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SUMMARY

A preliminary investigation made with temporary test liners in the RAE 3ft × 3ft tunnel has confirmed that there are significant advantages in using working sections with sound-absorbing walls for aeroelastic tests at subsonic and transonic speeds. In particular, tunnel resonances and flow unsteadiness can be reduced just as effectively in a large wind tunnel as in the small tunnel used for the previous pilot tests.

The reduction in flow unsteadiness obtained with sound-absorbing walls significantly improved wing buffeting measurements on an ordinary wind tunnel model.

* Replaces Technical Report 77120 - ARC 37618

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1 INTRODUCTION

A previous investigation[1] showed that the dynamic interference from the walls of a wind tunnel on the flow over a circular cylinder could be reduced by incorporating sound-absorbing walls in both closed and slotted working sections. However, this investigation was limited by the small scale of the facility (the 4in × 4in pilot tunnel of the RAE 3ft × 3ft tunnel) and the correspondingly high resonance frequencies (1 to 2 kHz). These limitations were removed by the present tests, which were made in a much larger facility (a working section of reduced height for the RAE 3ft × 3ft tunnel) with lower resonance frequencies (200 to 300 Hz).

The first part of this investigation extends the previous tests on small circular cylinders, at subcritical Reynolds numbers where vortex shedding occurs, to a larger scale and lower frequencies. The second part comprises buffeting tests on a model of a typical swept wing fighter aircraft. Both sets of measurements confirm the predictions of the original tests namely, that a working section with sound-absorbing walls gives a better approximation to the dynamics of the unconfined flow than a working section with hard walls as used in conventional wind tunnels. In particular, the sound-absorbing walls reduce resonances and flow unsteadiness.

2 EXPERIMENTAL DETAILS

2.1 Temporary test liners

Fig 1 shows the general arrangement of the temporary test liners in the RAE 3ft × 3ft tunnel (width w = 0.91 m). The test liners only run a short length, 2 w, of the working section and are bolted to the top and bottom slotted liners which are frequently used for transonic tests. Thus the test liners form reduced working sections only 0.57 m high (H) by 0.91 m wide, within the top and bottom slotted working section, which is 0.64 m high by 0.91 m wide (Ref 2, Fig 4). The top and bottom slotted working section is mounted within the closed subsonic liners, which form the reference working section of the tunnel (0.91 m × 0.91 m).

Fig 2 shows the closed temporary test liners, the circular cylinders used in the first part of the investigation and the schlieren windows. The noses bolted to the top and bottom slotted liners are common to the closed and slotted types of test liners, and were unchanged during the experiment. Alternative hard and laminate closed test liners are provided which form working sections with nominally identical sizes. The hard liners are 37 mm deep and made from plywood. The laminate liners are also 37 mm deep and are made with a commercially available laminate of thickness $t = 25$ mm (as used in the previous tests) glued to a plywood base 12 mm thick. Details of the physical and acoustic properties of this laminate are given in the Appendix of Ref 1.

Fig 3 shows the geometry of the alternative hard and laminate slotted test liners. After the initial straight taper downstream of the nose, the slots in these test liners are 18 mm wide. The slots in the test liners are aligned with the 25 mm wide slots of the top and bottom slotted section (Ref 2, Fig 4c) at a pitch of 180 mm, so that the open area ratio of the top and bottom is reduced from 14% to 10%. (This is equivalent to only about 6% based on the periphery of the working section.) Every slotted test liner has four complete slots and two half slots at the corners of the working section. The hard slats are 37 mm deep and made from plywood. The laminate slats are also 37 mm deep, and are made with $t = 25$ mm glued to a plywood base 12 mm thick. It should be noticed that the ratio of the slot depth/slot width, ℓ/s, for the test liners is 2.05, and this is much higher than the corresponding ratio for the top and bottom slotted liners $\ell/s = 0.25$. The high value of ℓ/s in the temporary test liners is a consequence of the thickness of laminate (25 mm) needed to produce significant attenuation in the frequency range from 200 to 300 Hz. (The value of ℓ/s in the pilot tunnel tests was even higher, 4.7.) Fig 4 shows three of the laminate slats bolted to the bottom slotted liner.

The four temporary test liners thus consist of hard or laminate, closed or slotted portions fitted to the top and bottom walls of the slotted working section. These temporary test liners were of restricted length because a set of closed and slotted liners of sound-absorbing material, running the full length of the RAE 3ft × 3ft tunnel (4.5 w), and covering all four walls would have taken much longer to manufacture. No alterations were made to the side walls of the working section during these comparative tests, just as in the previous tests.

2.2 Cylinders

The cylinder diameters, d, were chosen so that the vortex shedding frequency, f_* should coincide with the transverse resonance frequency across the height of the working section at the Mach numbers of interest (about $M = 0.24$ and 0.40). Now the vortex shedding frequency is given by

$$f_* = S^* \frac{U}{d} , \qquad (1)$$

where S^* = Strouhal number

and U = free-stream velocity.

The resonance frequency in a working section of height H is given[3] by

$$f_r = ka(1 - M^2)^{\frac{1}{2}}/2H \quad , \tag{2}$$

where a = velocity of sound

and k = constant (1 for closed working sections).

Inspection of equations (1) and (2) shows that for resonance at a fixed Mach number an increase in tunnel height, H , must be matched by a corresponding increase in cylinder diameter. In the previous tests with H = 101 mm , resonances were excited close to M = 0.24 and 0.40 with cylinders of 10 and 18 mm diameter. Hence in the closed test liners with H = 570 mm , an increase in scale by a factor of 5.7 was required, giving nominal diameters of 57 mm and 103 mm. The cylinder diameters actually used were 63 mm and 110 mm, because standard plastic drain pipes were selected for cheapness. These thin plastic tubes were stiffened with internally cast phenolic resin. They spanned almost the full width of the tunnel in an attempt to establish two-dimensional flow. The ends of each tube were supported by a pair of brackets which bolted to the outside slats of the bottom slotted liner (Fig 2).

Two pressure transducers were mounted on the top generator of each cylinder*. One transducer was on the tunnel centre line; the other was displaced half way between the centre line and the wall. Another pressure transducer of the same type was flush mounted in the sidewall just upstream of the schlieren window and opposite the reference static hole of the closed working section. This was used for the measurement of flow unsteadiness with the tunnel empty.

The transducers were of Bytrex type HFD 050 and the amplifier gains were adjusted to give a common sensitivity of 910 N/m^2/volt (0.27 in Hg/volt) with a flat frequency response up to 10 kHz.

2.3 Fighter aircraft model

Fig 5 shows the general arrangement of the model of a small fighter aircraft used for comparative buffeting measurements in the four temporary test liners. This complete model was selected primarily because the wing fundamental bending frequency (265 Hz) was close to the calculated closed-tunnel resonance frequency at M = 0.40 (270 Hz). Hence, if any resonance interference effects

*The choice of this circumferential position minimized the sensitivity of the measurements to small variations in angle of incidence, because previous pressure fluctuation measurements around a circular cylinder showed maxima on the top and bottom generators[4].

did occur, they should be noticed at that speed. In addition the model had been used for previous buffeting tests in the top and bottom slotted section[5] and in a much larger working section[6] (the perforated ARA 9ft × 8ft tunnel). These tests had shown that the separated flows on this wing which excite buffeting were relatively insensitive to the roughness band used to fix transition and to variations in Reynolds number. The aircraft has also been the subject of an extensive flight/tunnel comparison based on larger models[7], which achieved full-scale Reynolds numbers and showed that scale effects were small.

The present model was sting supported (Fig 4) and the normal force coefficient, C_N , and sting deflections were determined from an internal strain-gauge balance. Following normal practice for wing buffeting measurements, the tailplane was removed. Hence changes in wing buffeting could be related to changes in the model C_N .

Two active semi-conductor strain gauges at the starboard wing-root were combined with two passive resistances to detect the wing response, which was primarily at the wing fundamental frequency of 265 Hz, as in the previous tests on this model[5,6]. The rms bridge output, $\overline{V}$ was manually recorded on a Brüel & Kjäer 2107 spectrum analyser tuned to the fundamental frequency with a 35 dB bandwidth (12%). The rms wing-root strain measurements were then derived from the relation

$$\varepsilon = \frac{2\overline{V}}{V\sigma} , \qquad (3)$$

where V = dc bridge excitation voltage

and σ = gauge factor (120 for these gauges).

2.4 Test conditions

Different tunnel total pressures were selected for the cylinder tests and the buffeting measurements.

For the cylinders, about the same subcritical Reynolds numbers, Rd , were required as in the previous tests[1]. There the total pressure was just less than 1 bar for all Mach numbers. Hence with the six fold increase in size of cylinders used in the temporary test liners, the tunnel total pressure should have been just less than 1/6 bar (0.16 bar). However at this total pressure the time taken to evacuate the tunnel was excessive, and so the total pressure was increased to 0.20 bar. Even with this increase Rd still remained within the subcritical range ($Rd < 2 \times 10^5$).

For most of the buffeting tests, a tunnel total pressure of 0.98 bar was selected, to approximate the total pressure in the previous tests in the large perforated tunnel[6]. This gave Reynolds numbers $R\bar{c}$ between 0.8×10^6 and 1.2×10^6. The same total pressure was used for the measurements of flow unsteadiness.

The tunnel total temperature was maintained at about 20°C throughout the tests.

3 RESULTS

The improvements obtained with the sound-absorbing walls are now discussed in the order of their importance. Sections 3.1 and 3.2 extrapolate the previous tests to a scale an order of magnitude larger, whereas section 3.3 represents the first application of compliant walls when testing a small "dynamic model".

3.1 Reduction of resonances

3.1.1 Closed working sections

Fig 6 shows the pressure fluctuations measured on the top generator of the larger cylinder during an initial test with closed hard and laminate walls, when the cylinder was offset 18 mm above the centre line of the working section due to a rigging error. Fig 6a shows that with the hard walls the vortex shedding frequency increases almost linearly with Mach number from $M = 0.20$ to 0.35, according to equation (1) with $S^* = 0.22$. However, from $M = 0.35$ to 0.41 the vortex shedding 'locks onto' a frequency of about 255 Hz, just below the calculated closed-tunnel resonance frequency (f_r = 270 Hz, equation (2)). Over the speed range within which the vortex shedding frequency is constant, the rms pressure fluctuations increase rapidly to reach a maximum of $\overline{P}/q = 70\%$ at $M = 0.40$. The pressure fluctuations then fall rapidly to reach a minimum at about $M = 0.44$, then increase monotonically with Mach number (Fig 6b). In this top speed range the normal shedding frequency is restored, with $S^* = 0.21$. At the peak resonance condition at $M = 0.40$, the noise level outside the tunnel was alarming, despite the low kinetic pressure ($q = 0.02$ bar).

The replacement of the hard closed walls by the laminate closed walls makes a profound improvement to the pressure fluctuations measured on the cylinder. Thus the vortex shedding frequency increases monotonically with speed, and up to $M = 0.40$ agrees with equation (1) with $S^* = 0.21$ (Fig 6a). Although there is no obvious 'locking on' in vortex shedding frequency, there is still a peak of $\overline{P}/q = 42\%$ at about $M = 0.39$, corresponding to a weak resonance at a reduced frequency of 235 Hz. With the laminate liners the effective acoustic height must be greater than the working section height H , because the periodic air motion extends into the interstices of the laminate. It is plausible to assume that for frequencies as low as 250 Hz the air motion extends right through the laminate. Hence the effective acoustic height is the tunnel height plus the laminate thickness on each wall, *ie*

$$\text{effective acoustic height} = H + 2t = 570 + 50 = 620 \text{ mm} .$$

The resonance frequency with the laminate liners may then be estimated from the measured resonance frequency with the hard liners (255 Hz). From equation (2) we have for the laminate liners,

$$f_r = 255 \times \frac{570}{620} = 235 \text{ Hz} ,$$

which is consistent with the measurements. The reduction of the resonance at M = 0.40 by the laminate test liners was also independently attested by the greatly reduced external noise compared with the hard test liners.

Fig 7 shows similar measurements made with the larger cylinder on the tunnel centre line. Fig 7a shows that with the hard walls the vortex shedding initially accords with equation (1) with a Strouhal number, $S^* = 0.21$. However the shedding frequency 'locks onto' a strong resonance at about 245 Hz in the Mach number range from M = 0.35 to 0.40 . In contrast, with laminate walls the shedding frequency 'locks onto' a weak resonance at about 235 Hz in the Mach number range from M = 0.32 to 0.36 . The peak pressure fluctuations at the resonance conditions are $\overline{P}/q = 32\%$ at M = 0.40 and $\overline{P}/q = 17\%$ at M = 0.35 respectively for the hard and laminate walls (Fig 7b).

The pressure fluctuations measured during these tests are about 50% of those measured with the cylinder displaced above the tunnel centre line (*cf* Fig 6b). Two separate factors may contribute to this difference. When the cylinder is displaced from the tunnel centre line the static pressure distribution will be significantly asymmetric because of the large blockage ratio (19%). Hence there is a small steady lift on the cylinder and vortex shedding occurs asymmetrically. It is likely that this would increase the rms level of the fluctuating pressures in the absence of resonances (*eg* at M = 0.20 and 0.50) and this is certainly consistent with the measurements. In addition calculations suggest that the response of a duct to an acoustic source of sound at a resonance frequency is appreciably stronger when the source is displaced away from the duct centre line[8].

Fig 8 shows the pressure fluctuations measured on the top generator of the smaller cylinder in the closed working section, offset 18 mm above the centre line. With both hard and laminate liners the vortex shedding frequency increases monotonically with speed according to equation (1), with $S^* = 0.21$, and there is no discernible 'locking-on' on a resonance frequency. However, there are somewhat ill-defined maxima at $M = 0.24$ ($\overline{P}/q = 34\%$; $f = 265$ Hz) and at $M = 0.23$ ($\overline{P}/q = 30\%$; $f = 250$ Hz) respectively with the hard and laminate walls. These trends resemble those observed with the larger cylinder at $M = 0.4$, but they are inconclusive because at these low speeds it was impossible to control the tunnel velocity precisely with the manual speed control. In addition the kinetic pressure was extremely small (only $q = 0.008$ bar) so that the pressure transducers were recording small signals. Hence no further tests were made with the smaller cylinder.

3.1.2 Slotted working sections

The previous tests[1] suggested that it was difficult to excite strong resonances with circular cylinders in slotted tunnels at subsonic speeds, even in working sections with hard walls. Hence in the present tests a careful attempt was made to follow the decay of a strong resonance in a slotted working section with hard walls as the open area ratio was increased from zero. The procedure was to increase the number of slots progressively (Fig 9), but in an ideal experiment the number of the slots would be constant and the slot width would be increased progressively.

For the larger cylinder with all the slots sealed, the results for the closed working section were reproduced (Fig 7) with a severe resonance ($\overline{P}/q = 32\%$) at $M = 0.40$ at a frequency of 245 Hz. When the two slots closest to the tunnel centre line were opened in both the top and bottom walls, the resonance remained at the same speed but the level fell to $\overline{P}/q = 16\%$ and the frequency increased to 285 Hz. When all the slots were opened, the resonance speed increased to $M = 0.41$, but the level fell to $\overline{P}/q = 12\%$ and the frequency increased to 290 Hz. With all the slots open it was scarcely possible to detect the 'locking-in' experienced at the resonance condition (Fig 9a) and the pressure fluctuations at resonance were only marginally higher than the adjacent measurements. Hence this resonance was not considered of sufficient strength to justify a test with the laminate slotted liners. However, there is no *a priori* reason why the laminate slats should not attenuate resonances almost as well as the fully closed laminate walls. This view is directly supported by the measurements of flow unsteadiness, which are now discussed.

3.2 Reduction of flow unsteadiness

The addition of the hard slotted test liners (giving H = 570 mm) to the top and bottom slotted working section (with H = 640 mm) makes relatively minor changes in the broad band rms levels of the pressure fluctuations in the empty working-section (Fig 10a). These are primarily generated downstream in the mixing region at the ends of the liners and in the diffuser[2]. Although the deeper step down to the diffuser at the ends of the test liners slightly increases the pressure fluctuations at M = 0.60 and 0.80, the reduced diffuser velocities produced by the smaller working section provide a small net reduction in unsteadiness at M = 0.90. The deep narrow slots adopted for the slotted test liners generate no additional unsteadiness relative to the closed test liners (Fig 10b), confirming the conclusions inferred from previous tests[2]. Now the main interest in the present experiment is in the comparison of the working-section pressure fluctuations with hard and laminate walls of the same external geometry. Compared to the hard walls, the laminate walls clearly reduce the flow unsteadiness for both the closed and slotted working sections. These comparisons are almost identical for both the closed and slotted working sections; for brevity Fig 10c only shows the measurements for the slotted test liners.

Fig 11 shows the corresponding spectra of the pressure fluctuations measured with the slotted test liners. Fig 11a shows the direct difference in decibels between the pressure transducer voltages measured with the hard and laminate walls. The laminate walls clearly provide large reductions in flow unsteadiness over the frequency range of interest for buffeting or flutter measurements in the tunnel (say from 200 to 1000 Hz) in the Mach number range from M = 0.4 to 0.9. Fig 11a also shows that the attenuation provided by the laminate walls moves progressively towards lower frequencies as Mach number increases, *eg* there is still 4 dB reduction in voltage at 100 Hz at M = 0.9. This is a useful result, which was not observed in the previous tests as a much smaller scale. A similar result was observed over the Mach number range from M = 0 to 0.5 within a lined duct, for sound propagating upstream and there is no *a priori* reason why this trend should not continue as speed increases. (See discussion of Fig 5 in Ref 9.)

Fig 11b shows the non-dimensional spectra of the pressure fluctuations plotted in the usual form[2] of $\sqrt{nF(n)}$ v log n. The laminate liners reduce the pressure fluctuations by more than half over a wide range of frequencies at $M = 0.6$ and 0.8 , giving a flat residual spectrum with a low level

$$0.001 \sqrt{nF(n)} < 0.002 \quad .$$

For reference in 3.3 below, the frequency parameter corresponding to the fundamental wing bending frequency (265 Hz) of the model used subsequently for buffeting tests is indicated at all speeds.

There is a peak in the spectrum at $M = 0.40$ at a frequency of 50 Hz. This peak was unaffected by the changes in the wall material and was observed for all the tunnel configurations tested (*ie* both types of closed and slotted test liners and the original top and bottom slotted working section). This peak in the working-section pressure fluctuations is probably caused by a longitudinal resonance in the 3.6 m long, shallow plenum chamber of the top and bottom slotted working section. Hence it could be attenuated by appropriate measures in the plenum chamber. A longitudinal mode at about this frequency was excited at $M = 0.6$ in the 3.4 m long plenum chamber of the 3ft tunnel perforated working section. This longitudinal mode in the plenum chamber also influenced the working-section pressure fluctuations. It was attenuated by inserting baffles in the plenum chamber (see discussion of Fig 31 in Ref 2).

3.3 Improvement in buffeting measurements

Fig 12 shows the rms unsteady wing-root strain, ε , as a function of the steady normal force coefficient, C_N , measured on the fighter aircraft model in the closed working sections. When the flow is attached at low values of C_N , the wing response is appreciably smaller with the laminate liners than with the hard liners, consistent with the reduced level of aerodynamic excitation (3.2 above). Hence buffet onset is more sharply defined with the laminate liners than with the hard liners. In addition the buffeting measurements with flow separations are less scattered with the laminate liners than with the hard liners. This effect is difficult to quantify but is more obvious at $M = 0.60$, when the scatter of the measurements after buffet onset is rather large with the hard walls, but smaller with the laminate walls.

There is no evidence that resonance interference occurs in the closed working section, even at $M = 0.4$, when the measured transverse resonance frequency (255 Hz) is close to the wing bending frequency (265 Hz). This negative conclusion is consistent with the hypothesis advanced previously[1]. The pressure fluctuations which excite buffeting are generally independent of the motion of the structure and are correlated over small lengths. Hence they would not be expected to excite wind-tunnel resonances on ordinary wind-tunnel models when the response amplitudes are small. However, for aeroelastic models used for buffeting tests the amplitude of the wing response would be much larger, and some resonance interference might well occur when model natural frequencies coincide with tunnel resonance frequencies.

Fig 13 shows similar trends for the unsteady wing-root strain measurements in the slotted working sections. With the laminate liners buffet onset is more clearly defined and the buffeting measurements are less scattered because of the lower level of flow unsteadiness. The latter effect is again difficult to quantify, but it is most obvious at $M = 0.80$. The wing-root strain measurements around buffet onset at this speed are surprisingly badly defined with hard walls, despite the modest level of flow unsteadiness (only $\sqrt{nF(n)} = 0.002$ at 265 Hz in Fig 11).

It is interesting to note that for many conditions when the wing flow is attached, the rms wing-root strain measurements decrease as C_N increases. Quite large reductions in response occur at the higher speeds, when the wing shock system is moving monotonically downstream without provoking separation. Then a progressively larger area of the wing upper surface is isolated (by the development of local supersonic flow) from the large component of the flow unsteadiness which propagates upstream from the end of the working section[2] - thus the wing response falls as C_N increases because the excitation decreases. This effect is fairly large in the closed working sections at $M = 0.80$, but small at $M = 0.85$ because then the tunnel is so close to choking that unsteadiness generated downstream cannot easily propagate upstream into the working section (Fig 12). In contrast, the effect is large in the slotted working sections at $M = 0.80$ and 0.90 (Fig 13) and thus is clearly associated with tunnel-flow unsteadiness, rather than with any natural unsteadiness generated by the shock-wave boundary-layer interaction on the wing[10].

A similar, but somewhat smaller variation in response is also sometimes observed at lower speeds (*eg* with the hard closed liners at $M = 0.4$ or with the laminate liners at $M = 0.6$). Although no convincing explanation for these variations has yet been offered, they are still probably related with the levels of flow unsteadiness. This rather unusual* variation of dynamic interference

*Interference of this type was also observed over the speed range from $M = 0.60$ to 0.99 in the top and bottom slotted working section of the RAE 3ft × 3ft tunnel on a model of a fighter aircraft with highly swept wings. The wing fundamental bending frequency was 283 Hz (see Ref 5, Fig 22).

with C_N was also observed on this model at $M = 0.6$ and 0.8 in the much larger ARA perforated wind tunnel[6].

For all these tests on this small model the total damping measurements (for the first wing bending mode derived from auto-correlation of the tape records of the buffeting signals) were constant over this range of C_N , so that the reduction in response can only be attributed to a reduction in effective excitation. A small decrease in response at values of C_N below buffet onset was also observed on much larger half-models tested in the RAE 8ft × 8ft tunnel[7] at $M = 0.70$ and 0.80 , with a very low level of flow unsteadiness. (Again, no significant variation in the total damping occurred over this range of incidence, so that the reduction in response must be attributed to a reduction in effective excitation.)

The buffeting measurements given in Figs 12 and 13 are plotted against the model normal force coefficient, C_N ; rather than the geometric angle of incidence, α_W , because there were significant differences between the normal force measured in the test liners with hard and laminate walls at the same geometric angle of incidence. These normal force differences were equivalent to changes in zero lift angle of about 0.3^o with the closed walls (Fig 14) and about 0.1^o with the slotted walls (Fig 15). They were probably caused by small asymmetries in the laminate test liners. For these strictly comparative tests both sets of temporary test liners were uncalibrated and hence no blockage corrections were applied to the measurements. However, apart from these changes in zero lift angle, both sets of measurements are in fair agreement with the previous measurements in the large perforated working section of the ARA tunnel (Figs 14 and 15) , confirming that the flow on the model was not greatly influenced by the restricted height of the working section. (The difference in $dC_N/d\alpha$ between the closed and slotted working sections is small for two reasons. The closed working section incorporates small half slots at the corners, which are vented to the plenum chamber. The slotted working section also incorporates these half slots, but the slats are so deep ($\ell/s = 2.05$), that the slotted walls tend to function more like a closed tunnel than an open-jet tunnel).

4 DISCUSSION

The present tests confirm that the method used to reduce dynamic interference in the pilot tunnel experiment[1] can be employed in much larger wind tunnels[11]. In this discussion we shall consider the implications of the present tests for future tests of dynamic aeroelastic models in larger facilities.

Considering first the dynamic interference caused by resonances, we find that resonances at frequencies as low as 250 Hz were strongly attenuated (Fig 6) in the closed working section with sound-absorbing walls only 25 mm thick (*ie* exactly the same thickness as used in the closed working section of the pilot tunnel!). We know from the acoustic properties of the laminate (Ref 1, Appendix) that at frequencies in the range from 100 to 300 Hz much better attenuation can be achieved with a 50 mm thickness, and hence this larger thickness should be adequate for working section heights in the range from, say, H = 1 m to 3 m . In the slotted working section with hard slots the resonance excited at M = 0.41 was too weak (Fig 9) to justify a comparative test with laminate slats. However, a slotted wall with laminate slats should attenuate resonances even more effectively than a slotted wall with hard slats, because the slat area is generally greater than 90% of the wall area.

Some more general observations about resonances in slotted working sections with hard walls are appropriate at this point. Resonance interference in tests of dynamic flutter models in slotted tunnels is generally considered to be most serious in the speed range from M = 0.6 to 1.0 , although no specific experiment can be cited. [The slotted working sections used by Ruhlin *et al*[12] appeared free of interference, whereas the perforated working section apparently had large interference at M = 0.85 and 0.90 (Ref 12, Fig 4.)]. Hence a Mach number, M = 0.8 would be a better test speed for the sound-absorbing walls than M = 0.4 . However this higher speed is well above the critical Mach number for a circular cylinder (M = 0.45), and if equation (1) and equation (2) (modified for wall open area ratio[3] with k = 1.19) are satisfied, the cylinder blockage ratio required is d/H = 0.47 , destroying the credibility of the simple experiment. Hence verification of the wall interference at M = 0.8 will require more sophisticated tests with an oscillating model driven at the resonance frequencies of the wind tunnel.

It is often assumed that only the lowest resonance frequency in a slotted working section can be excited, but this assumption is erroneous. Tests by Pollock[13] in a 533 mm × 80 mm slotted tunnel demonstrated that multiple overtone resonances, up to about the 20th harmonic, could be excited in the speed range from M = 0.238 to 0.645. Thus Fig 16 shows the vortex shedding frequencies measured on a flat plate with a bluff trailing-edge. The vortex shedding frequencies lock onto overtone resonance frequencies at the speeds roughly indicated by the filled circles. A tenfold magnification of a small portion of this curve (Fig 17) clearly shows the resonant pauses, at which vortex shedding locks onto the overtone resonance frequencies; Fig 17 is directly comparable with the present measurements given in Figs 6a and 7a for the closed working section. Replacement of the hard slats by laminate slats should have strongly attenuated these overtone resonances. Fig 16 and 17 suggest that the designers of dynamic flutter models should keep all the structure modal frequencies away from tunnel overtone resonance frequencies, as well as from the fundamental frequency. It should be possible to remove this restrictive condition for working sections with sound-absorbing walls.

In the present experiment the sound-absorbing walls have significantly reduced the flow unsteadiness relative to the levels measured with hard walls for both closed and slotted working sections (Figs 10 and 11). Even though the laminate thickness was restricted to 25 mm (as in the closed working section of the pilot tunnel) significant reductions (6 dB or 50%) are found down to frequencies as low as 130 Hz at $M = 0.8$ (Fig 11a). Hence the 50 mm thickness proposed for working section heights from 1 m to 3 m should be effective down to frequencies as low as 100 Hz at $M = 0.8$.

The lower flow unsteadiness with the laminate walls reduces the response of the wing of the fighter aircraft model at 265 Hz under attached flow conditions, thus making buffet onset better defined than with the hard walls (Figs 12 and 13). In addition the measurements under separated flow conditions are less scattered with the laminate liners than with the hard liners. Both of these features would be valuable in future buffeting investigations. The small changes in zero lift angle between the laminate and hard walls (Figs 14 and 15) represent minor anomalies which could be eliminated by calibration or adjustment to the wall angles.

In view of the advantages of sound-absorbing walls for dynamic measurements, the reader may well ask "What are the disadvantages?" The only significant disadvantage is a small increase in tunnel drive power required because of the increased skin friction of the laminate walls relative to the hard walls. The skin friction increases because the perforations in the laminate act as distributed roughness elements; this effect has been observed in other tests of perforated acoustic liners[14]. In the present tests this small increase in tunnel power was detected at Mach numbers of 0.8 and above by an increase in the motor speeds and currents necessary to maintain a given nominal Mach number (Fig 18). In the temporary slotted test liners this small penalty will be reduced by a modification which will restrict the area of laminate to the region of constant slot width (Fig 3). This alteration is essential because at Mach numbers of 0.9 and above the slotted laminate liners distorted significantly in the expansion regions under the static pressure gradient from $x = 0$ to $x = 0.3$ m . No significant distortion was observed in the region of uniform flow from $x = 0.3$ to 1.5 m .

The small size of the working sections provided by the temporary test liners (only 0.91 m wide × 0.57 m high) limits their usefulness for routine tests of aeroelastic models. However, a slotted working section 0.91 m wide by 0.91 m high utilizing sound-absorbing walls could be provided without great expense as an alternative to the 0.91 m wide × 0.81 m high perforated working section. This relatively large slotted working section would provide a unique capability in the RAE 3ft × 3ft tunnel for interference-free dynamic aeroelastic tests at subsonic and transonic speeds.

5 CONCLUSIONS

Tests made with temporary test liners in the RAE 3ft tunnel have confirmed that there are significant advantages in using working sections with sound-absorbing walls for aeroelastic tests at subsonic and transonic speeds. In particular, tunnel resonances and flow unsteadiness can be reduced just as effectively in a large tunnel as in the small tunnel used previously for the pilot tests.

The reduction of tunnel resonances should allow the designers of flutter models to disregard coincidences between possible tunnel resonance frequencies and model response frequencies, which always occur within the transonic speed range as the Mach number approaches unity (see equation (2)). The reduction in flow unsteadiness should also facilitate the determination of both the sub-critical damping and the model flutter boundaries. The reduction in flow unsteadiness should also improve wing buffeting measurements on aeroelastic models, or on ordinary wind tunnel models as used in the present tests.

LIST OF SYMBOLS

a	local velocity of sound
$\bar{c}$	average chord
C_N	normal force coefficient
d	cylinder diameter
f	frequency
f_*	vortex shedding frequency
f_r	tunnel resonance frequency
$\sqrt{nF(n)}$	flow unsteadiness
H	tunnel height
k	constant (equation 2)
ℓ	depth of slot
M	Mach number
n	frequency parameter = fw/U
p_t	tunnel total pressure
$\bar{P}$	rms pressure fluctuation
q	kinetic pressure
R	Unit Reynolds number
s	slot width
S^*	Strouhal number = f_*d/U (equation 1)
t	laminate thickness
U	free-stream velocity
V	dc bridge excitation voltage
$\bar{V}$	rms bridge output
w	tunnel width
x	distance downstream from start of slot
α_W	wing-incidence
ε	rms wing-root strain
σ	gauge factor

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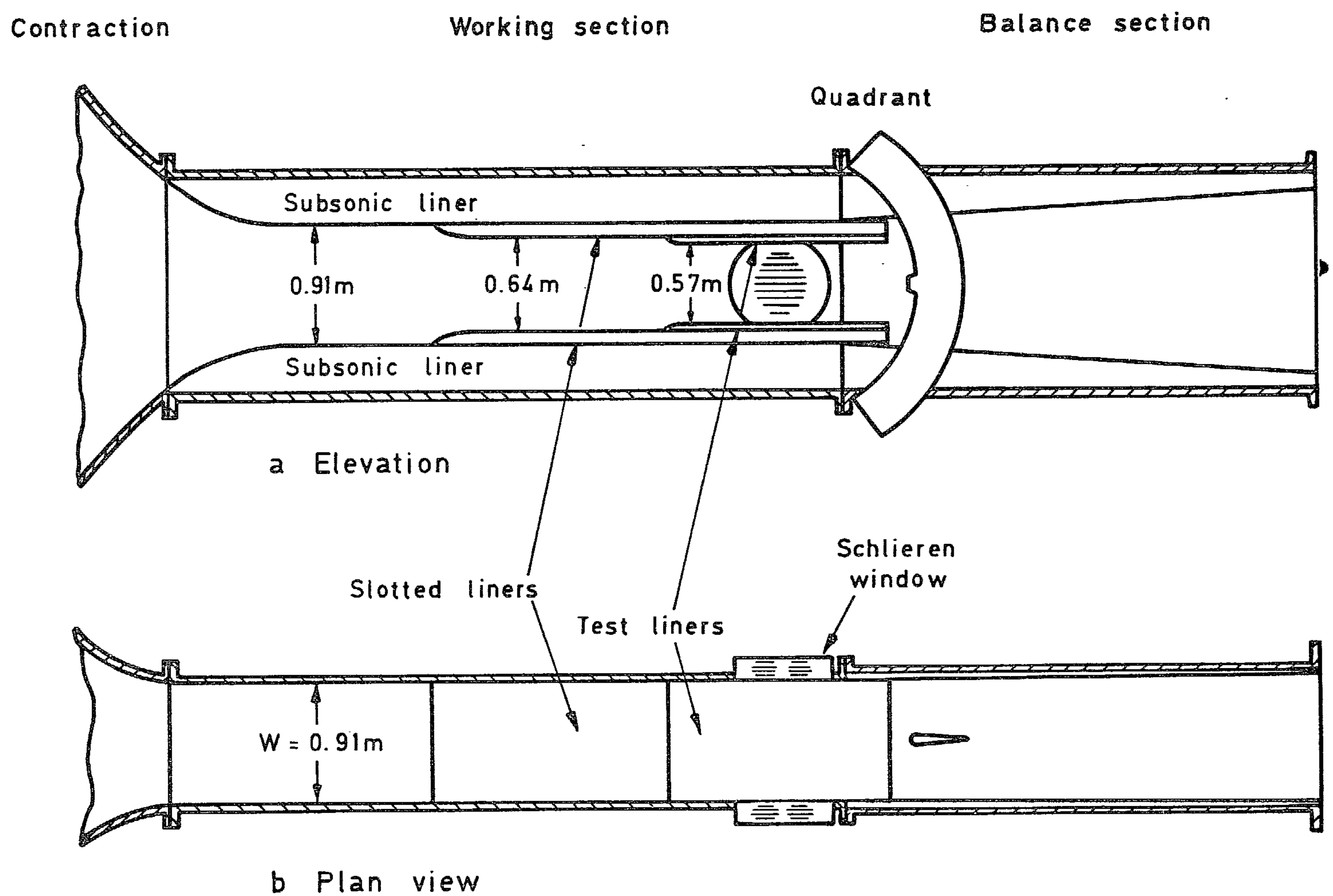


Fig 1 GA of test liners in RAE 3ft x 3ft tunnel

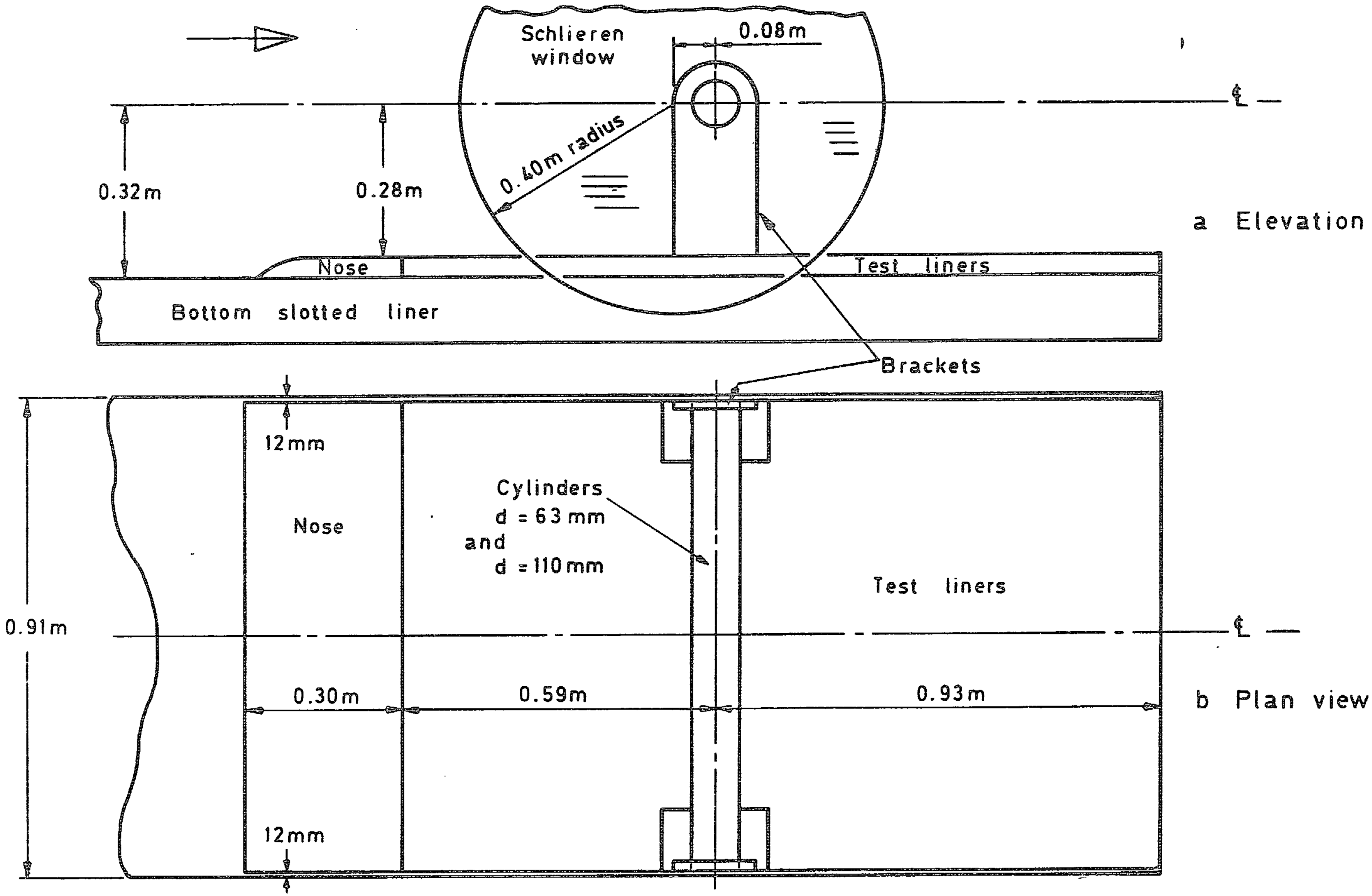


Fig 2 Test liners and cylinders

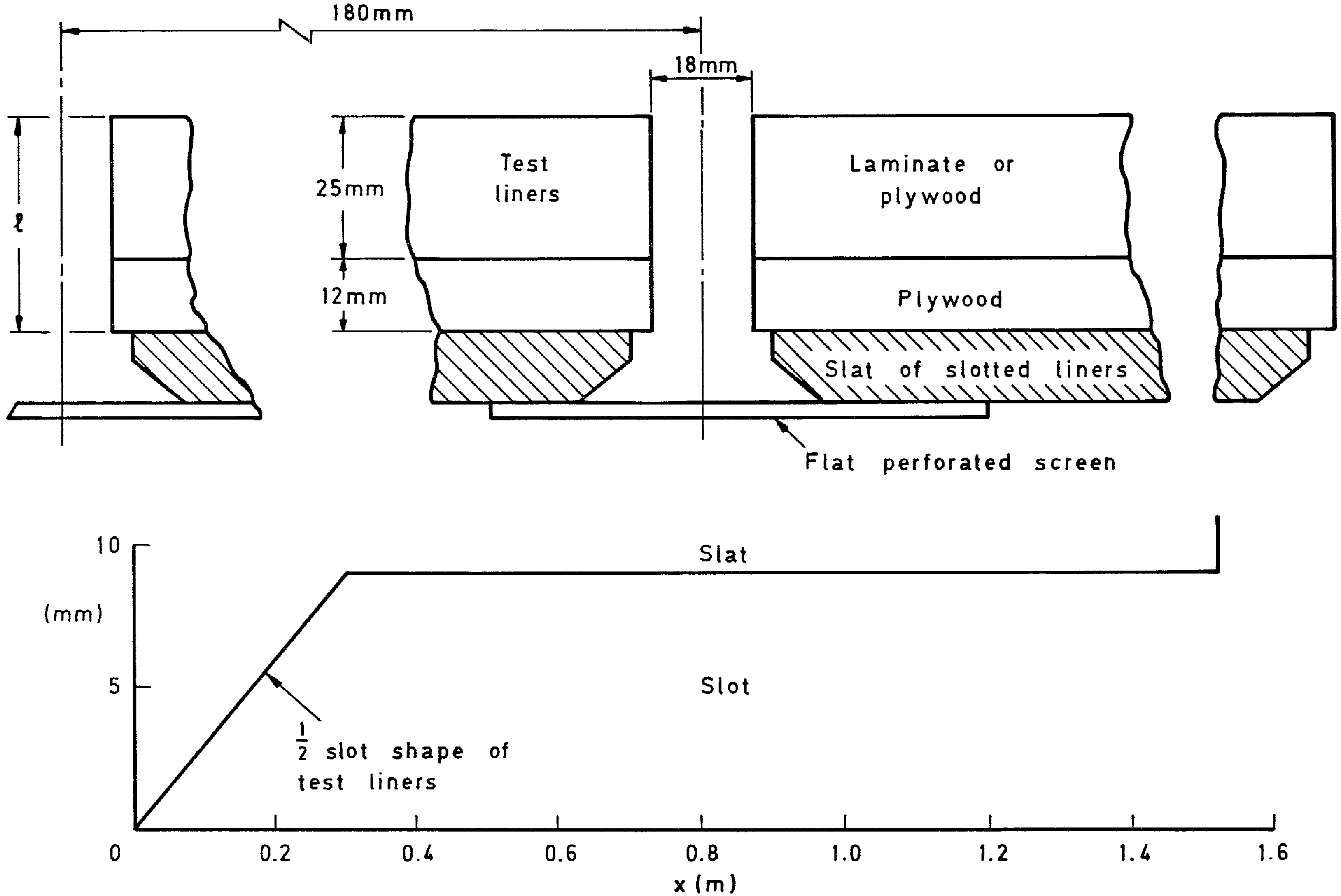


Fig 3 Geometry of slotted test liners

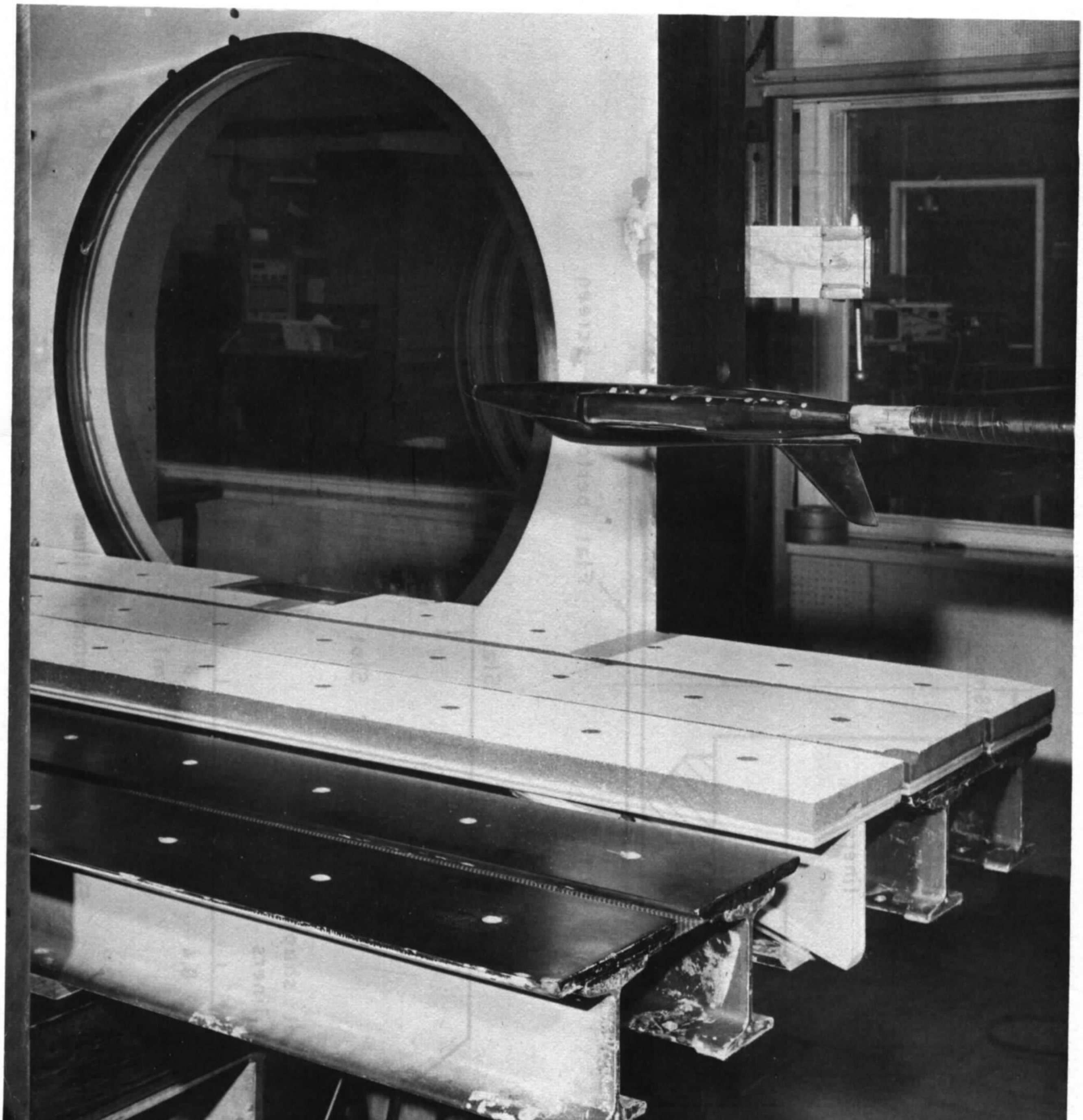


Fig 4 Partially assembled test liners

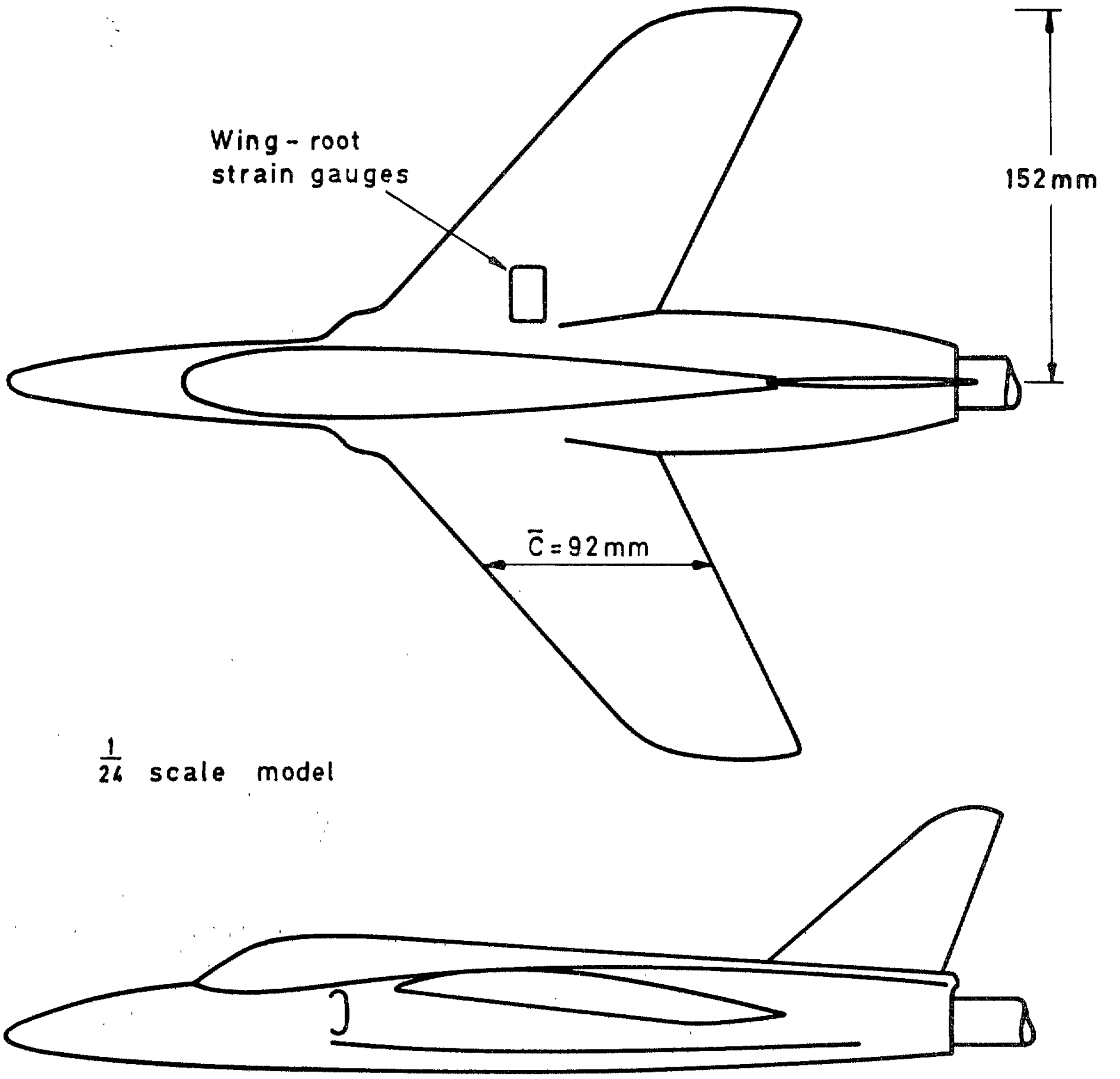


Fig 5 Model used for wing buffeting tests

Fig 6

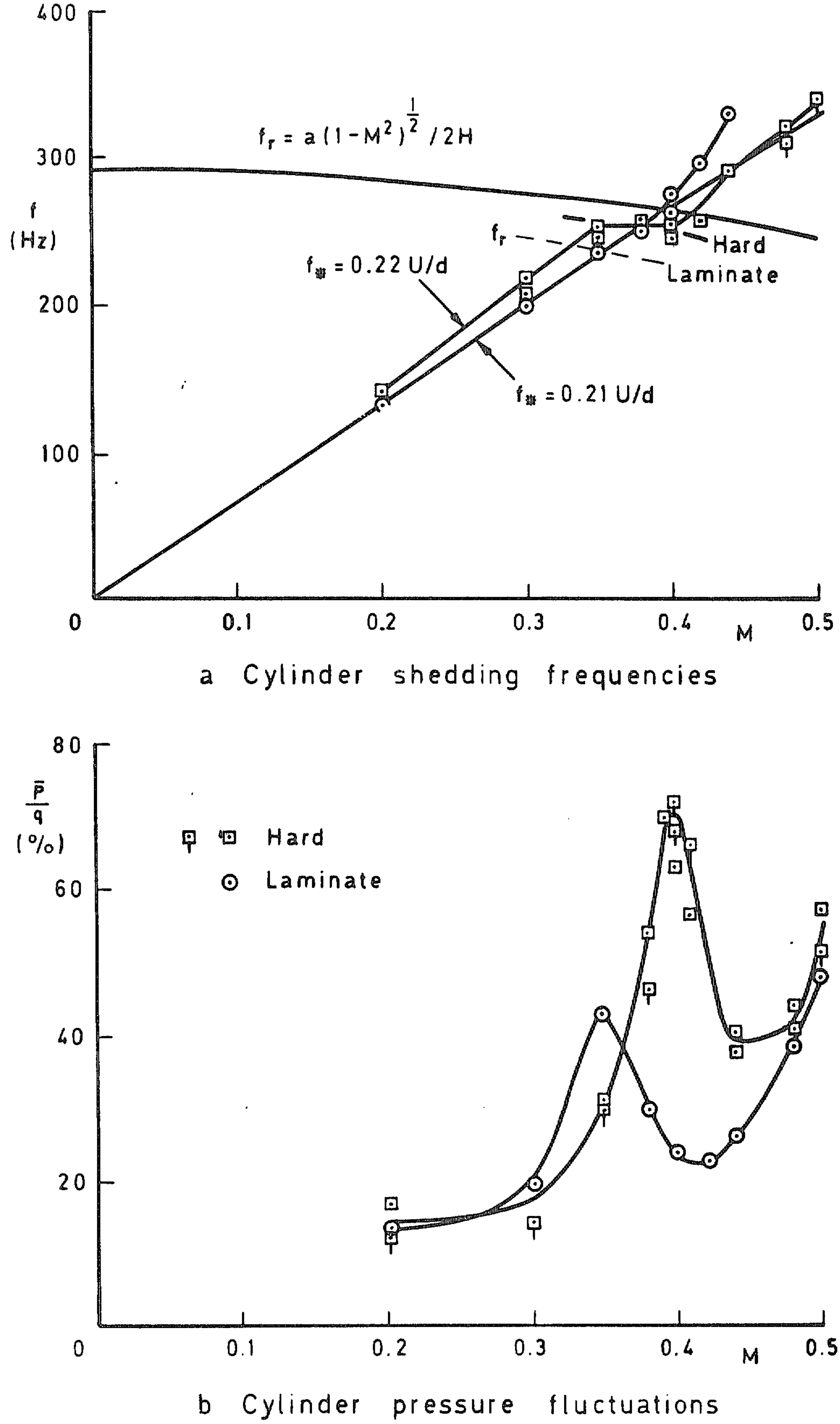
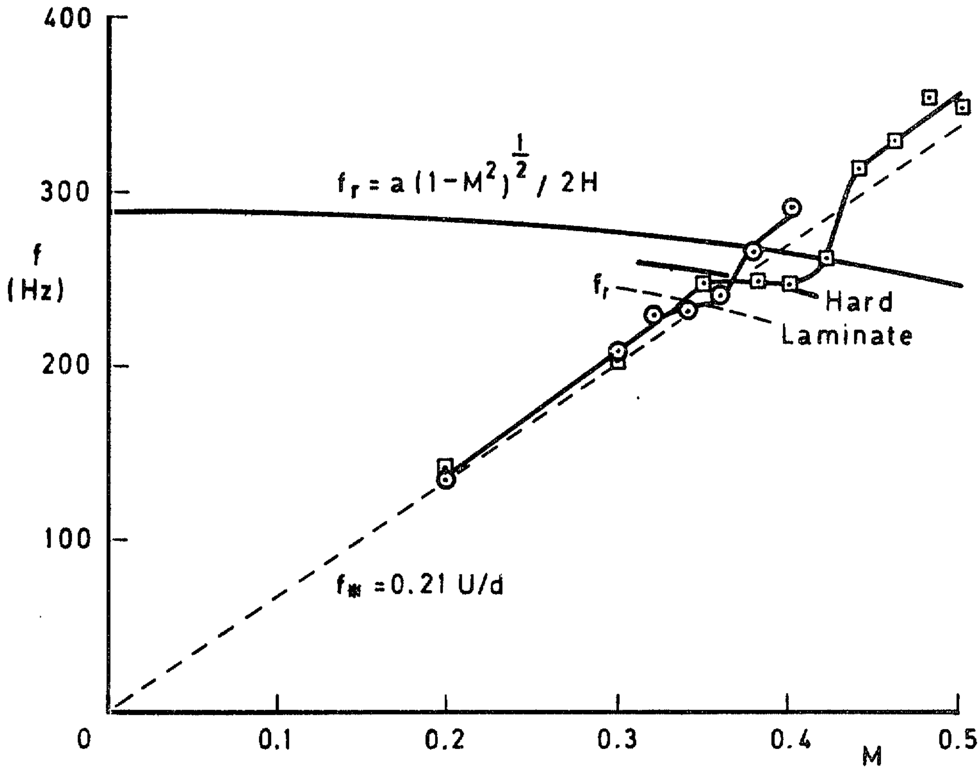
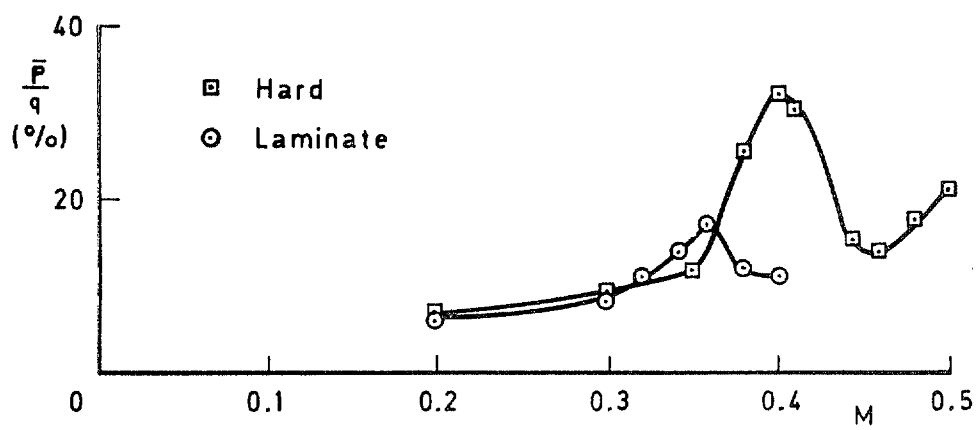


Fig 6 Cylinder (d = 110 mm) in closed working sections (18 mm above centre line)

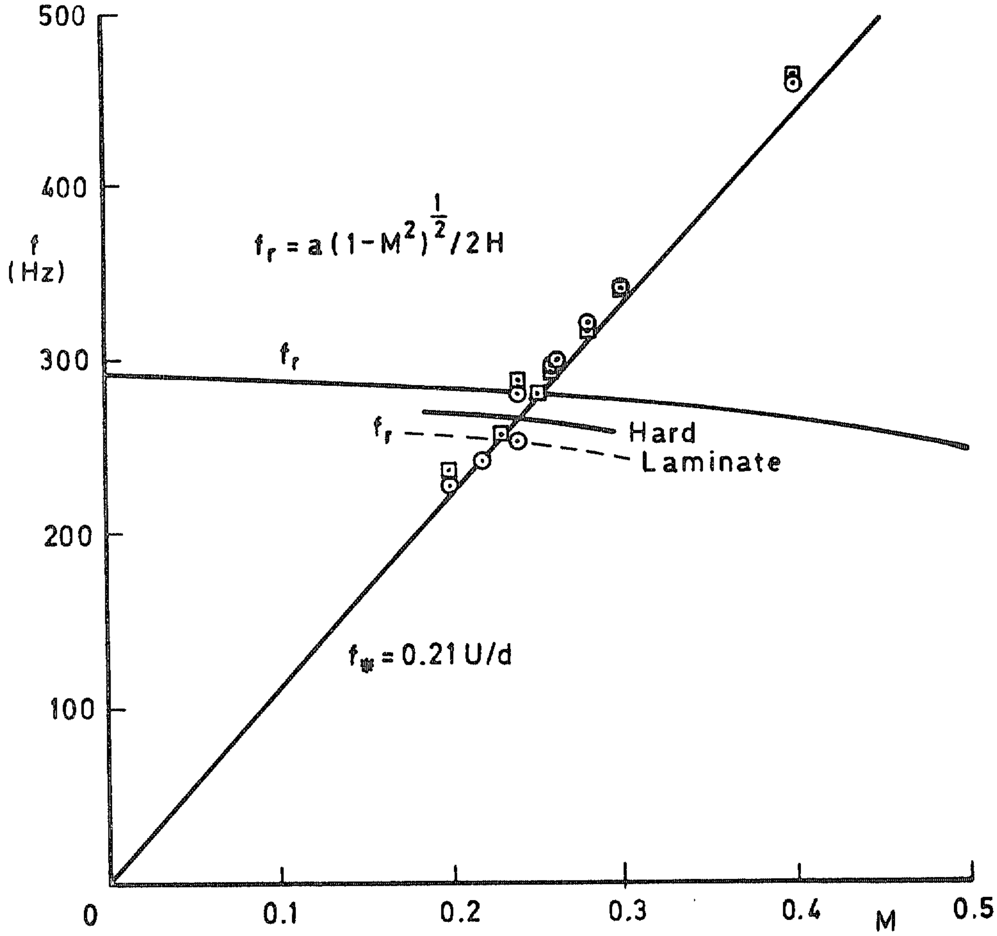


a Cylinder shedding frequencies

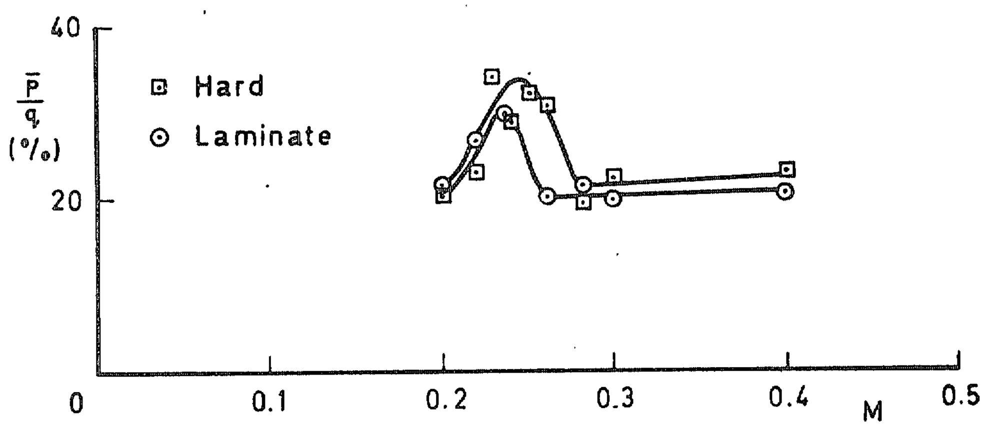


b Cylinder pressure fluctuations

Fig 7 Cylinder (d = 110 mm) in closed working sections (on centre line)



a Cylinder shedding frequencies



b Cylinder pressure fluctuations

Fig 8 Closed working sections – d = 63 mm (18 mm above centre line)

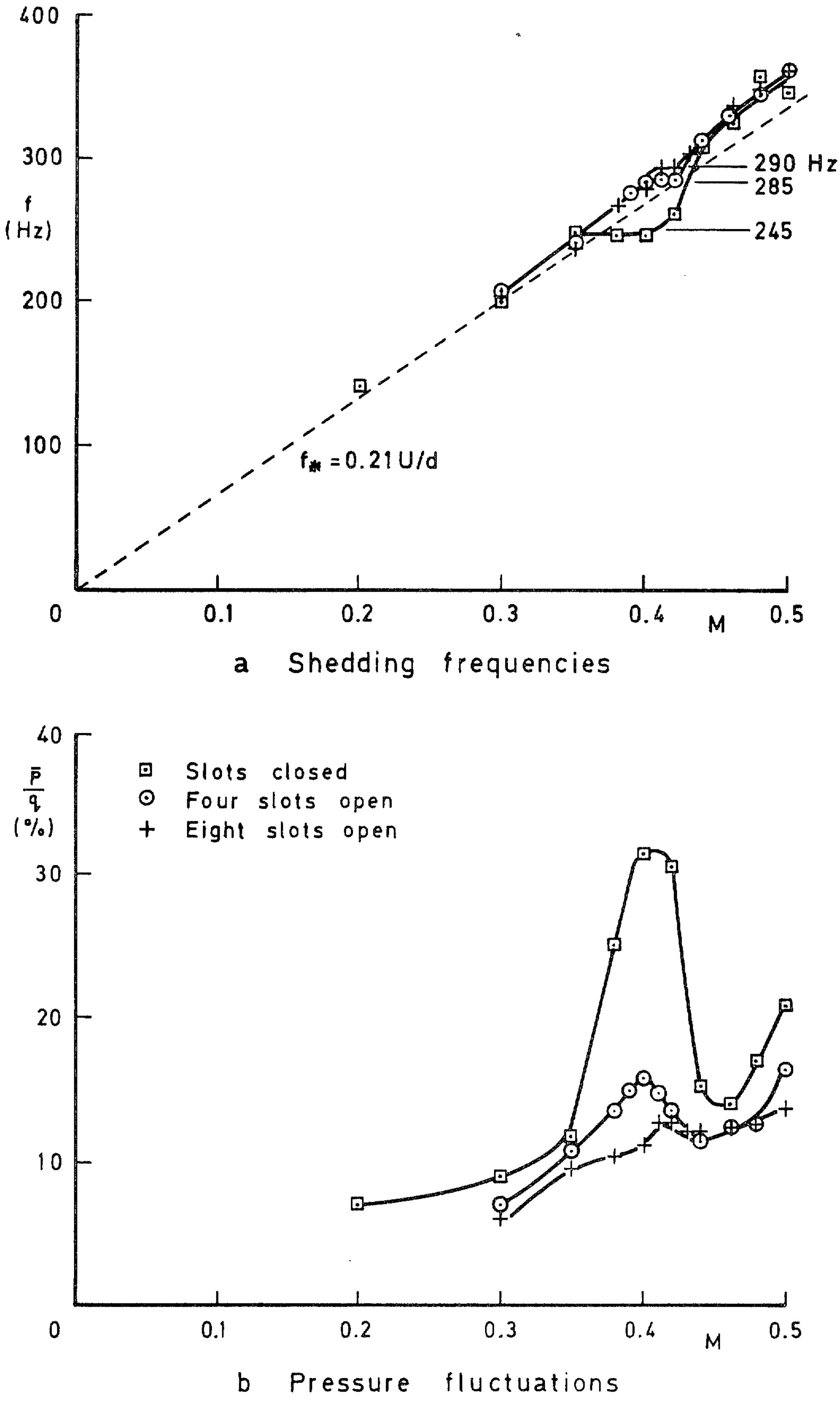
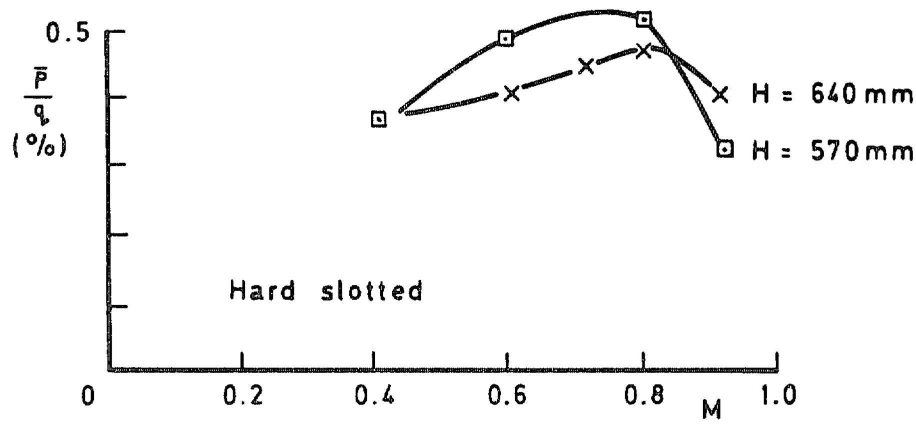
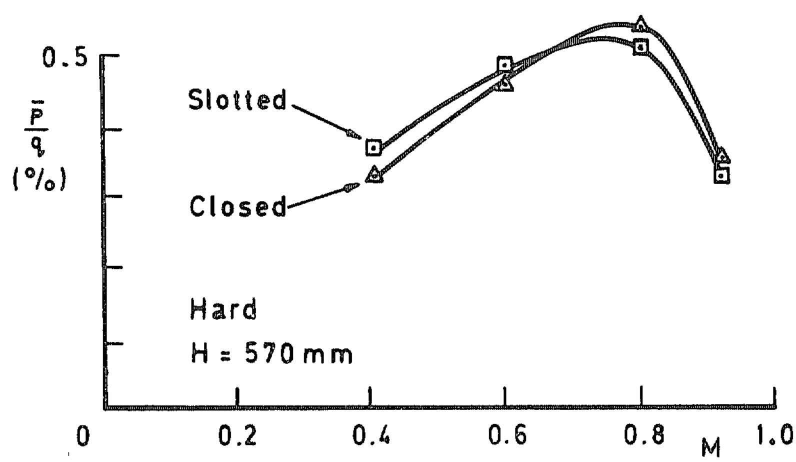


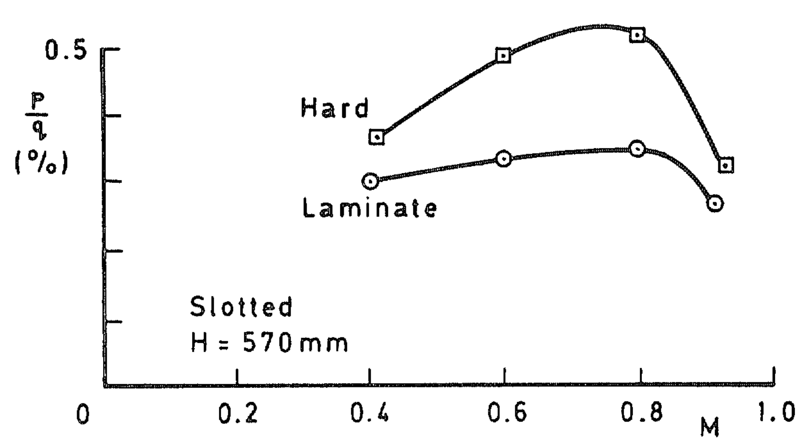
Fig 9 Influence of open area ratio on resonance conditions – d = 110 mm



a Influence of tunnel height (H)

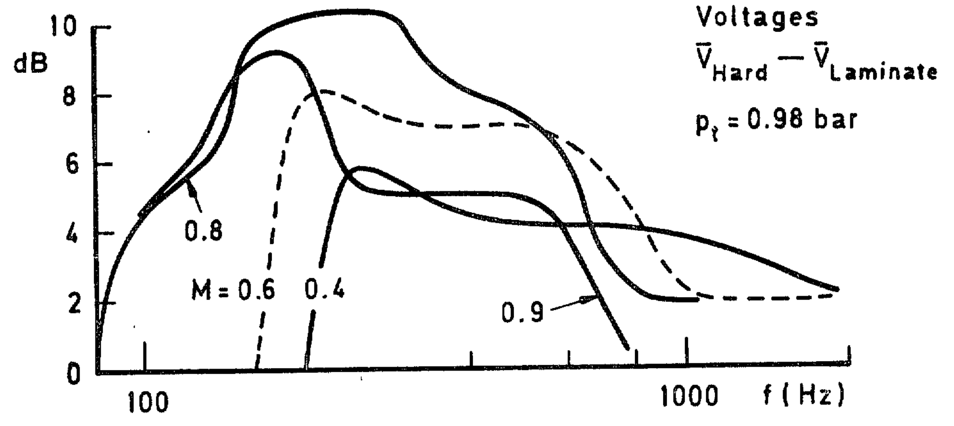


b Influence of narrow slots

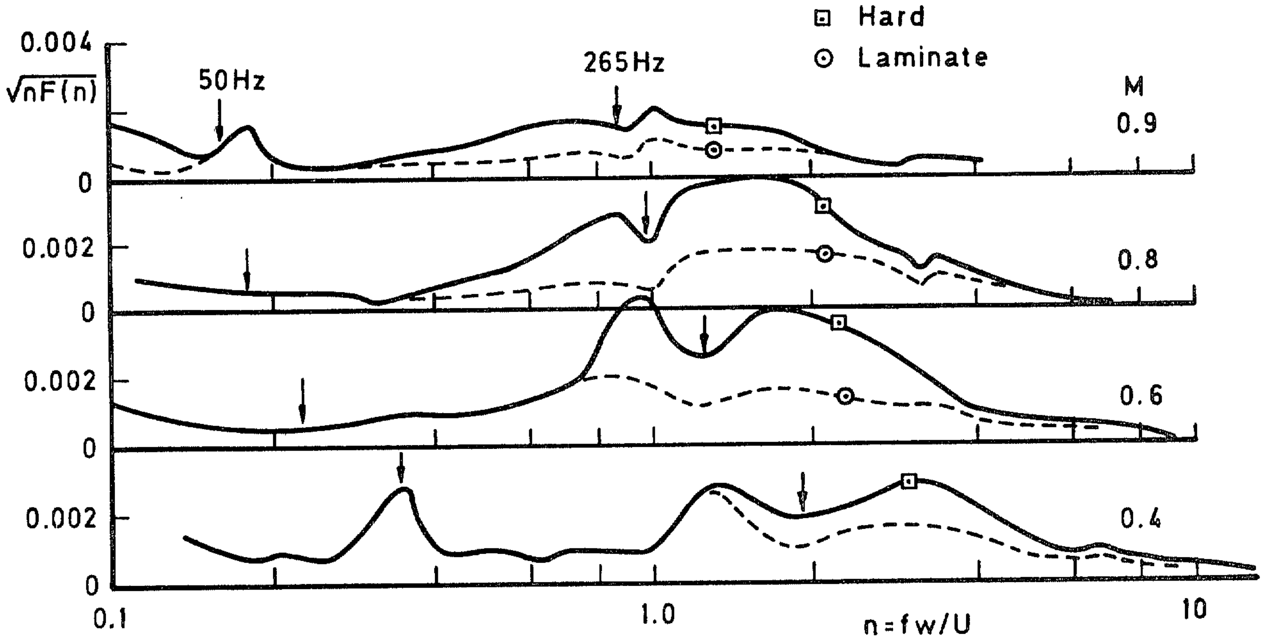


c Influence of wall material

Fig 10 Broad-band pressure fluctuations



a Transducer voltages



b Flow unsteadiness

Fig 11 Spectra of pressure fluctuations in slotted working sections

Fig 12

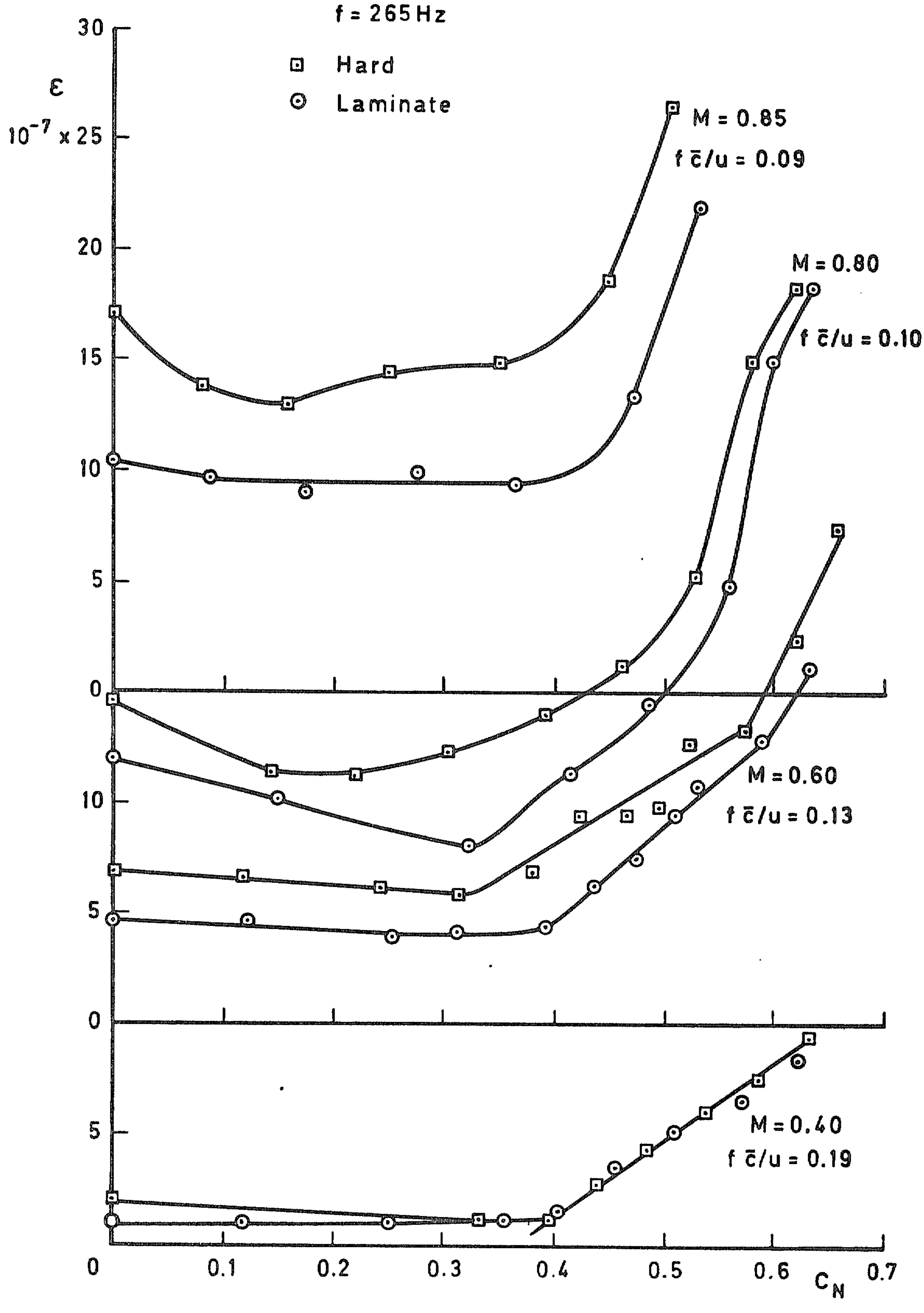


Fig 12 Closed working sections – unsteady wing-root strain (rms) v normal force coefficient

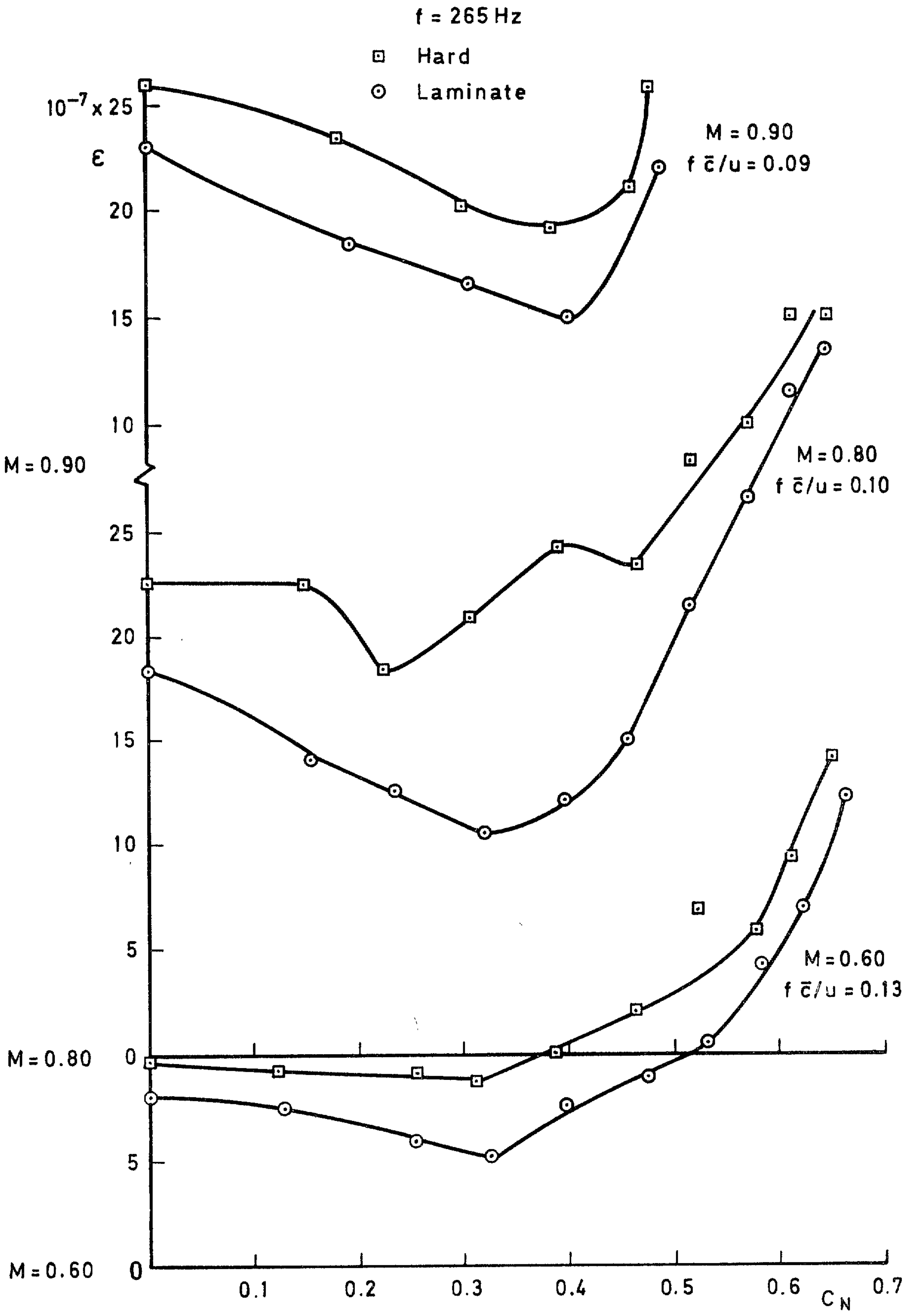


Fig 13 Slotted working sections — unsteady wing-root strain (rms) v normal force coefficient

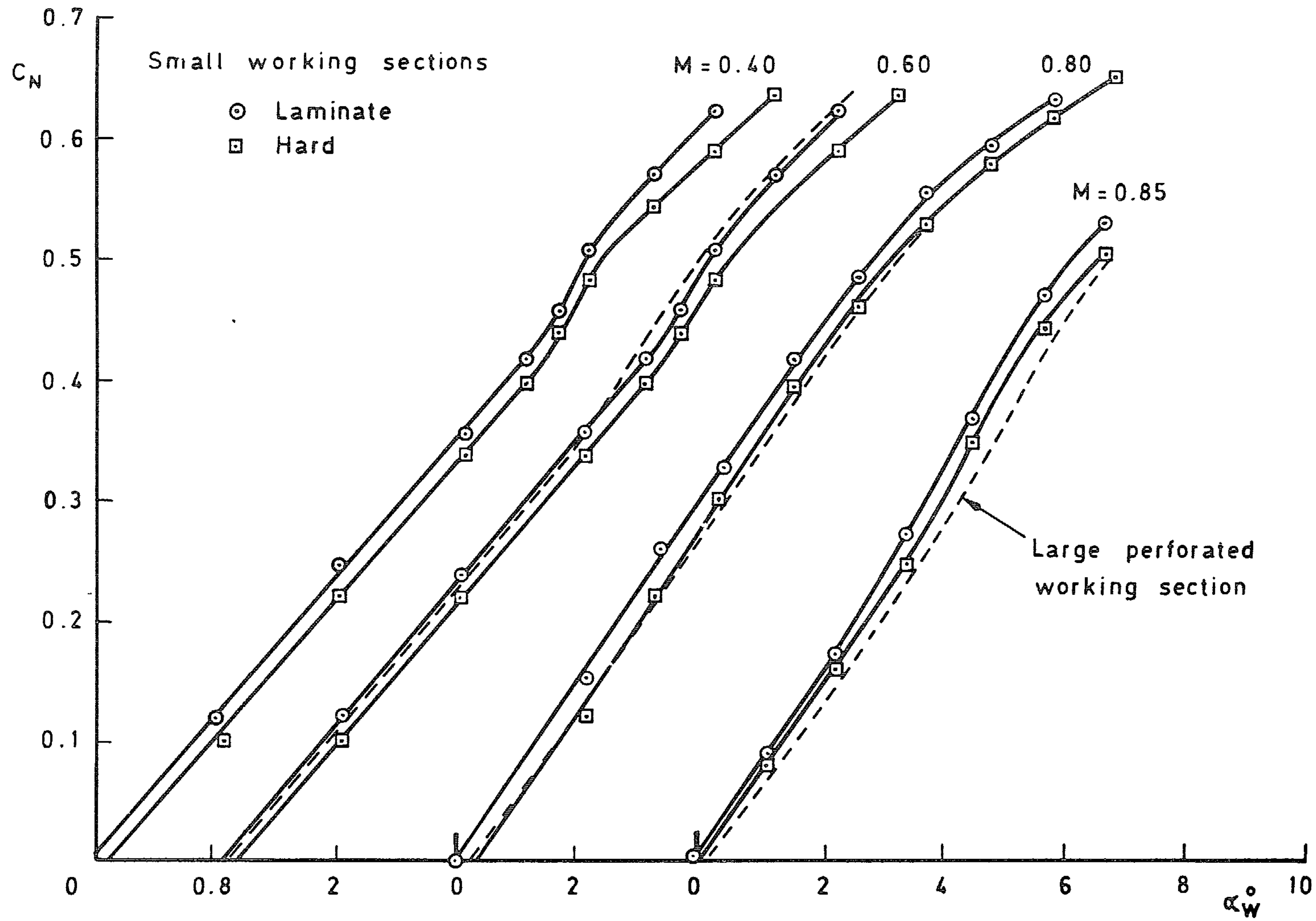


Fig 14 Closed working sections – normal force coefficient v angle of incidence

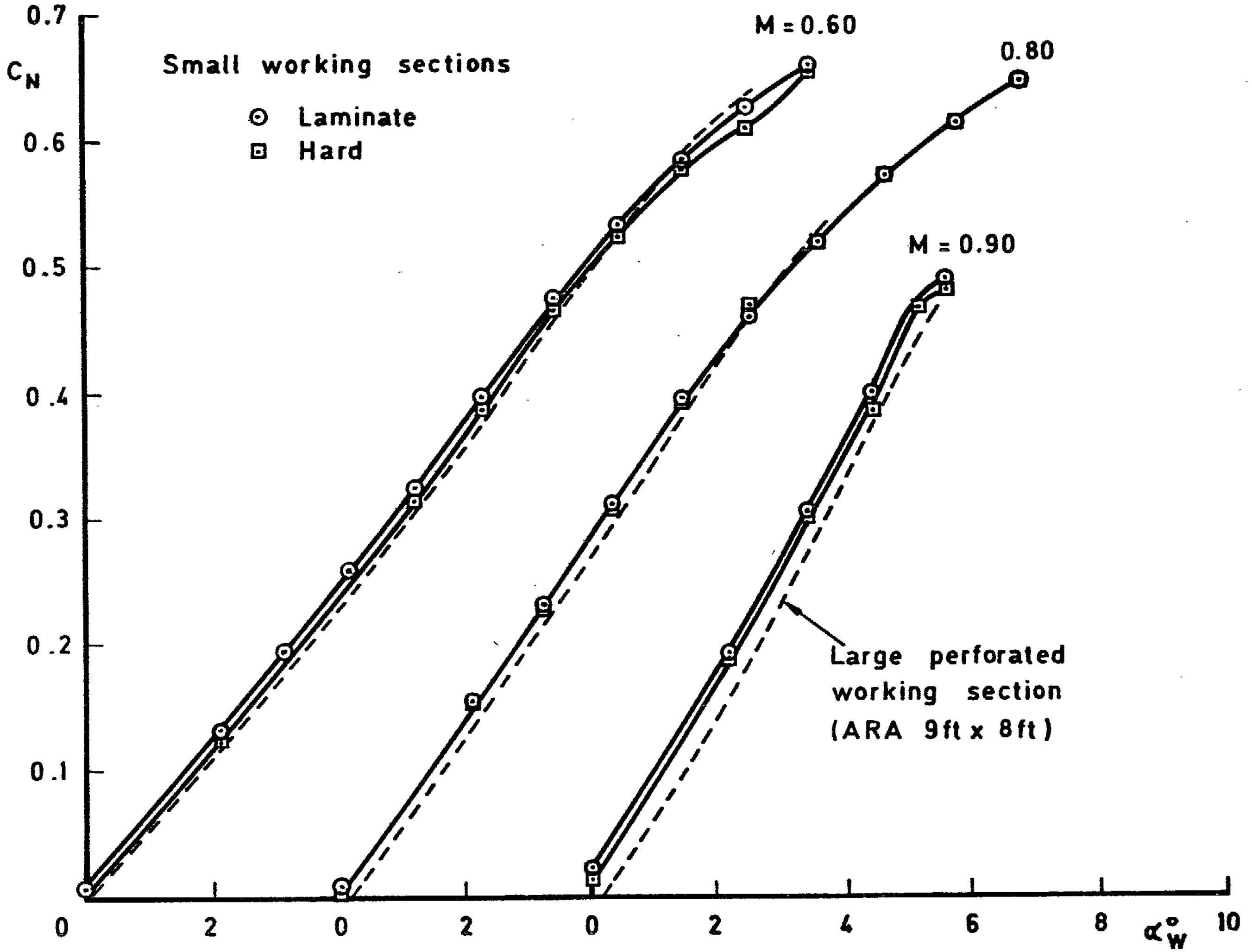


Fig 15 Slotted working sections – normal force coefficient v angle of incidence

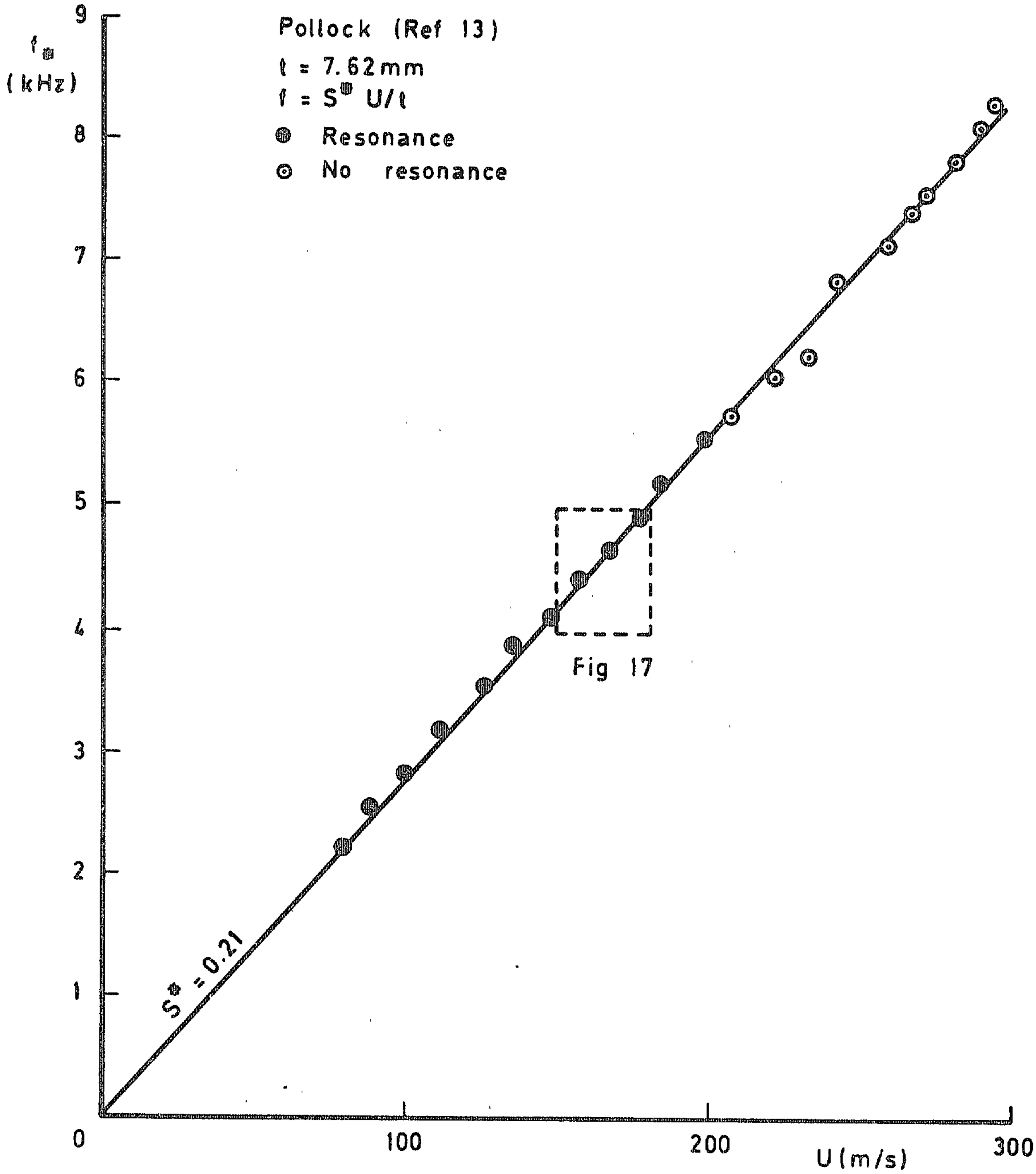


Fig 16 Variation of vortex shedding frequency with velocity

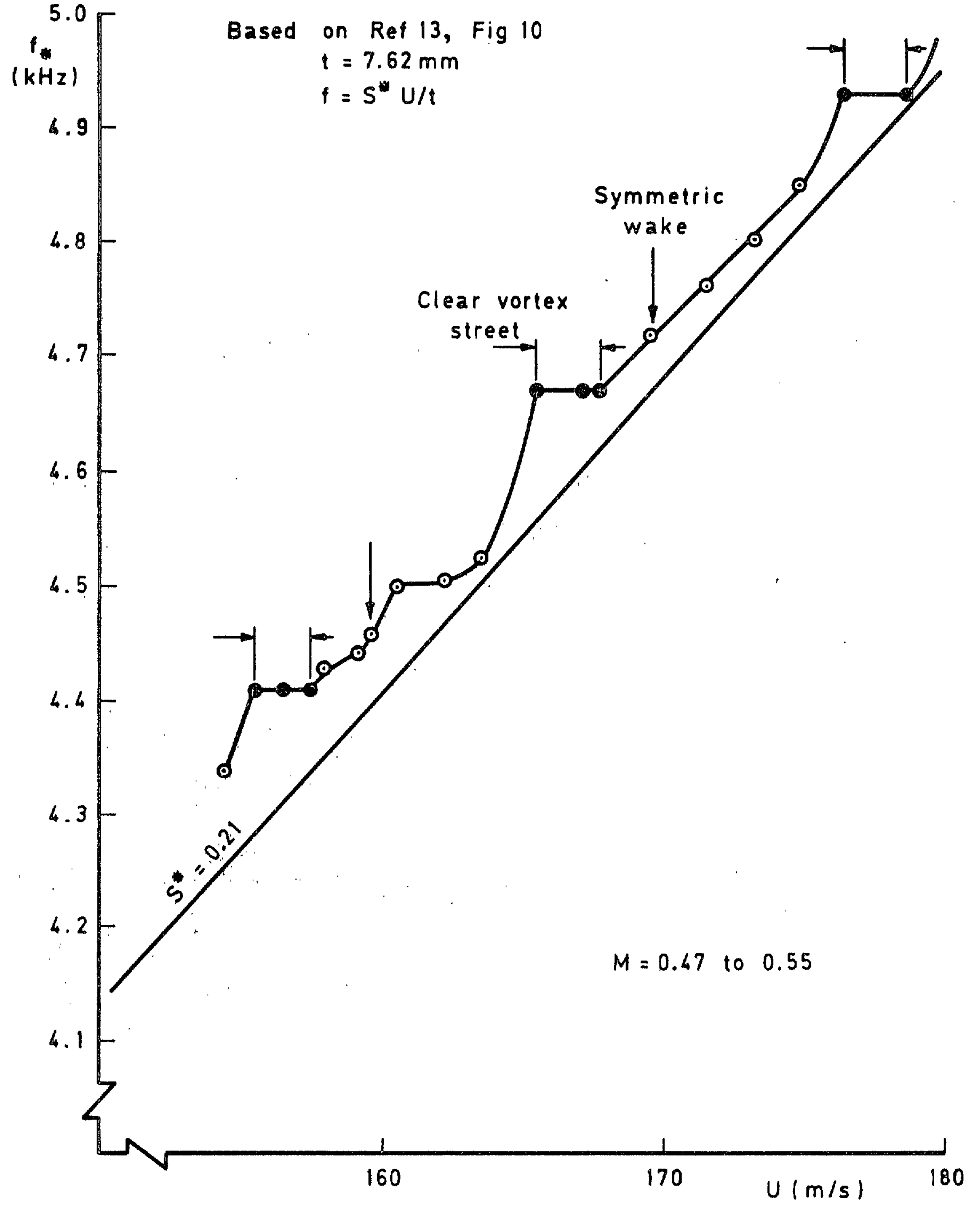
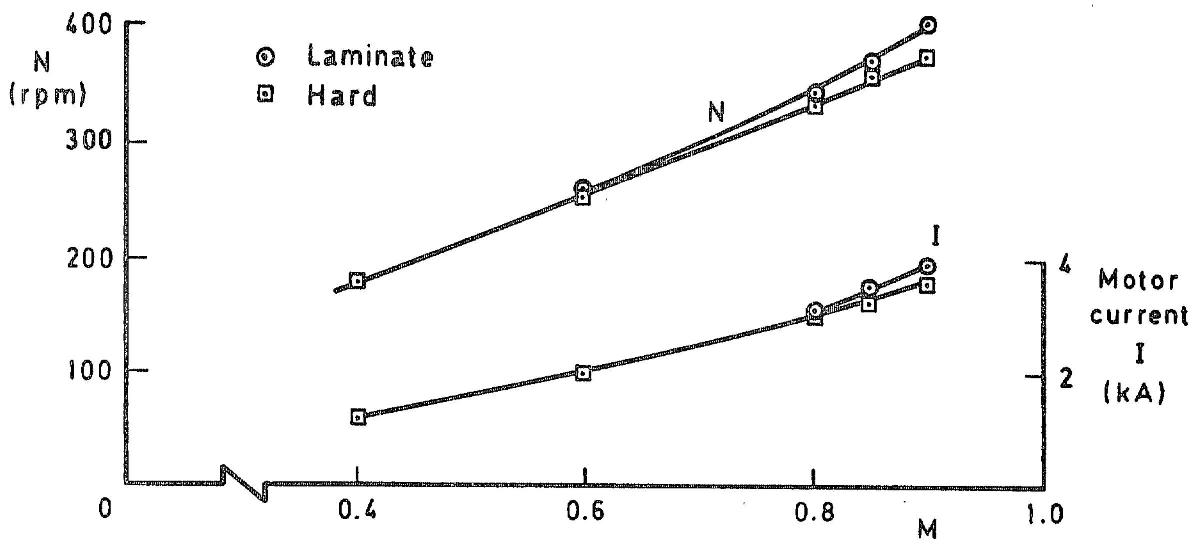
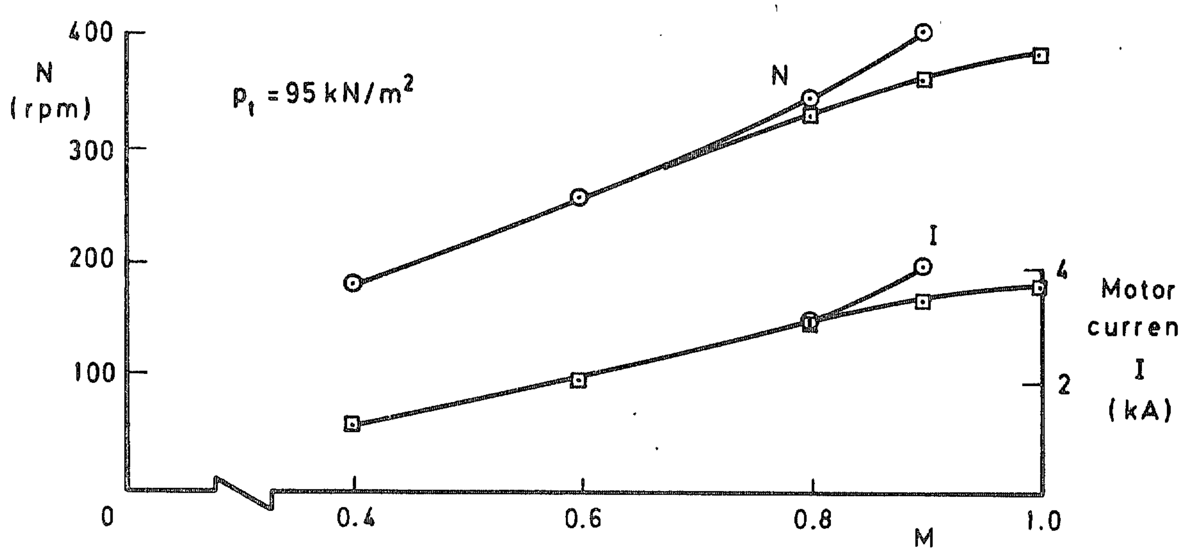


Fig 17 Variation of vortex shedding frequency with velocity showing resonant pauses



a Closed



b Slotted

Fig 18 Motor speed (N) and motor current (I) v Mach number

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