R. & M. No. 3527

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

The Effect of Turbulence on Static-Pressure Tubes

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1968
PRICE 5*s*. 6*d*. NET

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Reports and Memoranda No. 3527*
September, 1966

Summary.

Measurements on the centreline of a circular jet confirm the suggestion of Barat and Toomre that the error in static-tube reading due to turbulent fluctuations depends on the ratio of the size of the tube to the size of typical turbulent eddies. The reading of tubes of a size likely to be used in practice is nearer to the actual static pressure than to either of the theoretical predictions for tubes which are very large or very small compared with the turbulent eddies.

Introduction.

The problem of determining the reading of a pitot tube or static tube in a turbulent flow is a special case of the very important and very difficult problem of determining the loads on a structure in a turbulent wind.

Goldstein[1] and Fage[2] have suggested theoretical corrections to reduce the reading of a pitot or static tube to the true total or static pressure, and Fage reports experiments which show agreement with his theory and give $p_{\text{meas}} = p_{\text{true}} + \frac{1}{4}\rho(\overline{v^2} + \overline{w^2})$. However, the effect of turbulence found by Fage could be equally well explained by supposing that his static tube read $p + 0{\cdot}003 . \frac{1}{2}\rho U^2$ whether the flow was turbulent or not. Fage does not refer to any checks on the performance of his tubes in non-turbulent flow, but similar hemispherical-nose pitot-static tubes tested by Salter *et al*[3] had pressure coefficients of the order of 0·003.

More recently, Barat[4] and Toomre[5] have pointed out that the Goldstein-Fage argument used to derive the correction to a static tube reading is valid only if the turbulent eddies are small compared with the diameter of the tube (in this case the pressure fluctuation at the different holes are uncorrelated and the tube may be expected to read high by an amount of order $\frac{1}{2}\rho\,(\overline{v^2} + \overline{w^2})$, as suggested by Goldstein, because of the impact of the transverse turbulent motion). If the eddies are so large compared with the tube that the flow over the tube at any instant is the same as in steady flow in the appropriate direction ('quasi-steady' flow) the reading will depend on the yaw response of the tube. Jezdinsky[6] has used a small yawmeter in a jet flow (distance from nozzle/probe width 400) to obtain plausible values of v-component intensity. In the particularly simple but representative case where the yaw response in steady flow is given by

$$p_{\text{meas}} = p_{\text{true}} - a\psi^2 . \tfrac{1}{2}\rho U^2$$

where ψ is the yaw angle in radians and a is about 0·7 for the tubes discussed below, or 1·0 according to Toomre's theory, the tube reads

$$p - a\left(\frac{\overline{v^2} + \overline{w^2}}{U^2}\right) . \tfrac{1}{2}\rho U^2 \equiv p - \tfrac{1}{2}\, a\rho\,(\overline{v^2} + \overline{w^2})$$

*Replaces NPL Aero Report 1210—A.R.C. 28 327.

which is of opposite sign but similar magnitude to the result for small eddies. Toomre has sketched the way in which the measured pressure might vary between these two asymptotic values. It should be noted that Goldstein's well-known prediction for the reading of a pitot tube, $p+\frac{1}{2}\rho U^2+\frac{1}{2}\rho\,(\overline{u^2}+\overline{v^2}+\overline{w^2})$, can be derived by assuming quasi-steady flow and negligible yaw sensitivity: it is *not* restricted to small eddy sizes and can probably be relied on in general, provided that the pitot tube is sufficiently insensitive to yaw. The very small flattened pitot tubes used in boundary-layer work seem to be very sensitive to pitch unless great care is taken to make the forward face exactly plane.

In the present Report we describe the results of a short series of tests with static tubes made on the centreline of a circular jet over a range of ratios of eddy size to tube diameter. The advantages of this set up are that the flow is self-preserving, so that the velocity and length scales of the turbulence at the probe position can be altered without altering the typical eddy shapes; that the true static pressure, relative to the atmosphere, can be calculated at once when the turbulent intensity is known; that the mean flow is axially symmetric so that mean yaw angles need not be determined; that the turbulent intensity is high enough for the errors to be large and easily measured; and that it is in jet flows that appreciable static-tube errors will be most commonly encountered in practice. The measurements were made in the jet from a $\frac{1}{2}$ in. (1·27 cm) nozzle, at distances from the nozzle between 10 and 36 in. (25 and 85 cm) and at exit speeds from 200 to 1000 ft/sec (60 to 300 m/sec) (the speed at the static tube, which was measured independently, never exceeded 200 ft/sec and no compressibility corrections have been made). Four geometrically-similar static tubes were used, made to the 'modified ellipsoidal nose' design recommended by Salter *et al* for pitot static tubes and exhaustively tested by them. The shape of the tubes is shown in Fig. 1. Geometrical similarity ended where the diameter of the tapered support reached 3/8 in. (0·95 cm): the change in reading caused by adding an 'image' support on the other side of the tube was less than $0{\cdot}01.\frac{1}{2}\rho U^2$. Variation of tube diameter d, jet speed and distance from nozzle enabled the Reynolds number Ud/ν to be varied from 400 to 25000 while varying x/d from 50 to 800. x/d is proportional to the ratio of eddy size to a typical tube diameter. Since the speed on the axis of the jet from a nozzle of diameter D is about 6·4 D/x times the exit speed, the Reynolds number varied as x/d was varied at a given jet speed, but a Reynolds number range of about 4·7 : 1 could be obtained for a given tube and given x/d by varying the jet speed. Measurements were also made with the 0·156 in. tube with enlarged static holes, and with a 'wedge' static tube of 0·047 in. diameter, the length of the wedge being about 0·4 in. and the distance between the nose and the static holes about 0·15 in. The difference between the static-tube pressure and an 'atmospheric' reference pressure at a point some 20 in. (50 cm) on the upstream side of the nozzle was measured on a 13 in. (33 cm) Chattock manometer; some measurements taken with a Betz manometer agreed well, and a large reduction in the cross-sectional area of the bore of the support tube produced no effect on the readings so that any non-linear effects of tube lag must have been confined to the geometrically-similar part of the system.

Results.

The pressure coefficients measured are plotted against x/d in Fig. 2. The only large departures from the smooth curves are at the lowest jet speed for each tube.

Discussion.

Since measurements with a given tube at different speeds fall closely together, Reynolds number effects are *small* for $Ud/\nu > 400$ and will not be considered further. There is a significant trend in the results for the different tubes, larger than could be accounted for by Reynolds-number effects, and since Ud/ν and x/d are the only relevant dimensionless parameters it follows that the trend must be the result of failure to achieve exact geometrical similarity. The ratio of hole diameter to outside diameter varied from 0·14 for the largest tube to 0·21 for the smallest tube, the holes having been made with drills of standard sizes: the effect of enlarging the holes in the 0·156 in. diameter tube is shown in Fig. 3a but it is in the opposite sense to that required to explain the trend in Fig. 2. The effect of blocking one of the four holes in the smallest tube is shown in Fig. 3b: dirt accretion could lead to large inconsistencies in static pressure measurements.

The static pressure on the axis of the jet is

$$p_a - \rho\overline{v^2} + \int_0^\infty \rho\,(\overline{v^2} - \overline{w^2})\frac{dr}{r}.$$

Corrsin[6] gives $\dfrac{\overline{v^2}}{U^2} = \dfrac{\overline{w^2}}{U^2} = 0{\cdot}056$, or $\dfrac{\sqrt{\overline{v^2}}}{U} = 0{\cdot}24$, on the centreline;

the integral term, which is absent from two-dimensional flows, is very much smaller than this and negligible to within the likely accuracy of the hot wire measurements. The 'true' static pressure derived from Corrsin's figure is shown on Fig. 2, together with Fage's predictions for the indicated value by a static tube of diameter large compared with a typical eddy.

The almost exact coincidence of the end of the curve at smallest x/d with the Fage prediction is not significant: measurements were not taken at very small x/d because the tube diameter was no longer small compared with the local jet diameter and such large tubes would never be used in practice. The accuracy of the Fage prediction for small eddy-size/diameter ratios could be checked only in grid turbulence. The results for large x/d show signs of asymptoting to the quasi-steady value but this is not reached in the range of the experiments. Indeed, the assumption that the tubes read the correct static pressure is in error by less than $\pm 0{\cdot}02.\frac{1}{2}\rho U^2$ over the range of tube diameter that would be used in practice but it must be emphasized that this is not a licence to ignore the effects of turbulence altogether because these effects will depend on the properties of the turbulence and the shape of the static tube. Nevertheless it may be suggested that the reading of a typical static tube is probably nearer the true static pressure than to either of the asymptotic theoretical values. Rather surprisingly, the wedge static tube, which one would expect to be nearer quasi-steadiness for given x/d than the other tubes because of its shorter effective length, reads *higher* than the true static pressure.

There is no simple way of investigating the variation of static tube error with turbulent intensity: the only self-preserving flows whose intensity varies over a wide range are wakes of one sort or another, and self-preservation is not attained until the intensity is small, making measurements difficult and results of little value. Nor is it easy to investigate the effect of different sorts of turbulence, because of the large number of parameters that may be varied. For instance, the results may be considerably affected by any correlation between the u and v component fluctuations – that is, by any Reynolds shear stress: the effect of a mean velocity gradient as such is probably negligible by comparison. The shape of the curve of correlation between the v or w component fluctuations with separation in the longitudinal direction is the absolute minimum of information needed to specify the turbulence, and because this shape varies considerably between different flows or different parts of the same flow it is not easy to choose a single representative length scale of the turbulence. The frequency spectrum of the v or w fluctuations, which is easier to measure in practice, is the Fourier transform of the correlation curve (assuming that the convection velocity of the turbulence is unique). The radial-component spectrum measured on the centreline of a jet 20 diameters from a 1 in. nozzle is shown in Fig. 4. Probably the most useful scale to take for purposes of comparison is the wavelength at which the spectral density per octave is a maximum, so that $\phi \sim \omega^{-1}$: this defines the frequency or wavelength near which most of the turbulent energy is found. (The 'integral scale', related to the spectral density at zero frequency, is not a very useful choice). In the high-intensity portion of a mixing layer, this wavelength λ_1 say is about 0·3 of the distance from the origin, in the outer part of a turbulent boundary layer it is almost equal to the boundary layer thickness, and on the centreline of a circular jet it is about 0·12 of the distance from the origin. Thus, since the value of λ_1/d at which the tubes in the present experiment read the true static pressure is about 20, the corresponding ratio d/δ in a boundary layer is 1/20, which is perhaps rather larger than what one would try to attain in order to get sufficient spatial resolution but is nevertheless of the order of size likely to be used in practice.

Conclusions.

In the range of sizes likely to be used in turbulent shear flows, static-pressure tubes like those shown in Fig. 1 indicate a pressure rather closer to the true static pressure on the centreline of a circular jet than to either of the theoretical values for very large or very small tubes. The effects of Reynolds number are very small, at least for $\sqrt{\overline{v^2}}\ d/\nu > 100$. It is therefore suggested that the best course is to omit any corrections for the effect of shear-flow turbulence unless a proper investigation can be made in the flow actually being used.

Quasi-steadiness is a poor approximation if λ_1, the wavelength at which the spectral density varies as the reciprocal of the frequency or wave number, is less than about 100 times the tube diameter or 10 times the distance from the nose of the tube to the holes.

Acknowledgement.

The authors are grateful to Mr. E. Ower for suggesting this problem to them.

LIST OF SYMBOLS

D	Diameter of nozzle	
d	Diameter of static tube	
p_a	Atmospheric pressure	
p	Static pressure	
U	Mean velocity	usually on centreline of jet
$\overline{u^2}, \overline{v^2}, \overline{w^2}$	Mean-square fluctuations in x, y, z directions	
r	Radial distance from jet axis	
x	Axial distance from effective origin of jet to holes in static tube	
y, z	Perpendicular radii	
λ_1	Wavelength corresponding to frequency at which $\phi \sim \omega^{-1}$	
ν	Kinematic viscosity	
ρ	Density	
ϕ	Spectral density per unit $\omega x/U$, normalised by mean-square intensity	
ω	Radian frequency	

LIST OF REFERENCES

No.	Author(s)	Title, etc.
1	S. Goldstein	A note on the measurement of total head and static pressure in a turbulent stream. *Proc. Roy. Soc.* A *155*, 570. 1936.
2	A. Fage..	On the static pressure in a fully developed flow. *Proc. Roy. Soc.* A *155*, 576. 1936.
3	C. Salter, J. H. Warsap and D. G. Goodman ..	A discussion of pitot-static tubes and of their calibration factors with a description of various versions of a new design. A.R.C. R. & M. 3365. May 1962.
4	M. Barat	Influence de la turbulence sur les prises de pression statique. Comptes Rendus *246*, 1156. 1958.
5	A. Toomre	The effect of turbulence on static pressure measurements. A.R.C. 22 010. 1960.
7	S. Corrsin	Investigation of flow in an axially symmetrical heated jet of air. N.A.C.A. A.C.R.3L23. December 1943 (quoted by A. A. Townsend. *The structure of turbulent shear flow*, Cambridge. 1956, p. 187).
6	V. Jezdinsky	Measurement of turbulence by pressure probes. AIAA Jl. *4*, 2072–3 (1966).

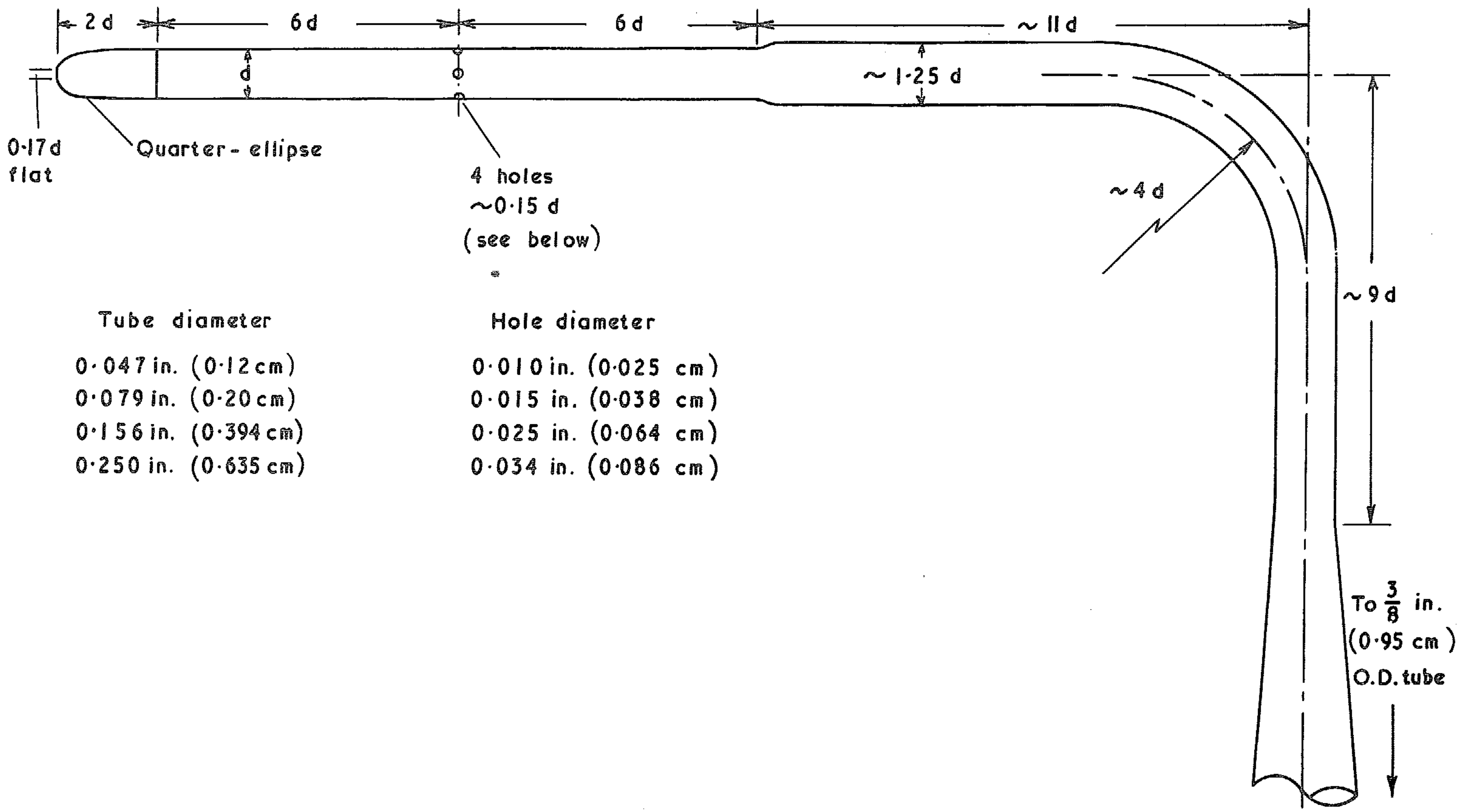


FIG. 1. Static tubes.

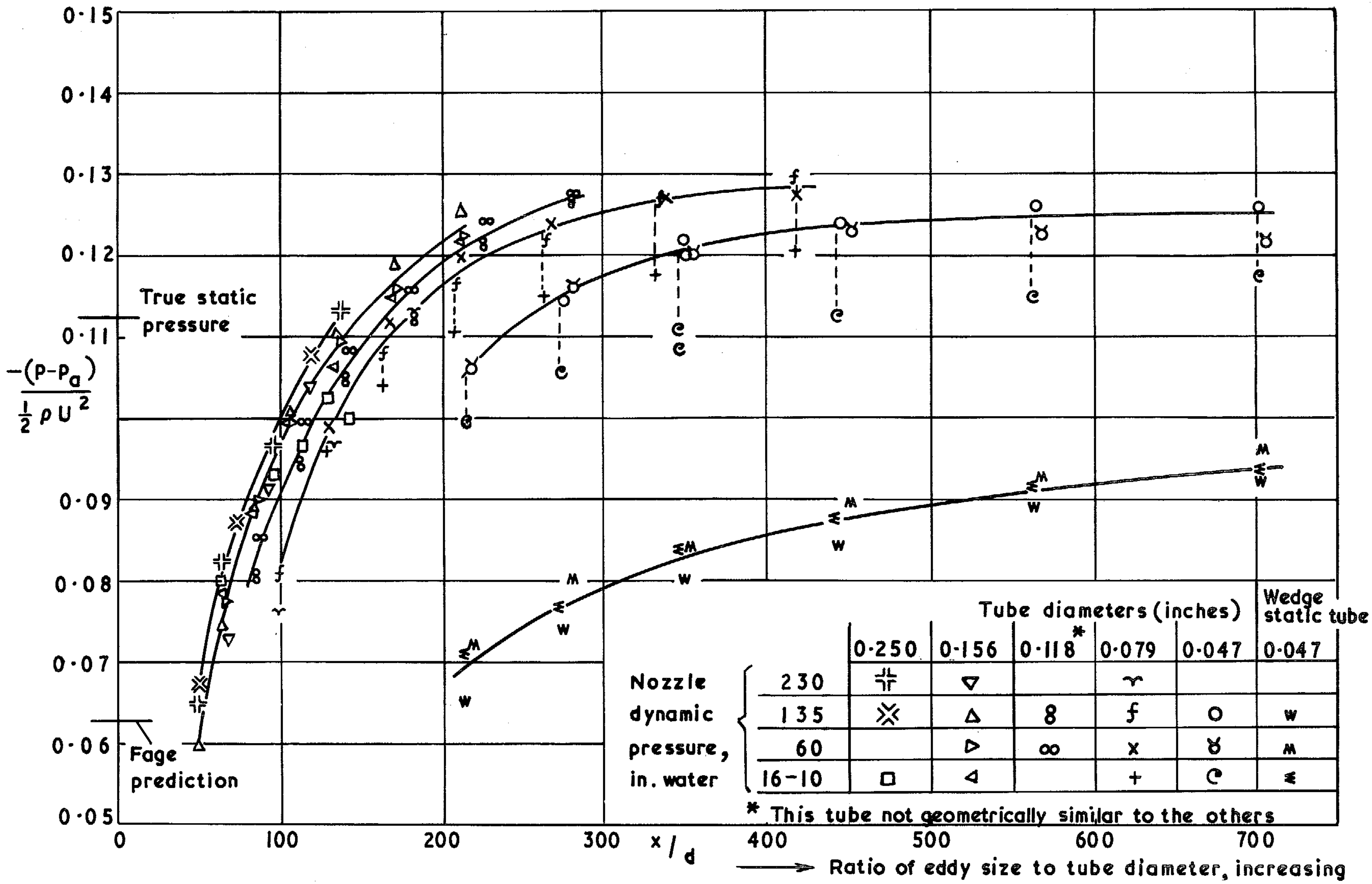
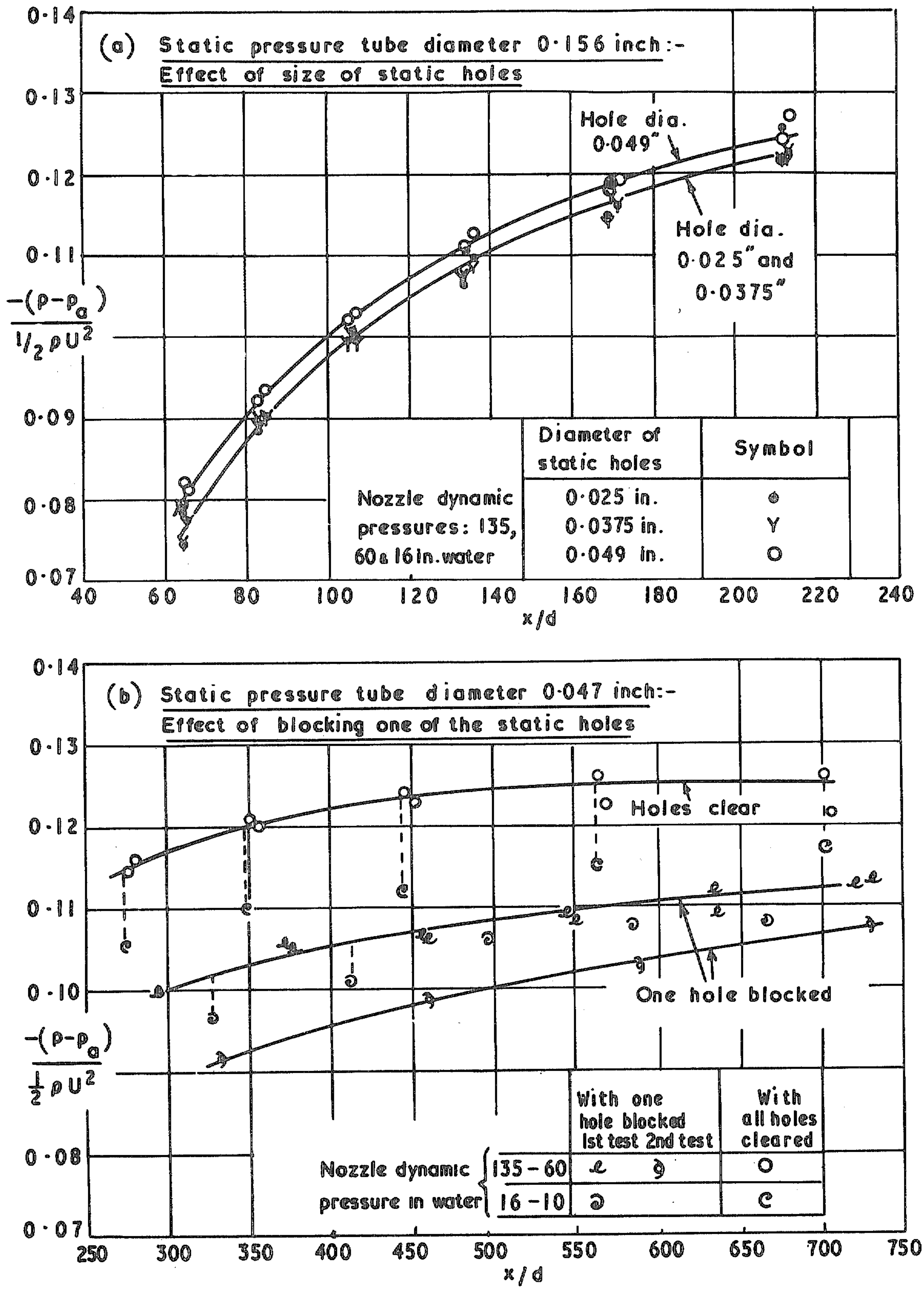


FIG. 2. Static pressure tubes in turbulent jet from $\frac{1}{2}$ in. nozzle.



(a) Static pressure tube diameter 0·156 inch:-
Effect of size of static holes
Hole dia. 0·049"
Hole dia. 0·025" and 0·0375"
Nozzle dynamic pressures: 135, 60 & 16 in. water
Diameter of static holes
Symbol
0·025 in.
0·0375 in.
0·049 in.
-(p-pa) / ½ρU²
x/d
(b) Static pressure tube diameter 0·047 inch:-
Effect of blocking one of the static holes
Holes clear
One hole blocked
With one hole blocked
1st test 2nd test
With all holes cleared
Nozzle dynamic pressure in water
135 - 60
16 - 10

FIG. 3.

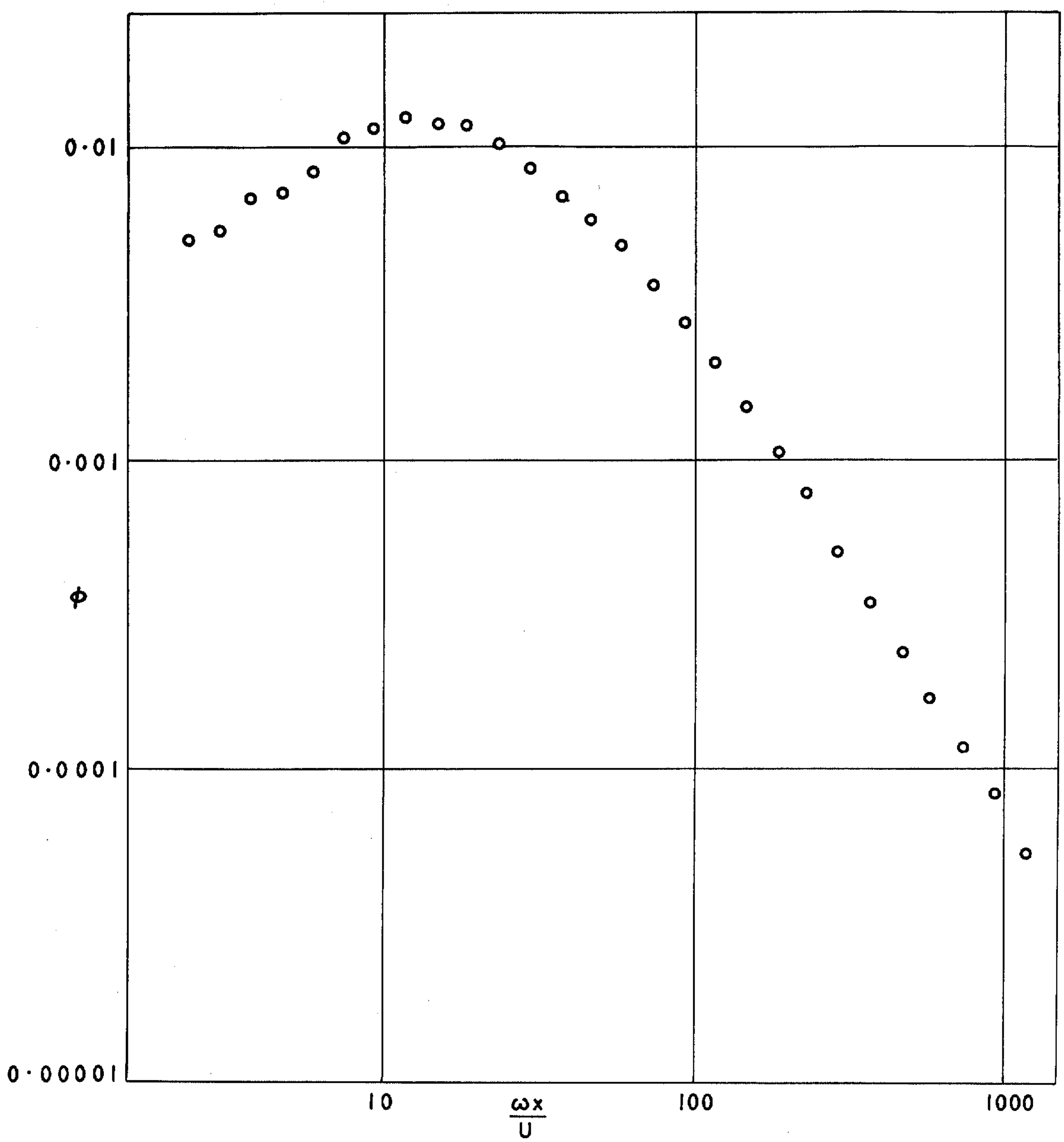


FIG. 4. Radial-component spectrum on axis of circular jet $x/D = 20$.

Printed in Wales for Her Majesty's Stationery Office by Allens Printers (Wales) Limited.
Dd.129527. K5.

R. & M. No. 3527

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