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Static Response of a Hemispherical-Headed Yawmeter at High Subsonic and Transonic Speeds

by

P. G. Hutton, D.C.Ae.

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SUMMARY

Details are given of the static calibration of a hemispherical-headed differential pressure yawmeter, in the Mach number range from 0.6 to 1.2; the instrument has a central pitot pressure hole and two pairs of holes in perpendicular planes for flow direction measurement.

The results show that the sensitivity to yaw (for angles up to 8°) as determined from pressure differences between opposing holes, varies smoothly with Mach number at transonic speeds; the sensitivity is little affected by a cross-flow normal to the line joining the holes.

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1 Introduction

For flight trials of missiles and free flight model tests an instrument was required to measure angles of incidence and yaw in perpendicular planes at high subsonic, transonic and supersonic speeds. A differential pressure type of yawmeter with pressure orifices in a hemispherical head was designed for this purpose, a hemispherical head being chosen because, having a detached bow wave and a large region of subsonic flow at supersonic speeds, it experiences little change in the qualitative nature of its pressure distribution from subsonic to supersonic speeds, and so the sensitivity of the instrument should vary smoothly through the transonic range.

The instrument had been calibrated at supersonic speeds by Beecham and Collins[1], and the tests described here were made to extend its calibration to the transonic and high subsonic speed ranges.

2 Details of yawmeter and test equipment

2.1 Yawmeter

The yawmeter head is shown in Figure 1. It consists of a 0.5 inch diameter cylinder 2.3 inches long with a hemispherical nose, drilled with a central hole and a ring of four holes, A, B, C and D, nominally equally spaced with their centre lines on radii of the hemisphere at 45° to the axis of the head.

The instrument tested was one of a production series and had several imperfections, some of which are shown in Figure 1. The actual positions of the holes were on radii of the hemisphere at angles of $52^{\circ}\ 20' \pm 10'$ to the axis of the head, but the axes of the holes were at $45^{\circ} \pm 10'$ to the axis of the head. The errors in the spacing of the holes round the head were of the order of 2°. One hole was burred, and a scar about 0.07 inches long, 0.01 inches wide and 0.0005 inches deep was present on the head, as shown in Figure 1. There were deviations of shape, including asymmetries, of about ± 0.001 inches from a true hemisphere.

2.2 Wind tunnel and installation of yawmeter

The tests were made in the 35 inch by 27 inch slotted transonic working section, described in Ref. 2, of the R.A.E. Bedford 3 ft wind tunnel.

The yawmeter head was mounted on a long sting support as shown in Figure 2. The sting was carried on cross-shafts linked to an external drive by which the yawmeter was rotated about the centre of the hemispherical head with slight movement along the centre line of the tunnel (about 0.25 inches for 5° rotation from the datum).

The yawmeter head was screwed into an adapter (Fig. 2) which fitted into a taper socket in the end of the sting. The adapter could be rotated to set the yawmeter holes B and D (Fig. 1) in either the yawing plane or a plane at 45° to it. The accuracy of setting was probably of the same order as that of the spacing of the holes round the head. A wooden fairing, shown in Figure 2, was fitted for most of the tests to fair the adapater and simulate the effect of the fuselage nose of a typical free flight model.

3 Details of tests

The main object of the tests was to measure the rate of change with instrument yaw of the pressure difference between opposite holes, both with the line of the holes approximately in the yawing plane, and inclined at an angle to it. In addition, it was required to determine the zero errors of the yawmeter, the flow direction in the tunnel at the yawmeter position and the effect of yaw on the pressure at the pitot pressure hole. Measurements were therefore made with the following nominal yawmeter settings:- (a) Holes B and D in the yawing plane; (b) as (a) but rotated through 180°; (c) with the lines of the two pairs of holes at 45° to the yawing plane.

Pressures were measured at the five holes of the yawmeter over a yaw range of -4° to +8° (measured from a datum aligned approximately with the tunnel centre line) at a series of Mach numbers between 0.60 and 1.19. With care to ensure that all settings were approached from the same direction, the sting could be set to ±0.02°. In some of the tests, however, not all settings were approached from the same direction and a correction for backlash has been applied (see para. 4). The full Mach number range was not covered in all cases.

Tests without the wooden fairing over the adapter were made at Mach numbers of 0.80 and 1.05 with holes B and D in the yawing plane.

The settling chamber pressure was 28 inches of mercury throughout. The absolute humidity was about 0.01%, and the stagnation temperature varied between 15°C and 25°C. The Reynolds number based on the diameter of the hemispherical head was about 2×10^5.

Manometers of the capsule and self-balancing weighbeam type were used to measure the pressures, giving a dial indication of absolute pressure with an accuracy (in these tests) of ±0.03 inches of mercury. The Mach number was deduced from measurements of the plenum chamber and settling chamber pressure and a previous calibration of the empty tunnel; over a length of ±3 inches from the yawmeter head position the Mach number in the empty tunnel was within ±0.003 of the Mach number calculated from these reference pressures at the low end of the speed range, and within ±0.008 at the high end of the speed range. The nominal Mach number could be set to within ±0.003.

In a preliminary investigation to determine the qualitative nature of the flow over the yawmeter head and the wooden fairing, a static probe was traversed along a line parallel to the sting and 4.35 inches from its centre line with the sting parallel to the tunnel walls. Traverses were made at nominal free stream Mach numbers of 0.90, 1.00, 1.05 and 1.125.

4 Methods of analysis

Where the measured Mach number varied from the nominal, the variations (which did not exceed ±0.003) were allowed for by plotting the pressure ratios p/H at the yawmeter holes against Mach number at constant sting setting and interpolating values at the nominal Mach numbers. In the case of the pitot hole pressures, normal shock tables were used to estimate corrections at supersonic speeds, and no corrections were made at subsonic speeds.

Rates of change with yaw of the pressure ratio, p/H, for individual holes, and the difference, $\Delta p/H$, for pairs of holes, were evaluated over a nominal range of ±4° by drawing straight lines through the experimental points. In cases where the yaw settings were not all approached from the same direction a correction of 0.06° for backlash in the sting pitch gear (and possible hysteresis in the pressure readings) was made as necessary to the yaw values before the slopes of the lines were measured. This allowance was estimated from the pressure measurements in one run in which a range of yaw was covered in both directions.

The zero error for the pair of holes B and D was found from the sting angle for zero pressure difference between them for the two settings with these holes in the sting yawing plane. The mean of these angles gave the angular position for the sting (or, more precisely, the centre line of the taper joint between sting and adapter) to be parallel to the flow in the yawing plane; the differences from the mean gave the yawmeter zero error relative to the sting.

The zero error for the pair of holes A and C was deduced similarly from pressure measurements at zero sting angle for the two cases with the line joining the holes perpendicular to the sting yawing plane. The mean of the two apparent angles of inclination of the sting to the flow in the plane perpendicular to the yawing plane gave the actual inclination, and the differences from the mean gave the yawmeter zero error relative to the sting.

The zero errors so obtained for both pairs of holes were corrected for slight measured misalignment of the tapered plug of the adapter and the cylindrical part of the yawmeter head.

5 Results and discussion

5.1 Pitot pressure

Figure 3 shows the variation of pitot hole pressure with yaw for several Mach numbers. The mean measured values of p/H at small angles are in all cases within 0.1% of unity for subsonic speeds and of the values behind normal shock waves at supersonic speeds. The measured pressure falls by about 0.6% at 8° incidence at supersonic speeds compared with 0.4% at a Mach number of 0.6. The accuracy of the measurements corresponds to about ±0.1% of H.

5.2 Yawmeter sensitivity and zero error

Figure 4 shows typical curves of variation of pressure difference with yaw for one pair of holes in the yawing plane. The response is linear for angles up to about 4° with sensitivity increasing slightly at higher angles for Mach numbers above 0.8 but decreasing slightly at a Mach number of 0.6. The different behaviour at a Mach number of 0.6 may be due to the relative proximity of shock waves on the yawmeter head at this Mach number. (The critical Mach number for a sphere is 0.55).

Figures 5(a), (b) and (c) show the variation with Mach number of the rate of change of pressure difference, for both pairs of holes, with the component of yaw in the yawmeter axial plane through the pair of holes; the angular range covered was ±4°. The figures show the results in three different non-dimensional forms; the presentation in Figure 5(a) in terms of $\Delta p/H$ (commonly used for transonic conditions) gives an approximately constant rate of change at high subsonic and transonic speeds, while the standard $\Delta p/q$ presentation in Figure 5(b) gives a linear curve at low Mach number; the results are also presented in terms of $\Delta p/p_o$ which is convenient for application to free flight conditions in which p_o is constant. The difference in sensitivity between the two pairs of holes is about 3% at some Mach numbers. The close agreement between sensitivities obtained for the pair of holes B and D with the line of the holes at 0° and 45° to the yawing plane shows that a cross flow at the holes has only a very small effect on the sensitivity.

Figure 6 shows that the zero errors for the two pairs of holes vary with Mach number. Some error is to be expected from the variations in angular position from hole to hole but this is clearly not the only source of the zero errors. If the pressure difference across a pair of holes were zero when the flow bisected the angle between the radii of the hemispherical head passing through their centres, the zero errors would be -0.13° for holes A and C and -0.12° for holes B and D, using the same sign convention as in Figure 6. The burr and scar shown in Figure 1 probably account for part of the zero errors but the unexplained errors are so large that individual calibration would be required before an instrument of this type could be used for absolute measurement of flow direction to better than 0.5°.

The angle of sidewash in the tunnel for Mach numbers between 0.8 and 1.1 was found to have a constant value of 0.08°, giving an effective yaw with the sting set parallel to the tunnel walls. There was a downwash or a sting droop of 0.02°.

5.3 Individual hole pressure and sensitivities

Figures 7(a), (b), (c) and (d) show typical curves of variation with yaw of the pressures at individual holes. They are for the pair of holes B and D in the yawing plane.

It will be noted that, as might be expected, the pressure variation with yaw is more nearly linear when the angle between the stream direction and the radius through the pressure hole is reduced (positive yaw in Figures 7(b) and (c)) than when it is increased (positive in Figures 7(a) and (d)). Further, it is when this angle is increased that the behaviour at a Mach number of 0.6 differs from that at higher Mach number (Figure 7(d)). This is consistent with the suggestion made above that the difference is due to the closeness of the shock waves which will be developing on the head at about this Mach number.

The rate of change of pressure at the individual holes with component of yaw in the axial plane through each hole are shown in Figure 8. The results from all three yawmeter settings (see para. 3) are included. For hole B, the sensitivity with the hole plane at 45° to the yawing plane appears to be consistently lower than with the hole in the yawing plane. This may be due to unequal spacing of the holes round the yawmeter head. Only about 2° error in hole position is needed to give 3% change in sensitivity when the hole plane is at about 45° to the yawing plane, and inspection of the head shows that manufacturing errors of this magnitude are present.

Figure 8 shows that the sensitivities of different holes differ by about 12% at some Mach numbers compared with only about 3% variation in the sensitivities of the pairs of holes. It appears to have been fortuitous that the sensitivities of the two pairs of opposite holes agreed so well, one of the pairs having consisted of a hole with high sensitivity and one with low sensitivity. The reason for such large variations in individual hole sensitivities is not known. Manufacturing errors such as variations in hole position and profile inaccuracies are quite small and would not be expected to produce variations in sensitivity of this magnitude. Variations in the state of the boundary layer due to profile inaccuracies and variations of surface finish could have quite large effects at the Reynolds number of the tests, which was around the critical Reynolds number for a sphere at low speed.

5.4 Effect of a change in shape of the support

Figure 9 shows the result of static pressure traverses along a line 4.35 inches from the axis of the yawmeter head at zero yaw. At supersonic speeds there were two distinct shock waves, a bow shock and a shock ahead of the nose of the wooden fairing, with an expansion round the shoulder of the yawmeter head between them, which suggests that the effect of the fairing should be negligible at supersonic speeds. This is confirmed by comparison of results with and without the fairing at a Mach number of 1.05 shown in Figures 10(a) and (b); removing the wooden fairing had no effect on the pressures at the yawmeter head.

The results with and without the fairing at a Mach number of 0.8 (Figures 10(a) and (b)) show that the effect of the fairing is to increase the pressures at the four yawmeter holes equally, by an amount which is independent of the incidence within the range covered. Thus, even when the yawmeter was not isolated from the supporting body by an intervening supersonic flow, its sensitivity was independent of the fairing downstream.

6 Conclusions

(1) The sensitivity of the yawmeter at yaw angles less than 4° varies smoothly with Mach number at transonic speeds.

(2) The sensitivity increases slightly with increase of angle up to 8° at Mach numbers of 0.8 to 1.2. At a Mach number of 0.6 the sensitivity decreases; the difference is probably due to the presence of shock waves relatively close to the pressure holes at this Mach number.

(3) The sensitivity of a pair of holes is little affected by a cross flow through the yawmeter axial plane containing the holes.

(4) There is a 3% difference between the sensitivities of the two pairs of holes at some Mach numbers. The sensitivities of individual holes vary by as much as 12% at some Mach numbers although the physical differences are very small. The much better agreement between pairs of holes than between individual holes is fortuitous.

(5) The zero errors of the two pairs of holes are shown in Figure 6. The magnitude of the errors is such that these instruments cannot be used for absolute measurements of flow direction to better than 0.5° without individual calibration.

(6) The sensitivity of the yawmeter is not affected by the change of support shape made during the tests.

(7) The pressure recorded at the central hole on the yawmeter head at small angles of yaw is, within the accuracy of the measurements, the free stream stagnation pressure at subsonic speeds and the theoretical stagnation pressure behind a normal shock at supersonic speeds. The reduction in pressure at the central hole when the yaw is increased from zero to 8° is about 0.5%.

List of Symbols

H	Tunnel settling chamber pressure,
	= free stream stagnation pressure.
M	Local Mach number
M_o	Free stream Mach number
p	Pressure at a particular hole in the yawmeter or Local static pressure
p_o	Free stream static pressure
Δp	Pressure difference between two opposite yawmeter holes
q	Free stream kinetic pressure
ϕ	Angle between axis of yawmeter and hemisphere radius through centre of orifice.
θ	Component of angle of yaw in plane of holes

References

No.	Author	Title, etc.
1	Beecham, L.J. Collins, S.J.	Static and dynamic response of a design of differential pressure yawmeter at supersonic speeds. RAE Report No. GW.19. February 1954.
2	Sutton, E.P.	The development of slotted working section liners for transonic operation of the NAE 3 foot wind tunnel. R.& M. 3085. March 1955.

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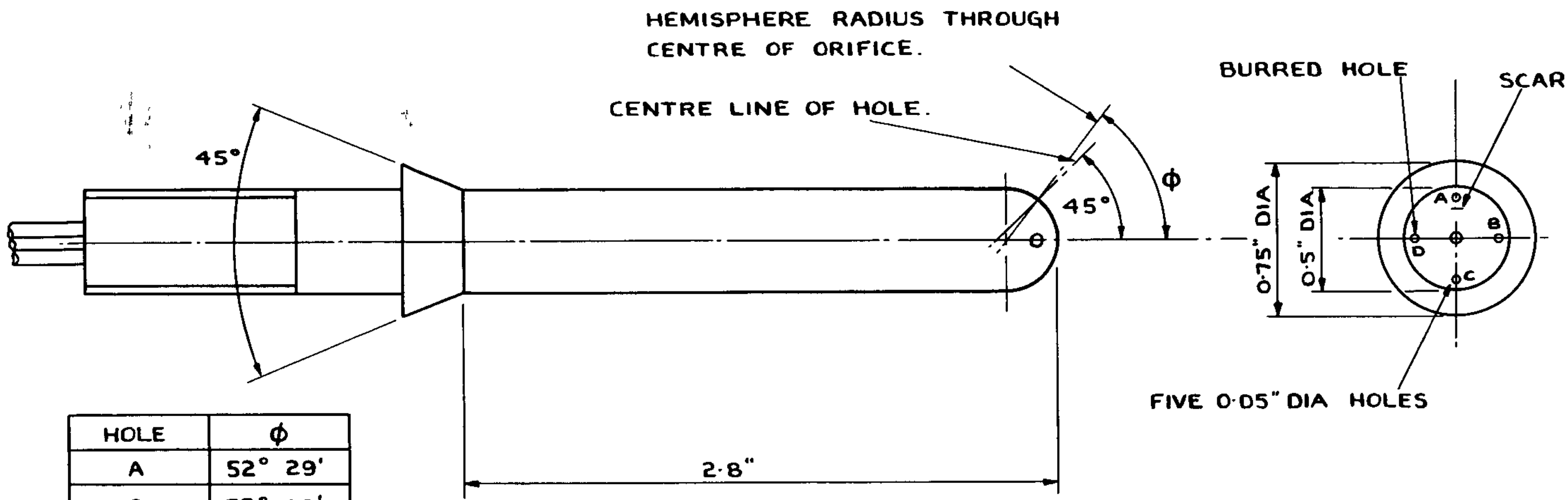

HOLE	Φ
A	52° 29'
B	52° 10'
C	52° 13'
D	52° 25'

FIG. 1. YAWMETER (INCLUDING FAULTS.)

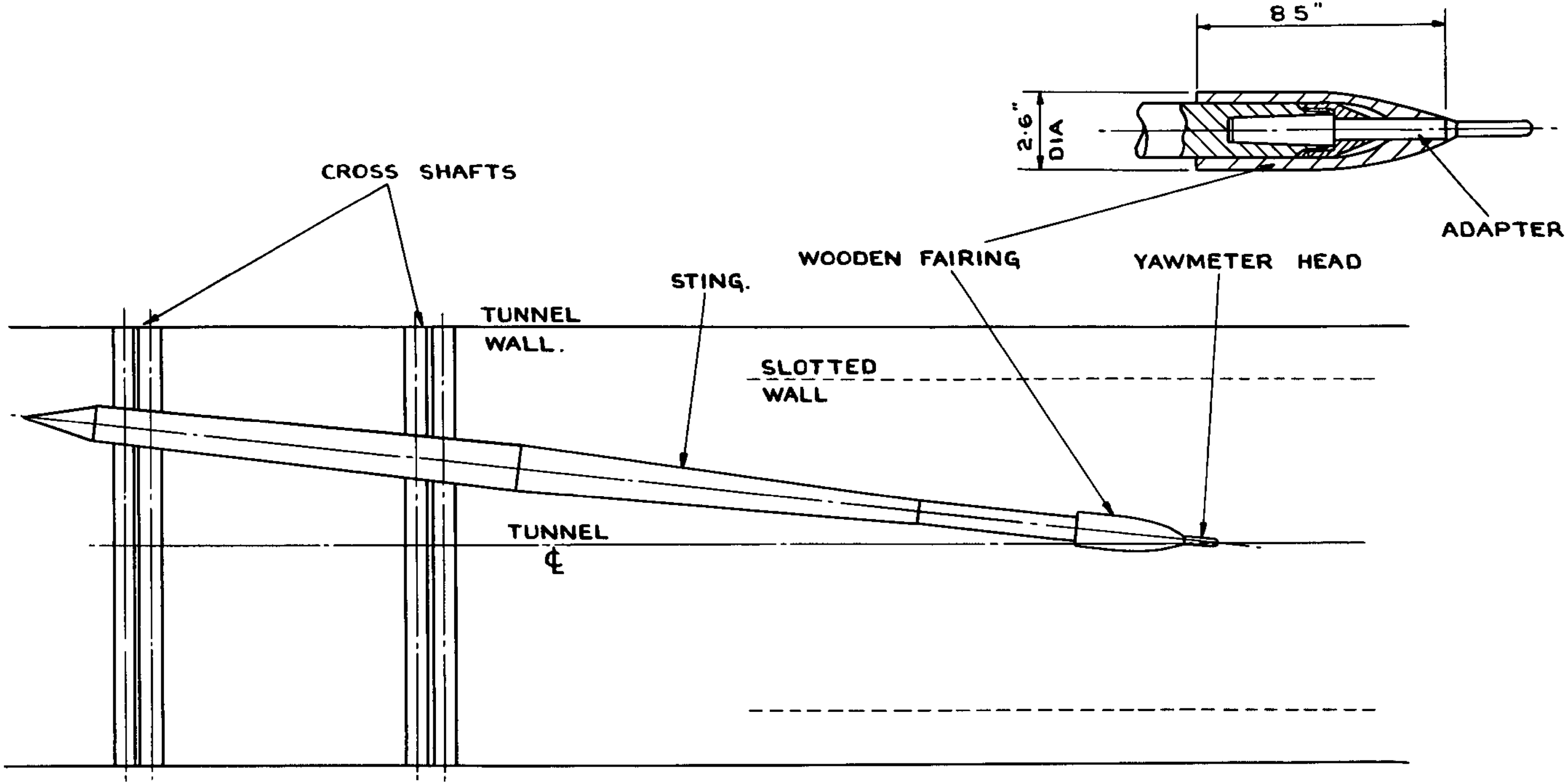

FIG. 2. ARRANGEMENT OF YAWMETER IN TUNNEL (PLAN VIEW.)

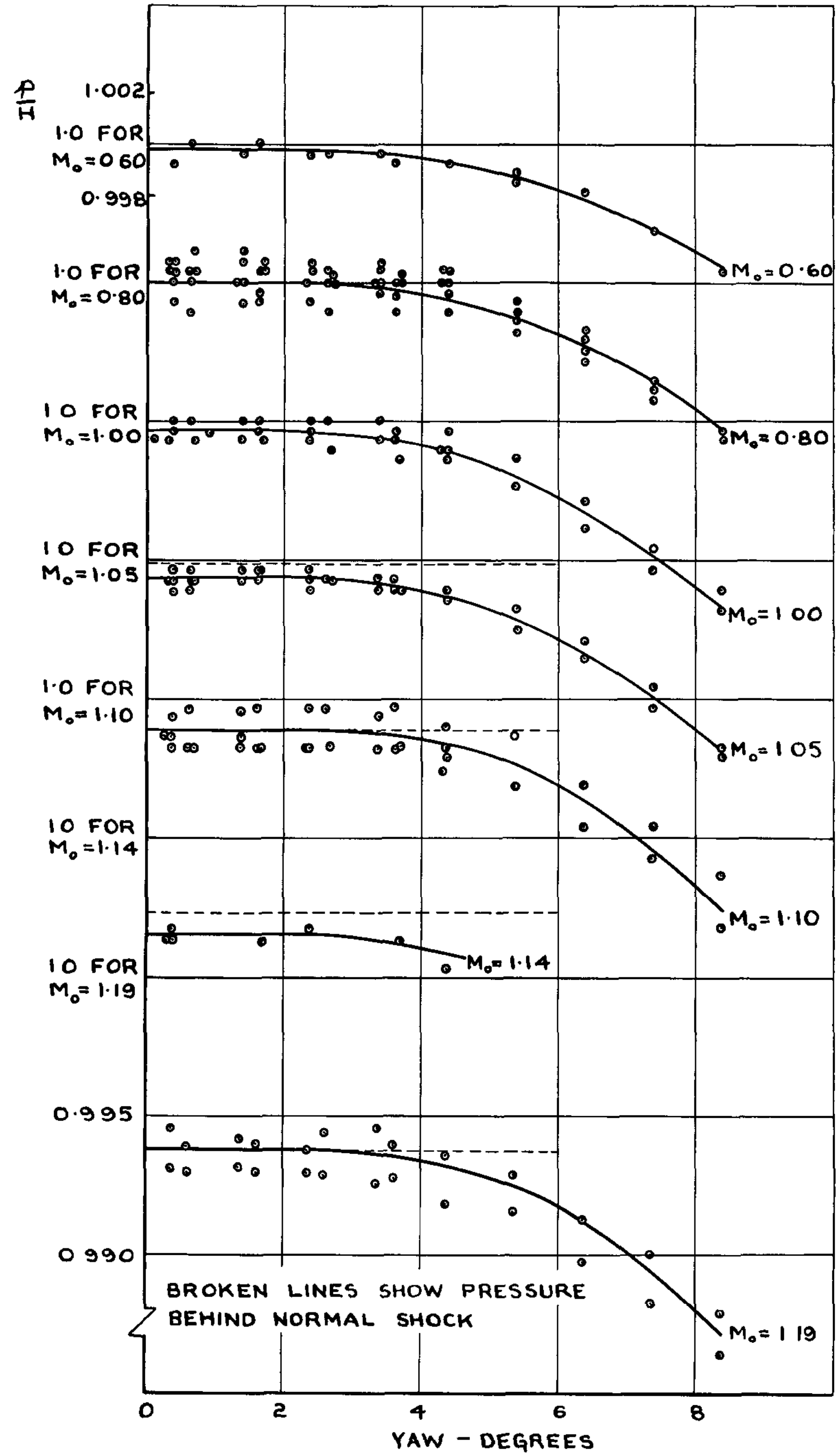

FIG. 3. VARIATION OF PRESSURE AT PITOT HOLE WITH YAW AT VARIOUS MACH NUMBERS.

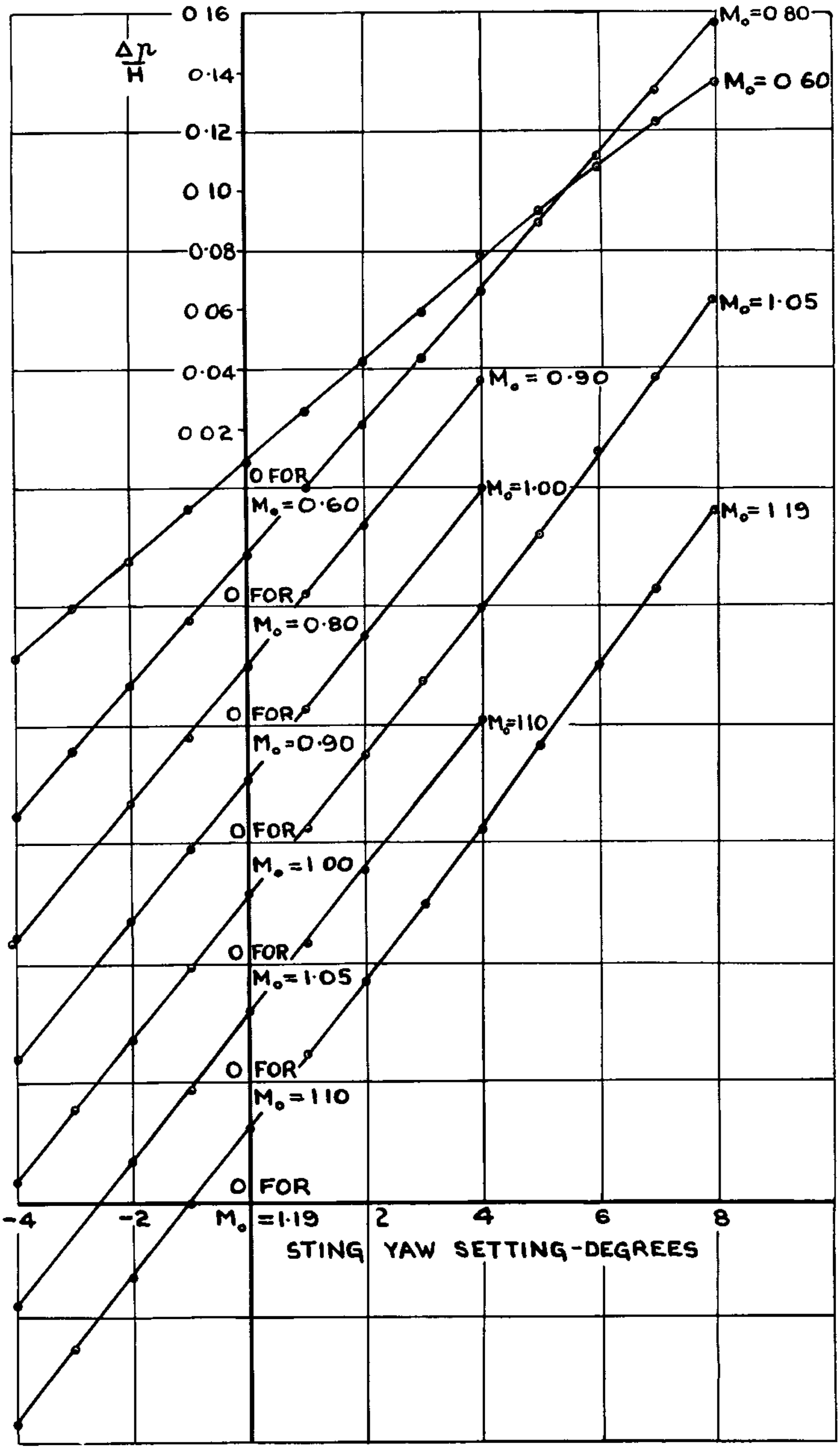

FIG.4. VARIATION OF PRESSURE DIFFERENCE WITH YAW AT VARIOUS MACH NUMBERS FOR THE HOLES B AND D IN THE YAWING PLANE.

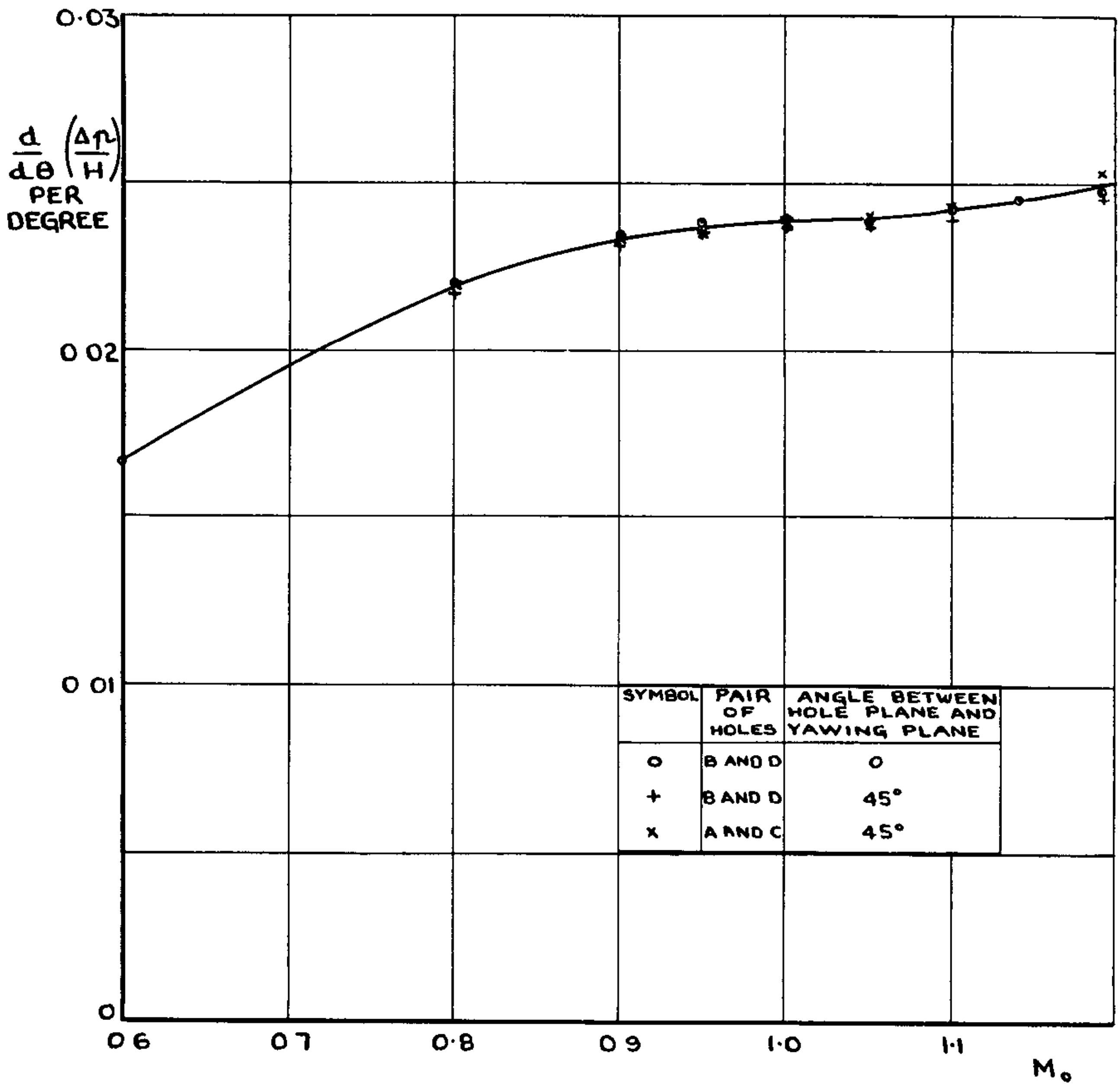

FIG. 5(a) VARIATION WITH MACH NUMBER OF RATE OF CHANGE OF RATIO OF PRESSURE DIFFERENCE TO FREE STREAM STAGNATION PRESSURE WITH COMPONENT OF YAW IN HOLE PLANE.

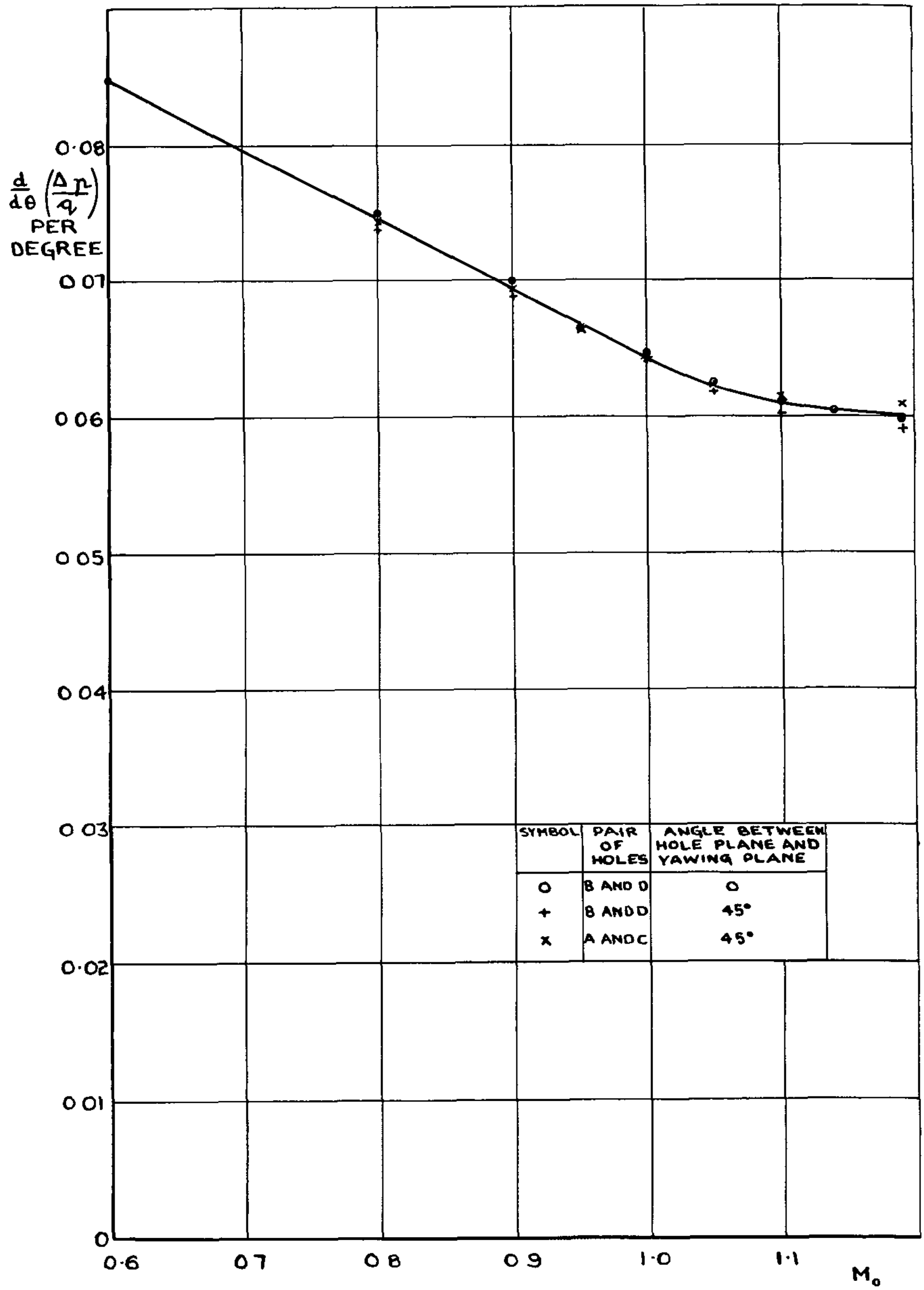

FIG. 5(b) VARIATION WITH MACH NUMBER OF RATE OF CHANGE OF RATIO OF PRESSURE DIFFERENCE TO FREE STREAM DYNAMIC PRESSURE WITH COMPONENT OF YAW IN HOLE PLANE.

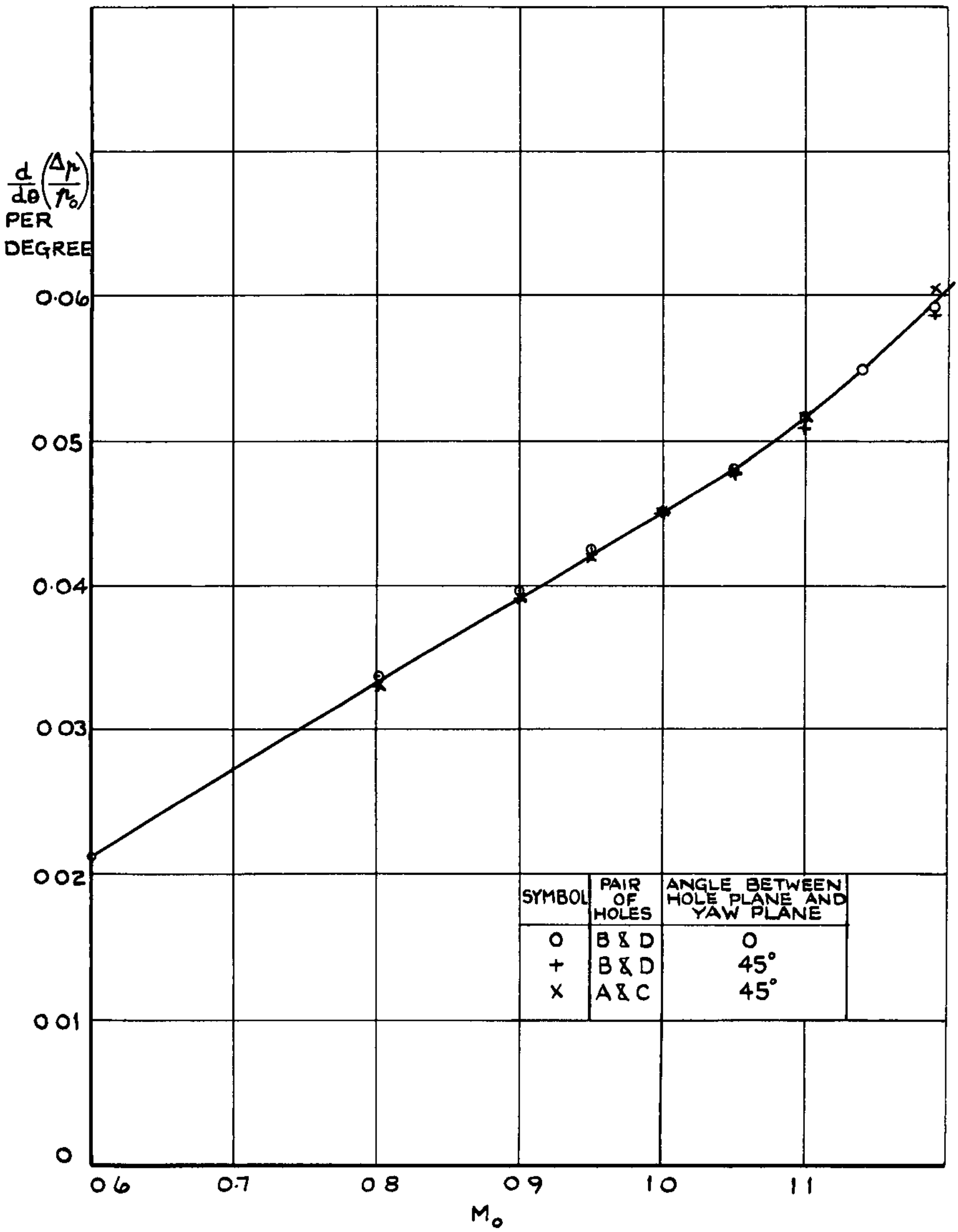

FIG. 5 (c) VARIATION WITH MACH NUMBER OF RATE OF CHANGE OF RATIO OF PRESSURE DIFFERENCE TO FREE STREAM STATIC PRESSURE WITH COMPONENT OF YAW IN HOLE PLANE.

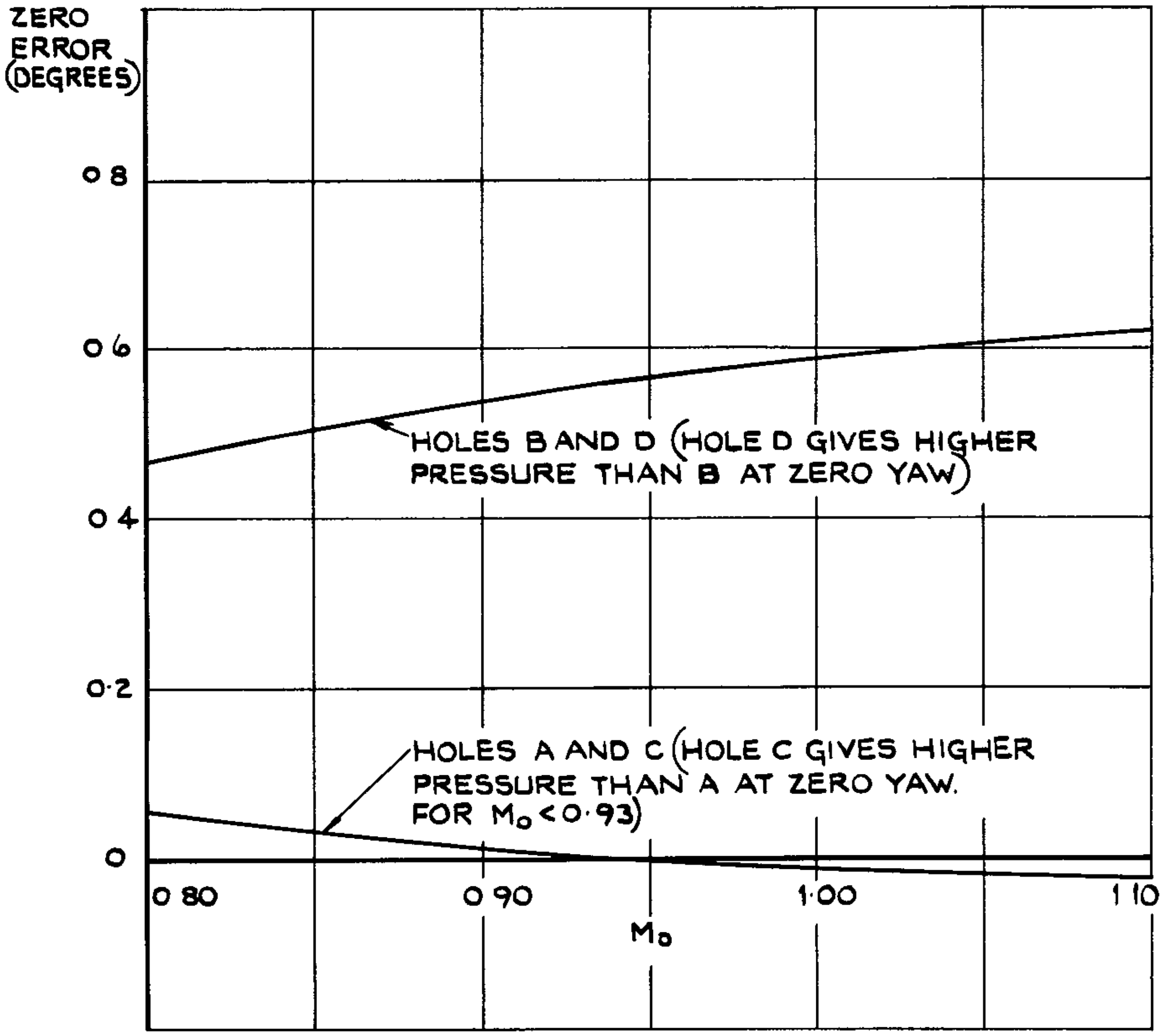

FIG.6. ZERO ERRORS FOR
THE TWO PAIRS OF HOLES.

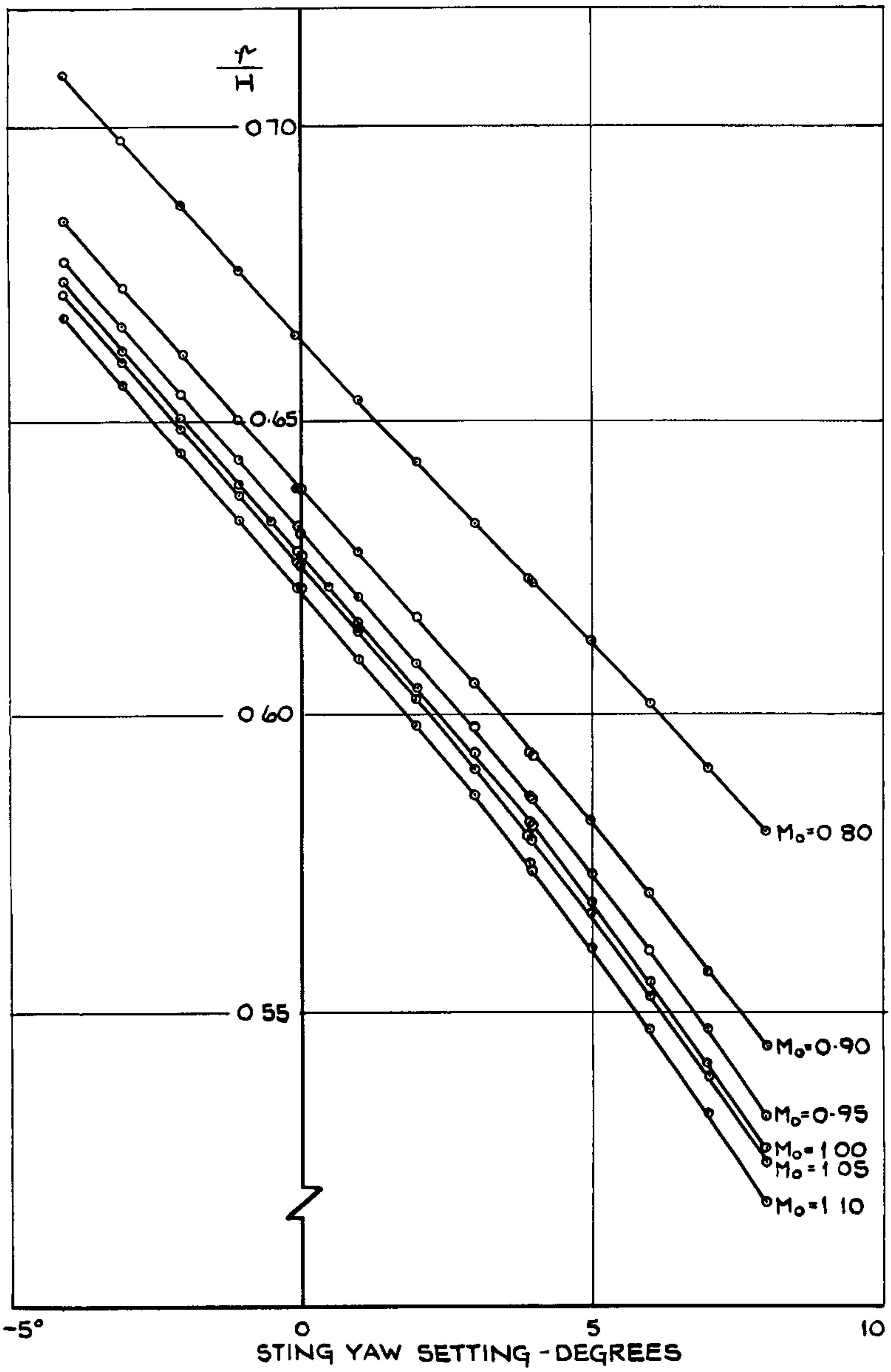

FIG. 7 (a) VARIATION OF PRESSURE WITH YAW, FOR HOLE B ON POSITIVE YAW SIDE OF HEAD.

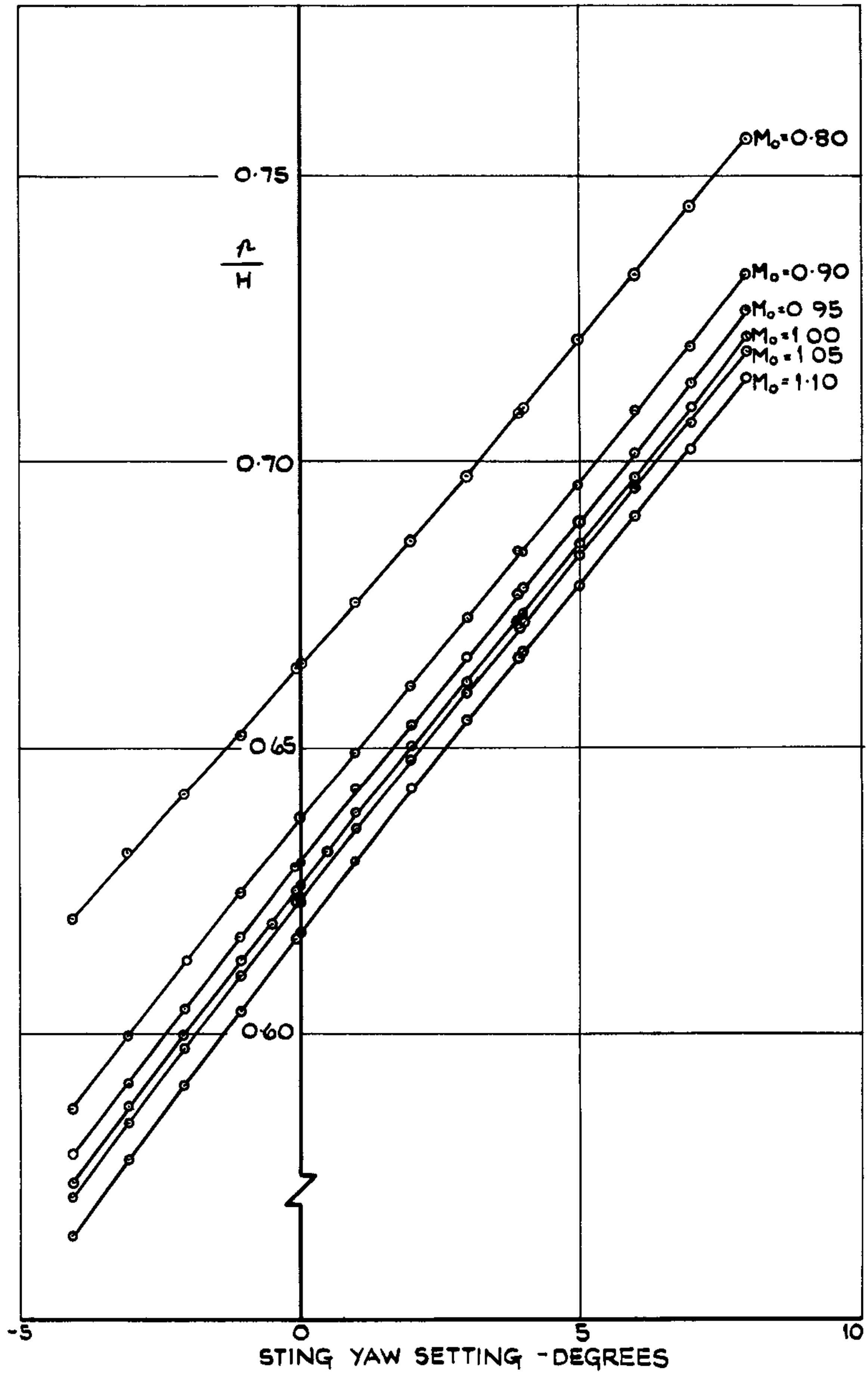

FIG.7.(b) VARIATION OF PRESSURE WITH YAW FOR HOLE D ON NEGATIVE YAW SIDE OF HEAD.

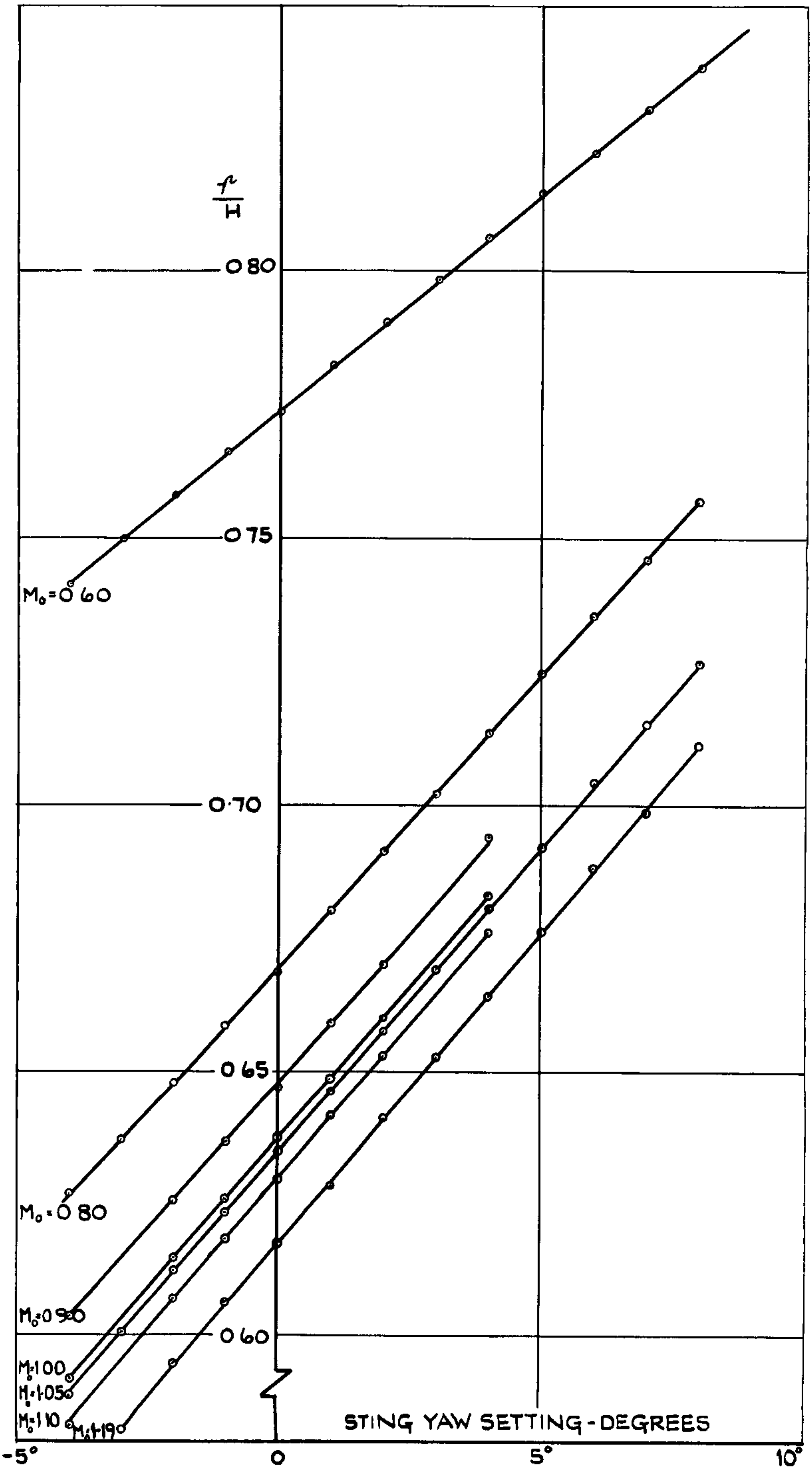

FIG.7 (c) VARIATION OF PRESSURE WITH YAW, FOR HOLE B ON NEGATIVE YAW SIDE OF HEAD.

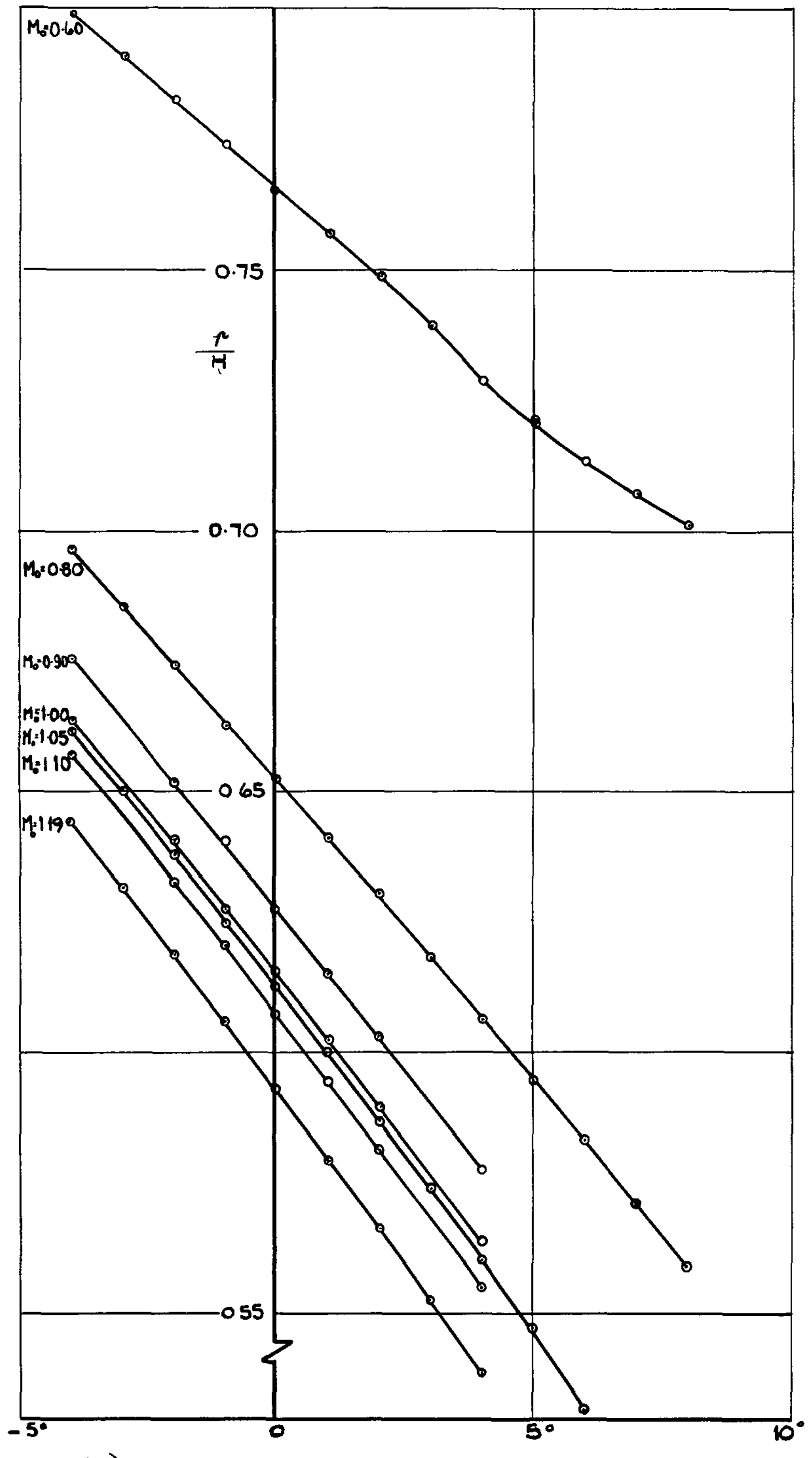

FIG. 7 (d) VARIATION OF PRESSURE WITH YAW, FOR HOLE D ON POSITIVE YAW SIDE OF HEAD.

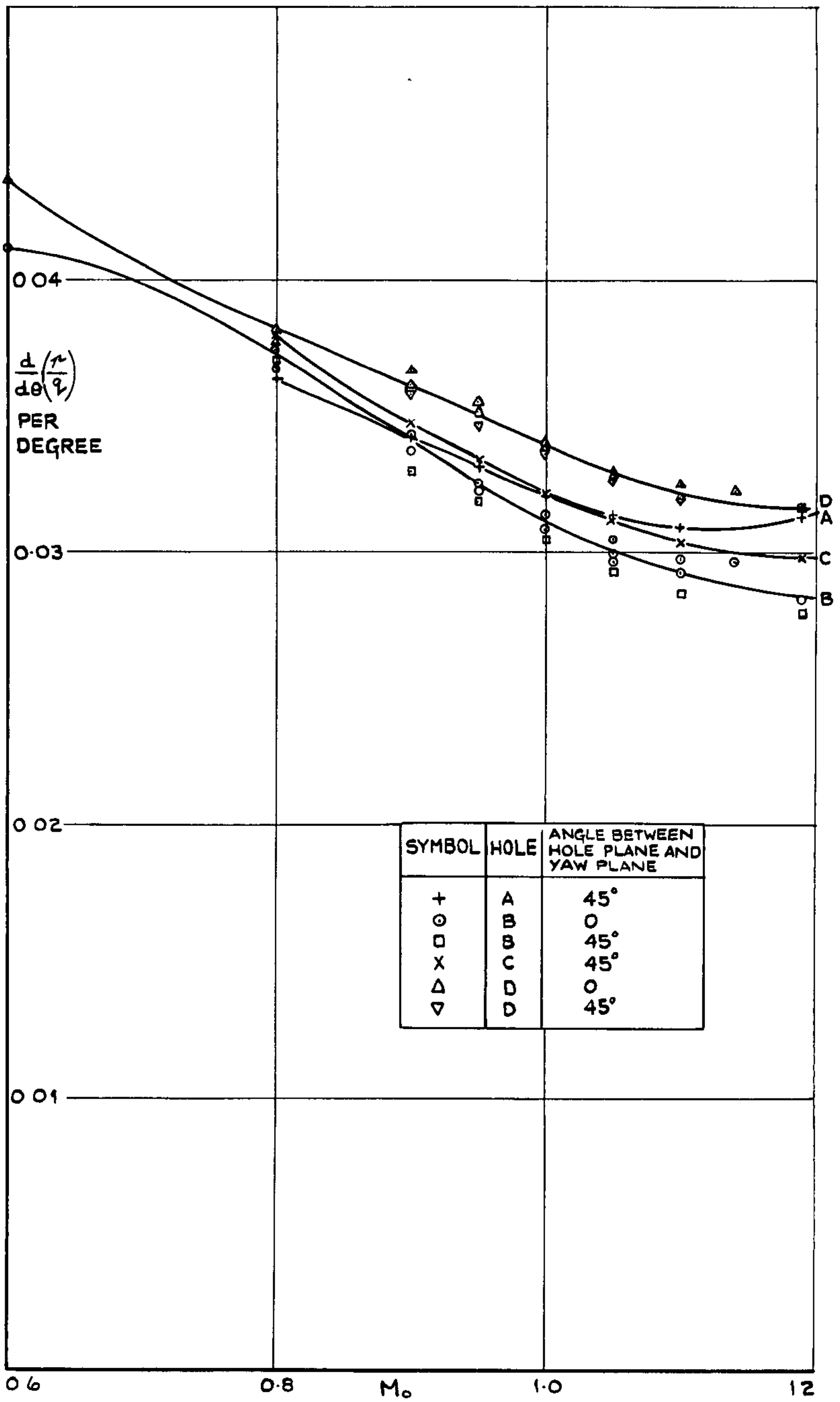

FIG.8 VARIATION WITH MACH NUMBER OF RATE OF CHANGE WITH COMPONENT OF YAW IN HOLE PLANE OF PRESSURE COEFFICIENT AT INDIVIDUAL YAWMETER HOLES.

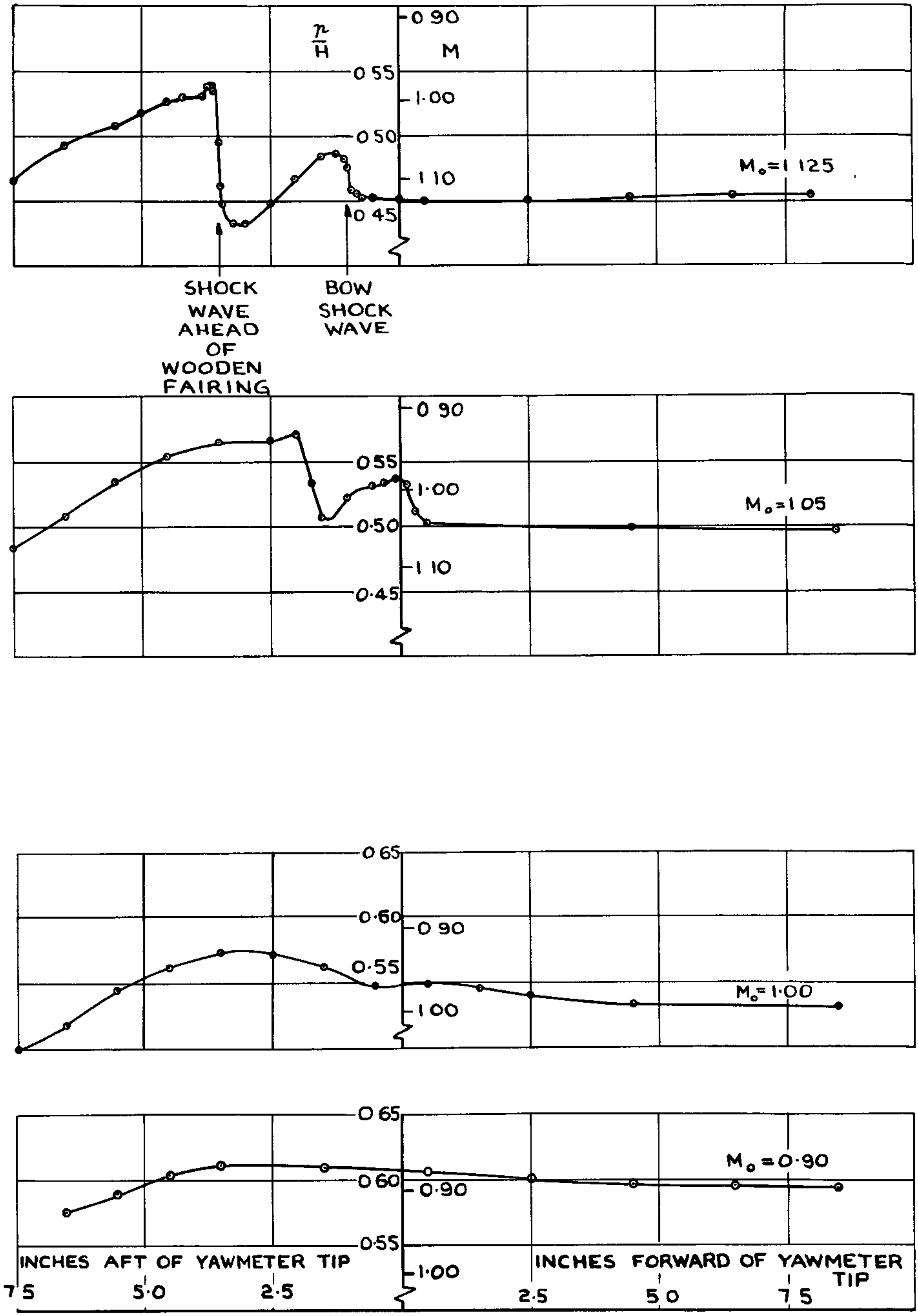

FIG. 9. RESULTS OF PROBE TRAVERSES.

VARIATION OF RATIO OF STATIC AND STAGNATION PRESSURES WITH POSITION ALONG A LINE 4·35 INCHES FROM THE YAWMETER AXIS.

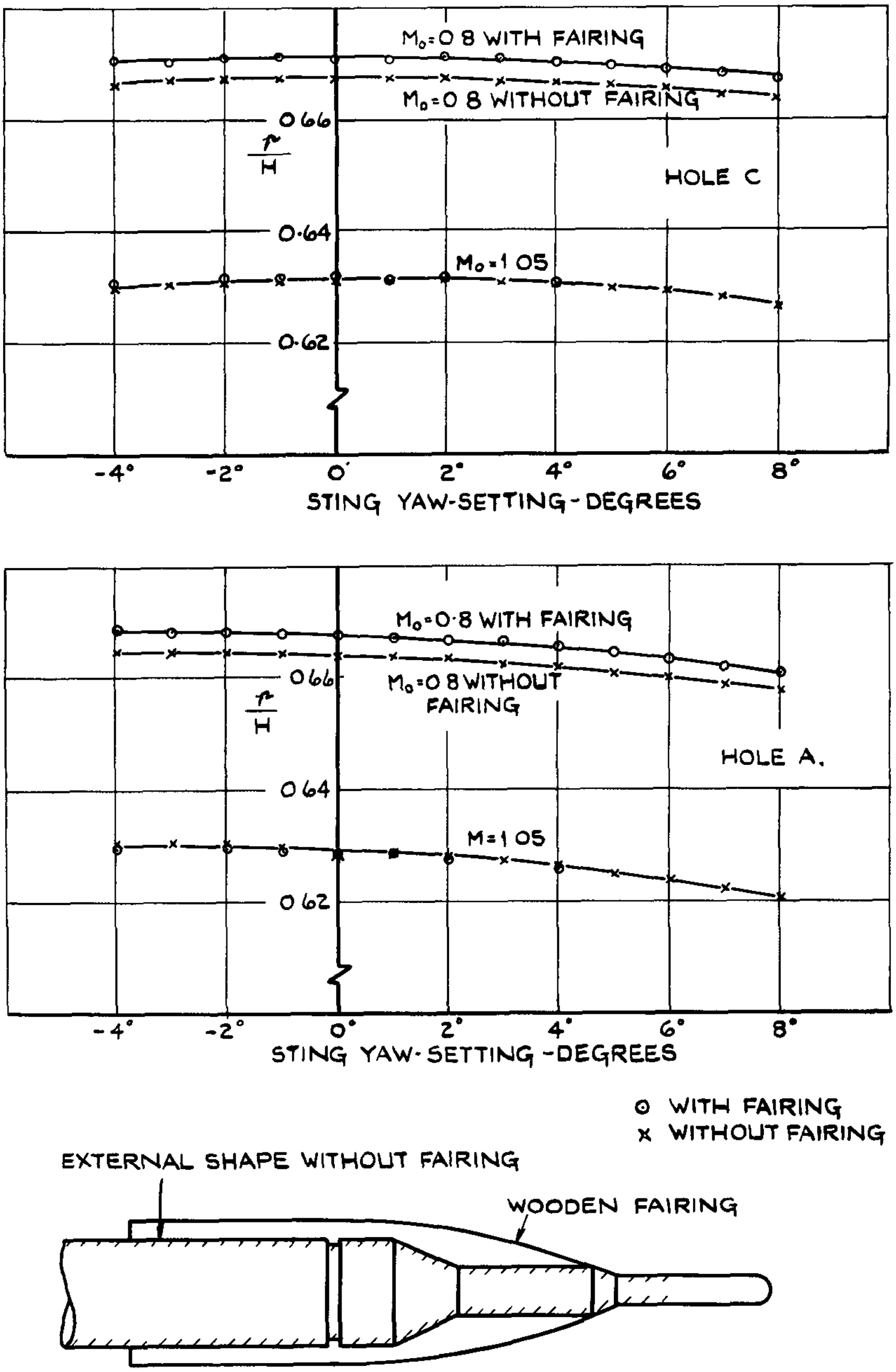

FIG.10(a) EFFECT OF FAIRING ON PRESSURES FOR HOLES IN PLANE PERPENDICULAR TO YAWING PLANE.

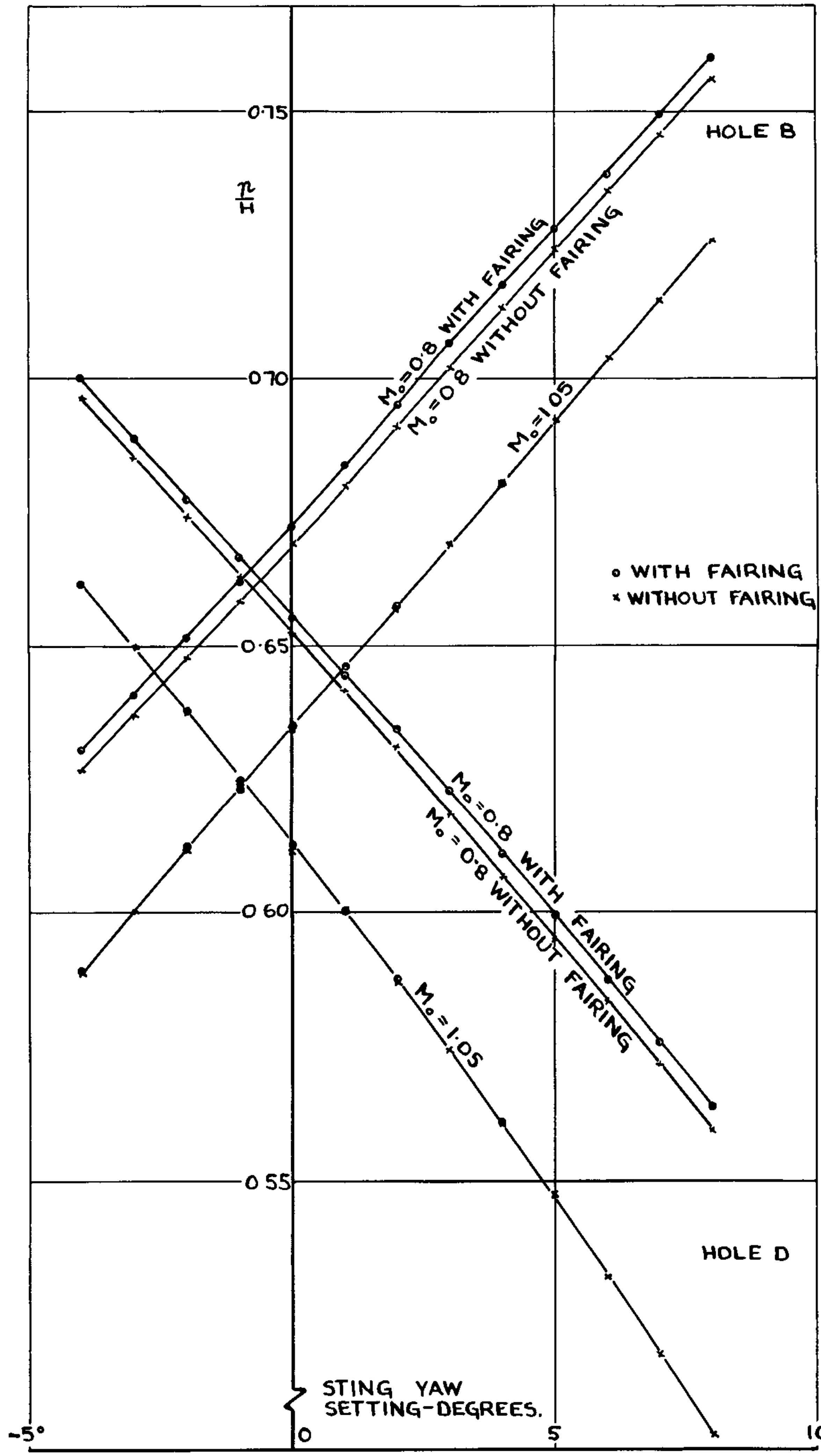

FIG. 10(b) EFFECT OF FAIRING ON PRESSURES FOR HOLES IN YAWING PLANE.

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