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FIVE-HOLE SPHERICAL PITOT TUBE

by

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HYDROMECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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FIVE-HOLE SPHERICAL PITOT TUBE

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ABSTRACT

The theory used in developing a 5-hole spherical pitot tube to measure three-dimensional flow is fully described. Some considerations in the design aspect of the tube are given. The procedures for calibration of the tube, test, and analysis of the test data are also included.

INTRODUCTION

A simple and reliable way to measure the magnitude and direction of the water velocity around ships and ship models has been sought by naval architects for a long time. A brief description of earlier developments and various types of instruments built in different towing tanks has been discussed in Reference 1*. At the David Taylor Model Basin a 13-hole spherical pitot tube was developed and built many years ago. Since then this tube has been used as a standard instrument in making wake surveys around ship models. The construction and calibration of the tube and the method of analyzing the test data are fully described in the above reference.

This method has been found quite successful except that it is very tedious and time-consuming to process the test data. In view of the fact that the value of knowing the water velocity distribution behind the hull becomes greater as propeller theory advances, the demand for wake survey tests on ship models is more frequent. A simplification of the existing method of wake survey became a necessity. A study of the possibility of simplifying the procedure of processing the test data has led to the development of a 5-hole spherical pitot tube for measuring three-dimensional flow.

THEORETICAL BACKGROUND

The pressure on the surface of a sphere in an incompressible nonviscous fluid with a uniform velocity is given in Reference 2 by the following equation:

$$\frac{p-p_o}{w} = \frac{V^2}{2g} \left(1 - \frac{9}{4} \sin^2 \beta\right) \qquad (1)$$

where V = velocity of undisturbed flow
p = pressure at a given point on a sphere
p_o = pressure in the undisturbed flow
w = weight per cubic foot of the fluid
β = angular distance measured from the stagnation point to the given point

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* References are listed on page 8.

Figure 1 shows a sphere in an ideal stream of uniform velocity V with a stagnation point S. From equation (1) we have,

$$\frac{p_a - p_o}{w} = \frac{V^2}{2g} \left(1 - \frac{9}{4} \sin^2 \angle soa\right) \qquad (2)$$

$$\frac{p_b - p_o}{w} = \frac{V^2}{2g} \left(1 - \frac{9}{4} \sin^2 \angle sob\right) \qquad (3)$$

$$\frac{p_c - p_o}{w} = \frac{V^2}{2g} \left(1 - \frac{9}{4} \sin^2 \angle soc\right) \qquad (4)$$

where p_a, p_b, and p_c are the local pressures at points a, b, and c, respectively.

(4) - (2) $$\frac{p_c - p_a}{w} = \frac{9V^2}{8g} \left(\sin^2 \angle soa - \sin^2 \angle soc\right) \qquad (5)$$

(4) - (3) $$\frac{p_c - p_b}{w} = \frac{9V^2}{8g} \left(\sin^2 \angle sob - \sin^2 \angle soc\right) \qquad (6)$$

(6) + (5) $$\frac{2p_c - p_a - p_b}{w} = \frac{9V^2}{8g} \left(\sin^2 \angle soa + \sin^2 \angle sob - 2 \sin^2 \angle soc\right) \qquad (7)$$

(6) - (5) $$\frac{p_a - p_b}{w} = \frac{9V^2}{8g} \left(\sin^2 \angle sob - \sin^2 \angle soa\right) \qquad (8)$$

Since $\angle sda$ is a right angle, we have:

$$\cos \angle soa = \cos \angle sod \times \cos (\beta_h - a) \qquad (9)$$

$$\sin^2 \angle soa = 1 - \cos^2 \angle sod \times \cos^2 (\beta_h - a)$$

Likewise $$\sin^2 \angle sob = 1 - \cos^2 \angle sod \times \cos^2 (\beta_h + a) \qquad (10)$$

$$\sin^2 \angle soc = 1 - \cos^2 \angle sod \times \cos^2 \beta_h \qquad (11)$$

Combining (7), (9), (10), and (11) we have:

$$\frac{2p_c-p_a-p_b}{w} = \frac{9V^2}{8g} \quad \cos^2\angle sod \left[2\cos^2\beta_h - \cos^2(\beta_h - \partial) - \cos^2(\beta_h + \partial)\right]$$

$$= \frac{9V^2}{8g} \quad \cos^2\angle sod \left[\cos 2\beta_h - \frac{\cos 2(\beta_h - \partial) + \cos 2(\beta_h + \partial)}{2}\right]$$

$$= \frac{9V^2}{8g} \quad \cos^2\angle sod \left[\cos 2\beta_h - \cos 2\beta_h \times \cos 2\partial\right]$$

$$= \frac{9V^2}{8g} \quad \cos^2\angle sod \; (1 - \cos 2\partial) \cos 2\beta_h \qquad (12)$$

Combining (8), (9), and (10) we have

$$\frac{p_a - p_b}{w} = \frac{9V^2}{8g} \quad \cos^2\angle sod \left[\cos^2 (\beta_h - \partial) - \cos^2 (\beta_h + \partial)\right]$$

$$= \frac{9V^2}{8g} \quad \cos^2\angle sod \left[\frac{\cos 2 (\beta_h - \partial) - \cos 2 (\beta_h + \partial)}{2}\right]$$

$$= \frac{9V^2}{8g} \quad \cos^2\angle sod \times \sin 2\partial \times \sin 2\beta_h$$

$$= \frac{9V_h^2}{8g} \quad \sin 2\partial \times \sin 2\beta_h \qquad (13)$$

where $V_h = V \cos \angle sod$, the projection of V on xy plane

$$\frac{(13)}{(12)} \qquad \frac{p_a - p_b}{2p_c - p_a - p_b} = \frac{\sin 2\partial}{1 - \cos 2\partial} \times \tan 2\beta_h \qquad (14)$$

From equation (14), β_h can be computed, and then from equation (13) V_h can be obtained. Since V_z, the component of V perpendicular to the xy plane, does not enter equations (13) and (14), the two components of V, V_h and V_z, can be treated independently. It immediately suggests that a sphere with five holes, as shown in Figure 2, can be used to measure the velocity V. Use the pressures measured at a' c b' to obtain the values of V_v and β_v just as V_h and β_h were obtained, by using the pressures measured at a, b, and c, as described above. Then we have

$$V_x = V_h \cos\beta_h$$
$$V_y = V_h \sin\beta_h$$
$$V_z = V_v \sin\beta_v$$

where V_x, V_y, and V_z are the three components of V along X, Y, and Z axes, respectively. Also $V_v \cos\beta_v$ is equal to V_x. This can be used as a check.

It is of interest to note that a number of 5-hole pitot tubes were previously designed and built for this purpose. Admiral Taylor designed and built one in 1915[1]. The Dutch built one[3] and so did F. Gutsche of the Berlin Tank[4]. But in none of these designs was advantage taken of the fact that the velocity component in any plane in space can be obtained independently from the three pressure measurements in that plane. The utilization of this knowledge is the basis of the method here presented.

SOME IMPORTANT CONSIDERATIONS IN THE DESIGN OF A 5-HOLE SPHERICAL PITOT TUBE

The 5-hole spherical pitot tubes previously built at various towing tanks were very similar. However, two important items, the diameter of the spherical head and the angular distance between the center hole and side holes, deserve special attention and are briefly discussed below.

The Diameter of the Spherical Head

The diameter of the spherical head should be made as small as practical for two reasons: (1) the smaller this diameter, the smaller will be the interference effect of the instrument on the flow; (2) the smaller the diameter, the greater the accuracy in measuring the nonuniform velocity field around ship models. As will be described later, the calibration of the tube is performed in a towing tank where the water velocity relative to the tube is uniform. If the spherical head is small enough, the velocity field within the small radius of the sphere can be considered uniform in a nonuniform velocity field, so that the calibration curves obtained in a uniform velocity field can be used with good results in nonuniform flow.

The Angular Distance Between the Center Hole and Side Holes

The pattern of pressure distribution on a spherical surface in a uniform viscous stream is dependent upon the Reynold's number. However, there is a region, within about 40° angular distance from the stagnation point, where the pattern of pressure distribution is nearly independent of the Reynold's number.[2] If the angular distance between the center hole and side holes is in the order of 20 degrees, the measured velocity can be 20 degrees off the center hole, and the angular distance between the stagnation point and the furthermost side hole will still be about 40 degrees. Hence, the calibration curves obtained at one speed can be used for any other speed for a large range of β angles.

The angular distance between the center hole and side holes of the 5-hole spherical pitot tubes built in the past was in the order of 40 or 50 degrees. This might very well be one of the difficulties experienced with these tubes. Figure 3 shows a 5-hole spherical pitot tube built recently at TMB. The diameter of the spherical head is half an inch. The angular distance between the center hole and side holes is about 20 degrees. Two of the side holes are on a horizontal great circle and the other two are on a vertical great circle, while the holder of the tube is held in the vertical position. The diameter of the holes is about 1/32 inch.

CALIBRATION

Equations (13) and (14) are true only if the fluid has no viscosity, the sphere is perfect, and the diameter of the opening at points a, b, etc. for measuring the local pressures approaches zero. In actual practice none of these conditions is true. Thus the relationships of equations (13) and (14) have to be represented by curves obtained from calibration of a particular tube.

The calibration of the tube is performed by mounting the tube on a platform under the carriage, with the spherical head submerged, in such a way that the tube can be rotated either vertically or horizontally. The five holes are connected to a manometer board so that the pressures can be measured. The water is drawn up to the manometer board by partial vacuum created inside the manometers. Since only the pressure differences are of interest, the board reading, while the tube is at rest in the water, is insignificant. The carriage speed is kept constant at a given speed; e.g., 6 knots. The stagnation point is first adjusted to the position of the center hole by rotating the tube up and down or sideways until the board readings of all the side holes are equal and the center hole pressure reading reaches the maximum. This is the position of zero β angle. To check the vertical holes with the vertical plane, the tube is rotated to both the port and starboard sides about 20 degrees. The pressure reading of the two vertical holes should be the same. If they are not equal, the tube should be rotated about the axis parallel to the direction of motion and checked again until these readings are equal.

The tube is then turned to the left at intervals of about 3° of β_h angle. At each position the board readings are taken when they have reached steady values. The manometers are fitted with stopcocks by means of which the columns are closed off before the end of a run and opened again when the new run has reached the correct speed. In general, a few runs are needed before the manometers reach the steady state. This operation is repeated by rotating the tube to the right, upward and downward at intervals of 3 degrees. Figure 4 shows the calibration curves of the tube shown in Figure 3. The capital letters C, S, P, T, and B represent the board readings at center hole, starboard hole, port hole, top hole, and bottom hole, respectively. The capital letters V_h and V_v represent the velocity components in the horizontal plane and the vertical plane, respectively. A positive β angle means the stagnation point is on the starboard side or top side. Here $\frac{C - S}{V_h^2}$, $\frac{C - P}{V_h^2}$, etc. are plotted against β instead of $\frac{2C - P - S}{V_h^2}$, etc., since the latter factors, when plotted against β, give very flat curves.

These curves have been checked at different speeds (3 and 6 knots). No significant change has been found. It will be noted that these curves are not quite symmetrical with respect to the central position. This is due to the fact that the side holes may not be exactly equally spaced and there may have been some irregularity on the spherical surface of this particular tube.

TEST PROCEDURE

The tube is mounted on the model as shown in Figure 5. The centerline of the pitot tube is parallel to the shaft line in the case of velocity survey in the propeller plane. Sometimes it is necessary to rotate the vertical arm of the tube toward one side so that there will be enough clearance under the carriage. A target is set up on the deck of the model to facilitate the positioning of the tube. The water is drawn to the manometer board by creating a partial vacuum inside the manometers. The model is towed at the desired speed. The manometer board readings are taken for each position of the tube when these readings have reached steady values.

ANALYSIS OF TEST RESULTS

The procedure for analyzing the test is completely described in the analysis sheet and its accompanying instructions on pages 15 - 17. The method of analysis, of course, is based on the preceding development and the calibration procedure just described.

The end results of the velocities measured in a propeller plane are resolved into three mutually perpendicular components V_n, V_t, V_r, and tabulated. Where V_n is normal to the propeller plane, V_r is the radial component in the propeller plane and V_t is the tangential component in the propeller plane. In order to give a visual picture of the velocity components in the propeller plane, the resultant vectors of V_t and V_r are plotted at corresponding positions in the propeller plane. A typical result of a velocity survey in the propeller plane of a twin-screw ship model is shown in Figure 6.

DISCUSSION

The 5-hole spherical pitot tube and the procedure of analyzing the test data presented in this report are now adopted as a standard method for any velocity survey test around ship models at TMB. It is rather thought-provoking to note that the 5-hole spherical pitot tube, which had been abandoned a long time ago, becomes very useful again with a slightly different procedure.

The new method of analyzing velocity survey test data in a propeller plane has reduced the time involved from a week to a day. The new procedure is being adapted to UNIVAC computation, and further time-saving in processing the test data will thus be realized.

ACKNOWLEDGEMENT

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4. Gutsche, Fritz, Dipl. Ing., "Das Zylinderstaurohr" (Cylindrical Pitot Tube), Schiffbau, Schiffahrt, und Hafenbau, Vol. 32, No. 1 (January 1931) pp. 13-19. TMB Translation 172, Unpublished. Reference copy in TMB Library.

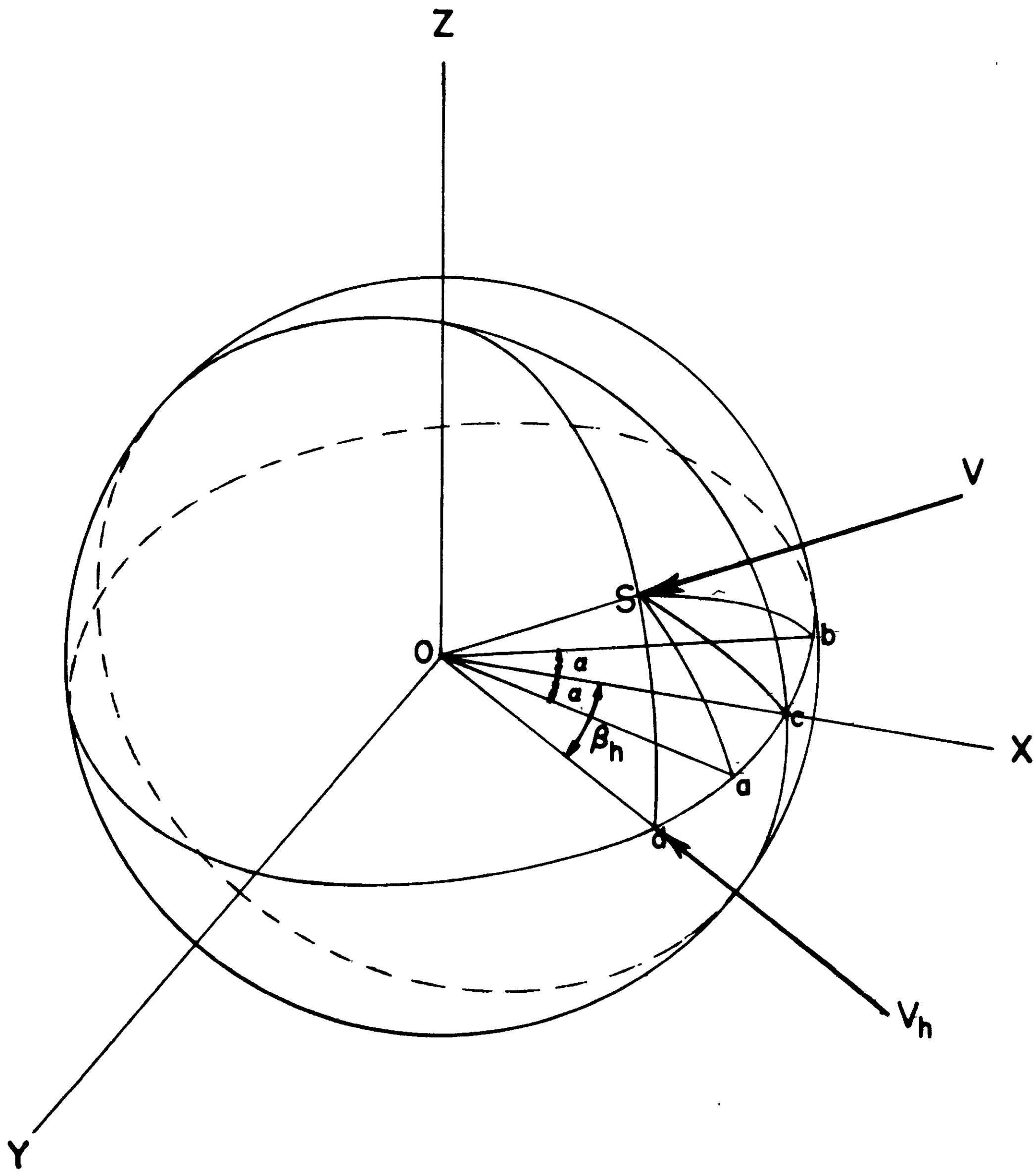


FIG. 1

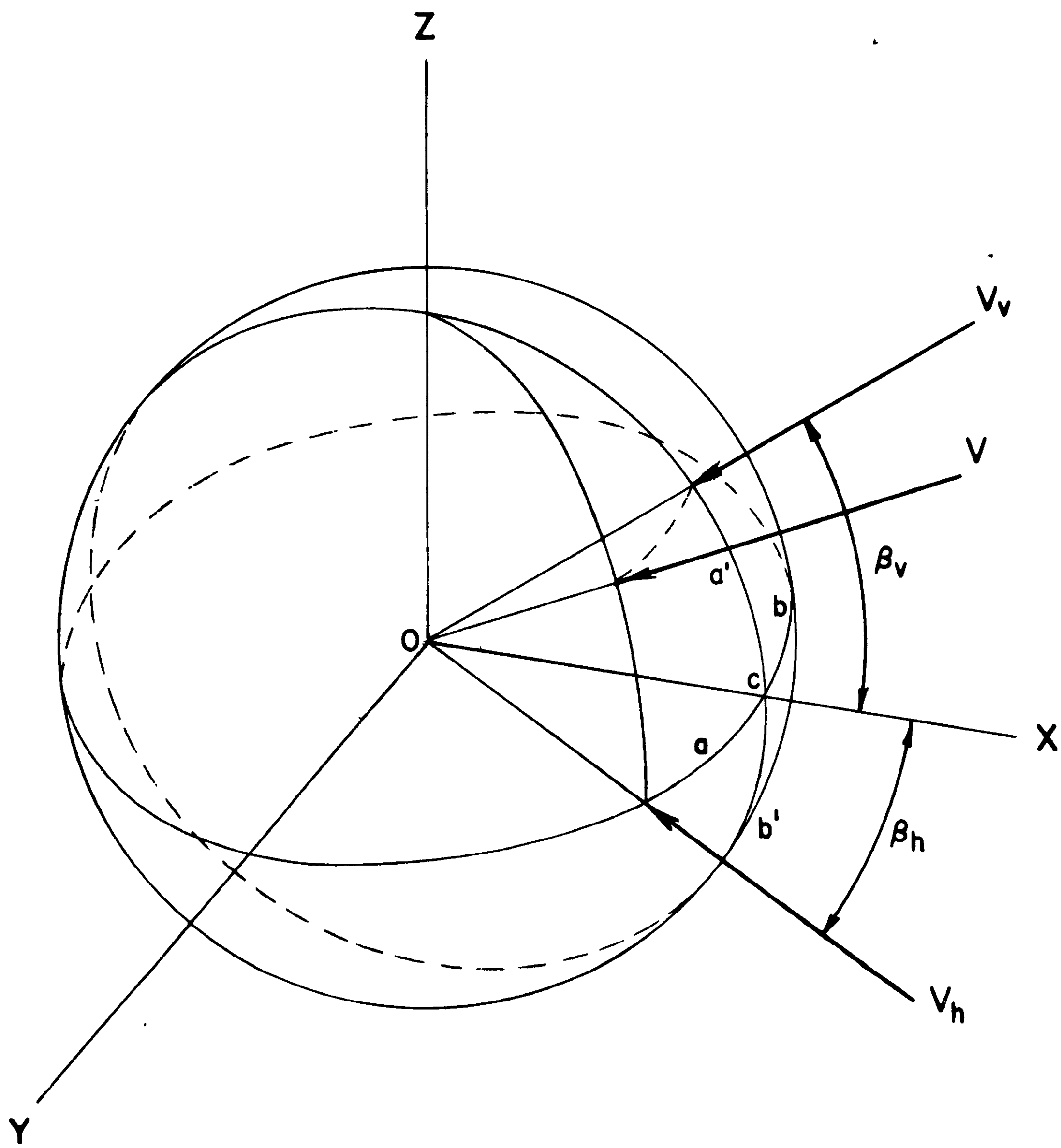


FIG. 2

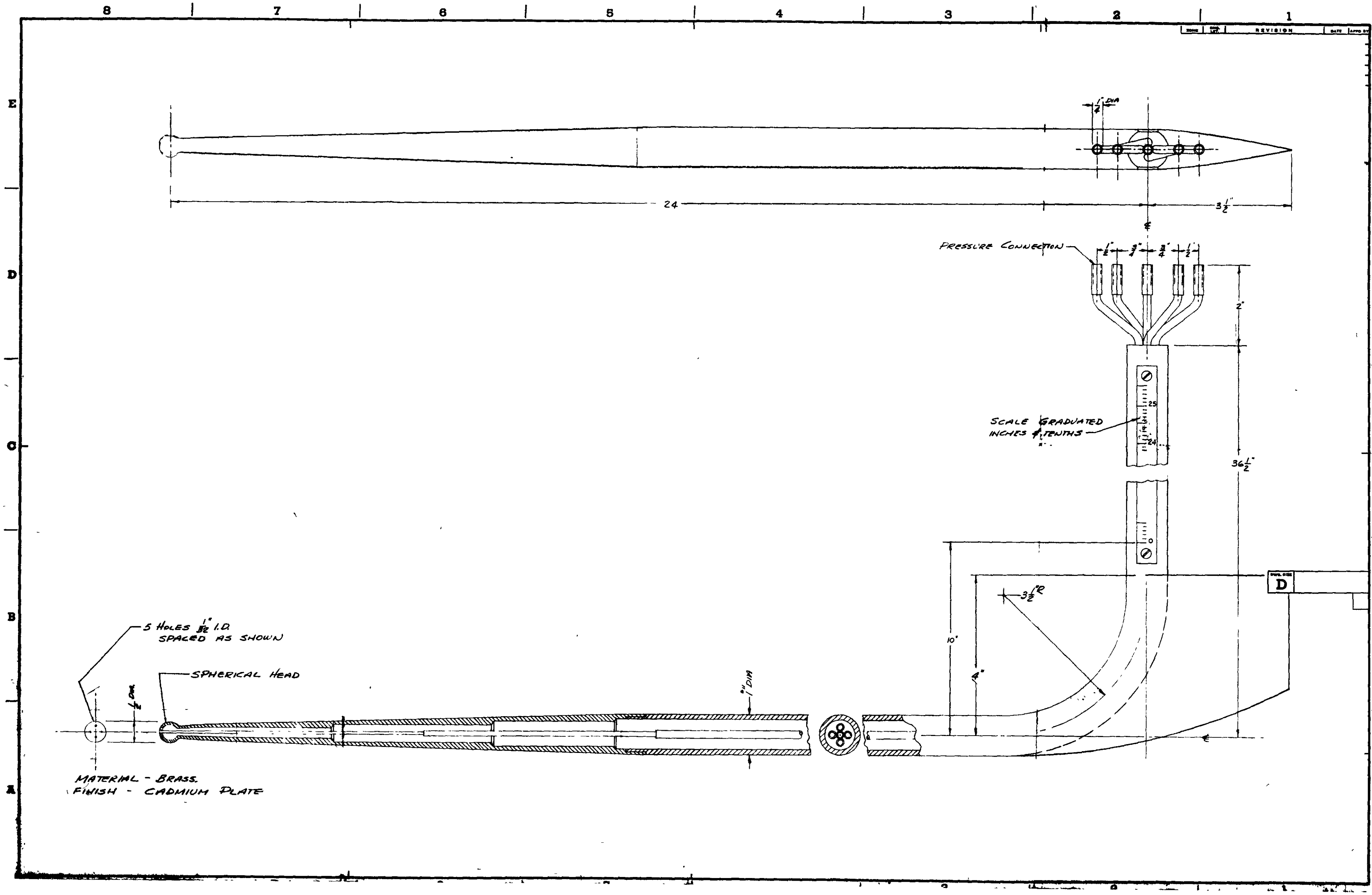

PRESSURE CONNECTION
SCALE GRADUATED INCHES & TENTHS
5 HOLES 1/32" I.D. SPACED AS SHOWN
SPHERICAL HEAD
MATERIAL - BRASS.
FINISH - CADMIUM PLATE
24
3 1/2"
36 1/2"
10"
4"
2"
3 1/2" R
1" DIA
1/2" DIA

FIG. 3

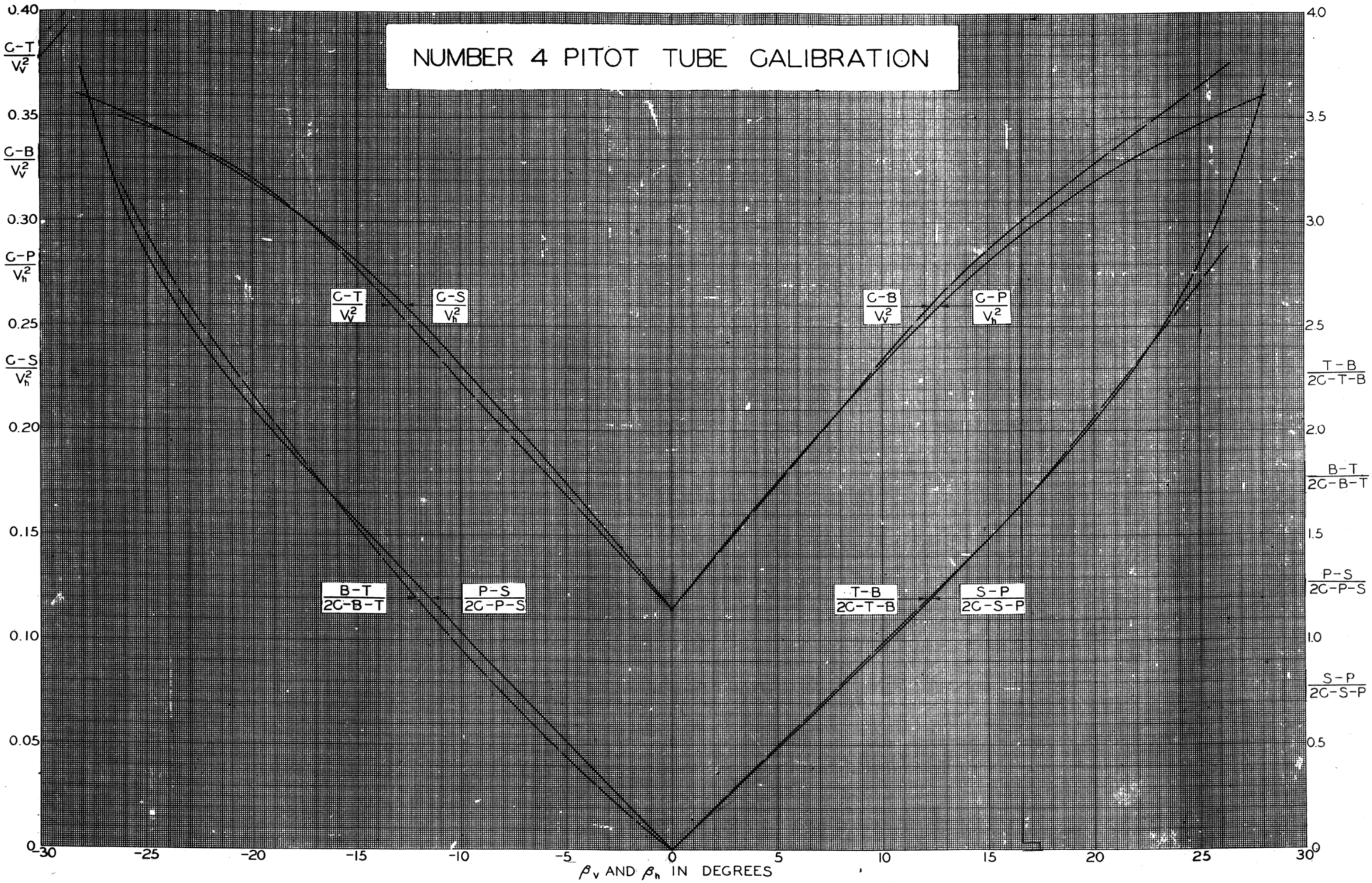


FIG. 4

STAGN. POINT ON STARBORD

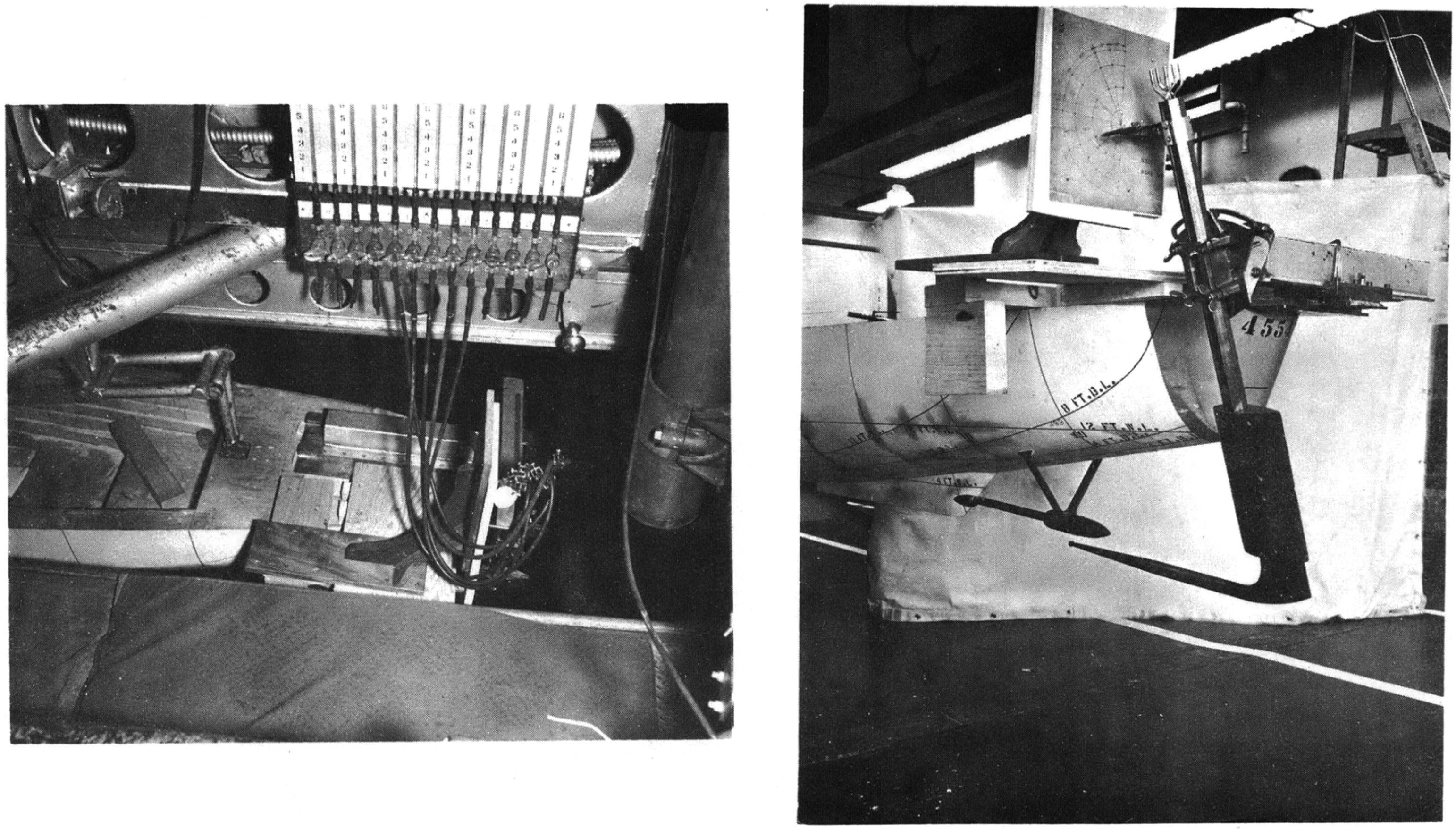


FIG. 5, FIVE-HOLE PILOT TUBE MOUNTED ON MODEL

VELOCITY SURVEY
FOR
A CARGO VESSEL

TABLE OF VELOCITY COMPONENT RATIOS

POSITION NUMBER	V_n/V	V_t/V	V_r/V	POSITION NUMBER	V_n/V	V_t/V	V_r/V
1	.76	.12	-.12	19	.98	-.02	.09
2	.67	.01	-.09	20	.97	.02	.10
3	.66	-.11	-.16	21	.95	.07	.09
4	.82	-.15	-.03	22	.98	.11	.05
5	.95	-.09	.03	23	.94	.17	.02
6	.96	-.06	.07	24	.86	.16	-.06
7	.97	-.03	.09	25	.86	.12	-.10
8	.96	.02	.09	26	.69	.01	-.04
9	.98	.06	.09	27	.90	-.05	-.05
10	.98	.10	.06	28	.96	-.16	-.03
11	.92	.15	.20	29	.96	-.10	.03
12	.83	.16	-.05	30	.97	-.07	.06
13	.83	.12	-.12	31	.98	-.02	.09
14	.72	.07	-.09	32	.98	.03	.10
15	.91	-.05	-.05	33	.99	.09	.09
16	.88	-.16	-.04	34	.96	.15	.09
17	.95	-.08	.03	35	.94	.18	.01
18	.96	-.06	.07	36	.89	.16	-.06

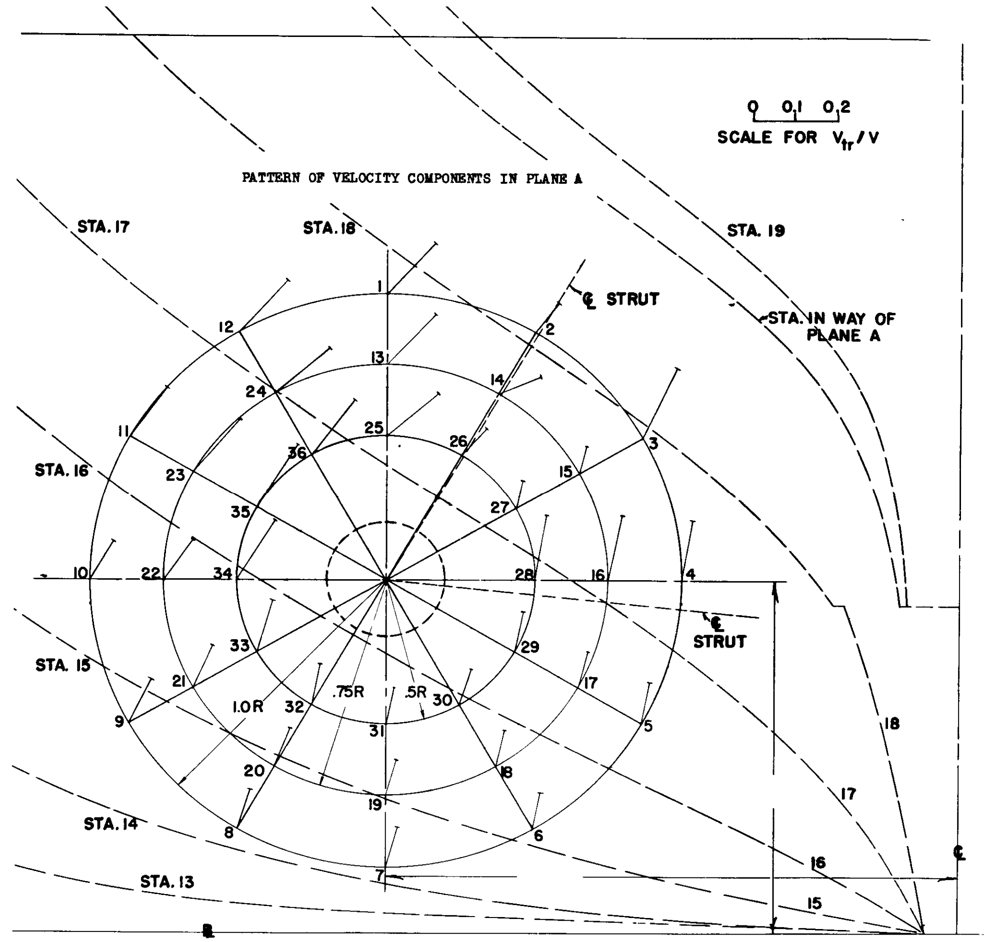
V IS THE SHIP SPEED.

V_r IS THE RADIAL COMPONENT OF VELOCITY IN PLANE A AND IS POSITIVE TOWARD THE CENTER OF THE PROPELLER.

V_t IS THE TANGENTIAL COMPONENT OF VELOCITY IN PLANE A AND IS POSITIVE IN THE CLOCKWISE DIRECTION.

V_n IS THE COMPONENT OF VELOCITY NORMAL TO PLANE A AND IS POSITIVE IN THE ASTERN DIRECTION.

V_t, V_r, V_n, AND V_{tr} ARE RELATIVE TO THE SHIP



NOTES:

PLANE A IS THE PLANE OF VELOCITY SURVEY WHICH IS PERPENDICULAR TO THE BASE LINE AND CENTERLINE AND INTERSECTS THE CENTERLINE 35 FEET FORWARD OF STATION 20.

VECTOR SHOWN IN DIAGRAM REPRESENTS MAGNITUDE AND DIRECTION OF TRANSVERSE COMPONENT OF VELOCITY RATIO DESIGNATED AS V_{tr}/V.

SHAFT, FAIRWATER AND DUMMY HUB WERE IN PLACE.

FIG. 6

VELOCITY SURVEY CALCULATION SHEET

MODEL NO. _______ VESSEL ______________________ TEST NO. ____ DATE OF TEST _________ PITOT TUBE NO. _____

SURVEY MADE ABOUT __________ SHAFT. VERTICAL ARM OF PITOT TUBE ROTATED ______ DEGREES (θ) SHEET NO. ___

HORIZONTAL PLANE

	1	2	3	4	5	6	7	8		9		10	11	12	13	14	15	16	17
	C	S	P	S-P	2C-S-P	$\frac{4}{5}$	β_h	$\frac{C-P}{V_h^2}$	$\frac{C-S}{V_h^2}$	C-P	C-S	V_h^2	V_h	V_y	V_{xh}	α	γ	V_{th}	V_{rh}
1																			
2																			
3																			
4																			
5																			
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26																			
27																			
28																			

VERTICAL PLANE

	18	19	20	21	22	23	24	25		26		27	28	29	30	31	32	33
	C	T	B	T-B	2C-T-B	$\frac{21}{22}$	β_v	$\frac{C-T}{V_v^2}$	$\frac{C-B}{V_v^2}$	C-T	C-B	V_v^2	V_v	V_{xv}	V_z	δ	V_{tv}	V_{rv}
1																		
2																		
3																		
4																		
5																		
6																		
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26																		
27																		
28																		

FINAL RESULTS

34	35	36	37	38	39	
V_n	V_t	V_r	$\frac{V_n}{V_m}$	$\frac{V_t}{V_m}$	$\frac{V_r}{V_m}$	
						1
						2
						3
						4
						5
						6
						7
						8
						9
						10
						11
						12
						13
						14
						15
						16
						17
						18
						19
						20
						21
						22
						23
						24
						25
						26
						27
						28

PROCEDURE FOR ANALYZING VELOCITY SURVEY

(5-Hole Pitot Tube)

1. Center hole reading in inches of water from the test data sheet.

2. Stbd. hole reading in inches of water from the test data sheet.

3. Port hole reading in inches of water from the test data sheet.

4. Col. 2 - Col. 3

5. 2 x Col. 1 - Col. 2 - Col. 3

6. Col. 4 + Col. 5

7. If Col. 4 is positive use $\frac{S-P}{2C-S-P}$ curve to obtain positive β_h angle, and if Col. 4 is negative use $\frac{P-S}{2C-P-S}$ curve to obtain negative β_h angle from the calibration sheet.

8. If β angle is positive, record the value of $\frac{C-P}{V_h^2}$, and if β angle is negative, record the value of $\frac{C-S}{V_h^2}$ from the appropriate curve.

9. Col. 1 - Col. 3 if β_h is positive. Col. 1 - Col. 2 if β_h is negative.

10. Col. 9 + Col. 8

11. $\sqrt{\text{Col. 10}}$

12. Sin β_h x Col. 11

13. Cos β_h x Col. 11

14. α, position angle measured from the vertical line, positive in the counter clockwise direction.

15. $\gamma = 90^\circ + \theta - \alpha$ where θ is the angle between the arm of the tube and the vertical line, positive in the counter clockwise direction.

16. Col. 12 x sin γ

17. Col. 12 x cos γ

18. Center hole reading in inches of water, same as Col. 1

19. Top hole reading in inches of water from the test data sheet.

20. Bottom hole reading in inches of water from the test data sheet.

21. Col. 19 - Col. 20

22. 2 x Col. 18 - Col. 19 - Col. 20

23. Col. 21 ÷ Col. 22

24. If Col. 21 is positive use $\frac{T-B}{2C-T-B}$ curve to obtain positive ϕ_v angle, if Col. 21 is negative use $\frac{B-T}{2C-B-T}$ curve to obtain negative ϕ_v angle from the calibration sheet.

25. If ϕ_v angle is positive record the value of $\frac{C-B}{V_v^2}$, and if ϕ_v angle is negative record the value of $\frac{C-T}{V_v^2}$ from the appropriate curve.

26. Col. 18 - Col. 20 if ϕ_v is positive. Col. 18 - Col. 19 if ϕ_v angle is negative.

27. Col. 26 ÷ Col. 25

28. $\sqrt{\text{Col. 27}}$

29. Col. 28 x cos ϕ_v.

30. Col. 28 x sin ϕ_v.

31. δ, 90° + Col. 15

32. Col. 30 x sin δ

33. Col. 30 x cos δ

34. (Col. 13 + Col. 29) ÷ 2

35. Col. 16 + Col. 32, positive is counter clockwise

36. Col. 17 + Col. 33, positive is outward from the center of prop.

37. Col. 34 ÷ V_m

38. Col. 35 ÷ V_m

39. Col. 36 ÷ V_m

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May 1958. 18p. illus., refs. UNCLASSIFIED

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2. Pitot tubes – Design – Theory
3. Three-dimensional flow – Measurement
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II. NS 715-102

David Taylor Model Basin. Report 1229.
FIVE-HOLE SPHERICAL PITOT TUBE, by P.C. Pien.
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