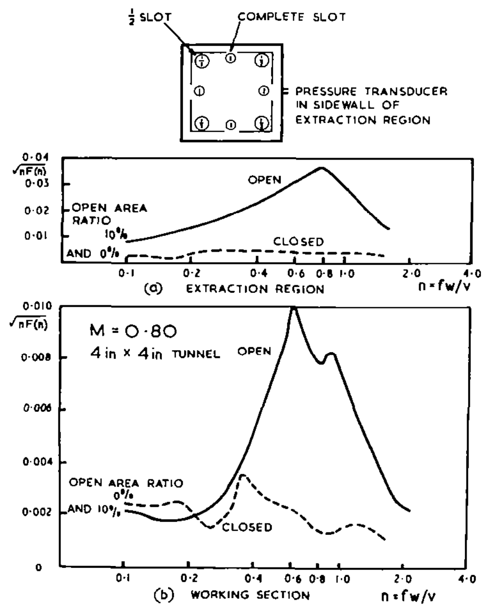


Figure 21. Origin of pressure fluctuations in slotted section.

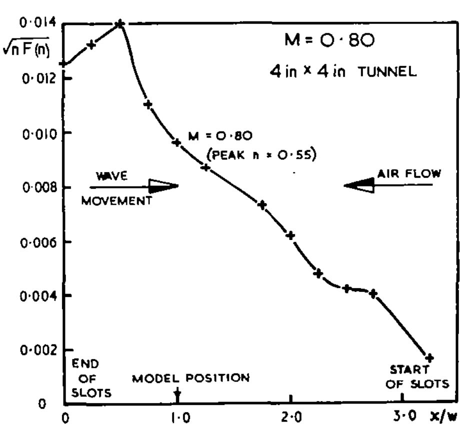


Figure 22. Attenuation of pressure fluctuations in slotted working section.

$$0.030 \leqslant S^* \leqslant 0.040$$

where $S^* = fW_S/V$

and W_S = slot width

and that the level of the pressure fluctuations decreases as the number of slots increased (for fixed open area ratio). Hence, to minimize the flow unsteadiness created by slotted working sections, we should try to use a large number of narrow slots[3].

According to the theory developed by Eggink[35] weak compression waves moving upstream through the working section at high subsonic speeds must intensify into shock waves and then be dissipated as heat. Hence, the corresponding wall pressure fluctuations would first increase and then decrease. This theory was verified in the model tunnel top and bottom slotted working section by measuring the sidewall pressure fluctuations at M = 0.80 as the transducer was moved upstream. The measurements (fig. 22) show a small initial increase in the peak pressure fluctuations just upstream of the ends of the slots (probably just significant) and then an almost monotonic decrease. There is no alteration in the frequency of peak excitation (about 1360 Hz) along the working section. [The high speed cine-film also suggests that the waves are attenuated moving upstream.]

Similar results have been observed in other slotted working sections (see fig. 6 of ref. 36).

It is interesting to notice that the pressure fluctuations in slotted working sections may be further reduced by covering the slots with flat screens (fig. 23). These must inhibit the slow mixing process between the free stream flow and the plenum chamber along the working section, and stabilize the separation line at the rear of the slots. (This method of reducing the flow unsteadiness may alter the Mach number distribution in the working section and the wall interference.)

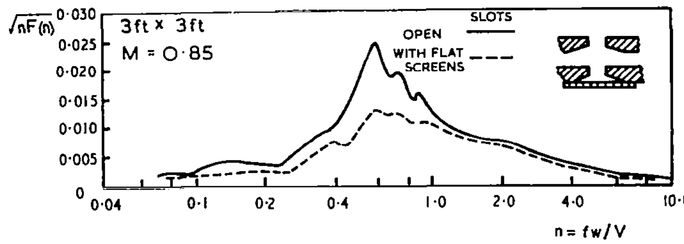


Figure 23. Reduction of pressure fluctuations in slotted working section.

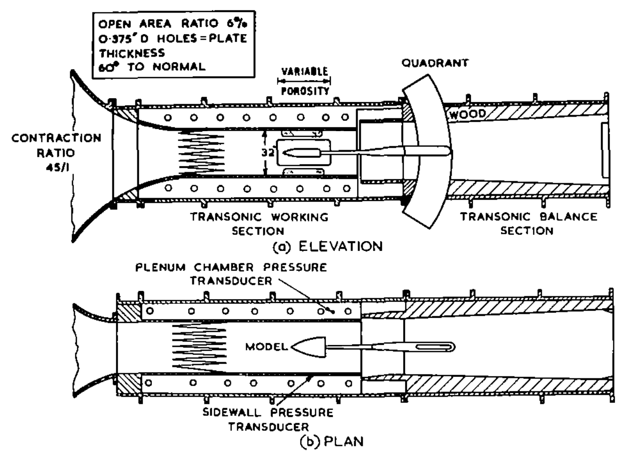


Figure 24. 3 ft x 2.7 ft perforated transonic section.

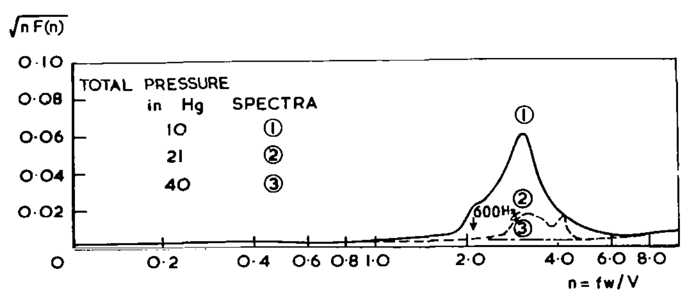


Figure 25. Effect of total pressure on pressure fluctuations, M = 0.80.

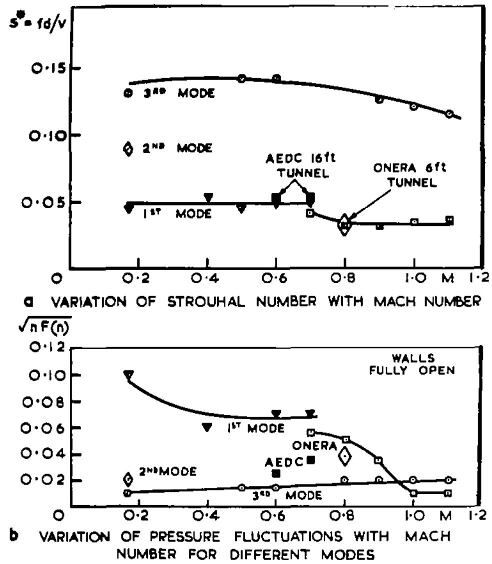
5.4.2 EDGE-TONES FROM 60° PERFORATIONS

The perforated transonic working section supplied for the RAE 3 ft x 3 ft transonic tunnel (fig. 24) encountered a serious problem of flow unsteadiness. When operated at low Reynolds numbers (e.g., as obtained when starting the tunnel or when running at high subsonic speeds, but low density) strong high frequency edge-tones were emitted from the holes which seriously impeded dynamic measurements. Figure 25 shows how the pressure fluctuations at M = 0.80 increased from $\sqrt{nF(n)} = 0.004$ to 0.060 at the edge-tone frequency as the tunnel total pressure was reduced from 136 to 34 kN/m^2 (20 to 5 lb/in^2). The measured Stouhal number of these edge-tones (based on the hole diameter d rather than the tunnel width w) did not vary much with Mach number although first, second and third modal frequencies could sometimes be distinguished (fig. 26a). The amplitude of the pressure fluctuations at the edge-tone frequency did not vary strongly with Mach number up to M = 0.70 (fig. 26b) so that acoustic resonances at fixed frequencies in the plenum chamber, working section or diffuser (whose amplification factor would vary as frequency changed) could not influence this phenomenon. It is interesting to note that the Strouhal number derived from previous measurements in the ONERA 6 ft x 6 ft tunnel at M = 0.80, P_t = 102 kN/m^2 (14.8 lb/in^2) agreed exactly with that measured in the RAE 3 ft x 3 ft tunnel at M = 0.80, P_t = 34 kN/m^2 (5 lb/in^2) (fig. 26a) and that even the pressure fluctuation amplitudes were comparable ($\sqrt{nF(n)}$ = 0.038 and 0.050 respectively in fig. 26b) despite many detailed differences between the tunnels. Hence, edge-tones from the holes were generating the pressure fluctuations in both facilities.

In both facilities the edge-tones were completely eliminated by taping over the wind swept surfaces. When one of the sidewalls of the RAE 3 ft x 2.7 ft tunnel was then untaped (fig. 27a), edge-tones were generated almost as strongly as with four walls untaped+. However, as this open sidewall was progressively taped over again, working upstream from the end of the liner, the pressure fluctuations were reduced and the unit Reynolds number for the onset of edge-tones was also reduced. This suggested that the effect of reducing unit Reynolds number was to increase the boundary layer thickness δ^*, and that edge-tones were generated when δ^*/d exceeded some critical value. As the tapes were extended upstream the boundary layer at the open holes just upstream of the tape became thinner at any given unit Reynolds number. Hence, a progressively lower unit Reynolds number was required to achieve the critical value of δ^*/d necessary to initiate edge-tones. A critical value of about $\delta^*/d \geq 0.4$ to 0.5 can be inferred from the measurements given in fig. 27a.

Tests in the ONERA 6 ft tunnel[37] showed that the edge-tones could also be eliminated by reducing the wall porosity from 6 percent to 3 percent. This variation of wall porosity was achieved, not by sealing 50 percent of the holes, but by moving perforated plates extending over the full length of the plenum chamber side of the top and bottom liners. A comparable experiment was made using the small length of variable porosity sidewall of the RAE 3 ft x 2.7 ft tunnel, the remaining walls being taped over. Figure 27b shows that the pressure fluctuations fell suddenly as the open area ratio was reduced from 3 percent to 2.2 percent. This modification was then applied over a wider area by sticking perforated cardboard underneath the rear 2 ft of the top and bottom liners from which the tapes were removed. The cardboard was displaced so as to give the desired open area ratio of 2.2 percent and a large reduction in pressure fluctuations was achieved (fig. 28a). Aluminium strips were subsequently used to modify every hole in the liners in this fashion. This modification virtually eliminated the edge-tones (fig. 28b) at the fundamental mode, although the third mode (fig. 26) still persisted.

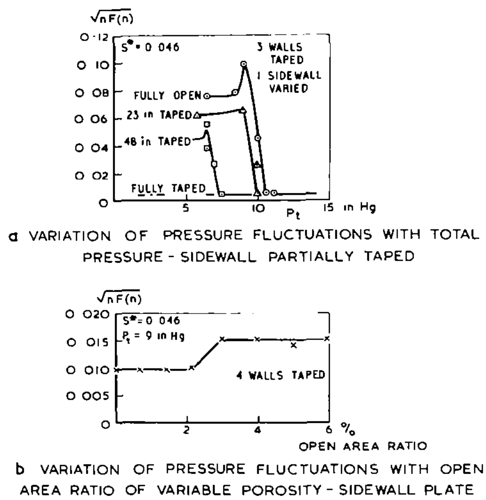
An hypothesis to explain the generation of the edge-tones is suggested by the flow patterns found in individual holes (fig. 29). This shows a herring-bone pattern, indicative of a complex three-dimensional shear layer spearating from the upstream edge of the hole. The mean shear layer contains streamwise vorticity components of opposite sense on either side. Under certain conditions (e.g., as δ^*/d increases), the mean shear layer may not reattach to the inner surface of the hole. The shear flow is probably always unsteady, but the degree of unsteadiness may be much greater when the mean shear layer does not reattach onto a solid surface. The mass flow into the hole would then vary strongly with time, which would generate stronger edge-tones from the downstream edge of the hole. The downstream movement of the variable porosity plate reduces the edge-tones either by permitting reattachment or by severely limiting the amplitude of the shear layer oscillation. There is not enough evidence to confirm this hypothesis, but the flow model inferred is at least consistent with Roshko's explanation[38] of the effect of splitter plates on the flow in the wake of bodies with a bluff base.



a VARIATION OF STROUHAL NUMBER WITH MACH NUMBER

b VARIATION OF PRESSURE FLUCTUATIONS WITH MACH NUMBER FOR DIFFERENT MODES

Figure 26. Frequency and amplitude of edge-tones.



a VARIATION OF PRESSURE FLUCTUATIONS WITH TOTAL PRESSURE - SIDEWALL PARTIALLY TAPED

b VARIATION OF PRESSURE FLUCTUATIONS WITH OPEN AREA RATIO OF VARIABLE POROSITY - SIDEWALL PLATE

Figure 27. Reduction of edge-tone intensity, M= 0.60.

An interesting further study of the edge-tones generated by 60° inclined holes was given by McCanless and Boone[4].

5.4.3 PLENUM CHAMBER DESIGN

Little attention has been given to the influence of plenum chamber design on working section flow unsteadiness, although this can be important. Thus, during the first runs of the perforated working section of the RAE 3 ft x 3 ft tunnel large working section pressure fluctuations ($\sqrt{nF(n)} = 0.10$)

+ Interference between the four walls produced this apparently anomalous result; large mutual interference effects were clearly demonstrated in additional experiments.

Detailed measurements of the boundary layer thickness in the corners of the working section would probably have been needed to interpret these anomalous pressure fluctuation measurements correctly.

were measured which increased in frequency from 30 to 50 Hz as speed increased. This phenomenon recalled the unsteadiness observed in a slotted water tunnel which was traced to edge-tones shed from the diffuser collectors and eliminated by changing the geometry of the collectors[39]. A similar process seemed possible with the perforated working section because the side collectors had a small leading-edge radius. Hence, bluff side baffles were added to the side collectors and these reduced the audible noise and the working section pressure fluctuations (fig. 30). (No further improvement was obtained with more streamlined baffles.) These side baffles suppressed the shedding of vorticity inevitably associated with a stagnation point oscillation on the sharp collector nose. (No comparable unsteadiness was observed in the slotted transonic section with these collectors because the streamwise flow was then constrained to a few discrete areas downstream of the four complete slots.)

Significant unsteadiness remained at 50 Hz and another experiment* was made to determine its origin. All the holes in the perforated working section were covered with adhesive tape and the working section pressure fluctuations reduced as anticipated (fig. 31a). Then the tapes were removed progressively from every wall in the sequence illustrated; the unsteadiness at 50 Hz only returned when both sidewalls were uncovered (fig. 31b). (This effect was also observed in the plenum chamber.) This suggested that the generation of edge-tones depended on a symmetric side-wall configuration and also that the edge-tones might be influenced by the degree of interconnection between the side plenum chambers. Hence, longitudinal wooden baffles were inserted in every corner of the plenum chamber. These reduced the unsteadiness at M = 0.60, but introduced large pressure fluctuations and excessive external noise at other speeds. These solid baffles were then removed and perforated with 2 in diameter holes drilled halfway between the transverse venting holes spaced every 8 in along the longitudinal I beams (these venting holes are 4 in diameter). When the perforated corner baffles were inserted, the pressure fluctuations at 50 Hz were reduced (fig. 32) and there was no increase in pressure fluctuations or external noise at other speeds. Perforated corner baffles are desirable to equalize small static pressure differences between the plenum chambers induced by lifting models.

For the next series of tests another pressure transducer was placed near the downstream end of the plenum chamber. Figure 33a shows that in the plenum chamber the pressure fluctuations at 50 Hz were higher than those in the working section, suggesting resonance at the longitudinal organ pipe frequency (the 11 ft length corresponds with a closed/closed mode of 50 Hz). This hypothesis was confirmed by the insertion of a paper honeycomb at the end of the plenum chamber. This introduced attenuation between the diffuser and the plenum chamber and thus reduced the plenum chamber pressure fluctuations at 50 Hz. However, the honeycomb did not alter the working section pressure fluctuations (fig. 33b), indicating that the unsteadiness was excited in the diffuser or working section rather than the plenum chamber.

*This was suggested by Mon. R. Destuynder in the light of comparable experiments in the ONERA 6 ft tunnel.

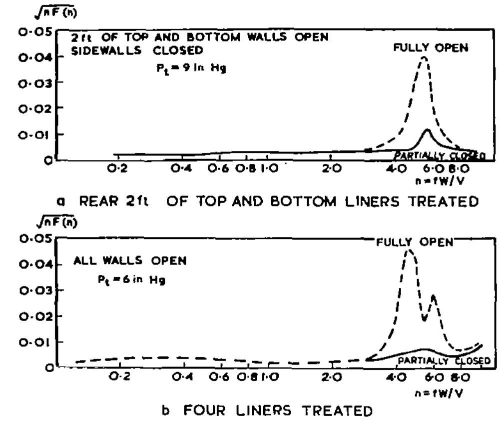


Figure 28. Elimination of edge-tones, M = 0.60.

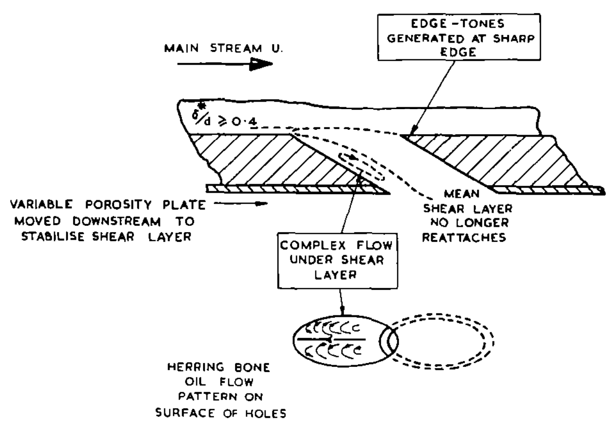


Figure 29. Possible flow model for edge-tone excitation.

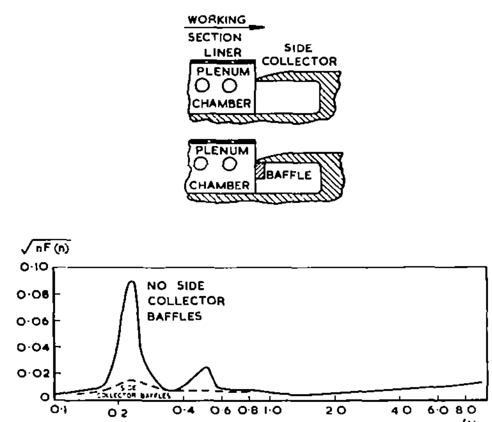


Figure 30. Effect of side collector baffles on edge-tones, M = 0.60.

The honeycomb was then removed because it interferred with the flow through the downstream end of the perforated liners and absorbed extra power. The honeycomb was replaced by a series of plenum chamber baffles wedged through the 4 in diameter transverse venting holes. In the upstream part of the plenum chamber these baffles were set at 45° to produce high acoustic damping for the longitudinal model. In the downstream part of the plenum chamber, the baffles were set at zero incidence to provide some limited acoustic damping and to partially inhibit the unsteady lateral flow in the plenum chamber indicated by nylon tufts. These combined baffles reduced the plenum chamber pressure fluctuations more effectively than the honeycomb and also reduced the sidewall pressure fluctuations over a wider range (fig. 33c). This improvement probably came from a more stable plenum chamber flow although no noticeable improvement in steadiness of the nylon tufts was observed.

Apart from the investigations reported by Starr and Schueler[40] and Anderson, et. al.,[41] little work has been done to determine the optimum plenum chamber volume V_P, relative to the working section volume V_S. For the RAE 3 ft x 3 ft tunnel, these ratios are relatively low, with no apparent adverse effects.

WORKING SECTIONS FOR RAE 3 FT TUNNEL

		V_P/V_T
3 ft x 3 ft	(4 sides slotted)	1.8
3 ft x 2.7 ft	(4 sides perforated)	2.1
3 ft x 2.2 ft	(top and bottom walls slotted)	0.4

The low value for the top and bottom slotted section should be particularly noted. For reference purposes, it is worth noting that Starr and Schueler's tests ranged from V_P/V_T = 8.3 down to only 0.8.

		V_P/V_T
i.e.	Standard	8.3
	Large	3.0
	Medium	1.8
	Small	0.8

Small, but useful capital cost savings can probably be achieved by adopting the smallest reasonable plenum chamber volume. A small plenum chamber volume would help to reduce the starting time of an intermittent tunnel, and hence, reduce the running costs. A small plenum chamber, carefully designed to avoid resonances, should contribute very little to the flow unsteadiness in the working section.

Some additional discussion on the influence of the plenum chamber on flow unsteadiness is given in reference 3.

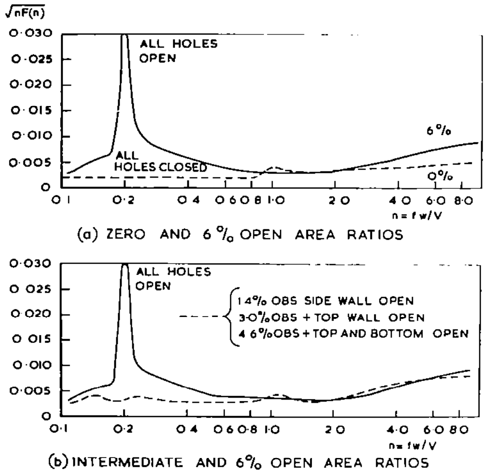


Figure 31. Effect of sealing holes on edge-tones, M = 0.60.

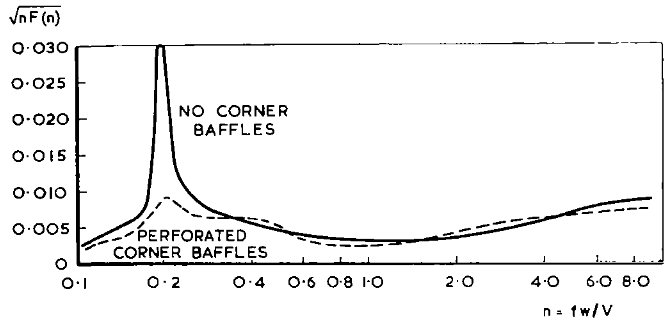


Figure 32. Effect of plenum chamber corner baffles on edge-tones, M = 0.60.

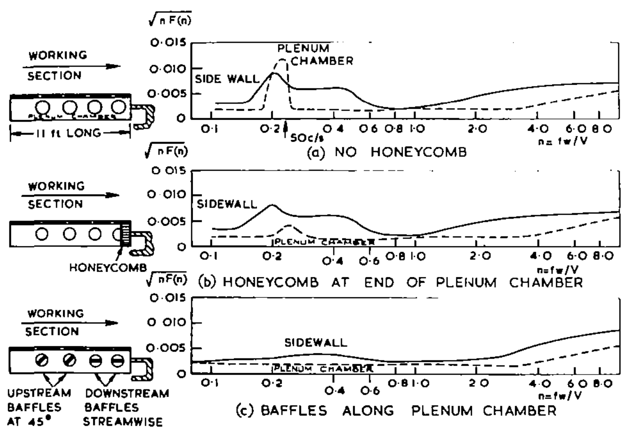


Figure 33. Effect on acoustic attenuators in plenum chamber.

6. CONCLUSIONS

Careful attention to the design of every element of the circuit is required to achieve low levels of flow unsteadiness in the working section of a transonic wind tunnel (fig. 5).

It is possible that the levels of flow unsteadiness in future transonic tunnels will be determined primarily by the working section design, rather than the drive system adopted.

Ventilated working sections with diffuser suction are widely used and further research into the mixing process in the extraction region is recommended.

ACKNOWLEDGEMENT

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