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A SEMI-EMPIRICAL THEORY OF THE NOISE IN SLOTTED TUNNELS CAUSED BY DIFFUSER SUCTION

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Abstract

A semi-empirical theory of the noise caused by diffuser suction in the working section of a slotted tunnel is developed on the assumption that the noise source can be modelled as an equivalent jet. Hence many of the noise characteristics can be obtained from conventional jet noise theory, with the mixing region at the end of the working section being replaced by a peripheral series of jets each with a diameter about 2 to 9 times larger than the slot width.

The theory predicts a peak in the working section pressure fluctuations at a Mach number of about 0.80, in fair agreement with experiment. The theory explains the slot/fan resonance which occurs in the RAE 8 ft x 6 ft Tunnel and which can be avoided in other facilities by careful design. The possibility of tailoring slot widths across the working section to obtain a uniform, low noise level spectrum is discussed.

Further measurements of the flow characteristics at the end of the slots are needed to evaluate the validity and usefulness of the modelling assumptions made in this theory.

1 Introduction

There is considerable interest both in modifying existing transonic tunnels to reduce their flow unsteadiness[1] and in designing new tunnels with low levels of unsteadiness[2]. Hitherto, progress towards both objectives has been hampered by the complexity of the problem (outlined in section 2) and the absence of any supporting theory. The situation is particularly serious with respect to transonic slotted tunnels with diffuser suction (Fig 1), which are widely used. Such tunnels generally have high levels of flow unsteadiness which can impair both steady and unsteady measurements.

This Report presents a semi-empirical model (section 3) which represents noise, as measured by pressure fluctuations within the flow, radiated upstream from the extraction region and conforms quite well with experiments. The semi-empirical model suggests ways by which flow unsteadiness might be reduced, some of which have yet to be verified.

2 Noise Characteristics of Transonic Tunnels

This section provides a summary of the observed noise characteristics of a typical transonic tunnel with diffuser suction (Fig 1), which will be represented in the mathematical model (section 3). Fig 1a shows the general arrangement of the tunnel. The transonic flow within the working section is generated by the diffuser suction provided by the sudden expansion in the extraction region at the end of the working section. In addition to providing diffuser suction, the complex three dimensional flow in the extraction region generates aerodynamic noise. This noise propagates upstream through the working section (against the free stream flow) and also upstream through the plenum chamber (where the air is virtually at rest). The noise in the plenum chamber can be important because, at relatively low frequencies, (ie long wavelengths) noise can also propagate from the plenum chamber to the working section and *vice versa*. An interesting consequence is that the transverse resonance frequencies of both slotted and perforated tunnels depend on the depth of the plenum chamber[3] up to a Mach number of M = 0.618.

Fig 1b shows the general slot/slat arrangement of a typical slotted wall of width w. There are several slots, usually formed with an initial taper, followed by a constant slot width, w_s. Hitherto the slots have been spaced evenly across the tunnel width. The combination of a uniform slot width and slot spacing gives an approximation of a 'homogeneous' wall boundary condition used in the calculation of resonance frequencies or the tunnel interference corrections for steady forces[4]. Fig 1b shows the streamwise dimension, x, measured positive upstream from the end of the slots.

Fig 1c compares typical measurements (from Figs 21 and 22 of Ref 1) of the noise spectra in the extraction region (at x = -0.2w) and in the working section (at x = +w). The frequency parameter, ν_s, based on the slot width is:

$$\nu_s = \frac{f w_s}{U} . \qquad (1)$$

The noise is much higher in the extraction region (close to what is interpreted as the noise source) than in the working section, but the spectra are similar. However the noise peaks at a lower frequency parameter in the working section than in the extraction region. This is because the noise spectrum at the extraction region is dominated by high frequencies, the local mixing region being thin. In contrast, the upstream regions can only be disturbed by upstream propagation. This is in the form of plane waves formed by the accumulation or amalgamation of the sound waves generated by the mixing region. The peak frequency of the entire mixing region is lower than that near the end of the slots. Thus for the extraction region the noise peaks at

$$\nu_S = 0.05 , \qquad (2)$$

whereas for the working section

$$\nu_S = 0.04 . \qquad (3)$$

When the slots are closed (dashed curves in Fig 1c) the noise levels in both the extraction region and the working section are greatly reduced. This is an important observation, and it leads to the basic hypothesis about the nature of the slot/slat flow.

The measurements in Fig 1c suggest that the noise in the extraction region is generated primarily by the mixing of the free stream flow with the almost quiescent air from the plenum chamber at the end of the slots. The step height at the end of the slats is typically 3 to 5 times the slot width. Hence it is plausible to idealise the flow in the extraction region as that of an ejector. The mixing region is represented as a series of thin jets, one associated with each slot (Fig 1d). The geometry of the slots and the plenum exit to the extraction zone suggests that each of these thin peripheral jets can be modelled as an equivalent jet of diameter

$$d = \lambda w_S , \qquad (4)$$

where we find λ to be between about 2 to 9 (see Discussion). This hypothesis implies that the noise generated by this equivalent jet is much greater than that generated by either the bubble flow behind each slat or the trailing vortices shed from the edges of the slat. We will show that each jet represents a quadrupole noise source, with an intensity that is directly proportional to U^8. Fig 1e shows that a jet mixing spectrum (appropriately scaled, cf Fig 12a) is similar to that of noise in the extraction region. The mean shear between the mainstream and the slot flow exhausting into the extraction region from the plenum chamber will produce a turbulent mixing region. This might be expected to grow linearly downstream and to have a mean convection speed of, say 0.50 to 0.65 of the difference between the slot and plenum chamber flow.

We shall see that this simple hypothesis gives a fair representation of a very complex, highly three-dimensional flow. Fig 2 (based on Fig 19 of Ref 1) shows the characteristic length scales associated with the single slot of the pilot slotted tunnel whose noise characteristics are presented in Fig 1c above. The slot flow actually reattaches in a streamwise length of only about $2w_S$ and has a width of only about $2w_S$. Here the step height is about $3w_S$. We shall see later that for this tunnel

$$d = 6.8\, w_S , \text{ or } \lambda = 6.8 . \qquad (5)$$

A tentative explanation of this value of λ will be offered in section 4.

Some detailed evidence for the observations made with respect to Fig 1 is presented elsewhere[5].

It must be emphasised that there are many other additional sources of noise in transonic tunnels (Fig 3). The only sources considered here are the noise from the extraction region and the noise at harmonics of the fan blade frequency, which can be influenced by the choice of slot width.

Here the spectra of the pressure fluctuations are plotted in the dimensionless form suggested by Owen[6] and now widely used. Thus the term $\sqrt{nF(n)}$ represents the rms pressure fluctuation level in a bandwidth Δf such that

$$\sqrt{nF(n)} = \frac{\Delta p}{q\sqrt{\varepsilon}} , \qquad (6)$$

where Δp = pressure fluctuation in a band Δf ,
f = frequency (Hz) ,
ε = $\Delta f/f$ = bandwidth ratio ,
and n = fw/U ,

where w = tunnel width. Owen showed that it is convenient to plot $\sqrt{nF(n)}$ against log n and this convention is followed.

3 Semi-Empirical Model

3.1 Description of model

The semi-empirical model consistent with section 2 is shown in Fig 4. The tunnel working section has a uniform velocity U and extends upstream from x = 0 to +∞, having a diameter D . The infinite dimension excludes longitudinal resonances in the working section. [There is assumed to be no boundary layer growth on these walls.] The tunnel plenum chamber also extends from x = 0 to ∞ and is of infinite depth. The infinite dimensions exclude both longitudinal and transverse resonances in the plenum chamber.

An important simplification and assumption is made about the plenum chamber. The air therein is assumed to be at rest and to have the same static temperature as the free stream, so that the density, ρ , is the same. This assumption provided good agreement between theory and experiment for the resonance frequencies in ventilated wind tunnels[3]. The infinite dimensions selected for the plenum chamber depth and the diffuser diameter also exclude any consideration of the effects of solid boundaries, which can be important in several ways (cf section 5.5 of Ref 7).

In the wall of the working section there will in general be a number of slots whose width, w_s , may vary from slot to slot. Here only one slot is considered initially. The flow from the end of this slot ($x = 0$) is assumed to be the prime source of noise in the extraction region, rather than the mixing at the end of the working section round the remainder of the periphery. This assumption is consistent with the measurements in Ref 1. Here the noise in the extraction region with a perforated wall is very low, and virtually the same as that measured on a slotted section with all the slots closed (cf Fig 1c). The equivalent noise source for the slot flow is assumed to act on the tunnel axis. The model avoids the complications of slot/slat geometry and the finite plenum chamber of a real tunnel. In this model the plenum flow must be zero.

3.2 Estimate of far field noise at low speeds

An attempt is made to estimate the far-field noise produced at low speeds by the turbulent mixing at the end of the slot. The low velocity slot flow (at a relative velocity U_o to the free stream and of density ρ_o) will be replaced by an equivalent jet of diameter d , which is proportional to the slot width, w_s . Then according to Lighthill's theory[8] of jet noise (Ref 8, equation (14)), the noise intensity, I , in the far field in terms of sound power/unit area will be

$$I = \frac{\overline{(p^1)^2}}{\rho a} \propto \frac{\rho_o U_o{}^8}{a^5} \left(\frac{d}{x_1}\right)^2 , \qquad (7)$$

where a = ambient velocity of sound,
p^1 = pressure fluctuation,
ρ = ambient density,
x = effective distance from source (to be defined later),
and $d = \lambda w_s$. Equation (7) indicates that the jet is a quadrupole noise source.

It is reasonable to assume that the slot flow velocity is very small so that $\rho_o = \rho$ and $U_o = U$. Then equation (7) may be rearranged to give

$$\overline{(p^1)^2} \propto \rho^2 U^4 M^4 \left(\frac{d}{x^1}\right)^2 . \qquad (8)$$

Hence the local radiated mean square pressure fluctuations, $\overline{(p^1)^2}$ becomes

$$\frac{\overline{(p^1)^2}}{q^2} \propto M^4 \left(\frac{d}{x^1}\right)^2 ,$$

and the rms value is

$$\frac{\bar{p}}{q} \propto M^2 \left(\frac{d}{x^1}\right) . \qquad (9)$$

Equations (7) and (9) are independent of Reynolds number. This is because the aerodynamic noise of a turbulent jet or slot flow is controlled by a turbulent eddy viscosity. This eddy viscosity is determined by a typical velocity and eddy size and is independent of Reynolds number. Thus equation (9) is consistent with the experimental observation that, for virtually all slotted transonic tunnels (including cryogenic facilities), $\bar{p}/q$ is indeed independent of Reynolds number.

3.3 Directivity of radiation due to convection of sound sources

Equation (7) relates to the intensity of noise from an omni-directional source and therefore takes no account of the direction of radiation. Lighthill suggests[8] that there is an important directional effect due to the convection of sound sources. In free air this effect on the noise emitted forward is to reduce the intensity, I , by a factor of $(1 + M_c)^{-5}$, where M_c is the convection Mach number of the sound sources (Ref 8, equation (19)). If the same factor were applicable to the noise radiated upstream from a slot the rms pressure fluctuations, $\bar{p}/q$, at a particular point would be reduced by a factor of

$$(1 + M_c)^{-2.5} . \qquad (10)$$

Fig 9 of Ref 8 suggests that a fair approximation to the convection Mach number in the mixing region of a jet would be

$$M_c = \frac{M}{2} . \qquad (11)$$

From equations (10) and (11), equation (9) becomes

$$\frac{\bar{p}}{q} = bM^2\left(1 + \frac{M}{2}\right)^{-2.5} \frac{d}{x^1} , \qquad (12)$$

where b is an empirical constant.

3.4 Effect of speed increases towards M = 1

Even if equation (12) is accepted, it could only be valid for very low Mach numbers or in the plenum chamber. For high speeds the upstream propagation of these pressure fluctuations into the working section must be altered radically. The upstream propagation velocity is reduced from a to $a(1-M)$ by the free stream velocity $U = aM$, as shown by high speed cine film of schlieren systems (Ref 1, Fig 11). Thus within the free stream at a distance x upstream of the end of the slots the noise source appears at an increased effective distance, x^1, given by

$$x^1 = \frac{(x + x_o)}{(1-M)}, \qquad (13)$$

where x_o = distance of noise source downstream from the end of slots. Replacing x^1 in equation (12) by equation (13) we find

$$\frac{\bar{p}}{q} = bM^2\left(1 + \frac{M}{2}\right)^{-2.5}(1-M)\left(\frac{d}{x + x_o}\right) . \qquad (14)$$

Equation (14) has a maximum at M = 0.590 which is too low since the maximum noise values are always observed close to M = 0.8. This could be because sound propagating into the working section from the plenum chamber does not suffer such a reduction. A maximum will be obtained at M_j if the term $(1-M)$ in equation (14) is replaced by $(1-M)^j$. Here j must be selected to match the particular experiments. Ref 5 shows that $j = 0.325$ gives a maximum value of $\bar{p}/q$ at $M_j = 0.800$, which is typical of most slotted transonic tunnels.

Hence we find by modifying equation (14) and replacing d with λw_s as in equation (4)

$$\frac{\bar{p}}{q} = bM^2\left(1 + \frac{M}{2}\right)^{-2.5}(1-M)^j\left(\frac{\lambda w_s}{x + x_o}\right) . \qquad (15)$$

It should be noted that equation (13), which is independent of the lateral position in the working section, implies that the acoustic waves moving upstream through the working section are almost planar. This consistent both with high speed cine film of schlieren systems (Ref 1, Fig 11) and the predictions of Ref 9 that "the sound generated by large scale turbulence in a pipe ... is in a form of plane waves". [However this problem is concerned with fully developed turbulent pipe flow].

3.5 Some applications and inferences from the theory

Before comparing equation (15) to the limited measurements available and inferring values of λ, x_o and b it is helpful to consider some of the applications and inferences that may be drawn (Fig 5).

Influence of open area ratio (T)

For a single slot

$$w_s = Tw_t , \qquad (16)$$

where w_1 = total perimeter of tunnel,

and T = open area ratio.

Hence

$$\frac{\bar{p}}{q} = TbM^2\left(1 + \frac{M}{2}\right)^{-2.5}(1-M)^j\left(\frac{\lambda w1}{x + x_o}\right) , \qquad (17)$$

and the pressure fluctuations are directly proportional to the open area ratio.

Influence of number of slots (m)

If the number of slots of width w_s is increased from 1 to m then

$$mw_s = Tw_1 . \qquad (18)$$

The energy intensities (equation (7)) combine linearly, as they should for uncorrelated sources (cf discussion of equation (7) in Ref 8)). Then the rms local pressure fluctuations for a single slot should be increased by a factor of $\sqrt{m}$ and the slot width w_s replaced by Tw_1/m to give

$$\frac{\bar{p}}{q} = \frac{TbM^2}{\sqrt{m}}\left(1 + \frac{M}{2}\right)^{-2.5}(1-M)^j\left(\frac{\lambda w_1}{x + x_o}\right) . \qquad (19)$$

In the limit when $m \to \infty$

$$\frac{\bar{p}}{q} \to 0 . \qquad (20)$$

Thus, for many slots, the noise of a slotted tunnel with diffuser suction should approach that of a closed tunnel or a perforated tunnel. Fig 5a shows how, according to the model of equation (19), the pressure fluctuations increase with the open area ratio and decrease with the number of slots. These variations match the design rules advocated in Refs 1 and 2. A large number of uniformly spaced slots has the additional advantage of providing a homogeneous wall boundary condition for interference studies[4].

It should be noted that equation (14) will only be valid as long as the effective jet diameter d ($\equiv \lambda w_s$) is much smaller than the working section diameter D. With a practical tunnel configuration with m slots of width w_s and effective jet diameter λw_s another condition is

$$\frac{m\lambda w_s}{\pi D} \leq 1 \ . \qquad (21)$$

If equation (21) is not satisfied, mutual interference could occur between adjacent slots and additional noise is likely to be generated. [The slot noise might even become coherent in certain circumstances.] Hence equation (21) provides a useful design rule once λ is known.

Influence of varying slot width

Equation (15) expresses the rms noise generated by a single slot of constant width w_s, which according to Ref 1 provides a peak in the excitation spectrum at a frequency, f, given by a frequency parameter ν_s, where

$$0.030 \leq \nu_s \leq 0.04 \ . \qquad (22)$$

It is apparent from equations (15) and (22) that, if the slot width could be varied from slot to slot, it should be possible to tailor the noise characteristics to give a fairly uniform, lower level of noise right across the spectrum. Garner suggested[10] how the slot width in the roof might be reduced to kw to make the lift (δ_0) and curvature corrections (δ_1) on small models identically zero. This type of working section would have appreciably lower noise levels at lower frequencies but higher levels at high frequencies, as shown by the idealised spectra in Fig 5b [drawn for k = 0.5 in the roof slots.] However, sections with a differing roof and floor are unlikely to be adopted because this would prevent model symmetry from being checked by inverting the model. In addition, there would be some uncertainty about the calculation of blockage corrections because of the lack of symmetry.

As a further example of varying slot width to reduce the peaks in the excitation spectrum, Fig 5c shows a more practical way to vary the slot width across a working section having many slots, preserving the symmetry between the roof and the floor. In the example shown the slot width is largest (w_s) at the outer slots (A), narrower $(0.5\ w_s)$ at the intermediate slots (B) and narrowest $(0.25 w_s)$ on the centre line slots (C). As a result of these variations in slot width, the noise is reduced up to a frequency parameter of about 0.05 but increased above this value. [Normally the high frequency excitation is less important with respect to model tests with fixed transition, though it may be important with respect to tests with free transition[1,2].] The best type of slot width variation with respect to achieving small spanwise lift and curvature corrections could be established using, for example, Steinle and Pejack's computer code[11].

Influence of fan design

Reference 5 discusses local peaks due to resonances. These resonances are not, of course, included in the formulation of the jet noise created by the slots and predicted by the semi-empirical theory. One common and troublesome source of resonances, particularly at subsonic speeds up to about M = 0.70, is the discrete noise provided at harmonics of the compressor or fan blade frequencies. If this excitation happens to coincide with that provided by the slot mixing, very high noise levels must be expected because excitation at the jet natural frequencies does increase jet noise. This can be particularly serious for a tunnel driven by a fan, which operates at a fixed blade angle, as will be shown below.

For such a fan, the working section velocity is often directly proportional to the fan speed so that

$$U = KN \ , \qquad (23)$$

where K = constant (having units of length) for a particular design and N = fan speed (Revs/s). The primary excitation frequency of the fan blade is given by

$$f = BN \ , \qquad (24)$$

where B = number of blades. Combining equations (23) and (24) we find

$$f = \frac{BU}{K} \ . \qquad (25)$$

The condition for coincidence between the fan blade excitation and the slot excitation is obtained by comparing equations (25) and (1):

$$w_s = \frac{\nu_s K}{B} \ , \qquad (26)$$

with ν_s given by equation (22).

The use of slots of this width should be avoided because otherwise the resonance will be established over the whole range of validity of equation (23), equation (26) being independent of the velocity. This condition obtains in the RAE 8 ft x 6 ft Tunnel and explains the very high level of flow unsteadiness observed at Mach numbers from M = 0.20 to 0.65 (cf Fig 43 of Ref 1). For this tunnel the slot width is w_s = 40 mm, the fan characteristic is K = 18.3 m and the number of fan blades is B = 13. Hence from equation (26) the value of the frequency parameter of the peak is

$$\nu_s = 0.028 \ . \qquad (27)$$

This particular value of ν_s is just outside limits given by equation (22), which were based on tests in two much smaller wind tunnels. For Mach numbers above M = 0.65 the velocity no longer increases linearly with the fan speed, so that this coincidence between the fan excitation and the slot mixing no longer occurs. Then the tunnel becomes much quieter[1].

Influence of plenum chamber

It is assumed in the present theory that the plenum chamber has no direct influence on the noise created by the slot mixing, apart from any second order influence on the jet diameter or its effective origin. Nevertheless, the plenum chamber should always be designed to eliminate or attenuate acoustic resonances, particularly longitudinal resonances along the tunnel axis, as recommended in Refs 1 and 2.

3.6 Verification of theory

Despite the high noise levels in most slotted tunnels with diffuser suction, there are few comprehensive measurements available which cover the full range of Mach number (from M = 0.2 to 1.0). Of the limited measurements available, few provide the noise in a convenient dimensionless form such as $\overline{p}/q$ (for (for total rms level) or $\sqrt{nF(n)}$ (for spectra).

Another difficulty in verifying the theory is that equation (15) relates solely to the noise associated with the slot mixing. However, when $\overline{p}/q$ is measured it includes contributions from all the other sources specified in Fig 3 which are unrelated with the slot mixing. Hence it is more useful to examine the pressure fluctuation spectra in the extraction region, the working section and the plenum chamber and first establish if a major part of these spectra could be characteristic of jet mixing. If so, the shape of these spectra should be invariant with Mach number, when expressed in terms of frequency parameter. However, the amplitude should vary with both Mach number and position. This method is now applied to the measurements presented in Ref 5 which relate to a pilot 1/9 scale model of the RAE 3 ft x 3 ft Tunnel and to the RAE 3 ft x 3 ft Tunnel.

Fig 6 compares a typical jet noise spectrum (from Ref 8) with some measurements of noise spectra at M = 0.80 on the sidewall of the pilot slotted tunnel having a single complete slot of width $w_s = 0.067w$ on all four walls and half slots in four corners (from Ref 1).

Choice of λ

For the slotted tunnel it is helpful to express the frequency parameter in terms of the slot width ($\nu_s = fw_s/U$) rather than the tunnel width. The jet noise in Fig 6c peaks at

$$\frac{fd}{U} = 0.27 \ . \qquad (28)$$

Fig 6a shows that the spectrum in the extraction region peaks at $\nu_s = 0.05$ and is broadly similar in character to that of the jet noise field (Fig 6c). Fig 6b shows that the spectrum in the working section peaks at a lower frequency, $\nu_s = 0.04$ and is also similar in character to that of the jet. It is reasonable that the peak excitation frequency should fall from the extraction region to the working section as discussed in section 2 with respect to equations 2 and 3. The theory ignores this change in the shape of the spectrum. If the frequency parameter in the working section is based on a length (0.27/0.04) $w_s \equiv 6.8\ w_s$, the peak in the tunnel noise spectrum would match that of the jet. Accordingly, the equivalent jet diameter would be

$$d = 6.8\ w_s \quad \text{or} \quad \lambda = 6.8 \ . \qquad (29)$$

Variation with M

The question must be addressed as to whether the spectral level varies with Mach number according to equation (15) at a fixed point and frequency parameter. This is a difficult question because most of the measurements in Ref 1 are confined to M = 0.6 to 1.2. In addition, these measurements are made in tunnels which have many of the noise sources represented in Fig 3, as well as some resonances, none of which are represented in the present model. In what follows typical spectra measured in the RAE 3 ft x 3 ft slotted working sections at different Mach numbers will be scaled according to equation (15) to predict the corresponding spectra for M = 0.80. A unique curve would be found if there were no extraneous sources or resonances and if equation (15) is valid.

Fig 7 shows typical measurements taken from Ref 1 and scaled according to equation (15) with j = 0.325. With the slots open the level of pressure fluctuations is high ($\overline{p}/q$ about 0.018) but a fair correlation is obtained over the Mach number range from M = 0.60 to 0.90.

It is significant that the correlation is better for frequency parameters higher than $\nu_s = 0.04$. Fig 6c (after Fig 7 of Ref 7) suggests that this part of the spectrum should be representative of the mixing region close to the end of the slots. Hence this should give a better correlation than the adjustment region, which may well be influenced by the diffuser geometry and flow reattachment. [Neither of these features are included in this theory.]

Variation with x

There remains the question as to where the effective noise source should be located. As shown in Fig 6c the noise from a jet in free air comes from two distinct regions downstream of the orifice.

(1) the mixing region - of length 4d and

(2) the region downstream of the end of the core of the potential flow. The effective noise source, corresponding to the peak in the spectrum, is located approximately a distance 4d downstream of a circular jet exit when the exhaust is uniform and of low turbulence intensity.

If the same streamwise proportions were preserved for slot mixing, the effective noise source would be also 4d downstream from the slots. We shall see that for slots the effective noise source is only about 1d downstream from the slots. Hence an exact correspondence does not exist between all the details of slot and jet mixing. Thus the only practical procedure is to use equation (15) to determine a distance, x_o , of the effective noise source downstream of the slots for every tunnel.

For the section of the pilot tunnel being considered, pressure fluctuations measurements are available at M = 0.80 in the extraction region (Fig 6a for x = -0.2w) and the working section (Fig 6b for x = w). We assume a streamwise variation of the pressure fluctuations according to equation (17), and a value

$$x_o = 0.6w = 9w_s . \qquad (30)$$

Fig 8a compares measurements in the working section with the extraction region pressure fluctuations reduced according to equations (17) and (30) ie reduced by a factor of $(x_o + [-0.2w])/(x_o + w) = (0.4w)/(1.6w)$. Ignoring the displacement of the peaks in the spectra (already noticed and not accounted for in the theory), the spectra for $\nu_s \geqq 0.04$ appropriate to the mixing region do correspond well. Fig 8b shows some measurements in the plenum chamber at x = 0.5w and 2.5w, ie distant 1.1w and 3.1w upstream of the effective noise source. Fig 8c shows that when the pressure fluctuations measured at x = 0.5w are reduced according equations (9) and (30) by a factor of $(x_o + 0.5w)/(x_o + 2.5w) = (1.1w)/(3.1w)$ they are in good agreement with the measurements at x = 2.5w, particularly for $\nu_s \geqq 0.04$.

Two other important details should be noticed with respect to Fig 8c. The first detail is that the spectra of the plenum chamber pressure fluctuations are similar to those in the extraction region (rather than in the working section). Hence the plenum chamber pressure fluctuations are determined primarily by the extraction region, although they are lower by a factor of about 6 at x = 0.5w. The latter difference must be due primarily to attentuation in the narrow gap between the lower surface of the slot and the diffuser collector. The second detail is that at different positions within the plenum chamber the similarity of the spectra does not extend to low frequencies. This is because the disturbances associated with such low frequencies have a large scale, comparable with the length of the plenum chamber. These disturbances are unrelated with the high frequency, small scale noise caused by the mixing at the slots.

Within the top and bottom slotted working section of the RAE 3 ft x 3 ft Tunnel there were no measurements along the walls or in the plenum chamber which would allow the streamwise variation of pressure fluctuations to be illustrated. However there were some detailed measurements at M = 0.80 made along the sidewall of the corresponding pilot tunnel, which had wider slots, such that $w_s = 0.055w$. Fig 9 shows that the peak pressure fluctuations (at $\nu_s = 0.030$) vary little from $\sqrt{nF(n)} = 0.014$ at the ends of the slots to x = 0.5w. The theory provides a good representation of the measurements from x = 0.5w to x = 2.5w if

$$x_o = 0.39w = 7.09w_s . \qquad (31)$$

The corresponding equation for the variation of the peak pressure fluctuations with x passing through the value observed at x = 0.5w is

$$\sqrt{nF(n)} = 0.014 \left(\frac{0.89w}{x + 0.39w}\right) , \qquad (32)$$

which is drawn in Fig 9. The good agreement between this curve and the measurements provides encouraging evidence for the validity of this aspect of the semi-empirical theory.

5 Conclusions

The semi-empirical model for predicting slot noise due to diffuser suction suggests seven main conclusions relating to tunnel design.

(1) Slot and jet noise spectra are similar, the equivalent jet diameter being about 8 times the slot width for several wind tunnels, but which may be different in other tunnels.

(2) The working section noise due to diffuser suction increases steadily with Mach number, reaching a maximum at about M = 0.80 and falling to zero at M = 1.0. This is in fair agreement with experiments (Fig 10).

(3) For a given Mach number the noise intensity decays as it propagates upstream according to an inverse square law. [The equivalent jet source is located about one jet diameter downstream of the end of the slots.]

(4) Slot widths which excite slot/fan resonances must be avoided (equation (26)).

(5) The slot noise may be reduced by using a larger number of narrow slots in preference to a few wide slots: this is in accord with experiments.

(6) It should be possible to tailor the slot noise by varying the slot width, either across the working section or between the roof and the floor. This has yet to be verified.

(7) A proper evaluation of the theory is impossible unless the experimental data relate solely to pressure fluctuations propagating upstream into the working section. Despite this caveat a preliminary estimate of the empirical constants is presented in Ref 5 and Fig 5a.

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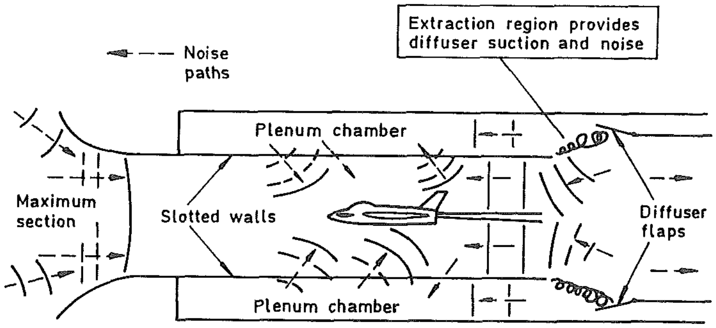
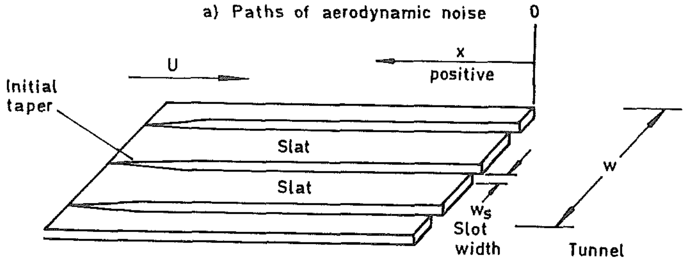
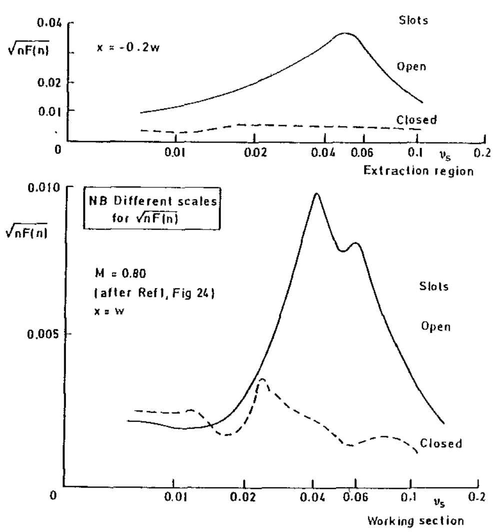


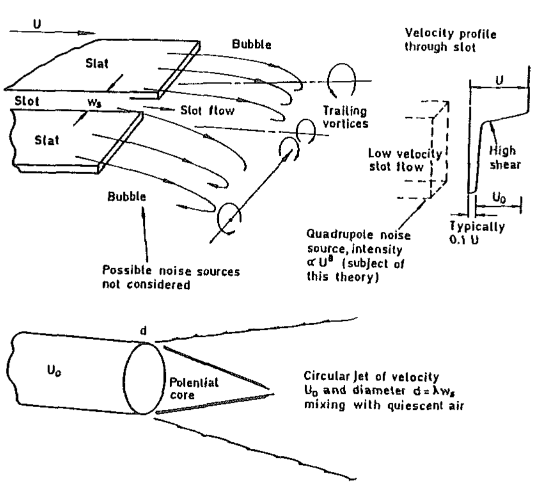
a) Paths of aerodynamic noise



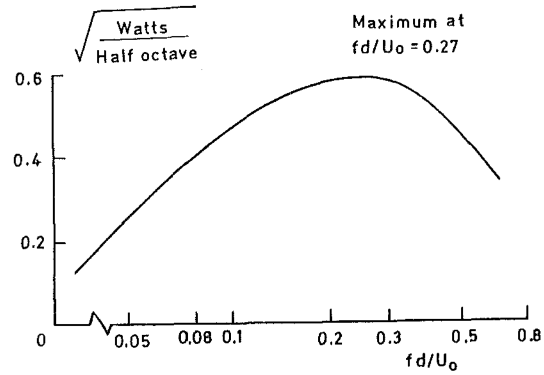
b) Typical slotted wall



c) Comparison of noise in extraction region and working section and effect of closing slots



d) Model used to compute noise from extraction region



e) Typical jet noise spectrum

Fig 1 Slotted tunnels with diffuser suction

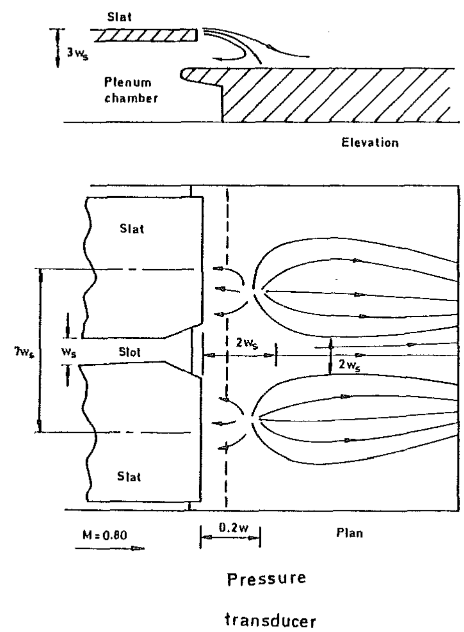


Fig 2 Flow in extraction region of pilot tunnel

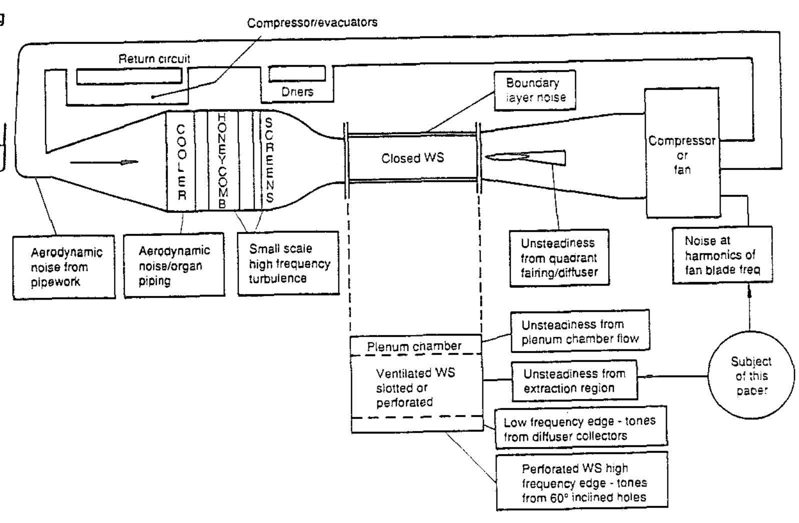


Fig. 3 Sources of unsteadiness in transonic tunnels

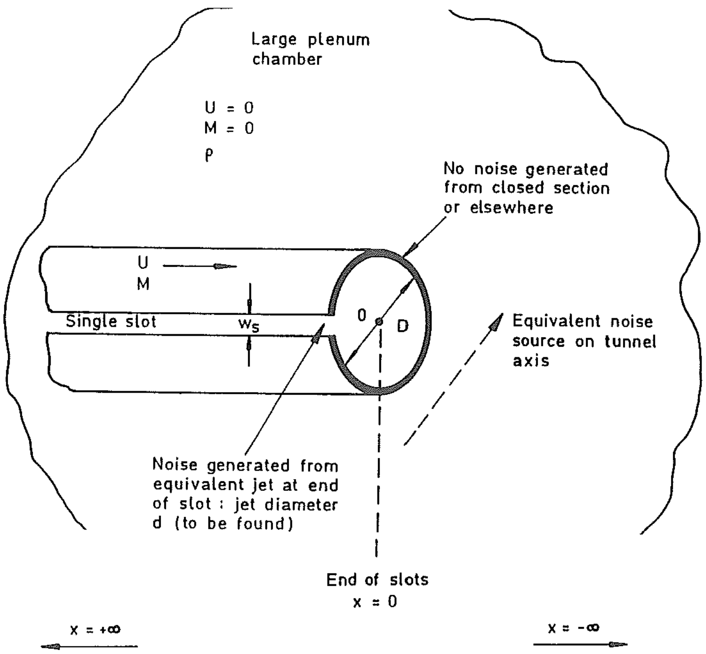
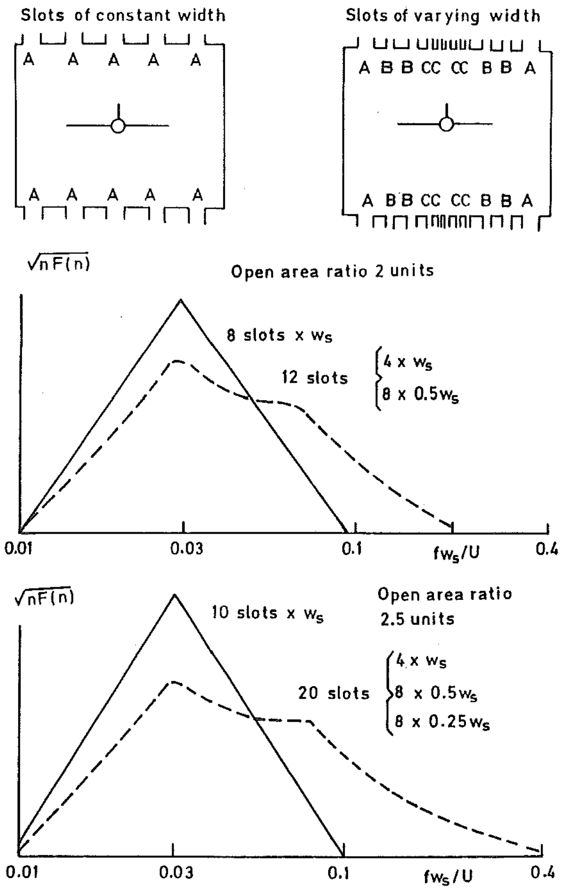
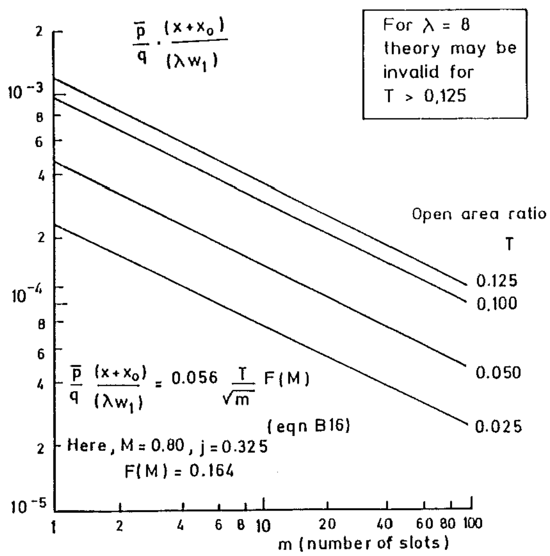


Fig 4 Idealisation of slotted tunnels with diffuser suction

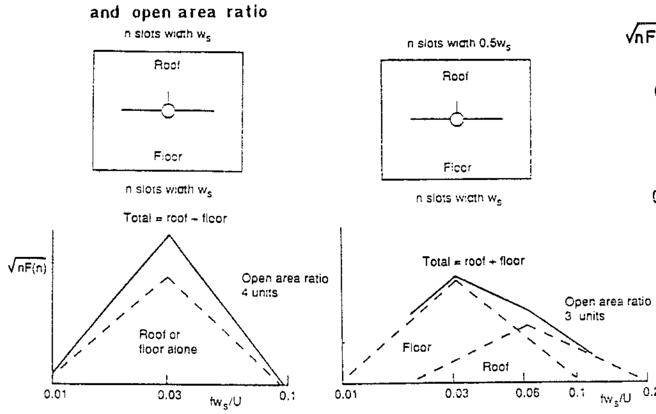


c) Symmetric sections with varying slot width

Fig 5 Inferences from semi-empirical theory



a) Variation of rms noise with number of slots and open area ratio



b) Influence of differing slot width on roof and floor

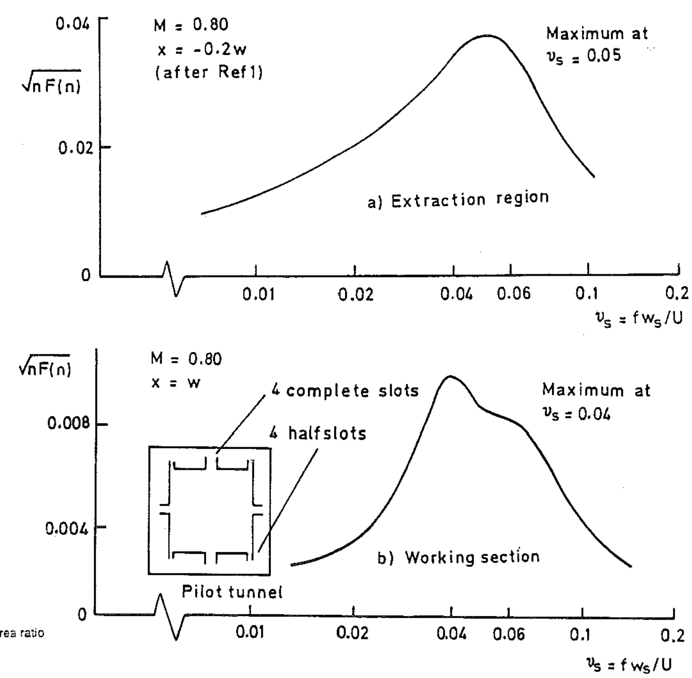


Fig 6 Comparison of noise spectra in a tunnel with four complete slots with a jet noise spectrum

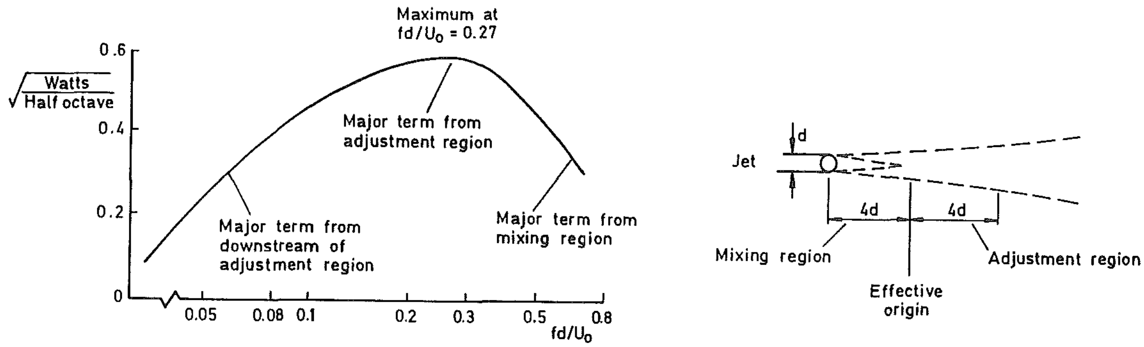


Fig 6c (concl) Jet (after Ref 11)

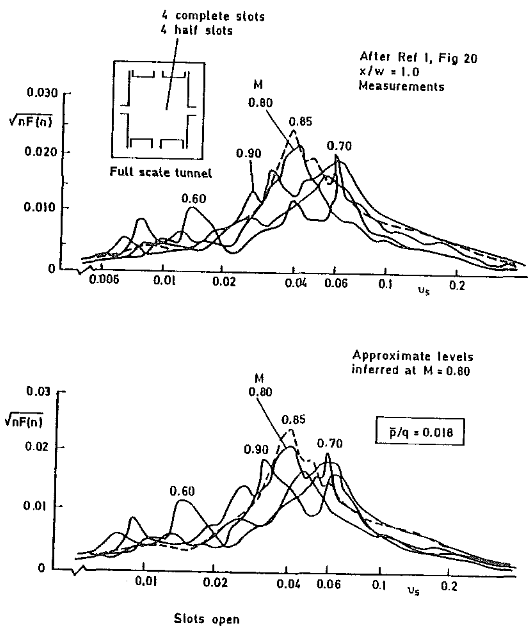


Fig 7 Working section pressure fluctuation in RAE 3ft × 3ft Tunnel inferred for M = 0.80 from measurements at other Mach numbers

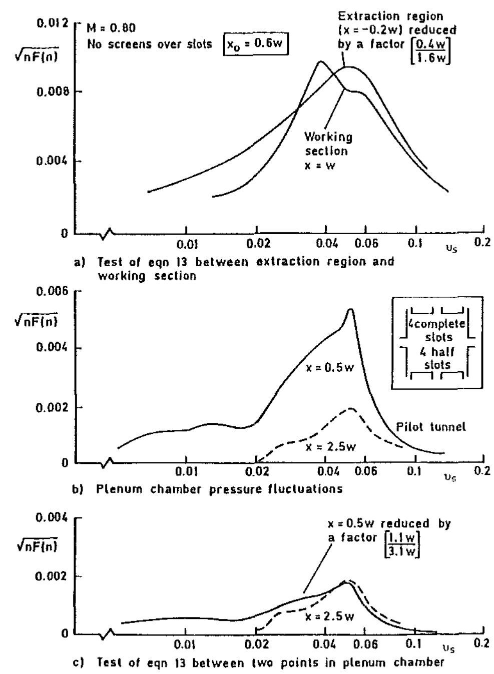


Fig 8 Comparison of streamwise variations in pilot tunnel with four slots with predictions according to theory

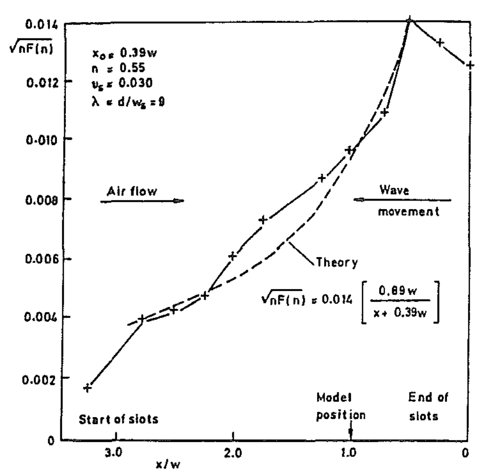


Fig 9 Comparison of streamwise variations in noise in pilot tunnel with eight slots with predictions according to theory

Fig 10 Noise function, F(M) for j = 0.250, 0.325, 0.400, 0.500 and 1.000