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AN EXPERIMENTAL INVESTIGATION INTO THE INFLUENCE OF ACOUSTIC DISTURBANCES ON THE DEVELOPMENT OF A TURBULENT BOUNDARY LAYER

by

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SUMMARY

An experimental investigation is described into the effects of acoustic disturbances on the mean flow in a turbulent boundary layer developing in a mildly favourable pressure gradient. A Hartmann generator, mounted on the centre line of the RAE 8ft × 8ft wind tunnel, was used as a noise source, and the mean flow in the boundary layer on the tunnel sidewall was examined for any effects of the noise. Even at noise levels up to $C_{\tilde{p}} = 0.08$ it was not possible to identify any effect of the noise itself on the boundary layer, and it is concluded that the acoustic disturbances generally found in the working sections of transonic wind tunnels are unlikely to exert a measurable influence on the development of turbulent boundary layers on wind-tunnel models - at least for mild pressure gradients.

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* Replaces RAE Technical Report 77035 - ARC 37524

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1 INTRODUCTION

With the aim of exploiting fully recent advances in wing design methods, much attention has been devoted to the specification of a wind tunnel capable of achieving Reynolds numbers close to, or equivalent to, full-scale values[1]. In so doing it has been recognised that several factors, in addition to the correct simulation of Mach number and Reynolds number, determine whether the flow over full-scale aircraft is correctly represented. This has resulted in research into the effects of aeroelastic distortion[2], heat transfer[3], and flow unsteadiness on wind-tunnel tests and it is with the last of these that the present report is concerned.

An investigation of the flow unsteadiness in several wind tunnels has been carried out by Mabey[4]. He found that in some tunnels the fluctuation level in the free-stream was so high that accurate measurement of the mean aerodynamic forces could not be made: in others, with a lower level of fluctuation, mean forces could be measured but accurate wing buffeting and flutter tests were not possible. In general the worst offenders were transonic tunnels with ventilated working sections, in which values of the pressure coefficient based on the rms fluctuating pressure, $C_{\tilde{p}}$, of up to 0.02 were recorded. Solid-walled tunnels gave rise to lower values of $C_{\tilde{p}}$ of around 0.005. Numerous possible sources of unsteadiness in the wind-tunnel circuit have been identified but for the present purpose they may be divided into two categories according to whether they produce convected vorticity fluctuations (turbulence) or radiated pressure fluctuations (acoustic noise). In the majority of cases Mabey was able to prescribe measures for reducing the unsteadiness to a level of $C_{\tilde{p}}$ of about 0.01 and this was found to be adequate to enable buffeting investigations to be carried out. However it is possible that even this level of unsteadiness might be sufficient to affect the development of the turbulent boundary layer on wind-tunnel models and hence give rise to data which do not correspond to those obtained in quiescent flow at the same Reynolds number. Green, in fact, has already investigated the influence of free-stream turbulence and found such to be the case[5]. The present investigation is concerned with the effect of acoustic noise on which little or no evidence is available.

In the experiment a Hartmann generator, mounted on the centre line of the 8ft × 8ft wind tunnel at RAE Bedford, was used as a noise source and the effects of its operation on the tunnel sidewall boundary layer were determined by measurements of the mean velocity profile of this layer. Tests were carried out in the Mach number range 0.32-0.86 and for values of $C_{\tilde{p}}$ up to 0.08 - far greater than those observed in practice. Although the free-stream kinetic pressure was limited to 4.2 kN/m^2 (0.6 lb/in^2) to keep the unsteady load on the schlieren windows within safe bounds, the value of the Reynolds number based on the momentum thickness of the sidewall boundary layer was about 3×10^4 which is typical of that on the wings of aircraft at full-scale Reynolds numbers.

Whilst the tests showed an apparent effect of the operation of the noise generator on the boundary layer profiles, manifest primarily as a reduction in the boundary layer thickness, an examination of the effects of the pressure field on the sidewalls, caused by the blockage of the Hartmann generator and its flow, indicated that this was at least a major cause of the observed reduction. Moreover, no effect of noise could be detected when the velocity profiles were plotted in law of the wall co-ordinates. The present data thus indicate that, in contrast to their sensitivity to free-stream turbulence, turbulent boundary layers may be regarded for most practical purposes as unaffected by acoustic noise. This conclusion is in agreement with that of Ross and Rohne[6], who recently investigated the effect of noise on the pressure distribution around a supercritical aerofoil.

2 DESCRIPTION OF THE EXPERIMENT

2.1 General

Fig 1 shows the experimental arrangement in the working section of the wind tunnel. The Hartmann generator noise source was mounted on the model support sting so that it lay along the tunnel axis, and was driven by high pressure air piped in through the model support quadrant. Its source centre was placed 1.448 m (4.75 ft) ahead of the tunnel datum (the centre of the schlieren windows), directly opposite a boundary layer rake (Fig 2) and an unsteady pressure transducer mounted in the port and starboard walls respectively. Under the conditions of the experiment the turbulent boundary layer thickness at the position of the rake was about 150 mm (0.5 ft) and its effective origin approximately 12 m (40 ft) upstream of this location. The pressure distribution on the port wall of the tunnel was measured in the vicinity of the rake and also for some distance upstream.

2.2 Mean flow measurements

The mean flow velocity profile in the boundary layer on the tunnel sidewall was measured using the same rake as that used by Winter and Gaudet[7] (Fig 2), mounted on the port wall of the tunnel as illustrated in Fig 1. Although 49 pitot tubes were available on the rake, the readings from only 24 were recorded in order that a high-precision pressure gauge, connected to the rake via a 24-way pressure switch, could be used to measure pressure. This gauge was of the quartz Bourdon tube type and had a resolution of 0.0025 mm (0.0001 in) of mercury. A similar gauge was used to record the free-stream total pressure as measured by the outermost pitot tube which was used as a reference. The static pressure in the boundary layer was determined by taking an average pressure from six static tubes on the rake connected to a common manifold, and was recorded on a quartz pressure gauge with a resolution of 0.025 mm (0.001 in) of mercury.

In addition to these boundary layer pressures, the pressure distribution along the centre line of the tunnel sidewall was measured both upstream and downstream of the boundary layer rake using capsule manometers having a resolution of 0.125 mm (0.005 in) of mercury.

2.3 Unsteady pressure measurements

The noise pressure field was monitored using an unsteady pressure transducer mounted on the starboard tunnel wall directly opposite the boundary layer rake as shown in Fig 1. Whilst the range of the transducer extended from 0-30 mm (0-1.2 in) of mercury, typical readings during the tests were of the order of 3 mm (0.1 in) of mercury. The rms value of the fluctuating pressure component $\tilde{p}$ was recorded on an rms voltmeter and the frequency spectrum was recorded using a spectrum analyser.

2.4 Hartmann generator

The Hartmann generator is a simple apparatus for the production of high intensity sound having predictable frequency characteristics. Fig 3 shows the design of generator used in the present experiments. Its basic components were a convergent nozzle with an exit diameter of 38 mm (1.5 in) and a resonance tube, closed at one end and with its open end at 1-2 diameters from the nozzle exit. A rod of 6.35 mm (0.25 in) diameter was mounted on the axis of the nozzle since this has been found to improve the performance of the generator[8]. The forward end of the apparatus was a circular disc of 229 mm (9 in) diameter on which the resonance tube was mounted and in which eight 25mm (1in) diameter venting holes were drilled*.

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* Because the experiment was planned and carried out at short notice, to take advantage of a period of enforced running of the 8ft tunnel at low power following an overhaul, little attention was given in the design and manufacture of the generator to its aerodynamic characteristics. In the event, the bluff nose of the generator assembly gave rise to blockage effects which have complicated the interpretation of the results and which could have been much reduced by a streamlined nose.

A detailed theory describing the flow processes in the operation of a Hartmann generator is given in Ref 8. In essence, the high pressure air issuing from the nozzle drives an intense standing wave system in the resonance tube. The wave length of the fundamental tone in the noise spectrum is approximately four times the length of the resonance tube. In the absence of any information on the sensitivity of turbulent boundary layers to acoustic disturbances it was conjectured that they would be most susceptible at frequencies between the passing frequency of the large eddies and the frequency, of order 1/M times greater, corresponding to a wave length of the same order as the boundary layer thickness - about 150 mm (6 in) in the present case. The lengths of resonance tube used in the test series were thus in the range 38-229 mm (1.5-9 in), giving fundamental frequencies in the range 250-1500 Hz.

To produce the noise levels required in the experiments the nozzle had to be supplied with air at pressures ranging from 135 kN/m^2 (20 lb/in^2) at a tunnel Mach number of 0.32 to 270 kN/m^2 (39 lb/in^2) at a Mach number of 0.86. Because the tunnel static pressure fell as Mach number increased (see section 2.5) this meant that the generator was operated at pressure ratios between $2\frac{1}{2}$ at M = 0.32 and 20 at M = 0.86. This latter is appreciably higher than is normally used for this type of device and is thought to contribute to the anomalous spectral characteristics observed in the tests at the two higher Mach numbers (see section 3.1).

2.5 Test conditions

Tests were made at a constant kinetic pressure of 4.2 kN/m^2 (0.6 lb/in^2); and a total temperature of approximately 295 K for nominal tunnel Mach number of 0.32, 0.6, 0.8 and 0.86 - although the actual Mach numbers varied slightly with the noise generator flow rate. Operation at a constant value of kinetic pressure with varying Mach number meant that tunnel static and total pressures fell as Mach number increased - the total pressure falling from 61 kN/m^2 (9 lb/in^2) at M = 0.32 to 13.5 kN/m^2 (2 lb/in^2) at M = 0.86. At each Mach number, measurements of the mean and fluctuating pressures on the sidewall and the mean pressures in the boundary layer were made with no flow through the Hartmann generator and then, for a range of resonance tube lengths, at one or two generator blowing pressures. However, not every resonance tube was employed at every Mach number.

3 RESULTS

3.1 Noise measurements

The noise measurements from the sidewall transducer have been reduced to the form which is currently used to describe flow unsteadiness in wind tunnels. The pressure coefficient $C_{\tilde{p}}$ is obtained by dividing the rms value of the pressure fluctuation $\tilde{p}$ by the free-stream kinetic pressure $q\left(= \frac{1}{2}\rho_1 U_1^2\right)$. A non-dimensional frequency parameter $n = fw/U_1$ is used, where f = frequency (Hz), w = tunnel width (m), and U_1 is the free-stream velocity (m/s), and a non-dimensional spectrum function $F(n)$ is defined such that

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

The presentation of excitation spectra in the form of $\sqrt{nF(n)}$ against $\log n$ has been widely used and this form is adopted here. Ref 4 describes the way in which these quantities are derived from the basic measurements.

Previous sidewall measurements at high subsonic speeds in the 8ft tunnel[4], which has a solid-wall working section, have produced a value of $C_{\tilde{p}}$ of 0.005 with $\sqrt{nF(n)} = 0.0005$ at small values of the frequency parameter $(n < 0.5)$ increasing to $\sqrt{nF(n)} = 0.0025$ by $n = 50$. This value of $C_{\tilde{p}}$ is close to the practical minimum and arises principally from the pressure fluctuations associated with the sidewall boundary layer. Even when the Hartmann generator was not supplied with air (noise-off) it was found to cause a considerable increase in the working section noise level as a result of the airflow over its bluff configuration. The measured noise spectra under these conditions at M = 0.32, 0.6, 0.8 and 0.86 are shown in Figs 4 and 5. Whilst the value of $C_{\tilde{p}}$ is always in the range 0.021-0.024 there are considerable differences in the frequency spectra, and in some cases distinct tones are observed. The sources of these tones have not been positively identified. Although the above spectra are described as 'noise-off', it may be noted that these noise levels are typical of the overall noise level measured in several ventilated-wall transonic tunnels.

Some examples of the noise spectra which are produced by the operation of the Hartmann generator are shown in Figs 6 to 9 (note change in scale for $\sqrt{nF(n)}$). Several lengths of resonance tube were used and the relationship between their length and the frequency of the fundamental tone, as given in Ref 9, is compared with the data in Fig 10. The data at M = 0.32 and 0.6 are seen to conform closely to theory (although at M = 0.6 the second harmonic was often as prominent as the first) but at the two higher Mach numbers the generator did not perform as expected. It is thought that the high pressure-ratio at which the generator was operated at the higher Mach number is the primary reason for the anomalous noise spectra, and it is possible that the peaks at approximately 110 and 220 Hz may be associated with a standing-wave pattern in the tunnel, but neither of these questions has been specifically investigated.

The maximum noise-level which could be achieved repeatedly corresponded to $C_{\tilde{p}} \doteq 0.08$ and an intermediate setting of $C_{\tilde{p}} \doteq 0.045$ was also used in some cases. Although the Hartmann generator did not perform as expected at the higher Mach numbers, the increase in noise-level was sufficient at all Mach numbers to enable an assessment of the sensitivity of the boundary layer to acoustic disturbances to be made. Because the tunnel has solid walls, there will have been little absorption of acoustic energy within the tunnel working section and the noise generated by the Hartmann source will have escaped by propagating in both upstream and downstream directions. The boundary layer approaching the rake will therefore have experienced a level of acoustic disturbance comparable to that at the measuring station from effectively its origin - ie from the beginning of the parallel walled section of the tunnel, some 12 m (40 ft) upstream of the measuring station.

3.2 Boundary layer measurements

The integral parameters for the measured boundary layer profiles which are of relevance to the present investigation are given in Table 1. Each profile is identified by a three digit number in which the first digit refers to the length of the resonance tube, the second defines the free-stream Mach number and the third refers to the noise-level (ie zero denotes 'noise-off', one denotes medium noise and two denotes maximum noise). Suffix 0 thus denotes values of the integral parameters when the Hartmann generator was inoperative. The Mach number in the free-stream at the edge of the boundary layer was derived from the outermost pitot reading and the average static pressure, as recorded on the rake. Variation of these quantities during the recording of the rake pitot pressures was found not to exceed 0.2% even under the most adverse test conditions. Velocity and density profiles across the layer were derived by the same technique described in Ref 7 using a value of unity for the recovery factor. The velocity distribution between the wall and the innermost pitot tube

($0 < u/U_1 < 0.55$) was assumed to conform to the accepted form for the flow in the wall region of turbulent boundary layers. This assumption was used to estimate the contribution to the momentum and displacement thickness from the flow in this region and hence obtain a correction to the measurements. By so doing the value of momentum thickness was increased by about 1% compared with the uncorrected data and the displacement thickness reduced by about the same proportion. It was not considered necessary to apply any further corrections (eg those for the finite hole size of the pitot tubes and their presence in a shear flow) in view of the fact that the deductions to be made were to be based on a comparison of the 'noise-off' and 'noise-on' data rather than on absolute values.

3.3 Wall pressure measurements

The pressure distribution on the tunnel sidewall upstream of the boundary layer rake was recorded several times at each condition of Mach number and noise-level. In view of the low kinetic pressure of 4.2 kN/m^2 (0.6 lb/in^2) the resolution of the pressure measuring system was limited to 0.004 in C_p and for the subsequent analysis a mean line has been drawn through all the data at a given condition. All the data obtained in two conditions at $M = 0.32$ and 0.86 are shown in Fig 11 and the scatter is seen to be about ±0.005 as expected. The mean pressure distributions for the four Mach numbers at which data were obtained are shown in Figs 12 and 13. It can be seen that in each case the blockage pressure field of the Hartmann generator results in the boundary layer rake being just downstream of a region of favourable pressure gradient. As would be expected the magnitude of this gradient increases with Mach number and is also increased by flow exhausting from the generator.

4 ANALYSIS

4.1 Sidewall pressure measurements

In order to identify the influence of the noise on the turbulent boundary layer it is necessary to first estimate the effect on the layer of the blockage pressure field arising from the Hartmann generator and its exhaust flow. The sidewall pressure measurements, described in the previous subsection, have shown that in the noise-off condition the boundary layer develops in a region of favourable pressure gradient which is augmented by the application of noise. The pressure field in general is three-dimensional, but the boundary layer measured by the rake develops along a plane of symmetry and its properties can therefore be estimated from a knowledge of the pressure distribution and flow divergence along the sidewall centre line. The pressure data have first been corrected for the empty tunnel pressure distribution[10] resulting in a typical correction to $C_{\tilde{p}}$ of 0.01 at M = 0.86 and 0.002 at M = 0.32. The flow divergence has then been estimated by the use of a simple model involving a source-sink distribution on the tunnel centre line chosen to generate a pressure distribution similar to that observed.

The characteristics of the flow around the Hartmann generator were assumed to be governed by the disc of 229 mm (9 in) diameter at the front of the assembly, by the high pressure air delivery tube of 114 mm (4.5 in) diameter which also acted as a support (Fig 3) and by the flow of air from the Hartmann nozzle. Ref 11 indicates that the flow about the disc is likely to give rise to a cavity extending about four diameters aft with a maximum diameter considerably greater than that of the disc itself. This cavity would thus extend downstream of the nozzle and the flow from the nozzle would further increase its maximum diameter. The cavity was represented crudely by a source at the position of the disc, a sink situated 726 mm (30 in) downstream of the disc and a further sink at infinity downstream, the last accounting for the blockage of the supply tube plus the wake of the disc.

The strength (E/U_1) of the sink far downstream was somewhat arbitrarily fixed at 0.041 m^2* and the strengths of the source and the other sink were varied together to obtain a satisfactory fit to the pressure measurements immediately upstream and downstream of the boundary layer rake. The results so obtained are compared with the corrected pressure data in Figs 14 to 17. It can be seen that, whilst the pressure distributions immediately upstream of the rake are generally well represented, the decay in the suction level downstream is underestimated especially at the lower Mach numbers. Good agreement is obtained in both noise-off and noise-on cases at M = 0.86. In general the level of agreement is as good as could be expected considering the simplicity of the flow model and, at least at M = 0.86 where the disturbances are greatest, suggests that an adequate estimate of the flow divergence can be made. This quantity is thus plotted in the lower half of Figs 14 to 17.

4.2 Boundary layer measurements

It is clear from the summary of the boundary layer data in Table 1 that the effect of operating the noise generator is to reduce the momentum thickness and

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* This figure was derived using a drag-coefficient of 0.81 for the disc and an effective area equal to 90% of its actual area to allow for the presence of the 25mm diameter holes.

the displacement thickness in about the same proportions and hence to leave the shape parameter almost unaltered (in other words the boundary layer thickness is reduced but the shape of the nondimensional velocity profile is unchanged). In Fig 18 the ratio θ/θ_0 is plotted as a function of $C_{\tilde{p}}$ and data for various lengths of resonance tube and free-stream Mach number are included. Though the extended scale of the ordinate makes the scatter appear large, the dominant variable is seen to be the free-stream Mach number and as this is increased the momentum thickness diminishes for a given value of $C_{\tilde{p}}$.

It is difficult to attribute these results to the influence of the noise *per se*. It is known that free-stream turbulence has the effects of increasing skin friction and promoting earlier transition, both of which would lead to an increase in momentum thickness. It seems unlikely that acoustic disturbances will have qualitatively the opposite effect, and the possibility that the observed changes in the boundary layer are due entirely to changes in the blockage pressure field is therefore examined. In Fig 19, θ/θ_0 is plotted against the ratio of the mass flow from the noise source to the tunnel mass flow and the data for all the values of free-stream Mach number are seen to lie together in a broad band. For M = 0.80 and 0.86, the two Mach numbers for which the change in momentum thickness appreciably exceeded the experimental scatter, boundary layer calculations were carried out using the method of Ref 12 in which flow divergence effects can be included. The estimated values of flow divergence on the centre line, illustrated in Figs 16 and 17, were used together with the computed fit to the measured pressure distribution. Fig 20 shows the calculated streamwise distributions of θ/θ_0 and $\bar{H}/\bar{H}_0$, where suffix 0 refers to the calculated values when the Hartmann generator is present but inoperative, rather than to values in an undisturbed flow. In all cases the general trend of the measurements is reproduced, and at M = 0.86 the actual reduction in momentum thickness is well predicted, although it is underestimated at M = 0.80. The predicted small reduction in shape parameter is also in good agreement with the measurement. Given the approximate nature of these calculations, and the degree of scatter in the experimental data, it has to be accepted that the observed changes in the boundary layer characteristics could well be the result solely of the blockage pressure field of the jet.

4.3 Velocity profiles

It has been suggested that acoustic noise could affect the production of turbulent energy in the boundary layer 'wall' region and that this would be apparent as a shift in the log-law relation. Some of the velocity profiles measured at Mach number of 0.8 and 0.86 have therefore been plotted in log-law co-ordinates in Figs 21 and 22. The skin friction coefficient was estimated from the measurements of H and R_θ using the relations given in Ref 12 and values of u/u_τ and yu_τ/ν_w were derived based on the flow properties at the wall. The significance of these plots in absolute terms is limited, both in view of the scatter evident in Figs 21 and 22 (which probably arises from uncertainties in the values of y) and of the implied assumption of the existence of a log-law made in evaluating C_f .

However it would appear from those cases shown, which are also typical of the remaining data, that the character of the mean flow in the wall region is unaffected by noise. This is in accordance with the conclusion of section 4.2.

5 CONCLUSIONS

A turbulent boundary layer having a value of momentum thickness Reynolds number comparable with that typical of aircraft wings, and developing in a mildly favourable pressure gradient, has been subjected to acoustic disturbances of far greater intensity than those observed in transonic wind tunnels. A reduction of about 5% in the boundary layer momentum thickness, together with a very small reduction in the shape parameter, was observed when the boundary layer was subjected to an overall noise-level of $C_{\tilde{p}} = 0.08$. These changes were contrary to those which would have been expected on the basis of previous evidence from the effects of free-stream turbulence, and calculations showed that they could well be attributed entirely to the effect of the blockage pressure field of the noise source. Furthermore, the boundary layer velocity profiles showed no change in character which could be attributed to the influence of noise. In view of the high noise level used in the experiment it can be concluded that the acoustic disturbances generally found in the working sections of transonic wind tunnels are unlikely to exert a measurable influence on the development of the turbulent boundary layer on wind-tunnel models - at least for the case of mild pressure gradients.

Table 1

SUMMARY OF BOUNDARY LAYER AND NOISE MEASUREMENTS

Length of resonance tube mm	Gap size mm	Profile No.	M_1	10^{-6} Re/m	$C_{\tilde{p}}$	θ (mm) uncorrected	θ (mm) corrected	(θ/θ_0) corrected	H corrected	$\bar{H}$ corrected	$(\bar{H}/\bar{H}_0)$ corrected
38.1	57.15	160	0.597	2.459	0.024	13.61	13.73		1.413	1.252	
		162/1	0.597	2.459	0.077	13.43	13.55	0.9869	1.409	1.249	0.9976
		162/2	0.598	2.463	0.083	13.37	13.49	0.9825	1.411	1.250	0.9984
		180	0.792	1.979	0.024	12.82	12.93		1.535	1.252	
		182	0.795	1.986	0.071	12.19	12.31	0.9521	1.525	1.242	0.9920
		190	0.861	1.930	0.023	12.13	12.24		1.572	1.240	
		191/1	0.866	1.933	0.039	11.83	11.94	0.9755	1.574	1.238	0.9984
		191/2	0.868	1.937	0.045	11.63	11.74	0.9592	1.570	1.233	0.9944
57.15	57.15	260	0.606	2.506	0.024	13.55	13.66		1.428	1.262	
		261	0.605	2.502	0.049	13.50	13.61	0.9963	1.417	1.252	0.9921
		262	0.607	2.509	0.075	13.26	13.37	0.9788	1.415	1.249	0.9897
		280	0.759	2.164	0.028	12.70	12.81		1.505	1.246	
		282	0.768	2.177	0.070	12.16	12.28	0.9586	1.503	1.239	0.9944
57.15	76.20	360	0.599	2.575	0.024	13.45	13.57		1.412	1.251	
		362	0.599	2.575	0.071	13.34	13.46	0.9919	1.411	1.250	0.9992
		380	0.797	2.098	0.025	12.62	12.73		1.531	1.246	
		382	0.805	2.108	0.068	11.88	11.99	0.9419	1.526	1.236	0.9920
76.20	57.15	430	0.324	4.291	0.023	13.91	14.04		1.295	1.248	
		432	0.325	4.304	0.081	13.79	13.92	0.9915	1.295	1.248	1.0000
		461	0.596	2.568	0.044	13.45	13.57	0.9941	1.412	1.252	0.9952
		462	0.597	2.568	0.083	13.29	13.41	0.9824	1.409	1.249	0.9928
		480	0.793	2.085	0.025	12.67	12.78		1.530	1.247	
		481	0.795	2.088	0.042	12.35	12.46	0.9750	1.527	1.243	0.9968
		482	0.794	2.088	0.081	12.12	12.23	0.9570	1.522	1.240	0.9944
		490	0.862	1.979	0.021	12.13	12.24		1.575	1.242	
		491	0.868	1.986	0.046	11.65	11.76	0.9608	1.569	1.233	0.9928
228.6	57.15	532	0.324	4.258	0.079	13.73	13.86	0.9871	1.295	1.248	1.0000

Note: In profile number the first digit denotes the length of resonance tube; the second digit denotes the tunnel Mach number and the third digit denotes the noise level (0 = noise off, 1 = medium noise, 2 = maximum noise)

LIST OF SYMBOLS

C_f	local skin friction coefficient
$C_{\tilde{p}}$	pressure coefficient based on rms fluctuating pressure
f	frequency
F	non-dimensional spectrum function (see section 3.1)
h	tunnel height
H	boundary layer shape parameter
$\bar{H}$	transformed boundary layer shape parameter (see Ref 12)
$\dot{m}$	air mass flow rate
M	Mach number
n	non-dimensional frequency parameter (see section 3.1)
p	mean static pressure
$\tilde{p}$	rms pressure fluctuation
q	free-stream kinetic pressure ($\frac{1}{2}\rho_1 U_1^2$)
R_θ	Reynolds number based on momentum thickness
u	velocity in boundary layer
u_τ	friction velocity ($\sqrt{\tau_w/\rho_w}$)
U	velocity in free-stream
w	tunnel width
x	distance measured upstream from tunnel datum
y	distance measured normal to the sidewall
z	co-ordinate perpendicular to x and y directions
ρ	density
τ	shear stress
ϕ	angular divergence in free-stream
θ	momentum thickness
ν	kinematic viscosity

Subscripts

w	denotes conditions at the wall
0	denotes 'noise-off' condition
1	denotes conditions at the edge of the boundary layer

REFERENCES

No.	Author	Title, etc
1	-	The need for large wind tunnels in Europe. Report on the Large Wind Tunnels Working Group. AGARD AR-60 (1972)
2	J.Y.G. Evans C.R. Taylor	Some factors relevant to the simulation of full-scale flows in model tests and to the specification of new high-Reynolds-number transonic tunnels. Paper 31 in AGARD CP 83 (1971)
3	J.E. Green D.J. Weeks P.G. Pugh	Heat transfer as a source of spurious scale effects in subsonic and transonic wind tunnels. RAE (unpublished paper)
4	D.G. Mabey	Flow unsteadiness and model vibration in wind tunnels at subsonic and transonic speeds. ARC CP 1155 (1971)
5	J.E. Green	On the influence of free-stream turbulence on a turbulent boundary layer, as it relates to wind-tunnel testing at subsonic speeds. RAE Technical Report 72201 (ARC 34457) (1972)
6	R. Ross P.B. Rohne	The character of flow unsteadiness and its influence on steady state transonic wind tunnel measurements. Paper 45 in AGARD CP 174 (1975)
7	K.G. Winter L. Gaudet	Turbulent boundary-layer studies at high Reynolds numbers at Mach numbers between 0.2 and 2.8. ARC R & M No.3712 (1970)
8	E. Brocher C. Maresca M.-H. Bournay	Fluid dynamics of the resonance tube J. Fluid Mech., Vol. 43, Part 2, pp. 369-384 (1970)
9	D.L. Martlew	The use of Hartman generators as sources of high intensity sound in a large absorption flow duct facility. AIAA Paper 75-529 (1975)
10	D. Isaacs	Further calibration of the 8ft × 8ft wind tunnel at subsonic speeds. RAE unpublished material (1974)

REFERENCES (concluded)

No.	Author	Title, etc
11	G. Birkhoff E.H. Zarantonello	Jets, wakes and cavities. Publishers Academic Press, New York (1957)
12	J.E. Green D.J. Weeks J.W.F. Brooman	Prediction of turbulent boundary layers and wakes in compressible flow by a lag-entrainment method. ARC R & M No.3791 (1973)

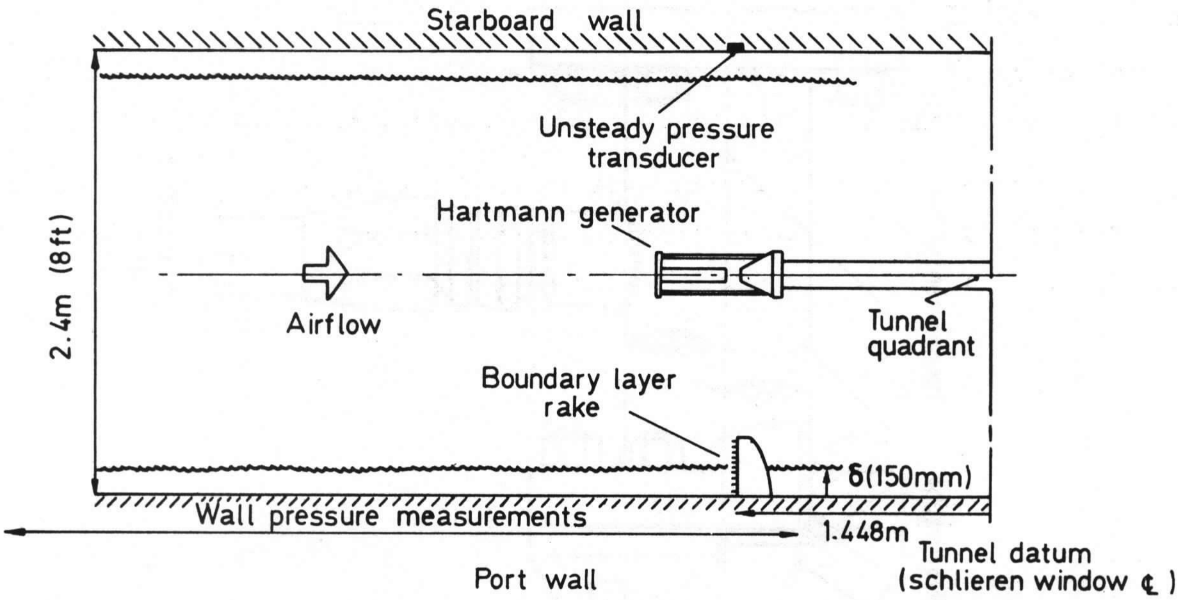


Fig 1 Layout of experiment

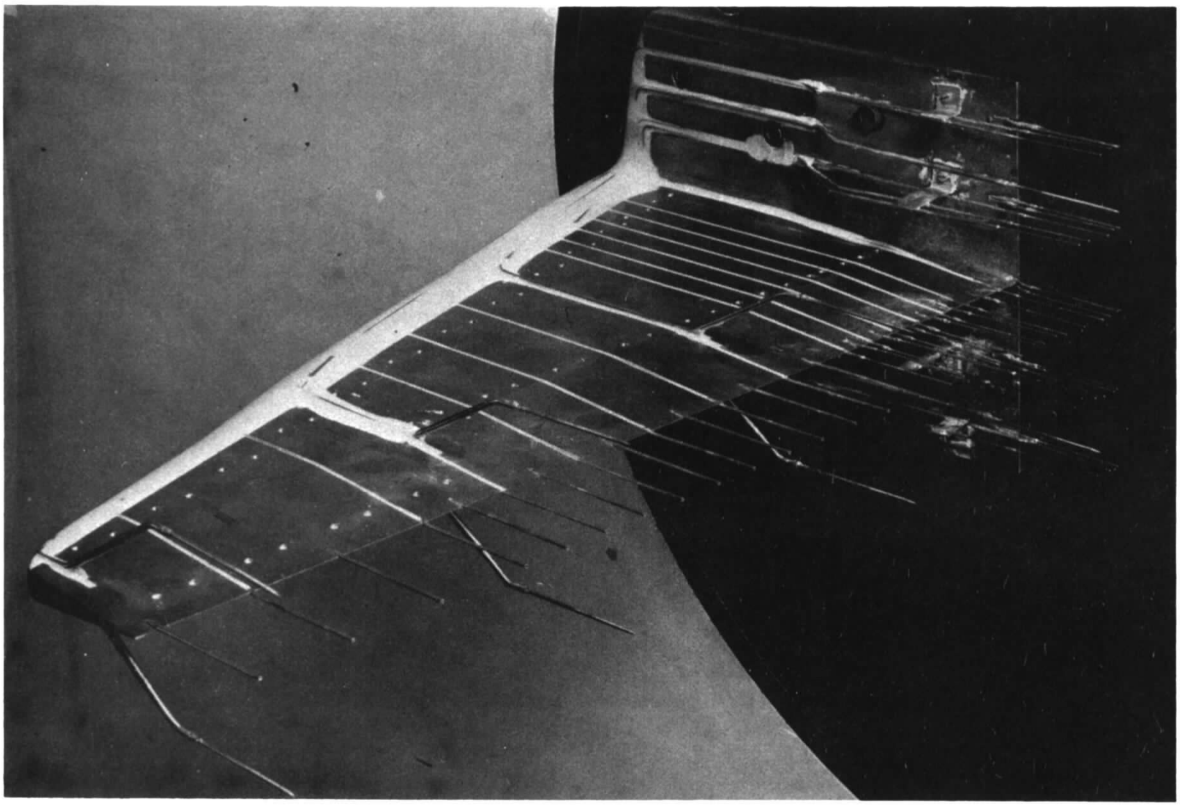


Fig 2 Boundary layer rake

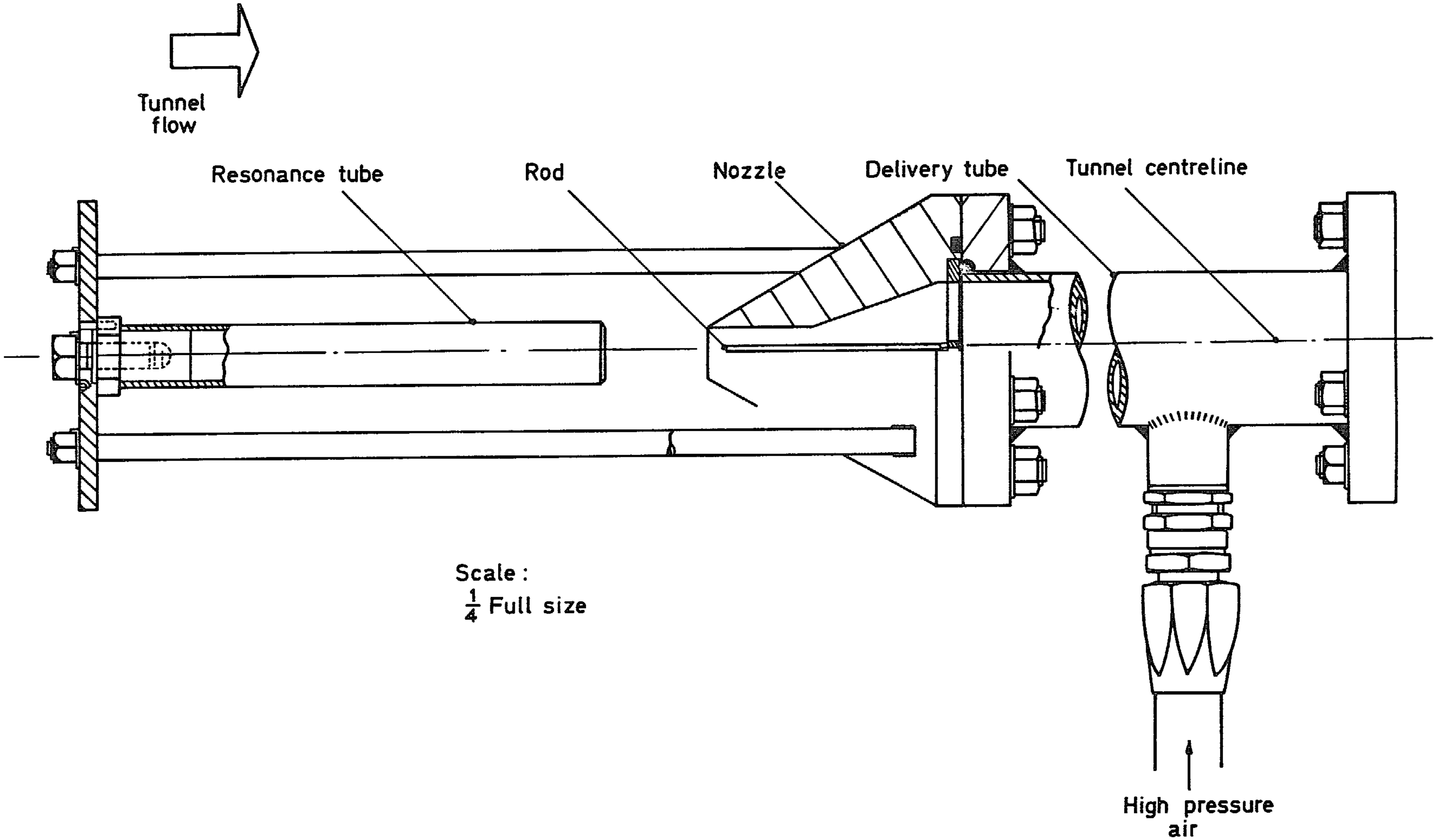


Fig 3 Layout of Hartmann generator

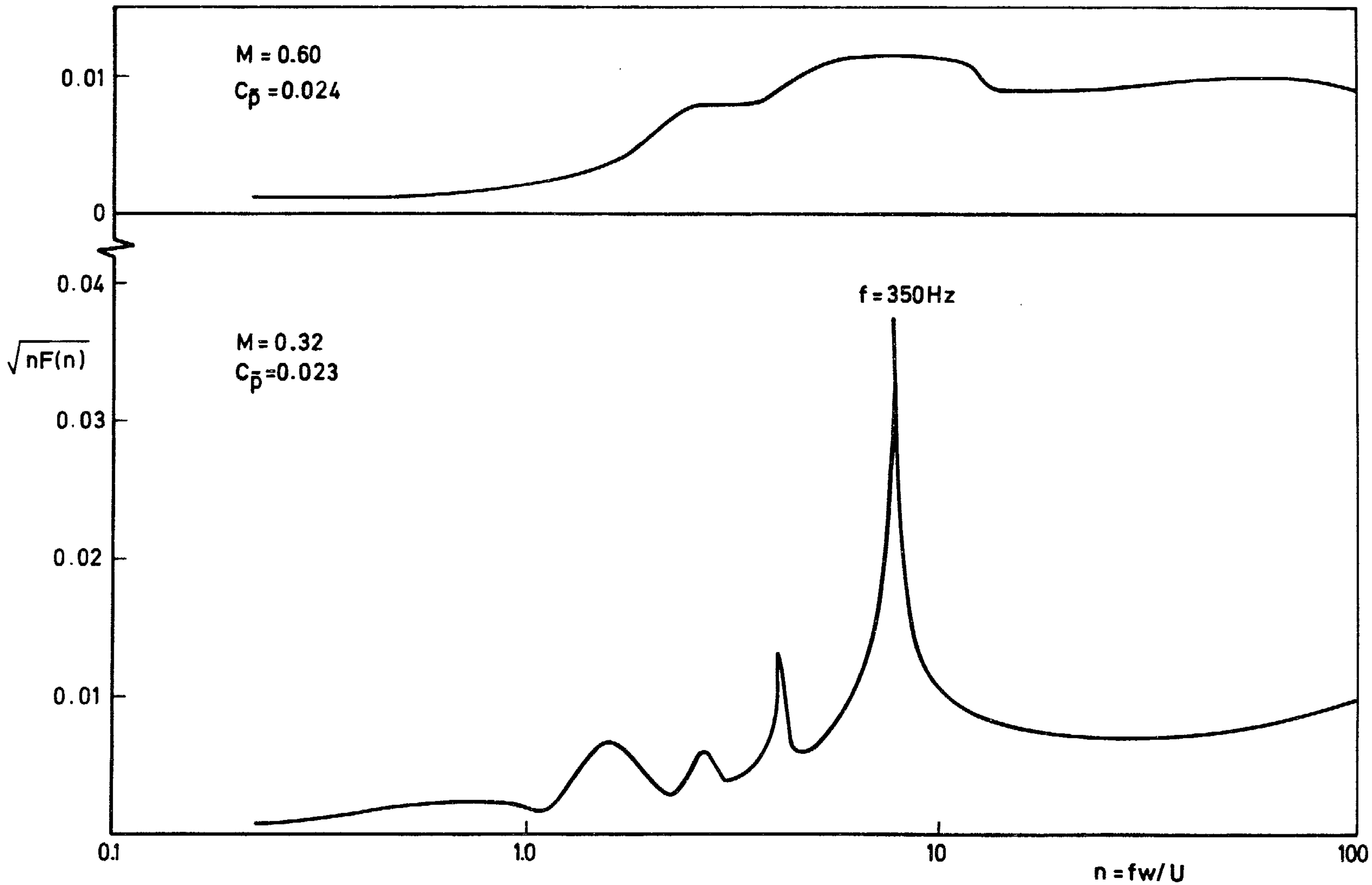


Fig 4 Noise-off spectra. M = 0.32, 0.60

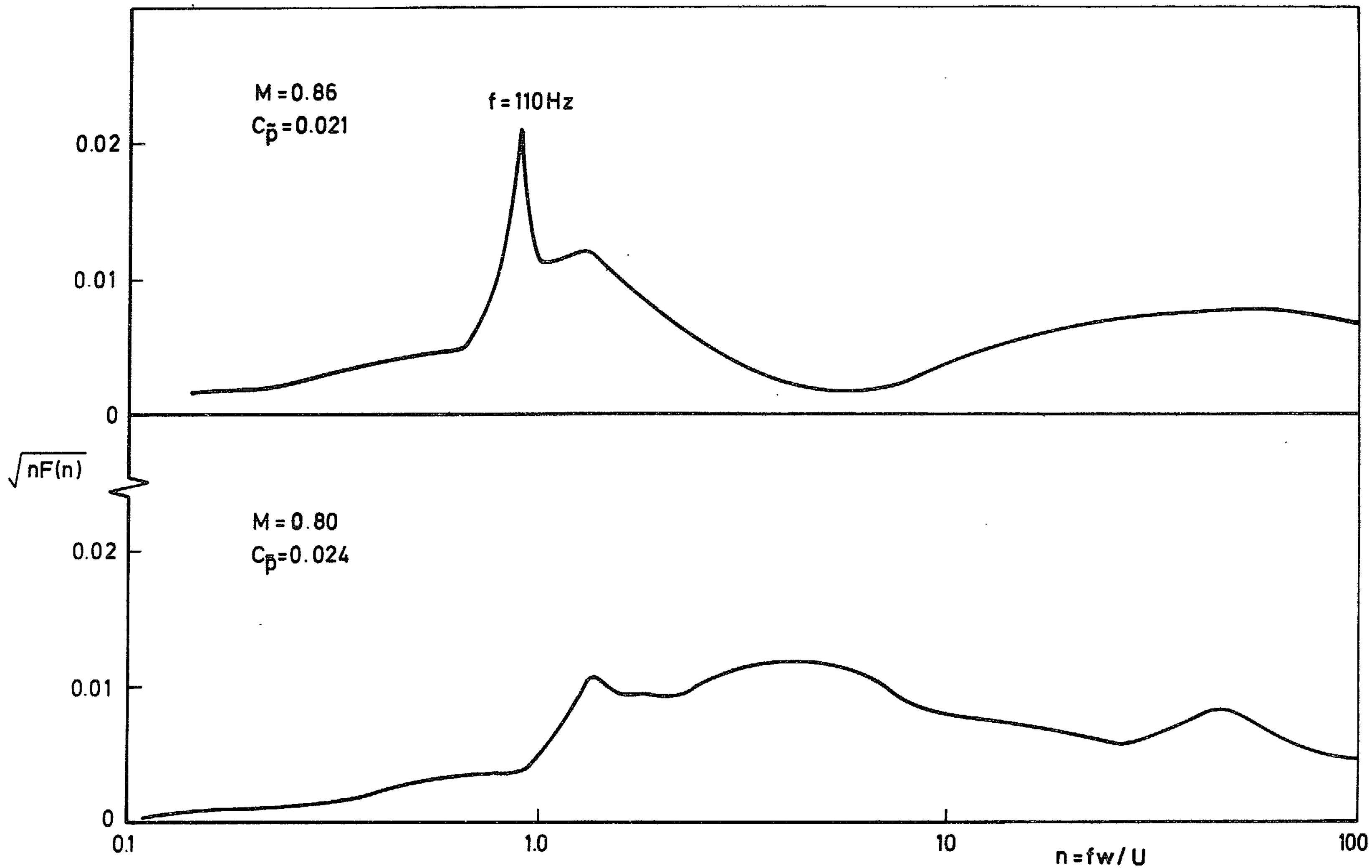


Fig 5 Noise-off spectra. M = 0.8, 0.86

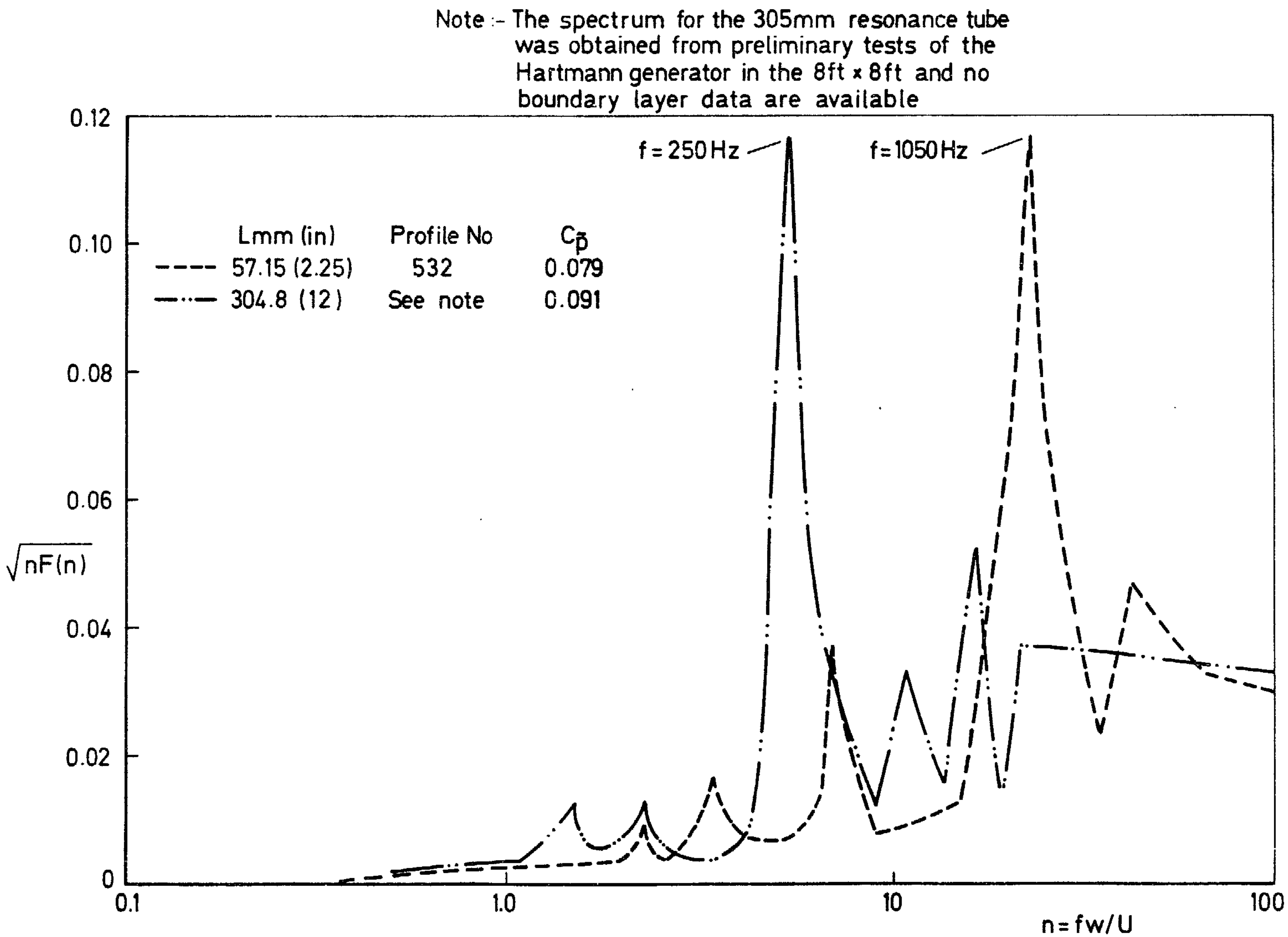


Fig 6 Noise-on spectra. M = 0.32

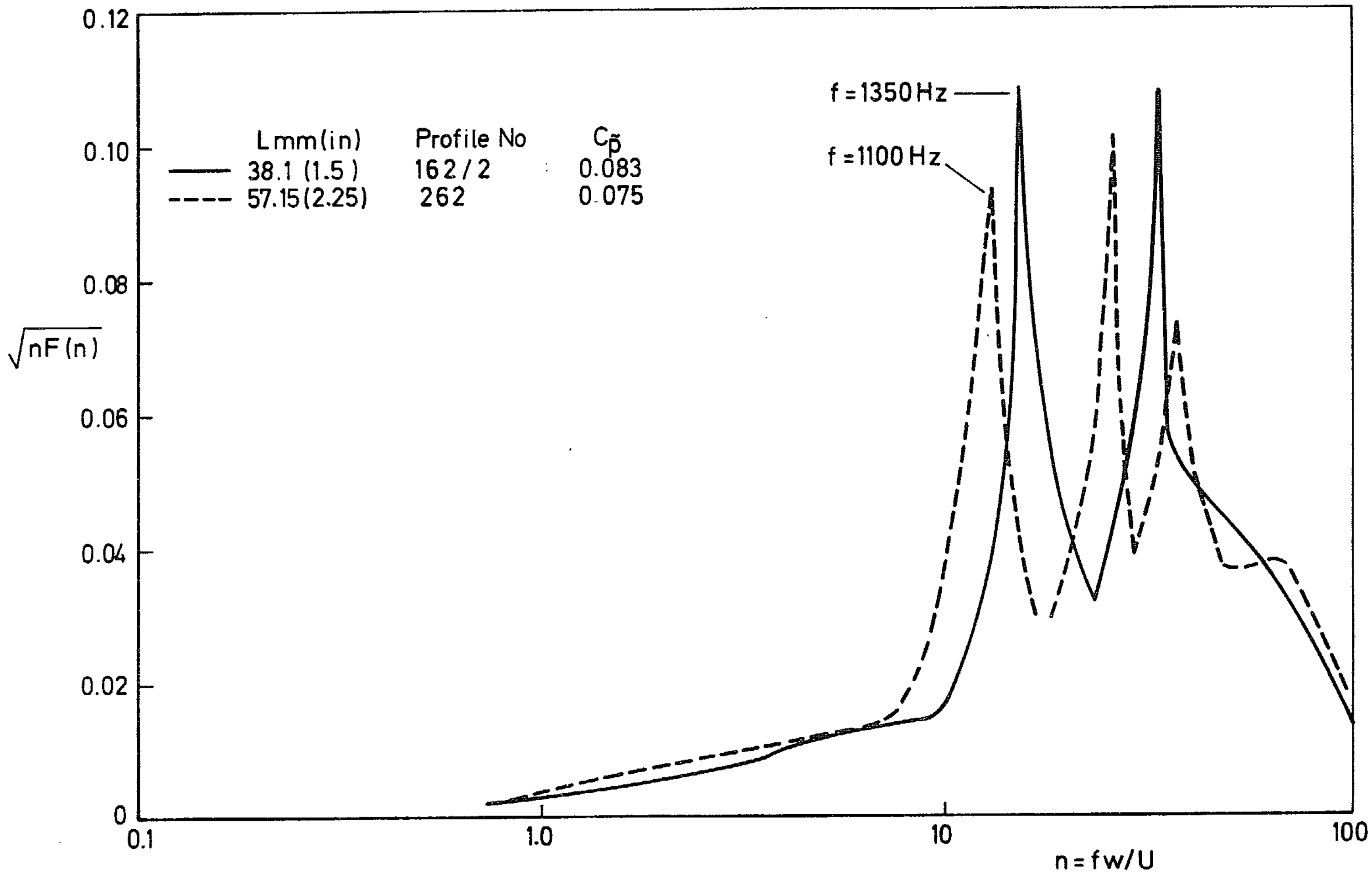


Fig 7 Noise-on spectra. M = 0.6

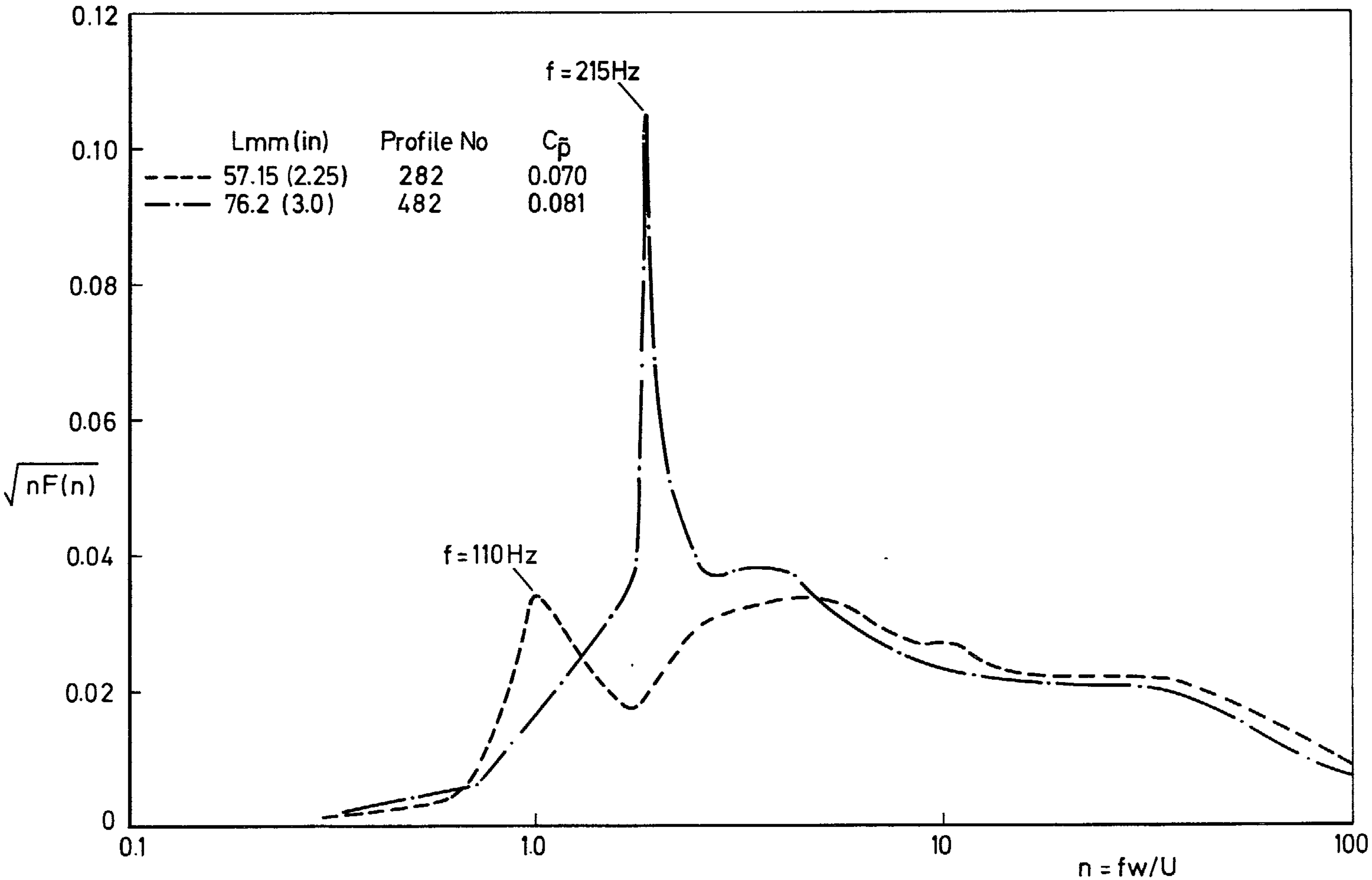


Fig 8 Noise-on spectra. M = 0.8

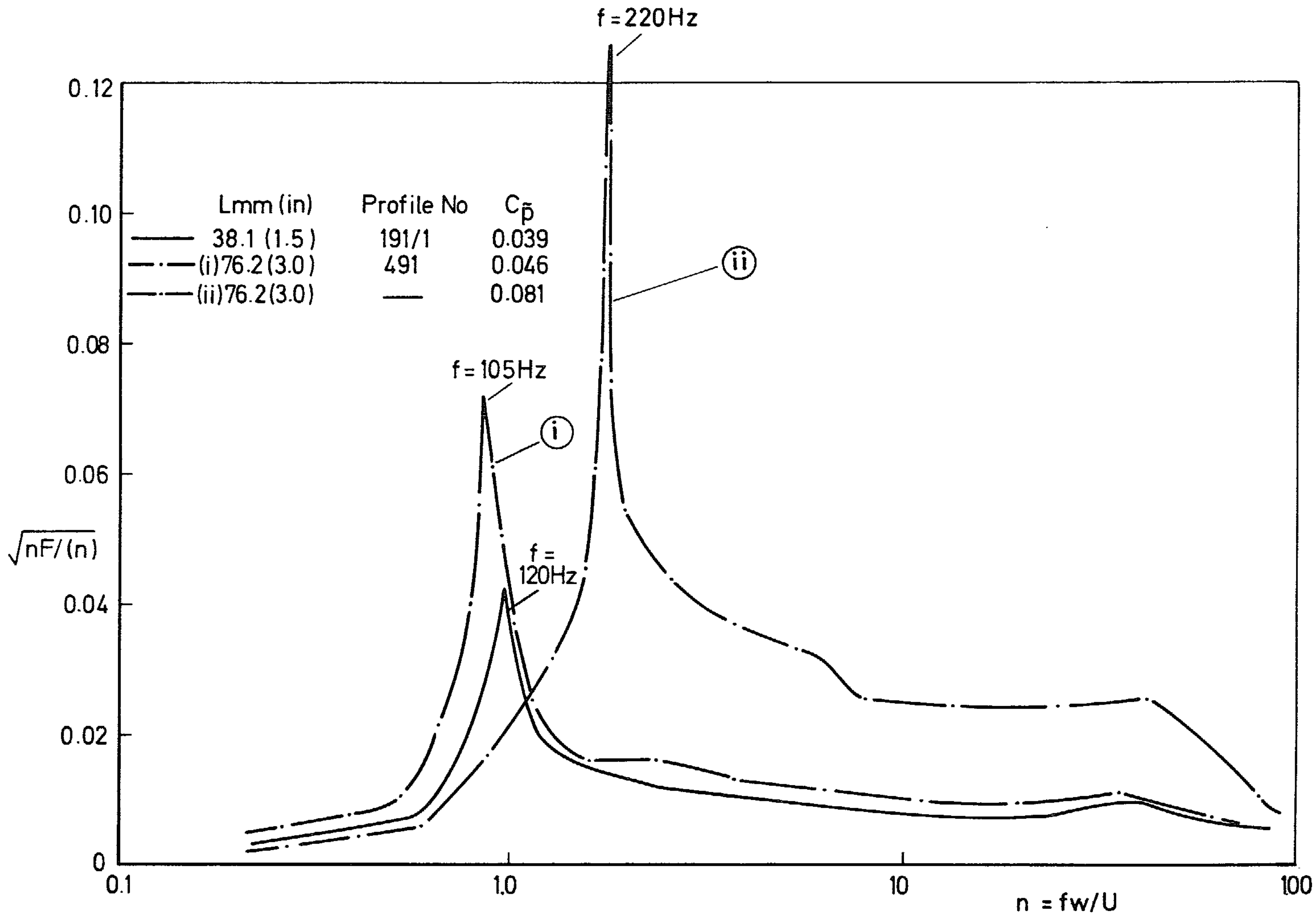


Fig 9 Noise-on spectra. M = 0.86

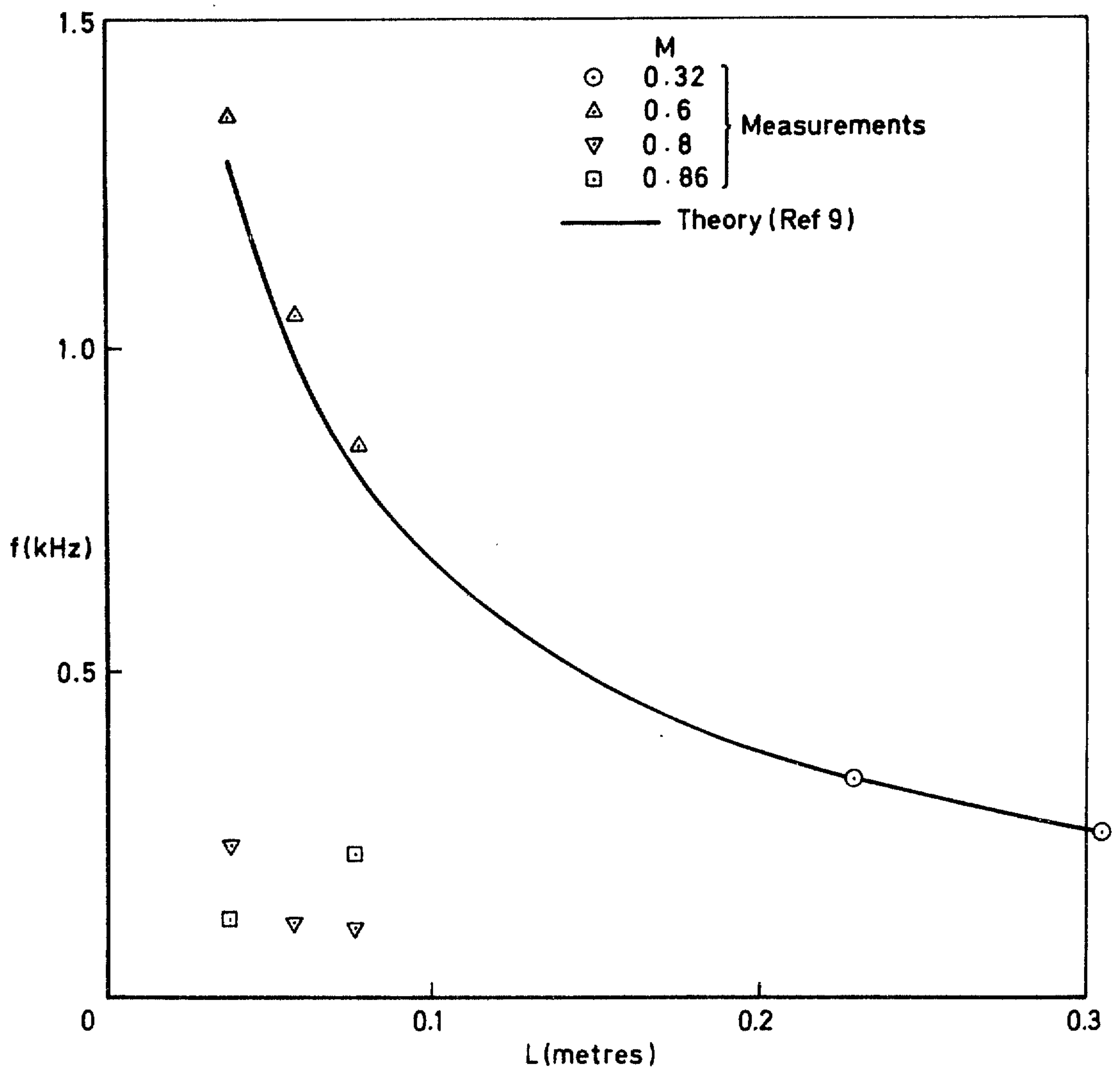


Fig 10 Variation in frequency of fundamental tone with length of resonance tube

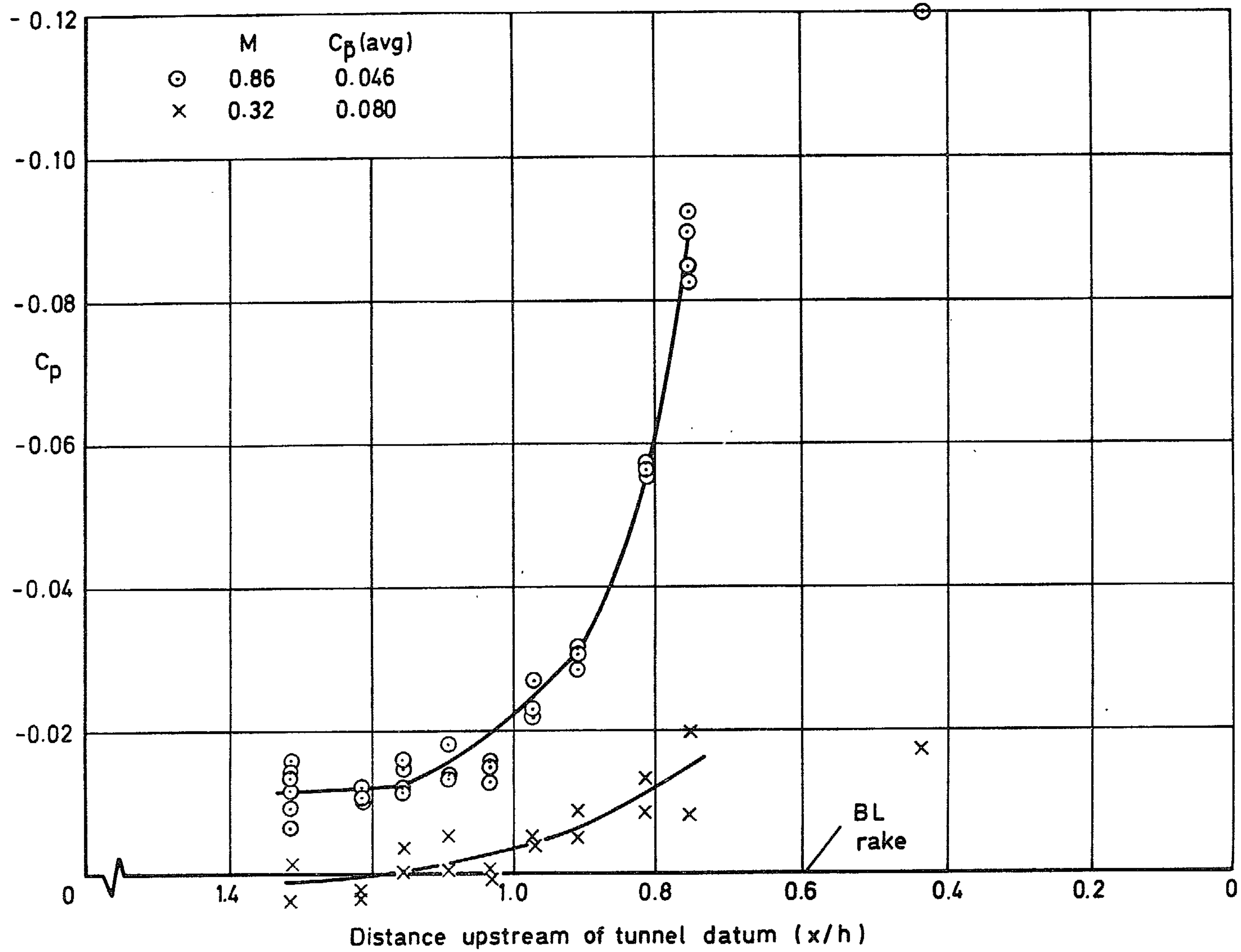
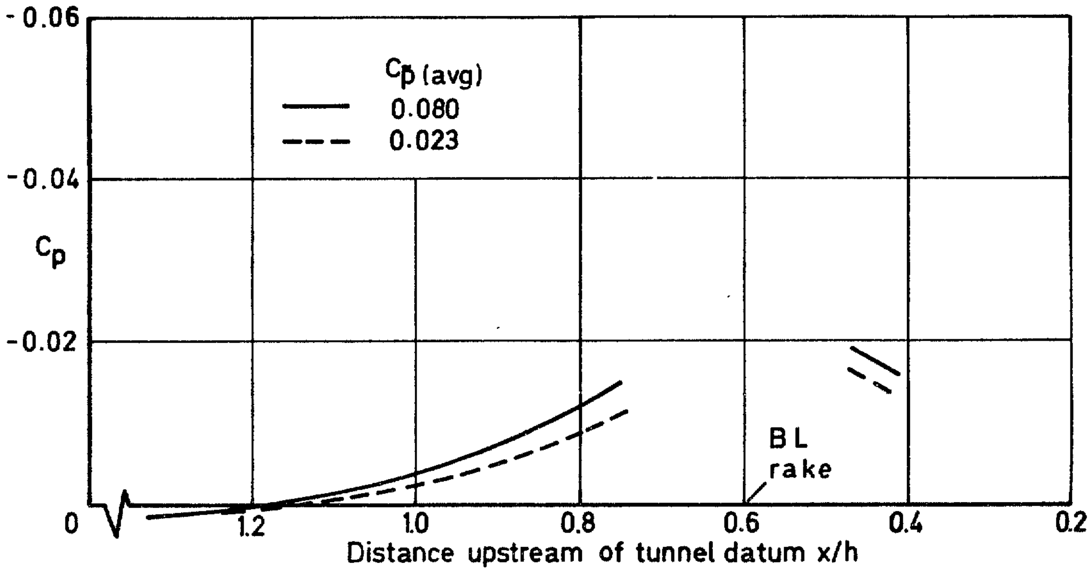
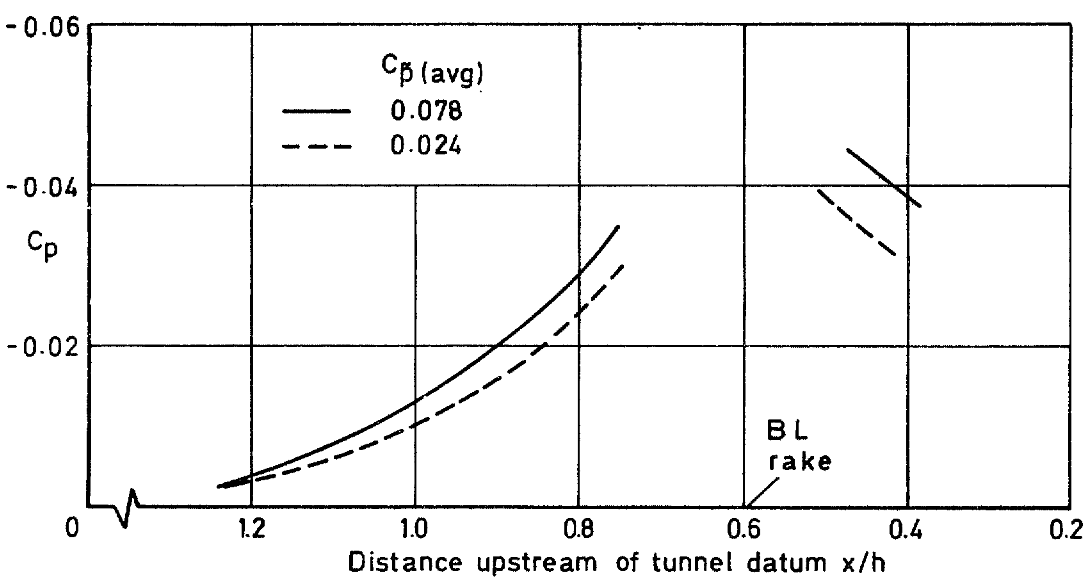


Fig 11 Illustration of scatter in wall pressure measurements



a M = 0.32



b M = 0.60

Fig 12 Measured pressure distributions on tunnel sidewall. M = 0.32, 0.6

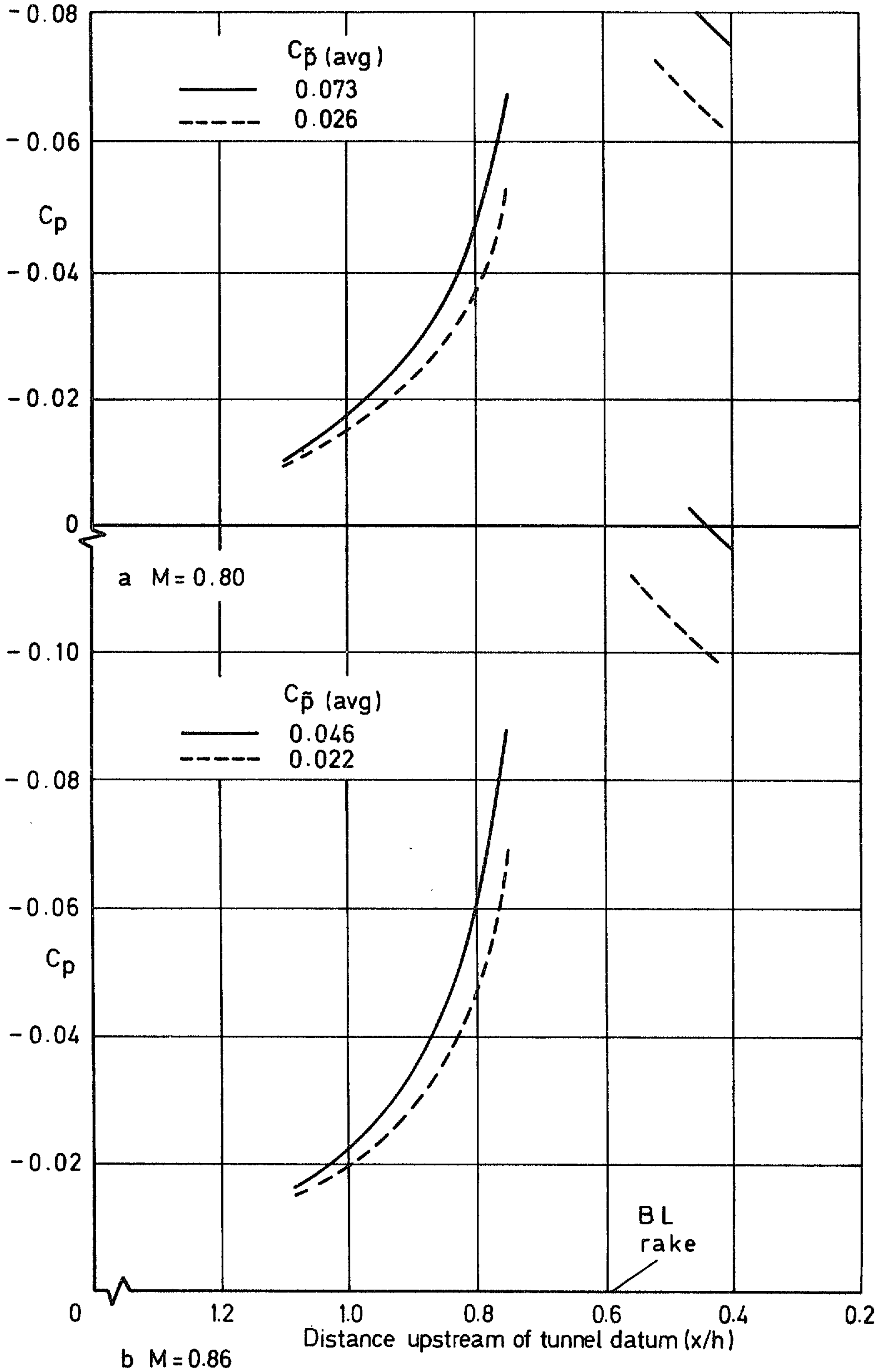
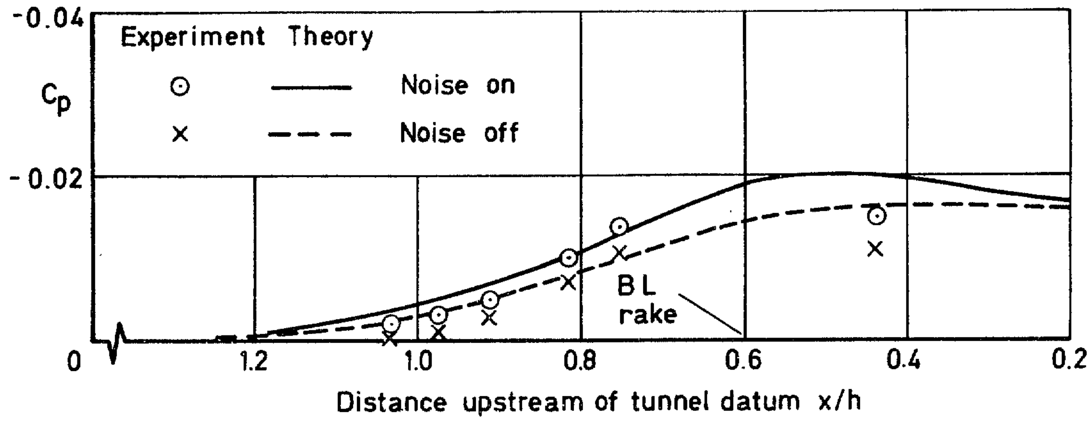
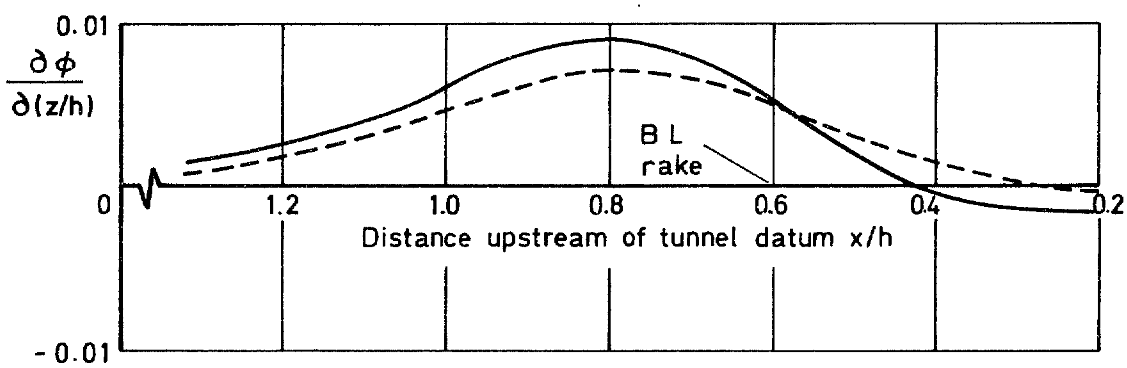


Fig 13 Measured pressure distributions on tunnel sidewall. M = 0.80, 0.86

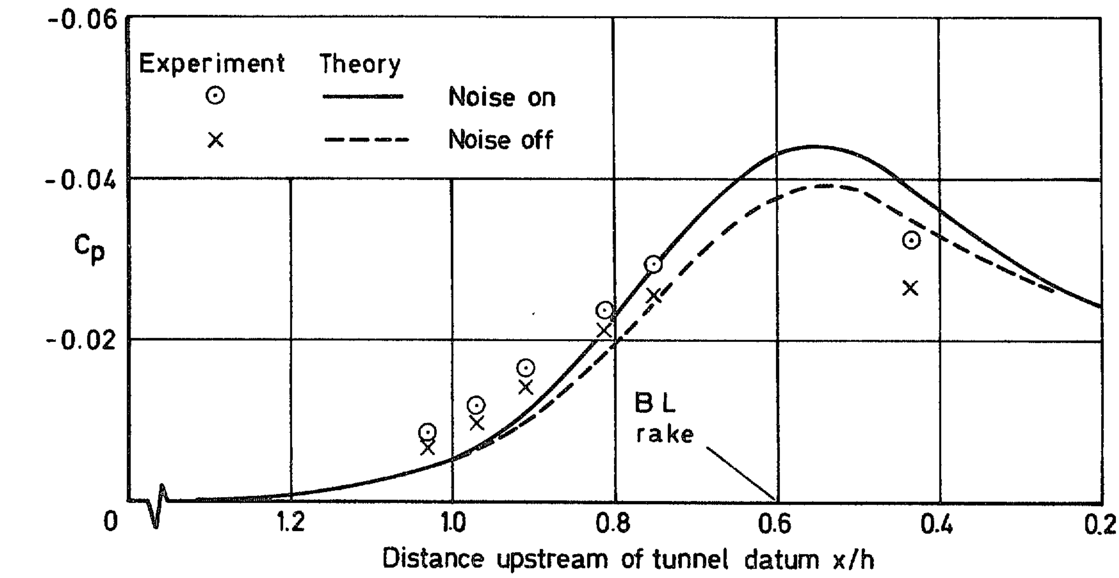


a Pressure distribution

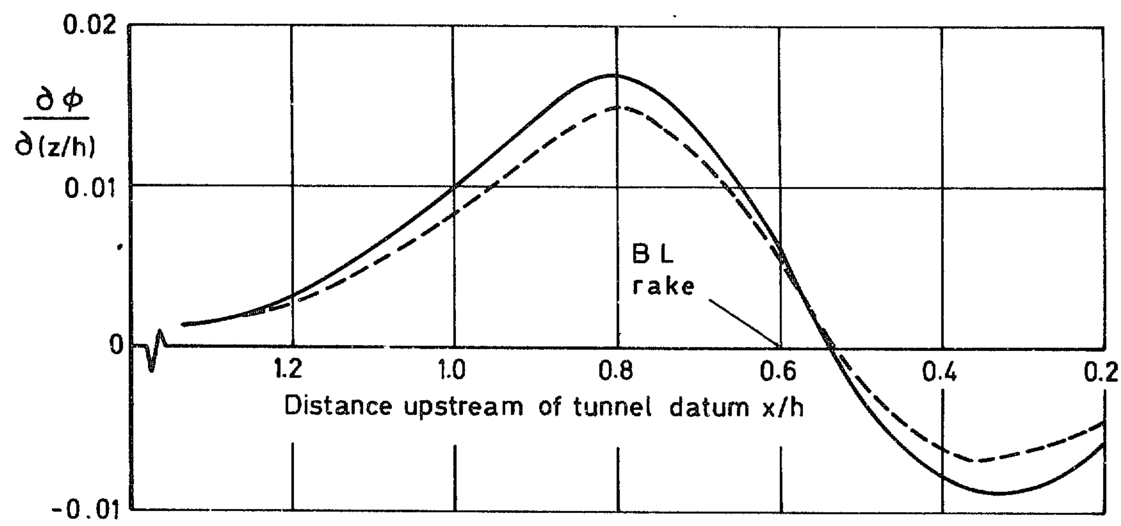


b Flow divergence

Fig 14 Computed and measured flow along sidewall centre line. M = 0.32

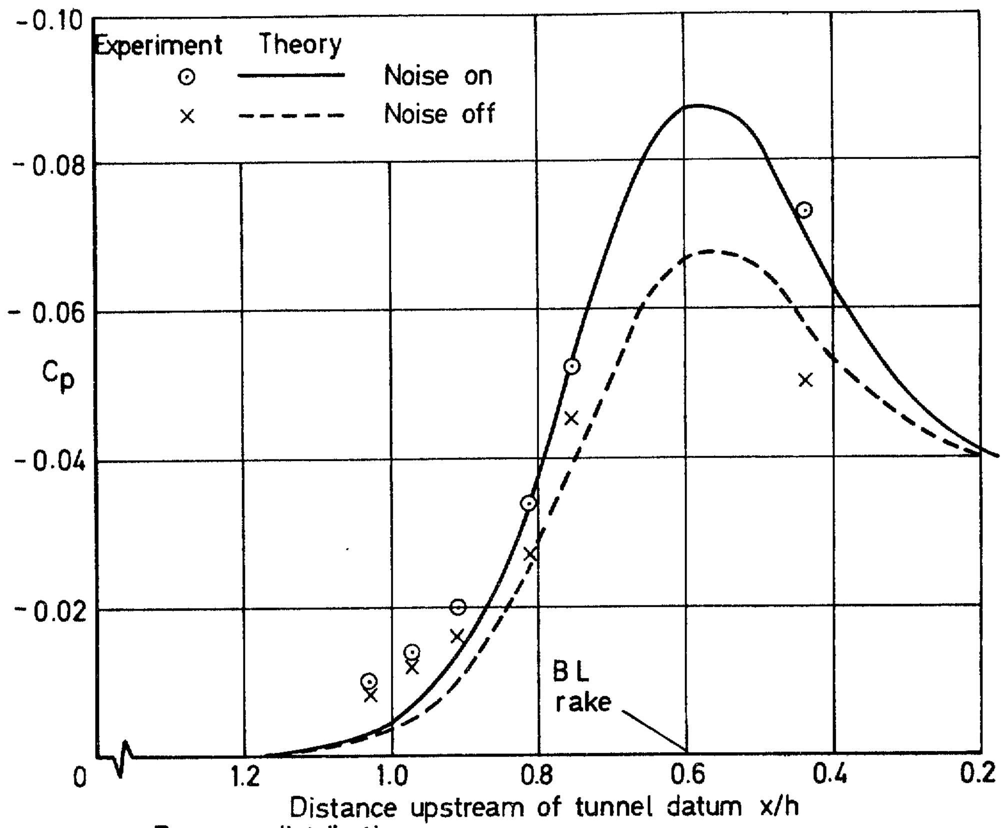


a Pressure distribution

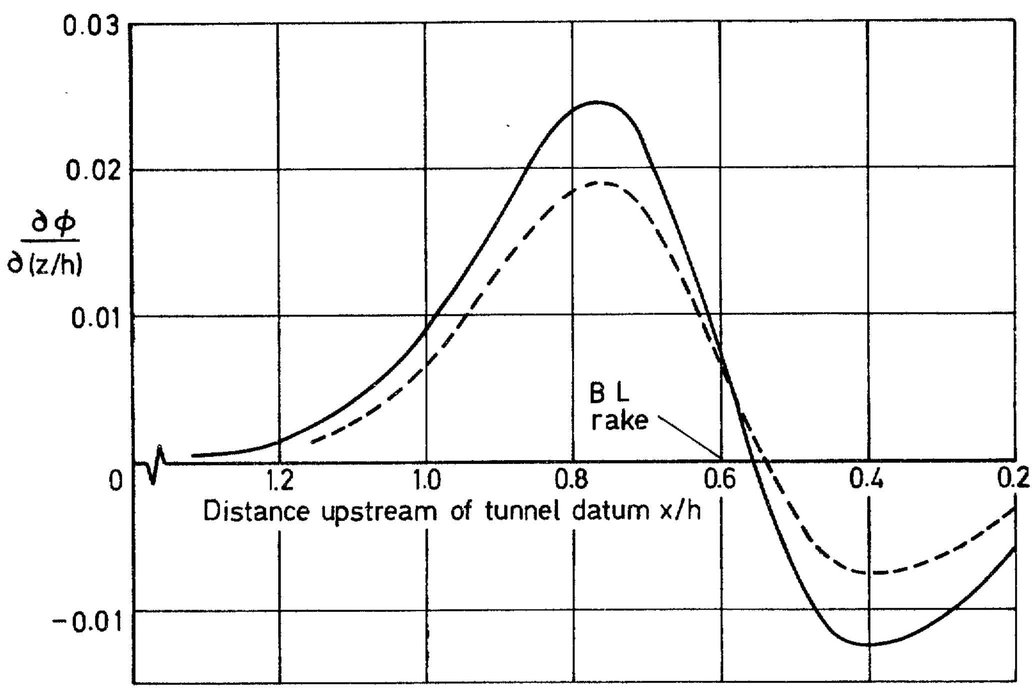


b Flow divergence

Fig 15 Computed and measured flow along sidewall centre line. M = 0.6



a Pressure distribution



b Flow divergence

Fig 16 Computed and measured flow along sidewall centre line. M = 0.8

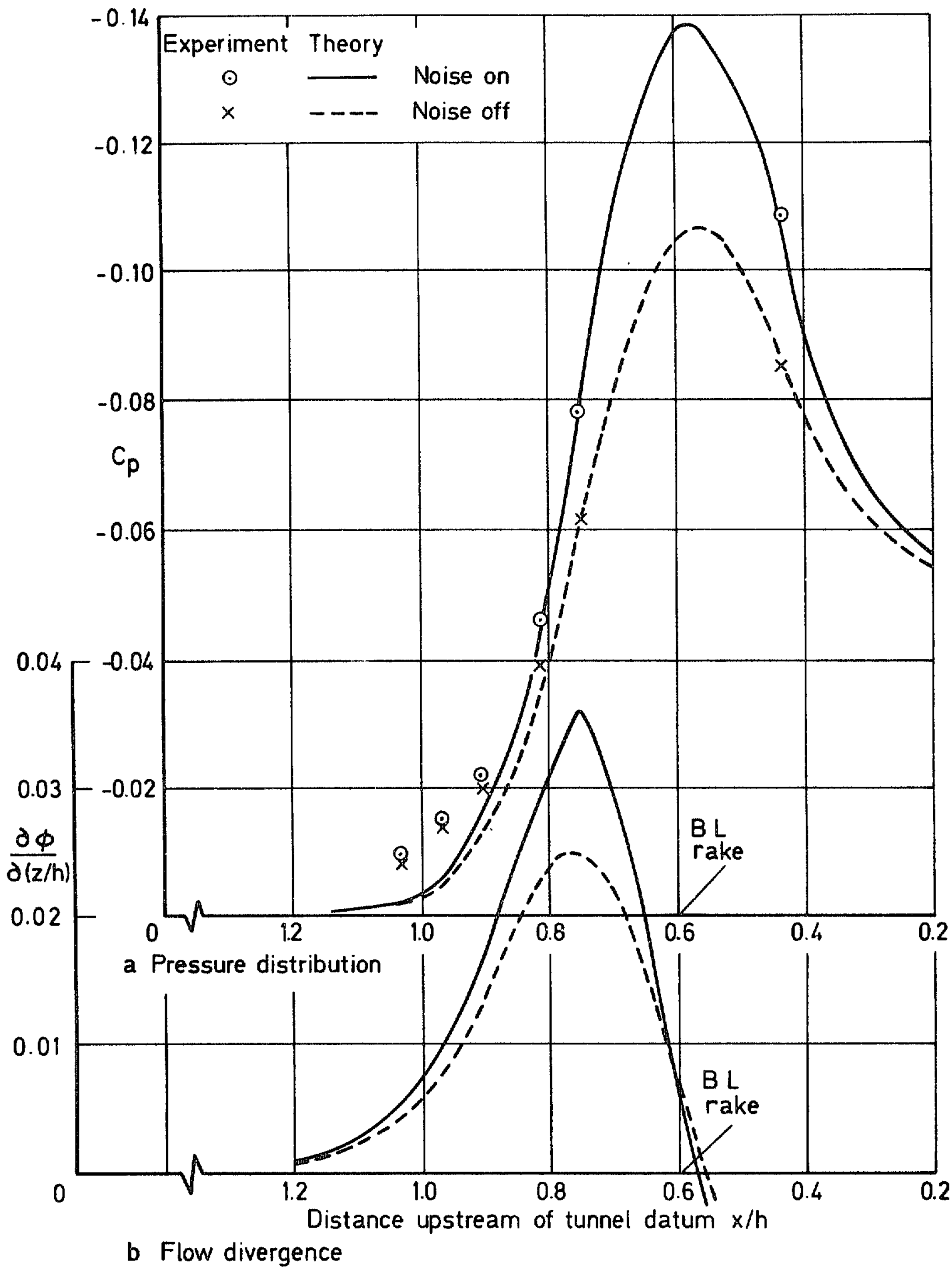


Fig 17 Computed and measured flow along sidewall centre line. M = 0.86

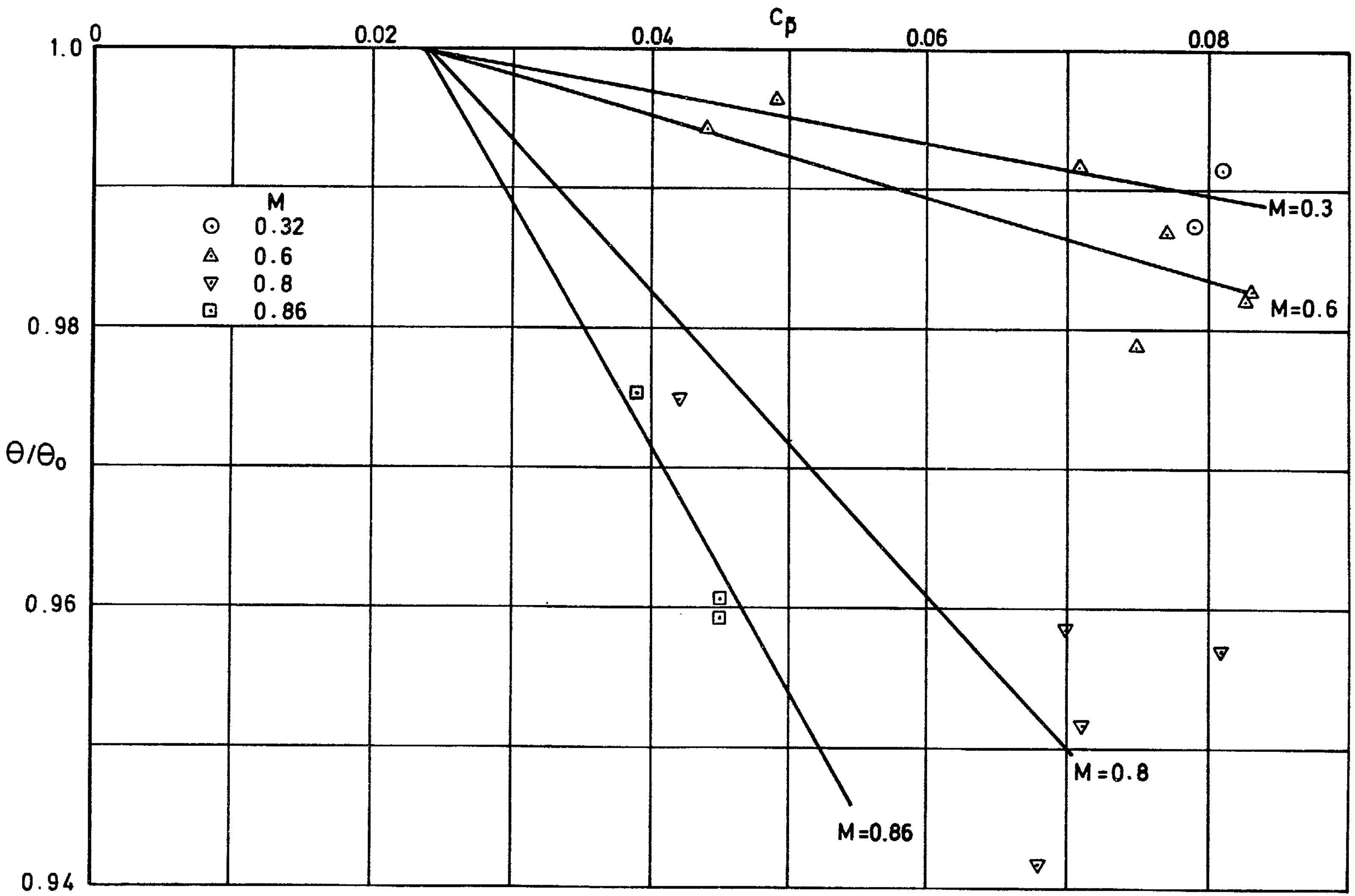


Fig 18 Effect of noise on boundary layer momentum thickness

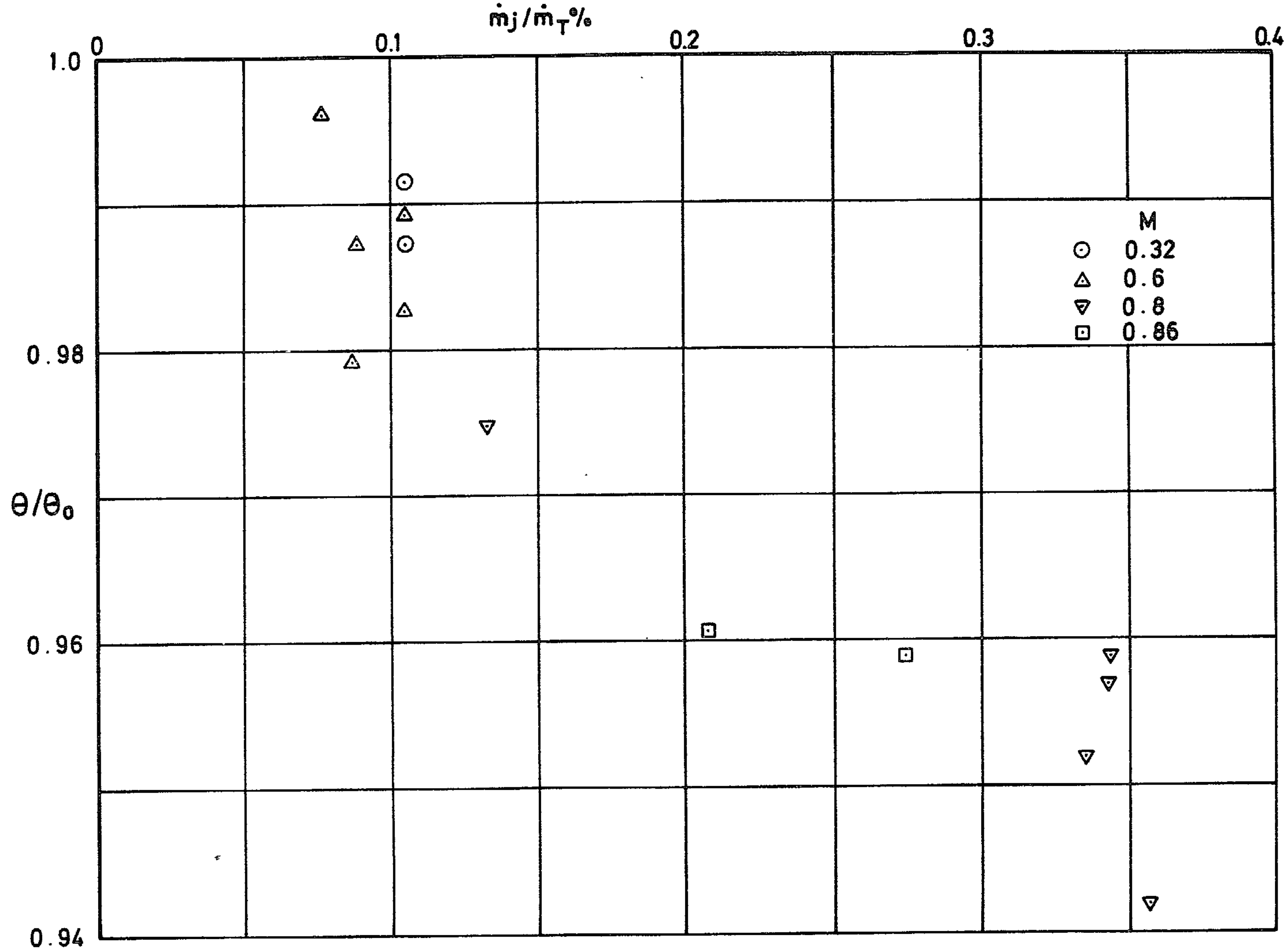
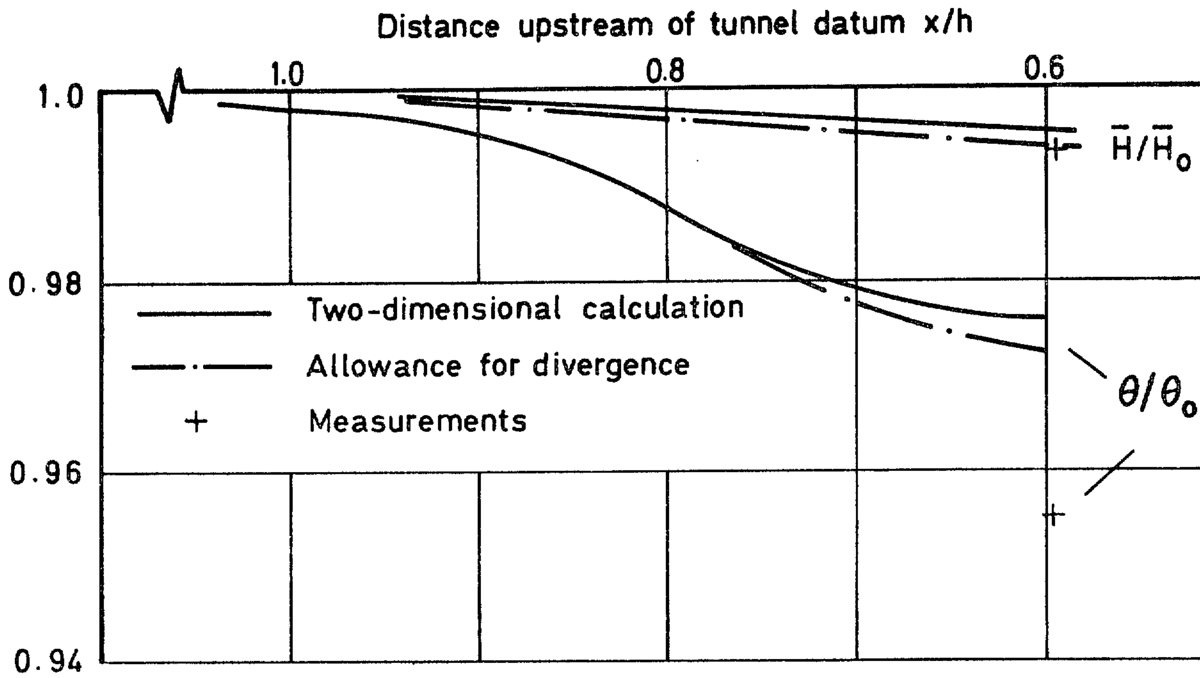
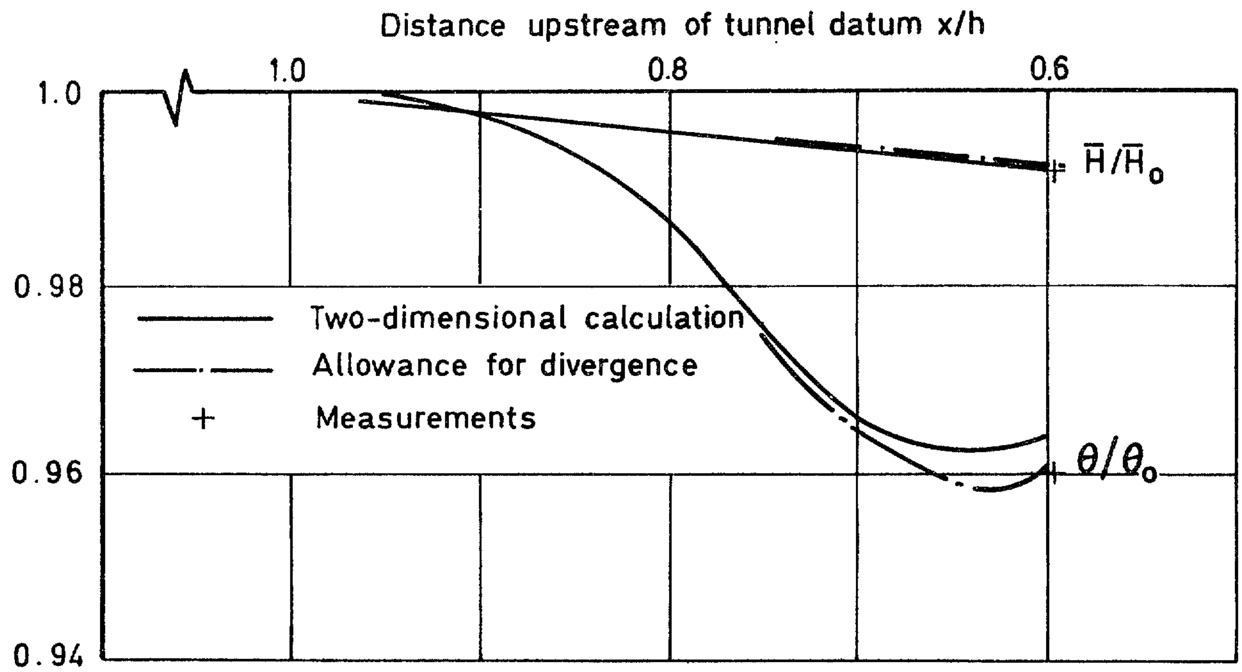


Fig 19 Effect of nozzle mass flow on boundary layer momentum thickness



a M = 0.80



b M = 0.86

Fig 20 Calculated changes in boundary layer development on tunnel sidewall. M = 0.8, 0.86

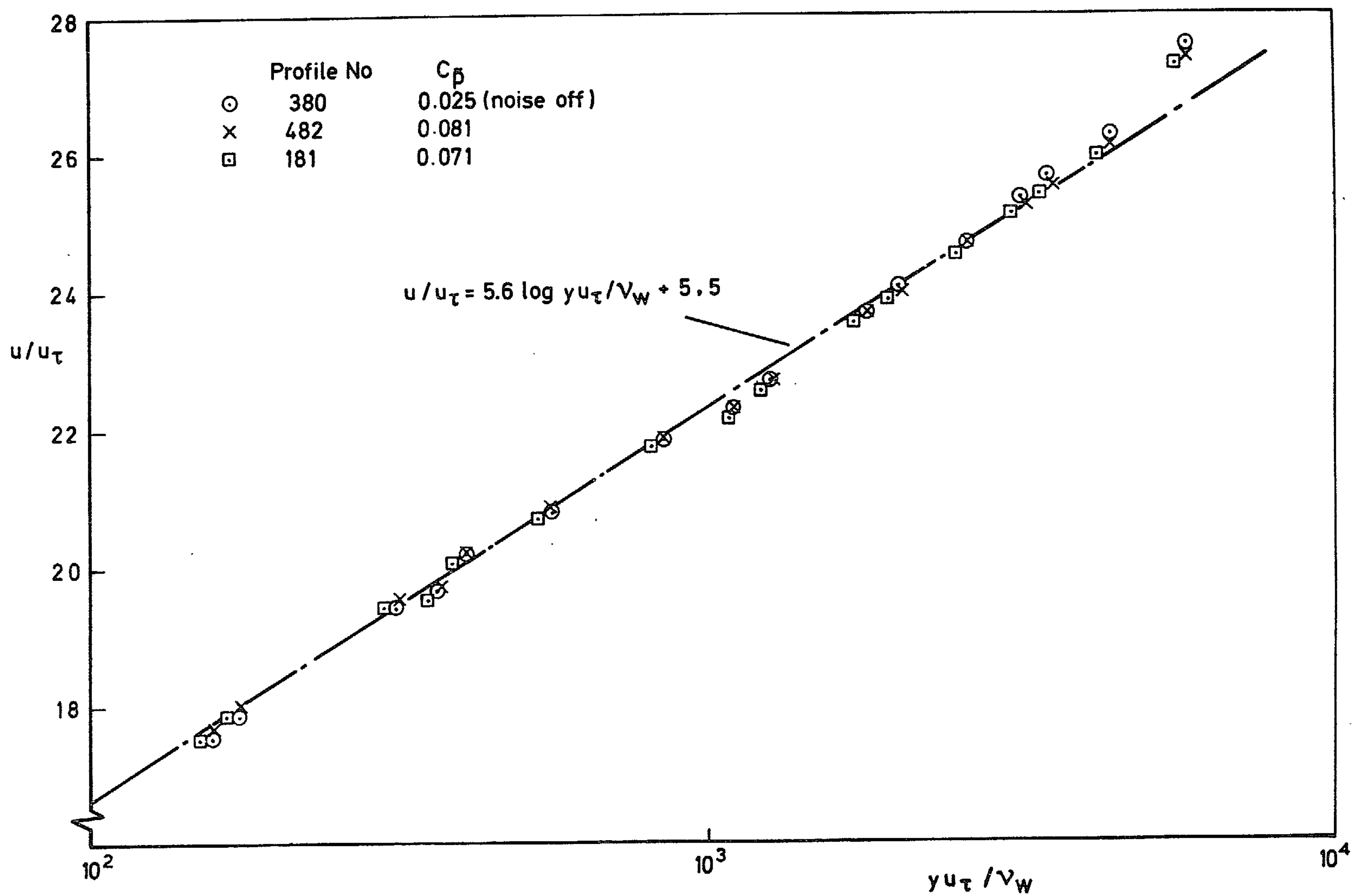


Fig 21 Effect of noise on boundary layer profiles in log-law coordinates. $M = 0.8$

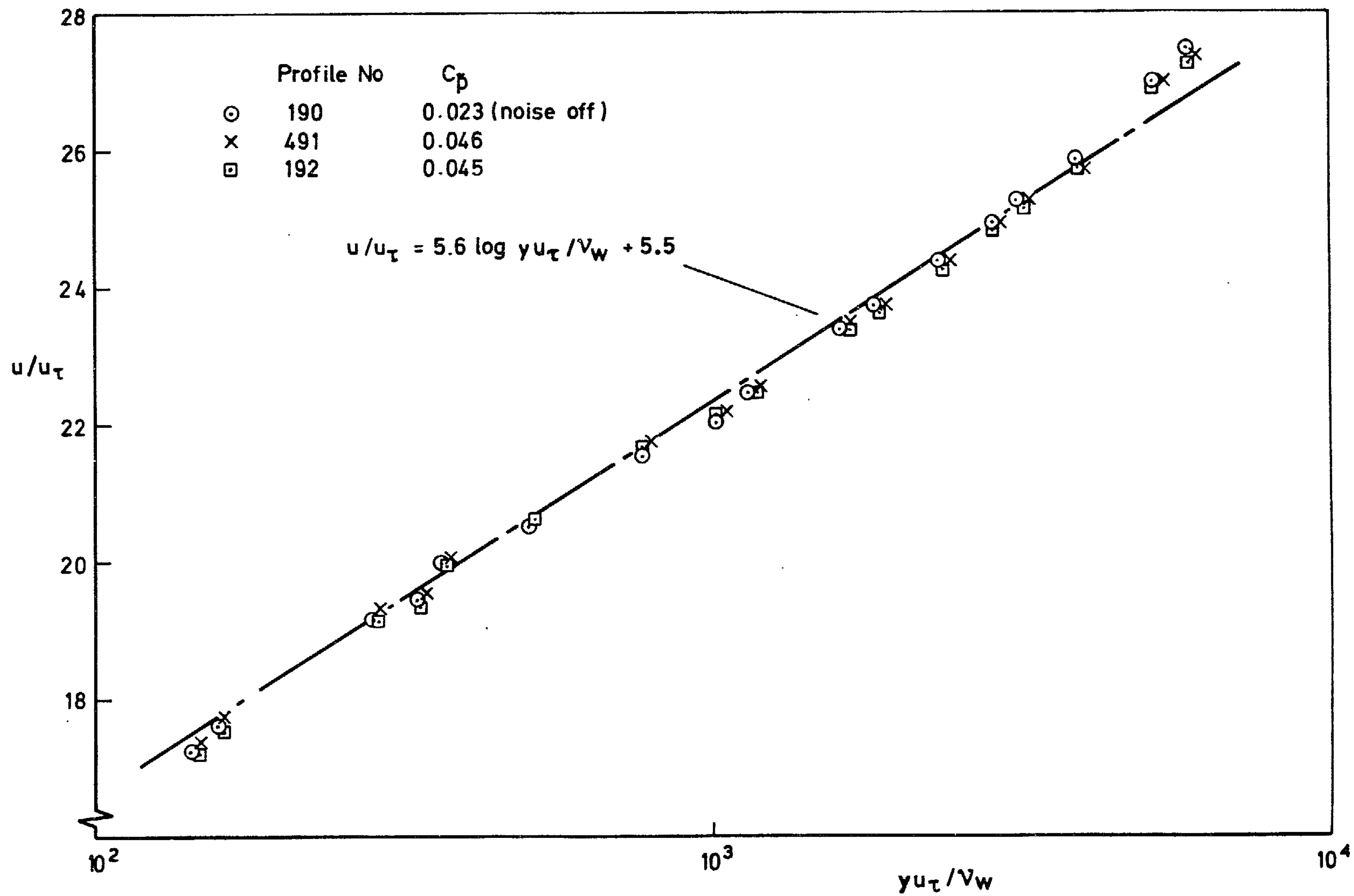


Fig 22 Effect of noise on boundary layer profile in log-law coordinates. M = 0.86

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