

THE DESIGN OF A SENSITIVE YAWMETER.

By J. R. PANNELL, A.M.I.M.E., and R. JONES, M.A.

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SUMMARY.—(a) *Introductory. (Reason for enquiry.)*—The investigation was undertaken in response to a request from the Technical Department of the Air Board for information as to the most sensitive form of yawmeter, and for a calibration curve for such an instrument. The original form of yawmeter suggested by Mr. (now Sir) Horace Darwin was used by Mr. E. T. Busk in his experiments in 1912 (see Rpt. 1912-13, p. 254) and a yawmeter on the same principle has been used in several wind channel investigations at the N.P.L. and has been described in R. and M. 156 and 371. A direct reading instrument of this type was described by Sir Horace Darwin in his Wilbur Wright Lecture of 1913.

(b) *Range of investigation.*—The variation of pressure with angle of inclination to the wind was determined on several sizes of pitot tubes, and from this curve it was predicted that the best angle between the axes of the two tubes of the yawmeter would be 120° . The sensitivity was found experimentally to be about 1.7 times as great as for the original form in which the angle was 90° . Various forms of yawmeter were tested until one was found which gave a result which could have been predicted from the experiment with the single pitot tube giving greatest sensitivity.

(c) *Conclusions.*—The experiments indicate that, in plan view, the arms of the yawmeter should be straight and bevelled to a sharp edge at the end. The embraced angle should be 120° and the tube should not be of very small diameter. A tube of 0.30 internal diameter was found to be satisfactory, and a calibration curve for this instrument is given in the report.

(d) *Applications and further developments.*—The instrument is capable of measuring angles with considerable accuracy, and can be used on aircraft or in the wind channel. If measurements are required in one plane only, they can be made very simply by turning the yawmeter till the pressure difference is zero, and reading off the angle from a degree scale.

A request was recently received from the Technical Department of the Air Board for information as to most suitable design of yawmeter for use on an aeroplane. Some preliminary measurements had already been carried out, and these were extended with the results described in the present report.

A yawmeter of the type described below appears to have been first used by Mr. E. T. Busk* in 1912 at the Royal Aircraft Establishment for the measurement of wind direction on an

* Report Advisory Committee for Aeronautics, 1912-13, p. 254.

aeroplane. A suction tube was also fitted behind a cone enabling the speed to be determined when the calibration of the instrument was known.

An indicator, by means of which the angle could be observed without the necessity for any adjustment, was devised for use with the yawmeter by Sir Horace Darwin, F.R.S.*

As the instrument has been described elsewhere, it will suffice here to state that the yawmeter consists essentially of two pitot tubes set with their axes inclined to the wind direction so that when that inclination is varied there is a difference of pressure between the two tubes. Two forms of yawmeter are shown diagrammatically in Fig. 2. An instrument was constructed at the National Physical Laboratory (and described in Report R. and M. 156) with two pairs of tubes for measurement of direction in two perpendicular planes; a suction tube, similar to the one on Mr. Busk's instrument, was added for measurement of velocity. The present investigation was directed to determining the most sensitive arrangement of tubes for measurement of direction only in one plane.

Method of experiment.—Since the sensitivity of the yawmeter depends essentially on the rate of change of pressure with angle in the tubes of which it is constructed, the first step was to determine this variation for a pitot tube alone. This was done for the pitot tube of the National Physical Laboratory standard head, and as the apparatus was erected it was thought useful to observe also the variation of pressure difference between the pitot and static pressure tubes of this head for various inclinations to the wind. Inspection of the curve thus obtained suggested that the maximum sensitivity would be obtained by placing the two tubes of the yawmeter with their axes inclined at 120° to each other (mutually at 60° to the wind direction) instead of at 90° as previously adopted. In order to test this assumption a yawmeter was made in which the angle between the tubes was 90° and after calibration this angle was increased to 120° (No. 1, Fig. 2). The sensitivity of the latter was found to be more than 1.7 times that of the former and this angle was adopted for all subsequent instruments. This yawmeter was constructed of tube 0".30 internal and 0".375 external diameter, but it was found that the sensitivity was less than that which was expected from an examination of the curve for the pitot of the standard head, on the assumption that the two tubes of the yawmeter did not interfere with each other. The sensitivity was improved somewhat by bevelling the tubes (as shown in Fig. 2), but the curve still fell below that deduced. Accordingly a yawmeter was constructed of the nearest tube to that of the standard head which was available, a single tube being shown at No. 3A in Fig. 1. An experiment showed this instrument to be rather less sensitive than the one constructed of the 0".30 tube. Both yawmeters

* Wilbur Wright lecture, *Aeronautical Journal*, July, 1913.

were next taken to pieces and the single pitot tubes (shaped like No. 3a, Fig. 1) were tested for variation of pressure with angle. A pitot tube of hypodermic syringe tubing similar to that used in constructing the N.P.L. instrument, was tested in the same manner. These three tubes all showed loss of sensitivity as compared with the pitot of the standard head. This loss was found to be mainly due, in the two larger tubes, to the bend, because when they were straightened (as No. 1 and No. 3 in Fig. 1) the large tube gave results in agreement with those for the standard, and the curve for the intermediate tube differed very little from it, the slope over the important part of the curve being almost identical in the two cases. Finally, a yawmeter of the type shown in Fig. 2 No. 2 was constructed of the 0".30 pitot tubes (the large tubes were chosen as the readings appeared to be steadier) and was found to have a sensitivity practically equal to the deduced value up to 15° and within 3 per cent. of it up to 30°.

The experiments on the N.P.L. standard head (Fig. 3) were carried out in the 3 ft. channel, those on the hypodermic tube in the No. 2, 4 ft., and the remainder in the No. 1, 4 ft. The wind speed was 40 ft./sec. unless the contrary is stated.

Results.—Values are given in Table 1 showing the ratio $P\theta/P_0$ (where P_0 is the pressure difference between pitot tube and atmosphere, or between pitot tube and static pressure tube, when the axis of the pitot tube is parallel to the wind direction, and $P\theta$ the corresponding pressure difference when inclined at the angle θ) for various angles of inclination of (a) the pitot of the standard head, (b) both tubes of the standard head, and (c) a pitot tube of an internal diameter of about 0".01 (see No. 4, Fig. 1). Results (a) and (b) are plotted in Fig. 3; C is plotted in Fig. 4 in comparison with (a) and a few observations made on tube No. 3 Fig. 1 of nearly the same diameter as the standard, but of a smaller outside diameter. Table 2 gives the results of experiments with various forms of yawmeter, the assumption being made that the ratio $\frac{1}{2}\rho V^2$ is independent of speed; these values are plotted on an angle base in Fig. 5. Table 3 gives values of the pressure difference for angles of 5, 10 and 15° when the speed is 100 m.p.h., taking a mean value of 0.094 per degree for $P/\frac{1}{2}\rho V^2$.

Discussion of the results.—The observations present several interesting features; the first, which may be noticed in Fig. 1, is the accuracy with which observations from the standard head at different speeds fall on the same curves. It is true the variation is only from 40 to 50 ft./sec., but even for this change the pressure is increased 1.5 times. The curve for the pitot and static tubes shows that in an observation of speed the maximum error possible due to inclination of this tube would be ± 6 per cent. if the angle did not exceed about 53°. This angle is presumably about as large as any likely to be attained by an aeroplane during a spin. The curves in Fig. 4 show the diminished

reduction of pressure which takes place in a pitot tube of very small dimensions. This tube was not similar in general shape to the larger ones, but it is unlikely that the change is due to this cause; there is a small change in P_0/P_∞ due to speed in the direction of less suction at higher wind speeds. This effect is opposed to that which would be expected if the loss of sensitivity in the small tube were due to a change of vl ; it would have been more satisfactory to have carried the investigation further, but other urgent work prevented more time being spent on these experiments.

The sensitivity of some of the yawmeters which were made is shown by the curves in Fig. 5; the reduced sensitivity of the bent tube yawmeters, which is presumably due to the interference of one part of the tube with another, is surprising, but was obtained with two instruments of very different diameters. It will be seen that the pressure difference in the No. 2 (Fig. 2) yawmeter is practically equal to that deduced from the measurements with the standard pitot.

It should be noted that a very direct and sensitive method of using a yawmeter is to turn the tubes till the pressure in the two is equal. The angle is then read off directly from a degree scale, and it appears that for the size of yawmeter likely to be employed in full scale work this plan could be adopted for measurement of direction in two planes.

If it is undesirable for the instrument to require manipulation of this kind it is important that the speed should be observed at the same time as the pressure difference in the tubes of the yawmeter, or that an instrument, such as that due to Sir Horace Darwin, should be used. In this device the pressures are led to two flexible diaphragms, each of which is connected to the indicating needle by a rod, in such a manner that the needle sets itself along the line of action of the resultant of the forces in the two rods. The direction of the resultant should be independent of speed and the apparatus therefore capable of direct calibration for angle. This instrument appears to be quite sound in principle, and its satisfactory working seems to depend on the production of sufficiently accurate mechanism.

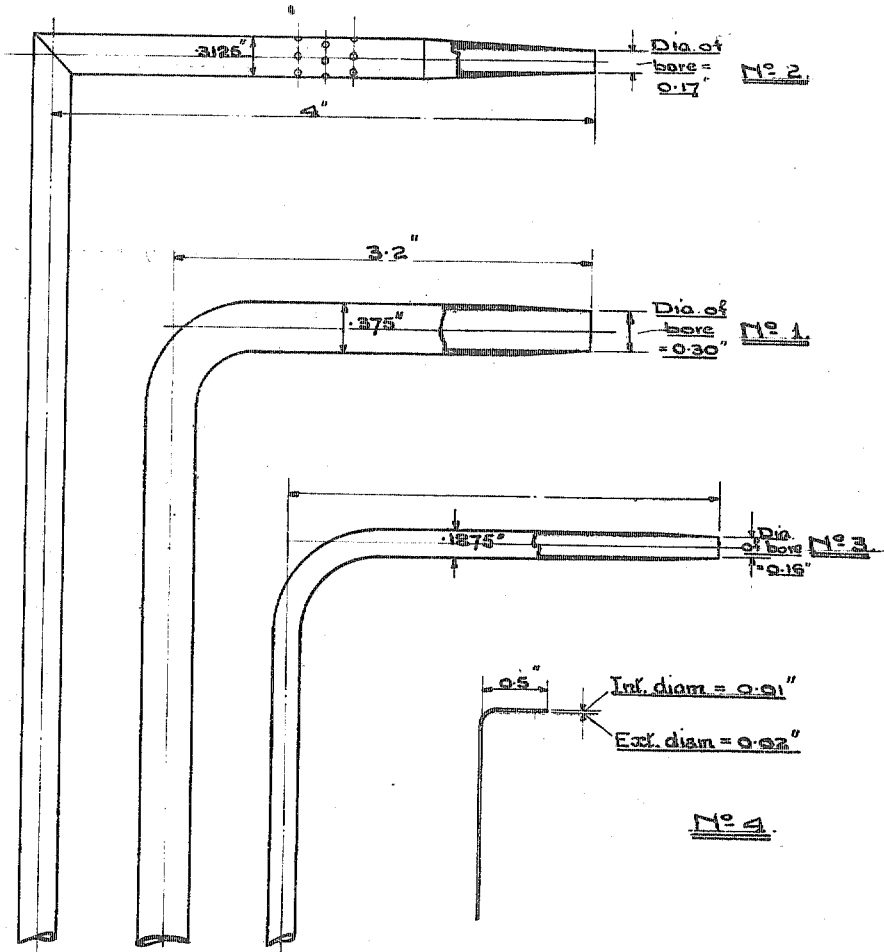
In wind channel work the yawmeter is usually "lined up" by turning in the unobstructed wind until equal pressure is obtained, but in cases where it is necessary to work to a datum line the direction of the axis of each tube near its mouth can probably be obtained by means of plugs which fit into the tube for a short distance, and which have shoulders to bear against the turned end of the yawmeter tube. The usual method of using a yawmeter in a wind channel and a convenient form of diagram for reducing the results are described in R. and M. 371.

TABLE 1.

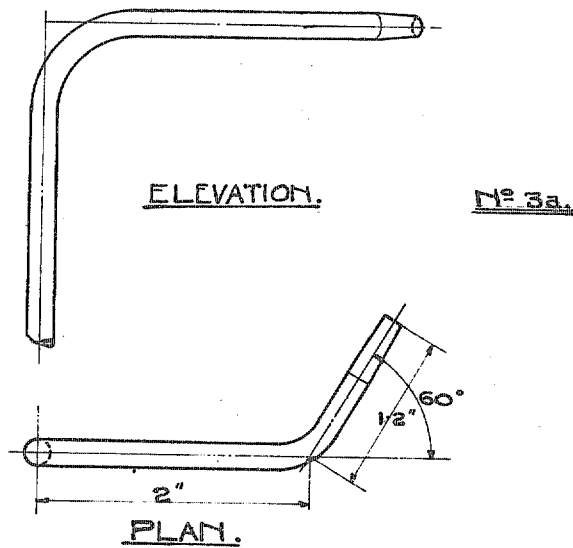
CHANGE OF PRESSURE DIFFERENCE BETWEEN PITOT TUBE AND ATMOSPHERE, AND OF THAT BETWEEN PITOT AND STATIC TUBES, WITH ANGLE OF INCLINATION.

Angle Degs.	Pitot of standard head (No. 2) and atmosphere. P_{θ}/P_0 .		Standard pitot and static tubes. P_{θ}/P_0 .		Hypodermic tube No. 4 and atmosphere. P_{θ}/P_0 .	
	Speed 40 ft. /sec.	Speed 50 ft. /sec.	Speed 40 ft. /sec.	Speed 50 ft. /sec.	Speed 40 ft. /sec.	Speed 70 ft. /sec.
0	+ 1.000	+ 1.000	+ 1.000	+ 1.000	+ 1.000	+ 1.000
5	1.000	—	1.010	—	1.000	0.998
10	1.000	—	1.027	—	1.000	0.988
15	0.998	—	1.050	—	0.986	0.976
20	0.987	+ 0.997	1.084	+ 1.089	0.965	0.940
25	0.977	—	1.110	—	0.924	0.808
30	0.958	—	1.131	—	0.848	0.821
35	0.883	—	1.124	—	0.746	0.734
40	0.785	+ 0.778	1.096	+ 1.110	0.648	0.650
45	0.628	—	1.040	—	0.519	0.511
50	0.449	—	0.935	—	0.368	0.439
55	+ 0.231	—	0.770	—	0.197	0.199
60	— 0.017	— 0.014	0.588	+ 0.576	+ 0.023	+ 0.005
65	— 0.258	—	0.358	—	— 0.159	— 0.182
70	— 0.532	—	+ 0.130	—	— 0.356	— 0.375
75	— 0.788	—	— 0.119	—	— 0.572	— 0.570
80	— 1.061	— 1.063	— 0.362	— 0.340	— 0.760	— 0.795
85	— 1.262	—	— 0.587	—	— 0.965	— 0.988
90	— 1.422	—	— 0.751	— 0.729	— 1.088	— 1.085
95	— 1.533	—	— 0.894	— 0.861	— 0.992	— 0.800
97	— 1.538	—	—	—	—	—
100	— 1.200	—	— 0.764	— 0.755	— 0.757	— 0.658
102	— 0.975	—	— 0.452	—	—	—
105	— 0.868	—	— 0.228	—	— 0.647	— 0.587
110	— 0.728	—	— 0.104	—	— 0.541	— 0.483
115	— 0.571	—	+ 0.019	—	— 0.443	— 0.404
120	— 0.458	— 0.477	+ 0.109	+ 0.126	— 0.375	— 0.348
125	— 0.403	—	+ 0.143	—	— 0.345	— 0.320
130	— 0.343	— 0.358	+ 0.162	+ 0.170	— 0.318	— 0.286
135	— 0.289	—	+ 0.187	—	— 0.296	— 0.262
140	— 0.260	—	+ 0.172	—	— 0.281	— 0.251
145	— 0.256	—	+ 0.113	—	— 0.254	— 0.246
150	— 0.258	—	+ 0.058	—	— 0.254	— 0.250
155	— 0.263	—	+ 0.006	—	— 0.227	— 0.226
160	— 0.255	— 0.266	— 0.036	— 0.036	— 0.197	— 0.213
165	— 0.227	—	— 0.064	—	— 0.174	— 0.189
170	— 0.193	—	— 0.081	—	— 0.152	— 0.162
175	— 0.145	—	— 0.073	—	— 0.125	— 0.128
180	— 0.098	— 0.111	— 0.047	— 0.055	— 0.114	— 0.122

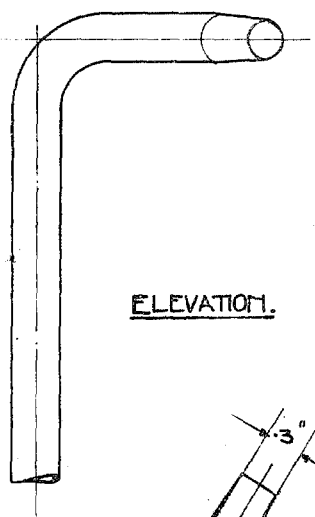
DESIGN OF YAW-METERS.



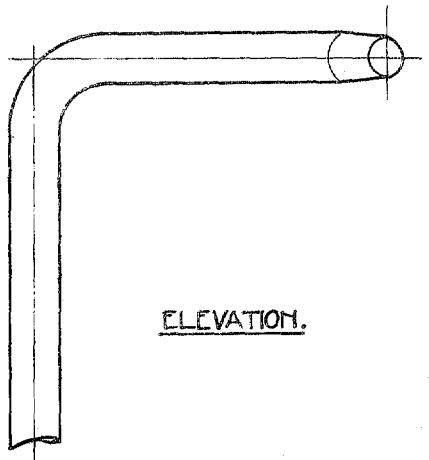
Tubes N° 1, 2, 3, & 4 are straight in plan view.



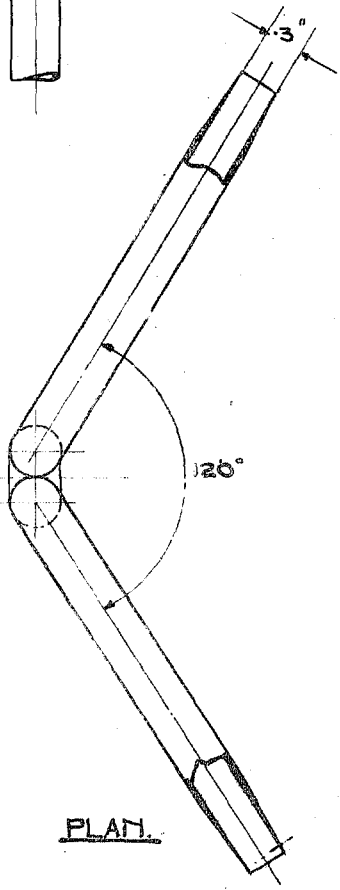
DESIGN OF YAW-METERS.



ELEVATION.

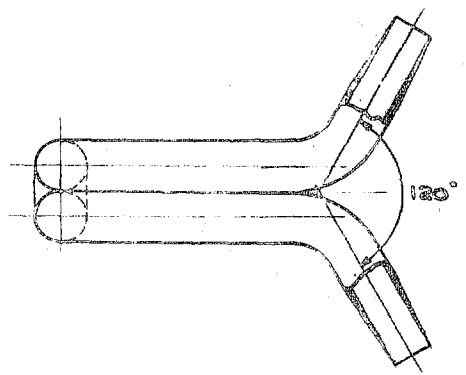


ELEVATION.



PLAN.

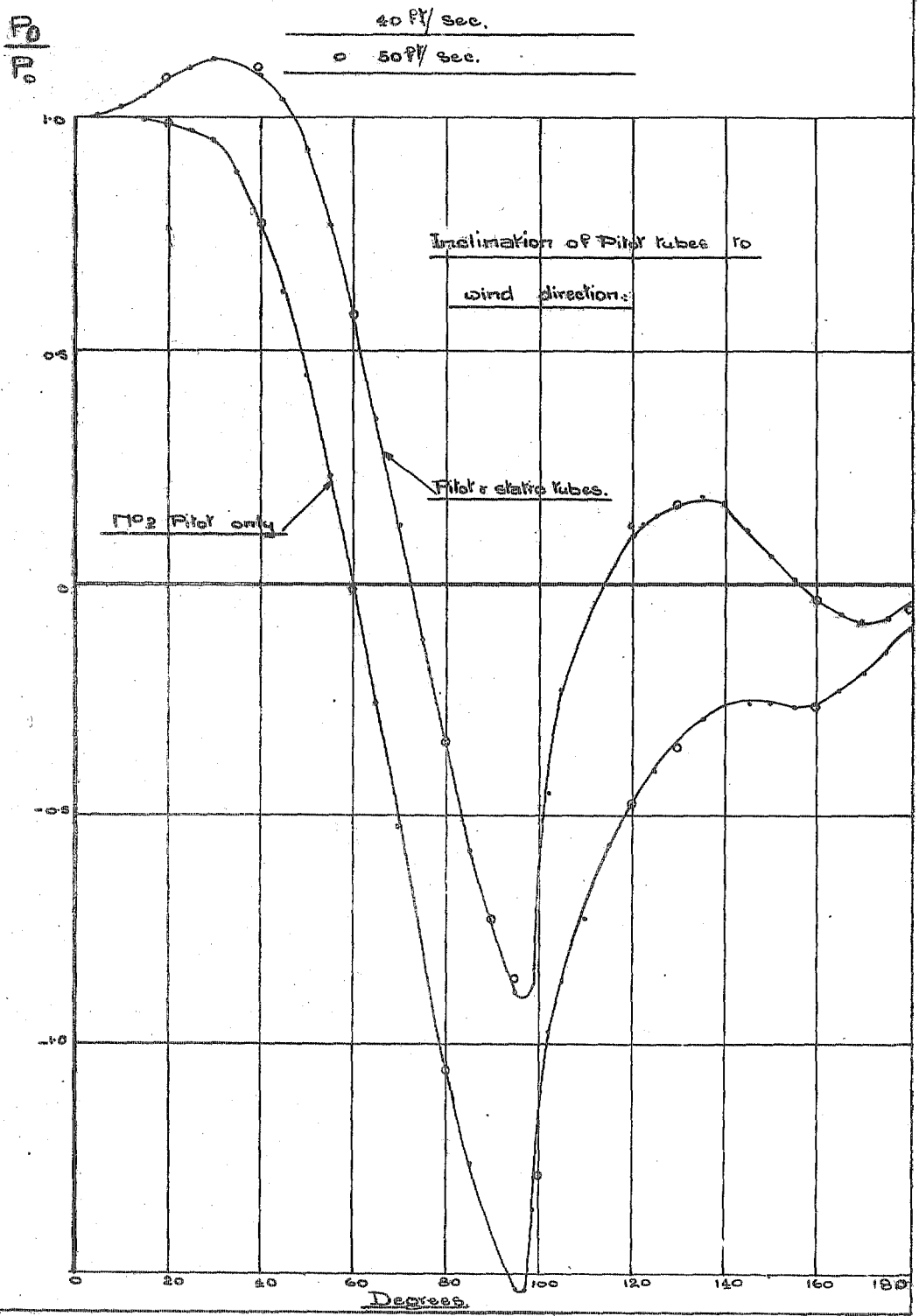
7° 30'



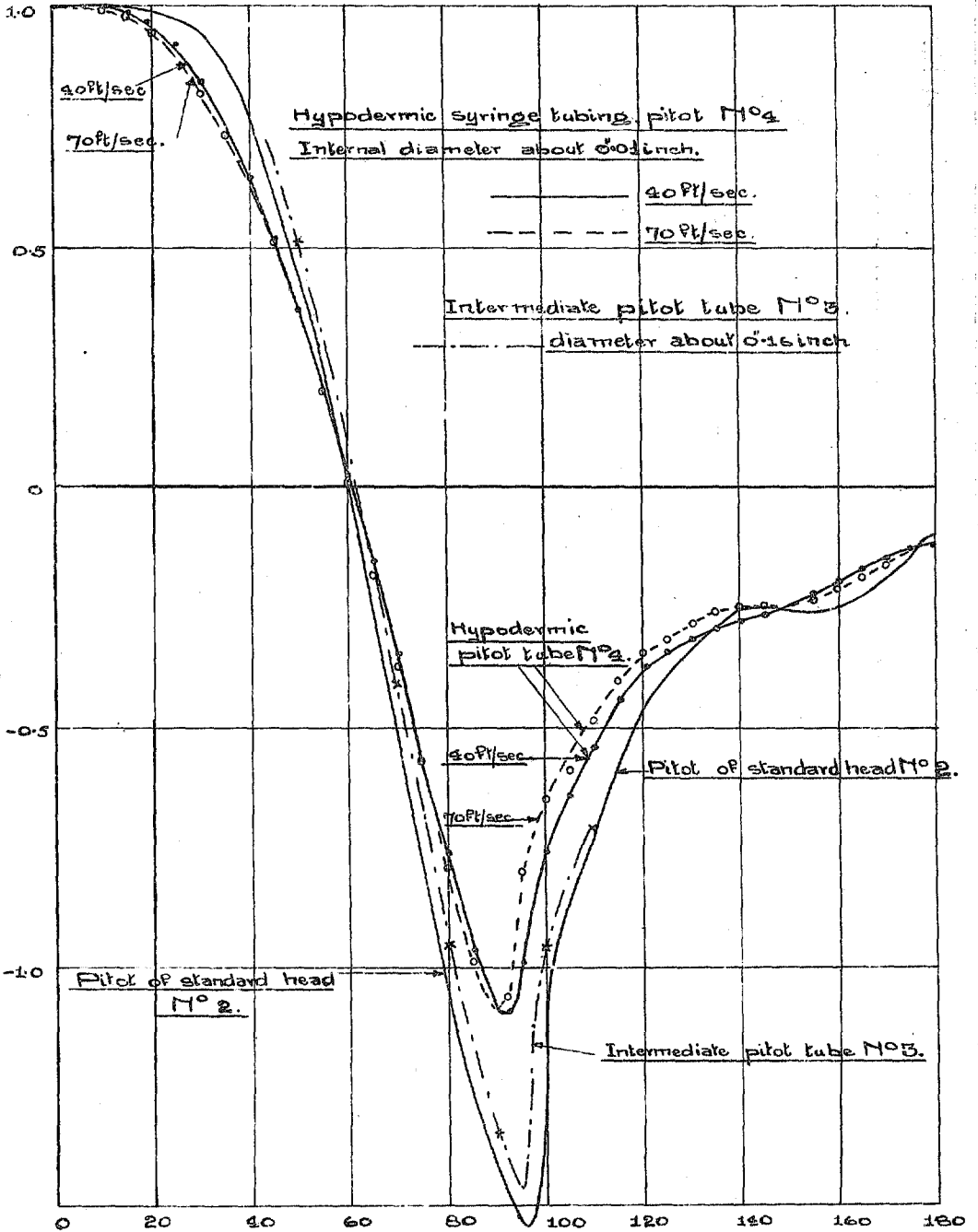
PLAN.

7° 4'

DESIGN OF YAWMETERS.



-DESIGN OF YAWMETERS.-



DESIGN OF YAWMETERS.

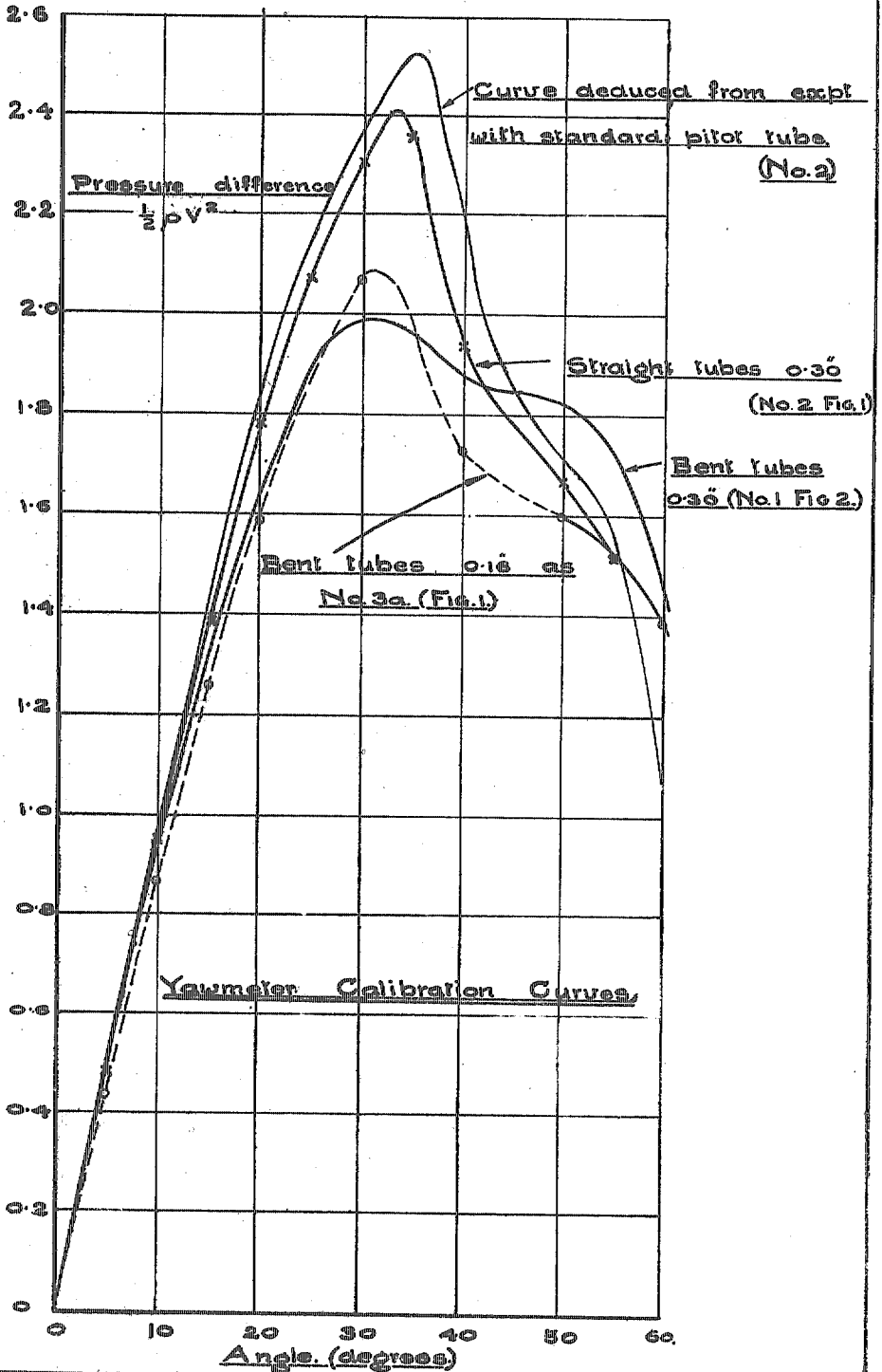


TABLE 2.
YAWMETER SENSITIVITY.

Values of $P/\frac{1}{2}\rho V^2$.

P = pressure difference.

V = relative speed.

ρ = density of the fluid.

Angle.* Degrees	Deduced values.	No. 1 type of yawmeter.		No. 2 type of yawmeter.
		Large tube.	Small tube.	Large tube.
0	0	0	0	0
5	0.477	—	0.434	0.480
10	0.970	0.914	0.867	0.953
15	1.405	—	1.26	1.39
20	1.84	1.63	1.59	1.78
25	2.14	—	—	2.07
30	2.36	1.99	2.07	2.31
35	2.53	—	—	2.36
40	2.20	1.87 ₅	1.73	1.94
45	1.86	—	—	1.90?
50	1.72	1.82 ₅	1.60	1.67
55	1.58	—	—	1.52
60	1.07	1.45 ₅	1.39	—

TABLE 3.

PRESSURE DIFFERENCE IN INCHES OF WATER AT 100
m.p.h. IN NORMAL AIR, CALCULATED FROM THE MEAN
SLOPE UP TO 15°, WHERE $P/\rho V^2 = 0.094$ PER DEGREE.

Angle.* Degrees.	Pressure difference. Inches of water.
0	0
5	2.31
10	4.61
15	6.92

* The angle between the vertical plane of symmetry of the yawmeter and the wind direction.