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THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

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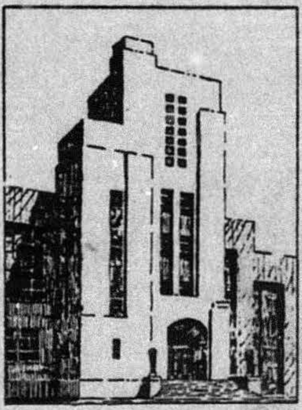
INSTRUMENTS AND METHODS FOR MEASURING THE FLOW OF WATER AROUND SHIPS AND SHIP MODELS

BY C.E. JANES



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INSTRUMENTS AND METHODS FOR MEASURING THE FLOW OF WATER AROUND SHIPS AND SHIP MODELS

ABSTRACT

This report outlines the development of instruments for measuring the flow of water around ships and ship models. The cylindrical and the spherical-ended pitot tube, the rotating wake meter, and the bow log developed by the U.S. Experimental Model Basin and the David Taylor Model Basin are described in detail, and the uses and limitations of each instrument are discussed.

Similar instruments used by other model basins are briefly described.

The method of operation of the spherical-ended pitot tube and the method of applying the data obtained with this tube are discussed in Appendixes 1 and 2.

INTRODUCTION

During the nineteenth century naval architects held several theories (1)* on the flow of water around a ship. Some asserted that the water was pushed far ahead of the ship as a carrier wave, others that it ran under the bottom of the ship, and still others that it was divided by the bow, ran along the sides, and united again at the stern. This last theory, which assumes that the flow of water follows the waterlines, was popular in England and was the basis of ship design (2). In 1878 Colin Archer (3) pointed out that the waterlines did not correctly represent the manner in which water was displaced or the path taken by the water particles along the ship's bottom.

To investigate the lines of flow, model-basin tests were undertaken. These tests proved that the flow of water was not two-dimensional. When it became apparent that the exact path of the water must be known to design ship's lines and to design and place bilge keels and other appendages which do not project far beyond the skin of the ship, all model-basin establishments devised some means of delineating the lines of flow on or near the surface of the model as it moves through the water. At the U.S. Experimental Model Basin and the David Taylor Model Basin the path of flow is marked on the model hull by a hydrogen sulfide solution which is ejected from openings at selected points and is carried over areas covered with white-lead paint. This method is described in detail in Reference (4).

Because of this streamline action of the water around the hull of a ship, the velocity and pressure** of the water near the ship's hull vary. Also

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* Numbers in parentheses indicate references on page 23 of this report.

** The method used by the Taylor Model Basin to measure the pressure at any number of points on the surface of a model is described in Reference (5).

the friction of the ship's surface produces a turbulent layer adjacent to the ship where the motion of the water is confused. The net result is a wake whose forward velocity, very close to the ship, is as great as 50 per cent of the ship speed and rapidly dies away as the distance from the ship's surface is increased. This turbulent layer is called the boundary layer. The velocity imparted to the water by the hull of the ship is commonly known as wake.

For the design of appendages such as struts, propellers, and rudders it is necessary to investigate the wake. Therefore, in 1910 the Experimental Model Basin extended its investigation of flow to areas beyond the hull surface. For this investigation acid, ejected from a tube which projected from the hull, made a mark on a net which extended from the model at some distance aft of the tube. This method measured direction only, and the tube and net interfered with the flow of water. To overcome these difficulties several instruments were designed and developed by the Experimental Model Basin and more recently by the Taylor Model Basin.

As speed is also a vital factor to the designer of a ship, attention has been given to the problem of measuring the speed of a ship through the water since the days of sailing vessels.

Before describing the cylindrical and spherical pitot tubes, this report describes the rotating wake meter, the bow log developed by the Experimental Model Basin and the Taylor Model Basin for measuring speed through the water, and the instruments for measuring the velocity of flow, the direction of flow, and the speed of a ship which were in existence at the time of the establishment of the Experimental Model Basin or which were developed simultaneously by others.

DEVELOPMENT OF EARLY INSTRUMENTS

Most of the instruments used to measure the velocity of flow, the direction of flow, and the speed of a ship are based on the pitot tube designed by Henri Pitot, a French physicist and engineer of the eighteeenth century. The original pitot tube was an L-shaped tube with a short right-angled bend at one end. The open end of the short arm was placed normal to the direction of flow and the other end was connected to a manometer which responded to pressure but which was calibrated to indicate velocity.

PITOT-STATIC TUBE

The basic pitot tube, when combined with a second tube with suitable orifices, is the common pitot-static tube shown in Figure 1. This tube measures speed only in the direction of its axis. It is used to measure the flow alongside ship models.

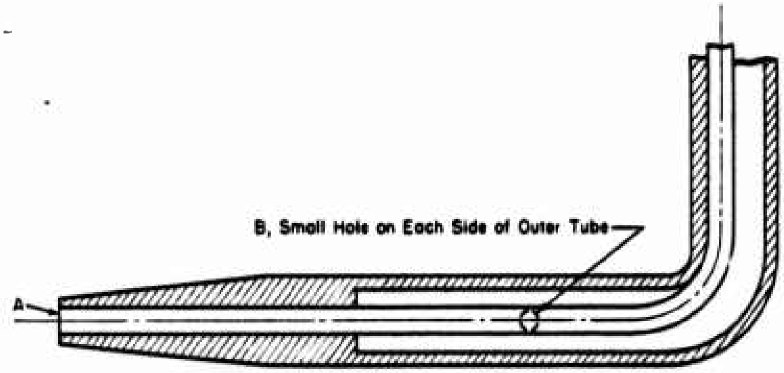


Figure 1 - Pitot-Static Tube

The impact pressure is transmitted from the orifice *A* through the inner tube to the manometer. The static pressure is transmitted from the orifices *B* through the outer tube to the manometer. The manometer may be arranged to show pressures separately or to read the difference between them.

An inner tube, as small as practicable, receives the impact of the fluid which is brought to rest at *A*, Figure 1, with a corresponding increase of pressure. This pressure is transmitted through the inner tube to a pressure-recording or pressure-indicating apparatus. The outer tube receives through the openings *B* the pressure of the moving fluid, which, by way of the outer tube, is also recorded or indicated.

The velocity of flow is determined from the well-known Bernoulli theorem

$$\frac{p}{w} + \frac{v^2}{2g} + z = h$$

where p is the pressure in the fluid per unit area,
w is the weight of the fluid per unit volume,
v is the velocity of the fluid in feet per second,
g is the acceleration of gravity in feet per second per second,
z is the height in feet of the tube from a fixed plane, and
h is a constant.

This formula holds for the points *A* and *B*. At *A* the fluid is brought to rest, that is, $v = 0$. Hence at *A*

$$\frac{p_A}{w} + z = h$$

At B

$$\frac{p_B}{w} + \frac{v_B^2}{2g} + z = h$$

Then, after subtracting,

$$v_B^2 = \frac{2g}{w}(p_A - p_B)$$

This equation determines v, the speed of flow, provided v_B is the same as the undisturbed speed of flow. The differences between v and v_B are minimized by proper design of the tube, and the errors are eliminated by calibration.

SPEED LOGS

The apparatus devised to measure accurately the motion of vessels through the water has, in general, been designed to measure either distance as a primary and speed as a secondary function or speed as a primary and distance as a secondary function. The earlier logs designed to measure the speed of ships through the water were towed from the side or stern of the ship. More recently, apparatus which can be installed in the ship was devised.

The earliest known log, a distance log, was the chip log used on sailing vessels and the earliest steam vessels. The chip was a thin wooden quadrant of 5 or 6 inches radius loaded with lead on the arc to make it float point up. It was towed by a line divided into equal spaces called knots, each bearing the same proportion to a mile that the time during which the run-out of the line is measured bears to an hour. The line ran freely from a log reel so that when the log was thrown the water held it from being drawn forward and the speed of the vessel was shown by the number of knots run out. This log was admittedly inaccurate as the slip of the chip was unknown and the time-measuring device, a sand glass, was a crude affair.

The chip log was supplanted by the so-called taffrail log which, in one form or another, has survived to the present day and is still in general use. The taffrail log consists of a mechanism which, being towed astern or from a boom projecting at the ship's side, shows the distance traveled through the water by the ship by registering the revolutions of a spinner either on a dial plate at the inboard end of the line or on the log itself. The spinner is supposed to be towed a sufficient distance astern so that it is not influenced by the wave system and by movement of water in the propeller race, but it has long ago been proved that no towline on a taffrail log is long enough to meet this requirement. Generally the log gives acceptable results because it is towed by the same length of line at nearly constant speeds.

A variation of the taffrail log was designed by Dr. G. Kempf of Germany (6). Kempf's log used a nonrotating towed form combined with a speed-recording apparatus. This instrument has been used by the Taylor Model Basin with some success.

Since the advent of high-power and high-speed steamships, a number of automatic logs of both the distance and the speed types have been developed which can be installed on the ship.

Most of the speed logs designed to measure speed as a primary function are of the pressure-tube type. The use of the pitot tube for measuring a ship's speed was advocated and tried by Henri Pitot himself in about 1732. The earliest record of practical application of a pitot tube which can be found is a pressure-tube log devised by James R. Napier and described in Reference (7). His instrument consisted of two bent tubes, one with its orifice pointing forward and the other with its orifice pointing aft. Their other extremities were connected to a glass tube containing mercury. The velocity of the ship was indicated by the height of the mercury. Napier placed his exposed orifices well below the waterline and at about midships. However, he overlooked the fact that the velocity which he was measuring was the velocity of the water in the boundary layer. His lack of success in obtaining consistent speed readings was, therefore, not at all surprising.

Experimenters of the later nineteenth century, realizing something of the complexities of the motions in the water alongside a ship, used the same principle but projected their tubes through the bottom of the ship, where they felt the effects of wave motion would be the least. They provided what they thought was sufficient extension of the log tube to place the orifice beyond the confines of the boundary layer, but it is not at all certain that they realized that the effect of streamlined motion was still present.

The pitometer log (8), which operates on the pitot-tube principle, is fitted in the bottom of the ship about one-third of the ship's length from the bow and as near to the centerline as possible. Both the impact and static orifices are placed beyond the influence of the boundary layer.

INSTRUMENTS USED BY THE TAYLOR MODEL BASIN

The cylindrical and spherical pitot tubes, the rotating wake meter, and the bow log, which are used by the Taylor Model Basin at present, are described in the following sections.

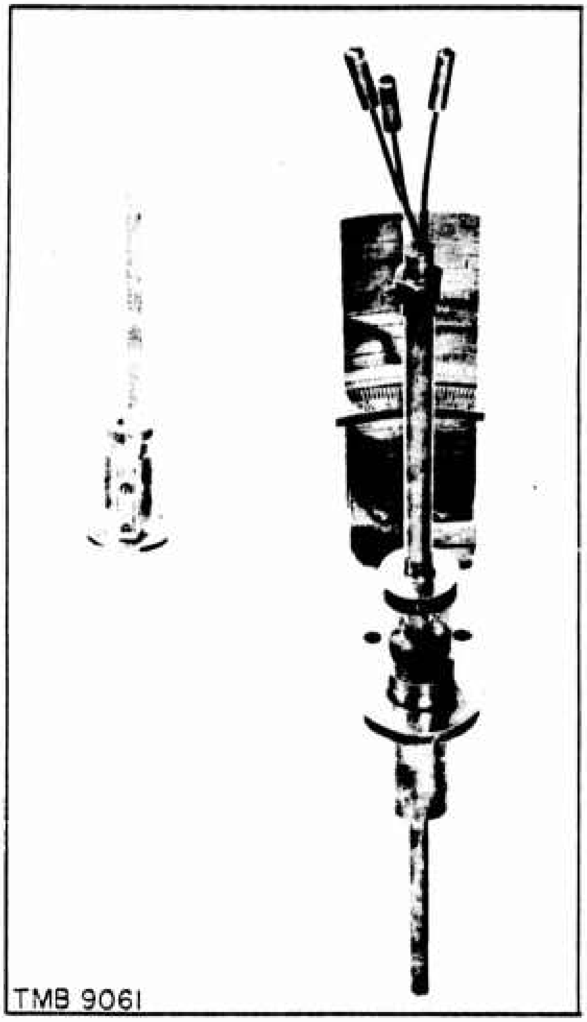
CYLINDRICAL PITOT TUBE

The cylindrical pitot tube was developed to measure direction as well as speed of flow. The theory upon which this tube is based is explained by Admiral Taylor in Reference (9).

The cylindrical pitot tube, shown in Figure 2, consists of a brass cylinder 0.39 inch in diameter which extends beyond the skin of the model. It has three orifices; the central orifice is 0.0625 inch in diameter and the side orifices are 0.032 inch in diameter. Brass tubing, 3/32 inch in diameter, extends from the orifices through the brass nipples to which rubber tubing is connected. This rubber tubing is then connected to a manometer.

Figure 2a - Photograph of Cylindrical Pitot Tube with Fittings Arranged to Measure Flow Angles

At the left is the stuffing box which is fitted with a scale to indicate the extension of the tube beyond the skin of the model.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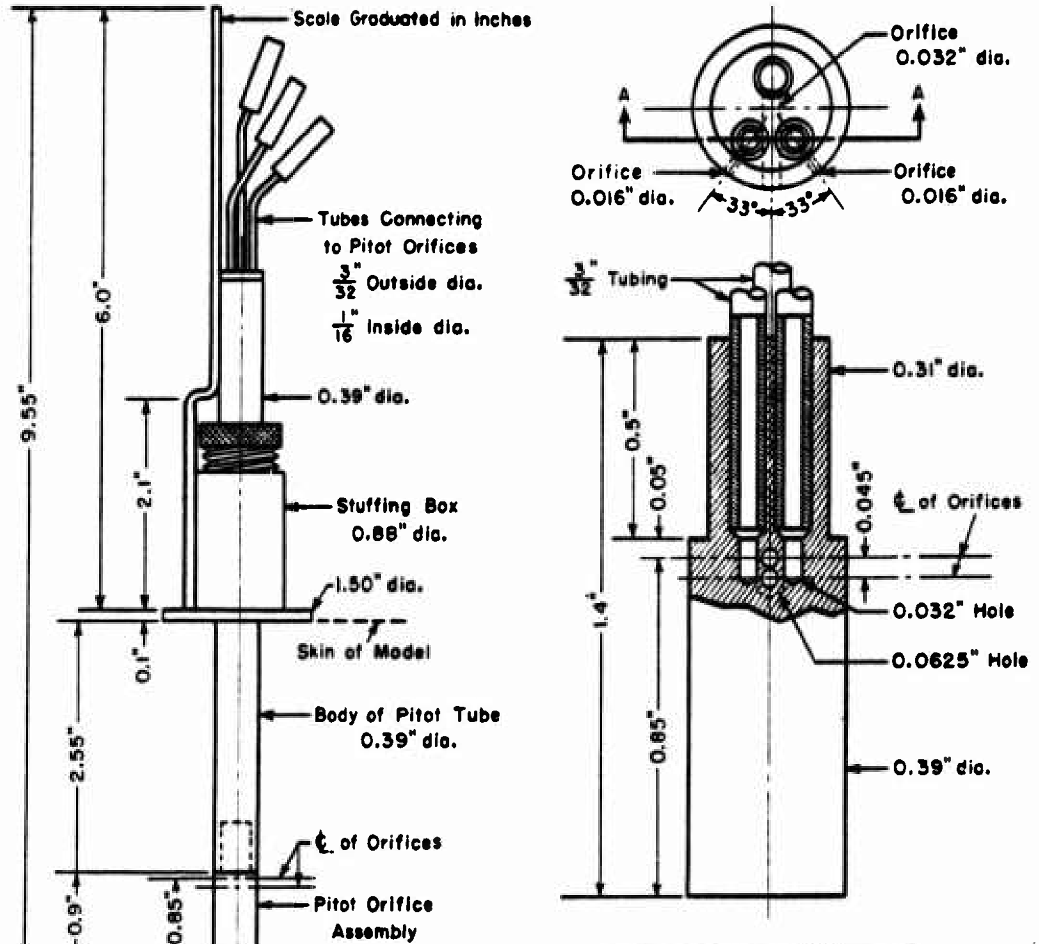
These pitot tubes protrude from the bottom of the model and may be extended, retracted, or rotated, as desired. In operation the pitot tube is extended outboard through its stuffing box until the pressure orifices are at the desired distance from the hull. When the model is underway at the proper speed, the tube is rotated until the side orifices read alike. The axis of the central orifice will then lie in the direction of flow. The speed of flow is indicated by the difference between the pressure reading at the central orifice and that at the side orifices.

A 3-tube manometer is used with the cylindrical pitot tube. The pressure head from the central orifice is measured with a mercury U-tube, and the small pressures from the side orifices are read on straight water tubes; see Figure 3. These manometers are usually mounted on the model since the rubber tubes leading from the pitot tube to the manometer can thus be made shorter.

The glass tubes are connected to a vacuum tank. A partial vacuum in the tank is used to raise the level of the water to a height in the manometer



Detail of Pitot Orifice Assembly

Figure 2b - Sketch Showing Arrangement of Orifices

Figure 2 - Cylindrical Pitot Tube

tubes convenient for observation, or, in the mercury manometer, to bring the water into contact with the mercury.

A difficulty introduced by the operation of a water manometer under reduced pressure is that some of the air in the water is released and forms bubbles which must be removed from the water columns. To facilitate this elimination of the air, the tubes from the pressure orifices to the manometer are made as nearly vertical as possible, and any downward bends are avoided as they are likely to cause air pockets.

The measurement of speed depends on the calibration of the pitot tube. For calibration the pitot tube is attached to the towing carriage in such a way that it projects down into the water and is immersed for most of its length. A brass plate is soldered to the pitot tube, normal to its axis and just below the surface of the water to prevent air from being drawn down behind the tube. When the towing carriage is in motion, the pitot tube is

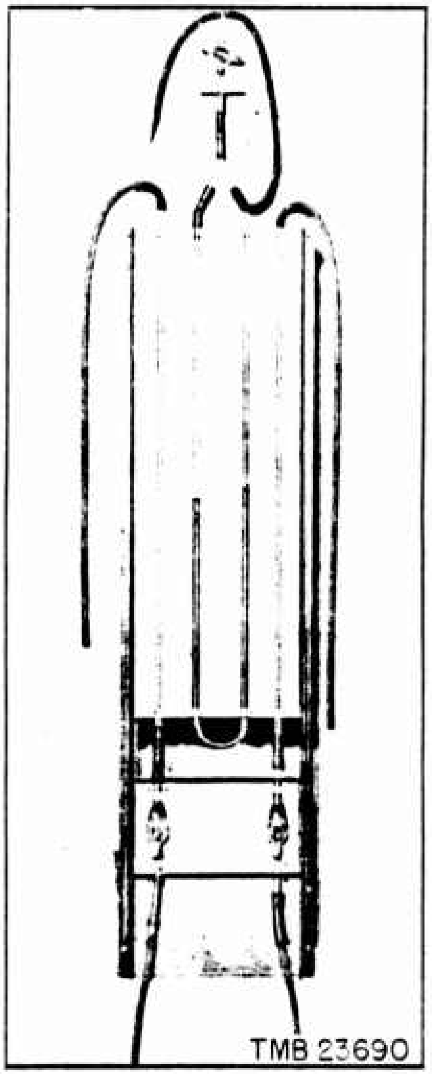


Figure 3 - Mercury-and-Water Manometer Used with Cylindrical Pitot Tube

rotated until the side orifices read alike. The tube is then assumed to be headed in the direction of motion. The pressure in inches of water or mercury and the corresponding carriage speed are recorded. Readings are made covering the desired range of speed. Figure 4 is a sample calibration sheet of a cylindrical pitot tube.

The cylindrical pitot tube has been used in full-scale tests as well as in model-basin tests. During 1934 and 1935 the Experimental Model Basin conducted trials of the USS HAMILTON (DD141) in which the flow around the hull of the ship was thoroughly explored with cylindrical pitot tubes. The tubes used in these tests were 3 inches in diameter and could be extended to measure the flow 42 inches from the skin of the ship.

The cylindrical pitot tube measures speed and direction in only one plane. When direction only is required, as in the aligning of strut arms with the flow, it produces acceptable results.

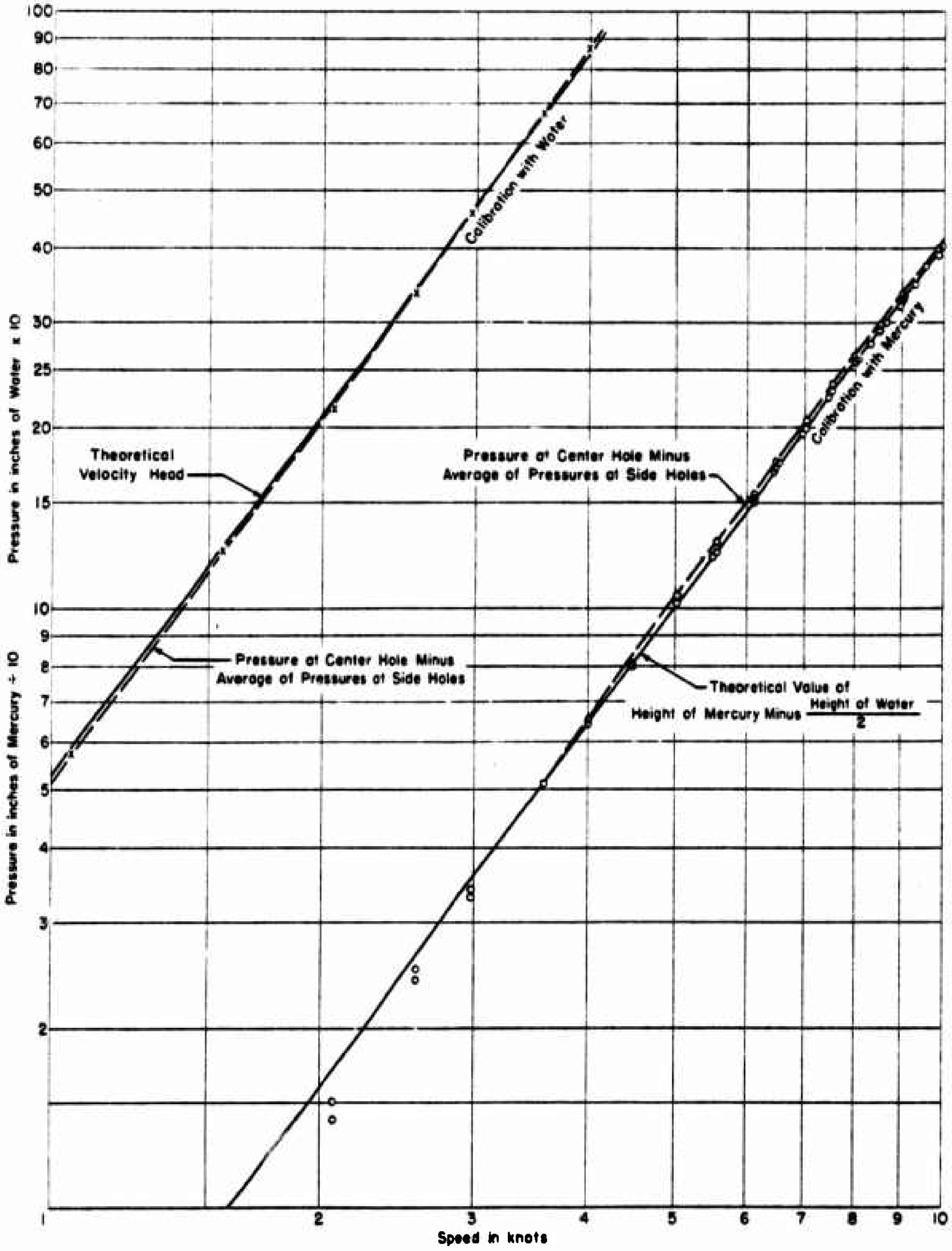


Figure 4 - Calibration Chart of a Cylindrical Pitot Tube

The tube with which this calibration was made was 0.376 inch in diameter, and was immersed 2.5 inches. An air guard was placed 0.73 inch above the midpoint of the holes. The calibration was made with a mercury-and-water manometer.

SPHERICAL PITOT TUBE

To obtain a more complete record of both speed and direction of flow, a spherical pitot tube was designed by Admiral Taylor.

The original spherical pitot tube is shown in Figure 5. In ordinary operation the upper arm was vertical and the lower arm extended forward with its axis fore and aft. The forward end of the lower arm terminated in a hollow brass sphere 3/4 inch in diameter with five orifices in the forward hemisphere. One orifice was on the axis, two were on a horizontal great circle and two were on a vertical great circle, each 49 degrees from the axis. Each orifice was connected by brass and rubber tubing to a vertical glass tube; water was drawn into these tubes by partial vacuum. By this means the change in pressure at the orifices could be measured.

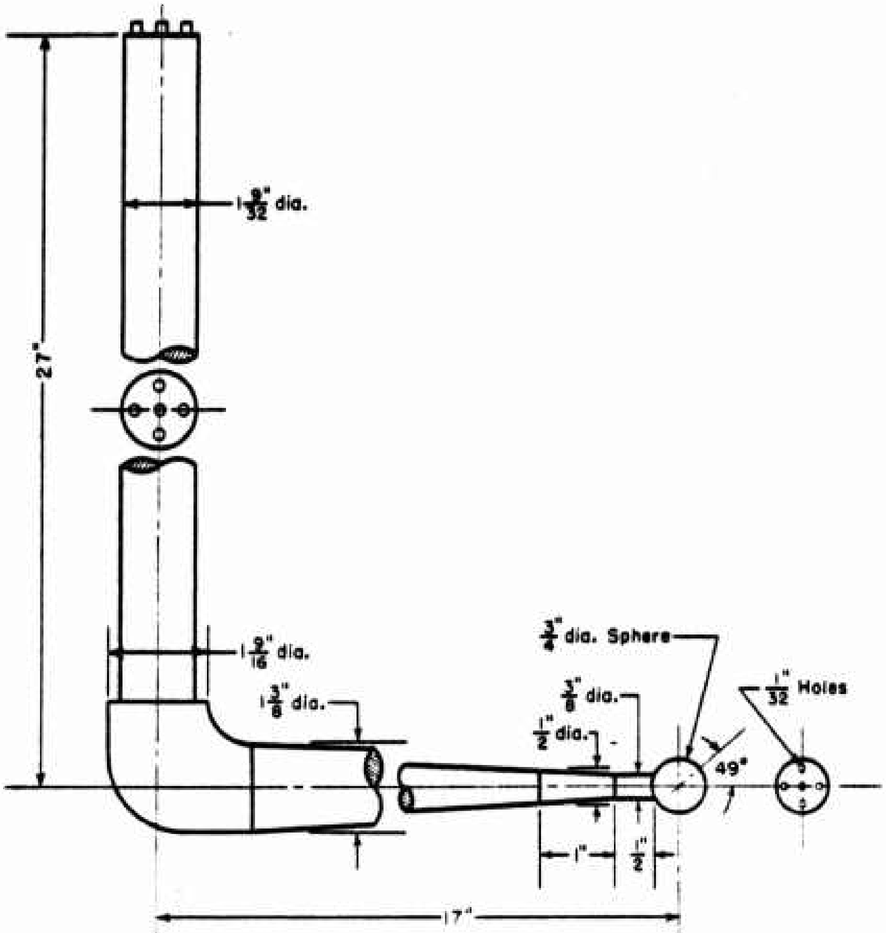


Figure 5 - Sketch of 5-Orifice Spherical Pitot Tube

This tube was calibrated in 1915 from the model-basin towing carriage by towing it through the water with the axis of the tube at various angles from both the vertical and horizontal. It was found that the

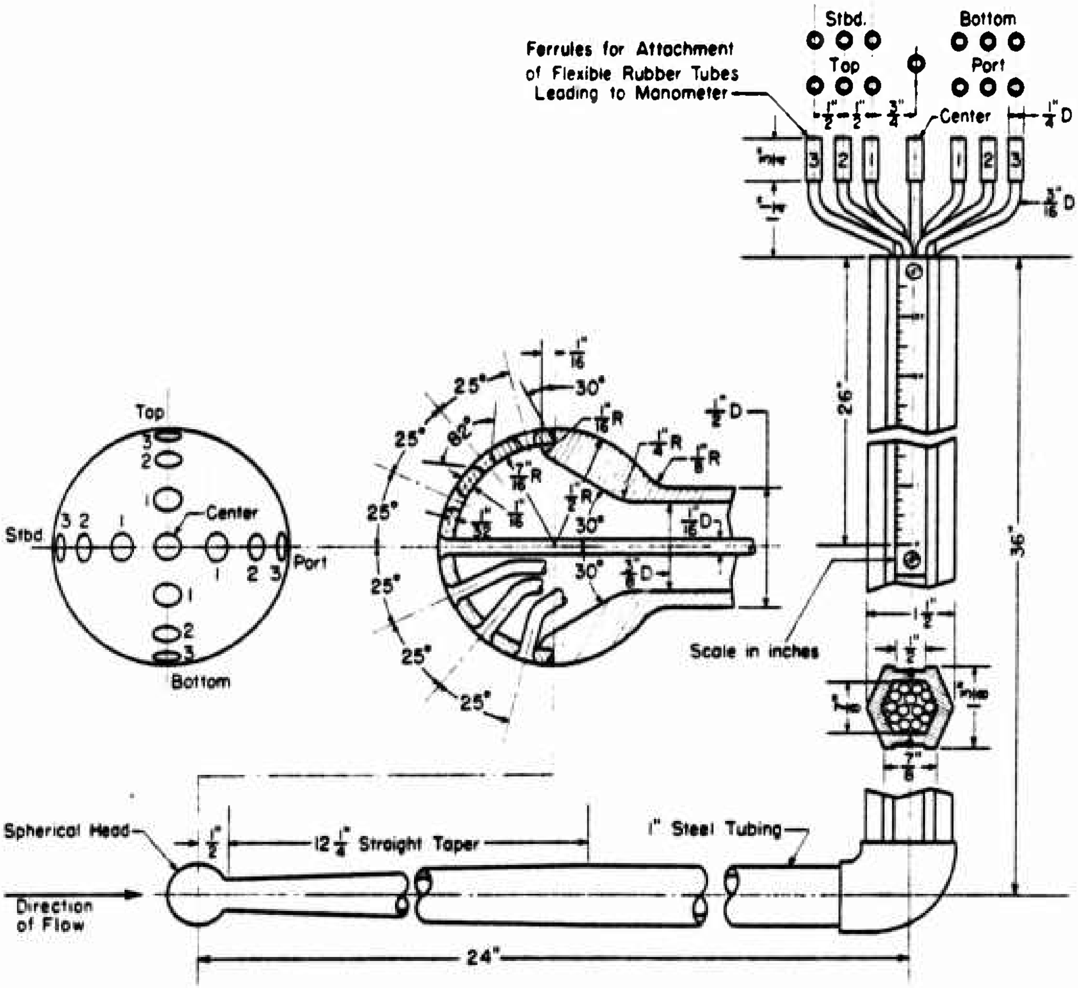


Figure 6 - Sketch of 13-Orifice Spherical Pitot Tube

difference between the pressure head measured at the central orifice and the average head at the other orifices indicated the speed, and the differences of pressure head shown in the tubes connected with the side orifices permitted the angle of advance to be determined.

The results obtained with this tube were accurate when the angularity of flow was small. However, when the angles exceeded 10 degrees, it was necessary to solve for them by a series of approximations; when the angles approached 20 degrees, the result was doubtful. Consequently, when the original tube was accidently damaged, new tubes were designed which had 13 orifices in a sphere 1 inch in diameter. As shown in Figure 6, there was a central orifice on the axis of the tube, 6 orifices on a horizontal great circle at 25-degree intervals, and 6 on a vertical great circle at 25-degree intervals. All orifices were 1/16 inch in diameter. Each orifice was connected by copper and rubber tubing to one tube of a manometer.

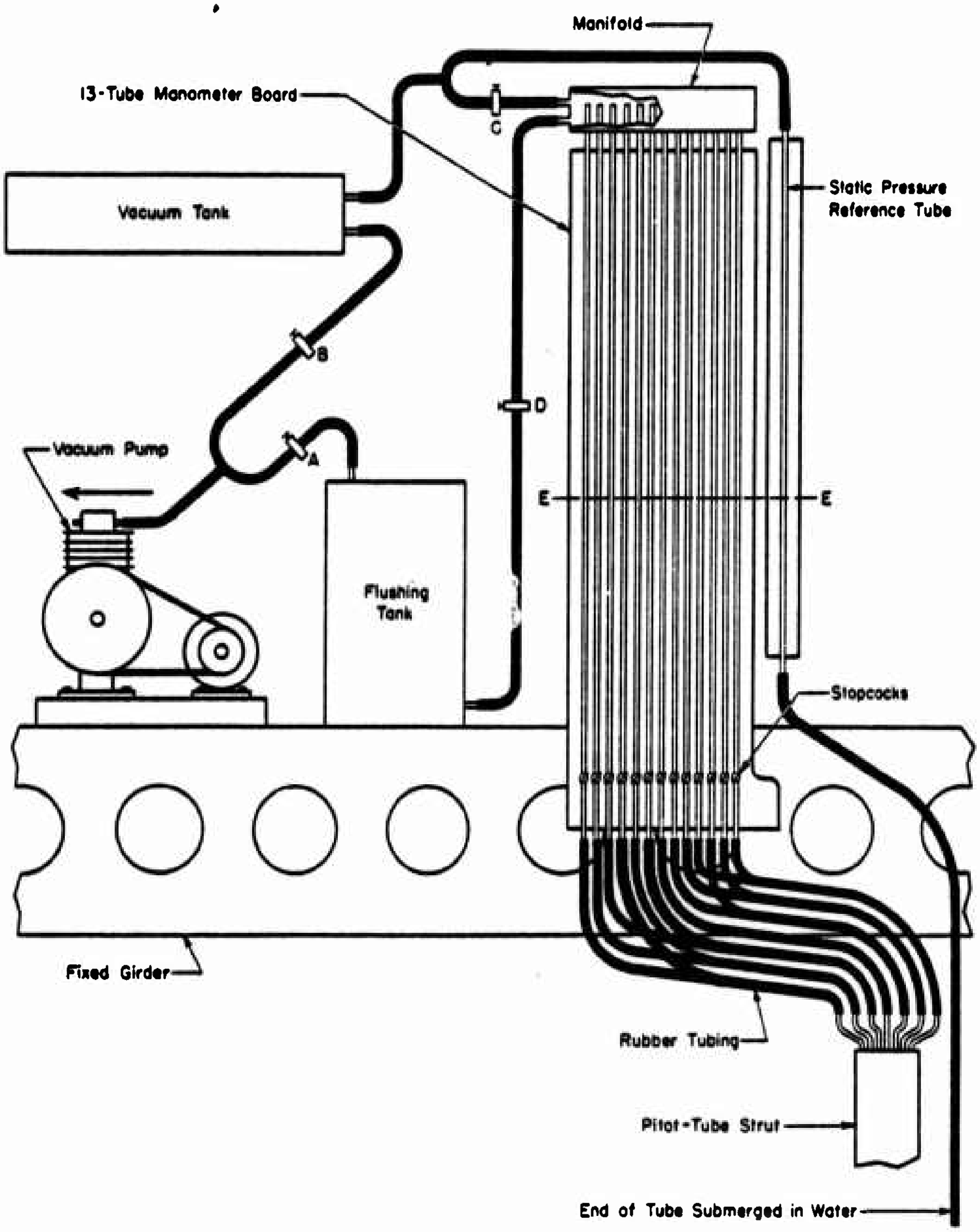


Figure 7 - Diagrammatic Arrangement of the Manometer and Pitot-Tube Connections

Each tube on the manometer board is connected to one of the 13 holes of the pitot tube. The system is then filled by opening the pinch clamps *A* and *D* and evacuating the flushing tank, thus drawing the water of the basin into the tubes and allowing it to spill over into the tank. The flushing is continued until all the tubes and leads are cleared of air bubbles. The pinch clamps *A* and *D* are then closed and *B* is opened. The pressure in the vacuum tank is reduced until the water column in the static reference tube reaches a convenient height E-E. The pinch clamp *B* is closed and *C* is opened to allow the water columns to settle to E-E. Pinch clamp *D* is then momentarily opened until the manifold is entirely drained of water. The manometer-tube water levels obtained from a run are maintained by closing the stopcocks before the carriage starts to decelerate at the end of each run. They are opened again on the next run after the carriage speed becomes constant.

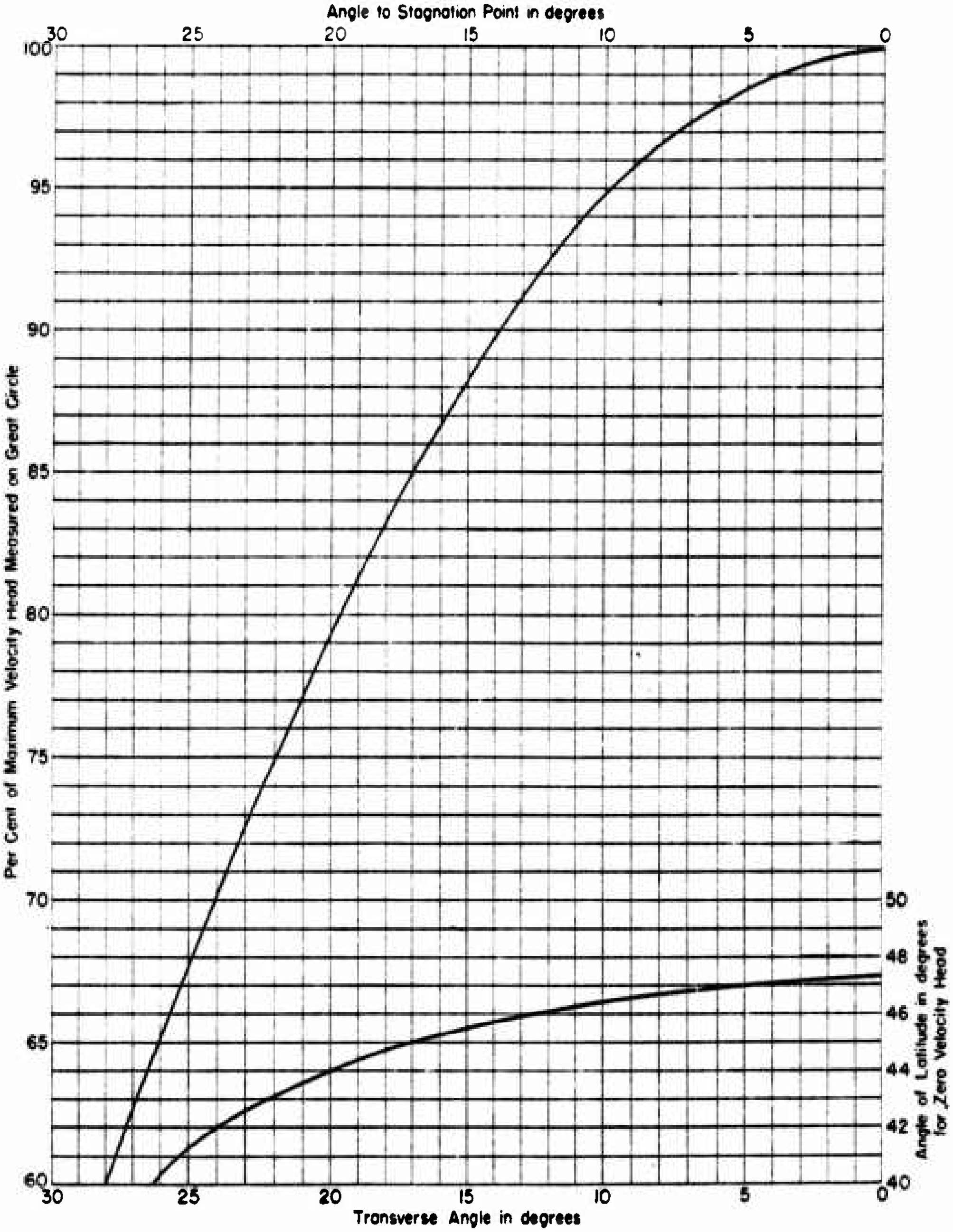


Figure 8 - Sample Calibration Chart of a 13-Orifice Spherical Pitot Tube

Ordinarily a straight-tube water manometer, shown in Figure 7, is used with the spherical pitot tube. This manometer is suitable for speeds below 7 knots. When it was desired to investigate the wake of models at higher speeds, it became necessary to have an instrument with a greater range of measurement. A 13-tube mercury manometer was designed for this purpose. This

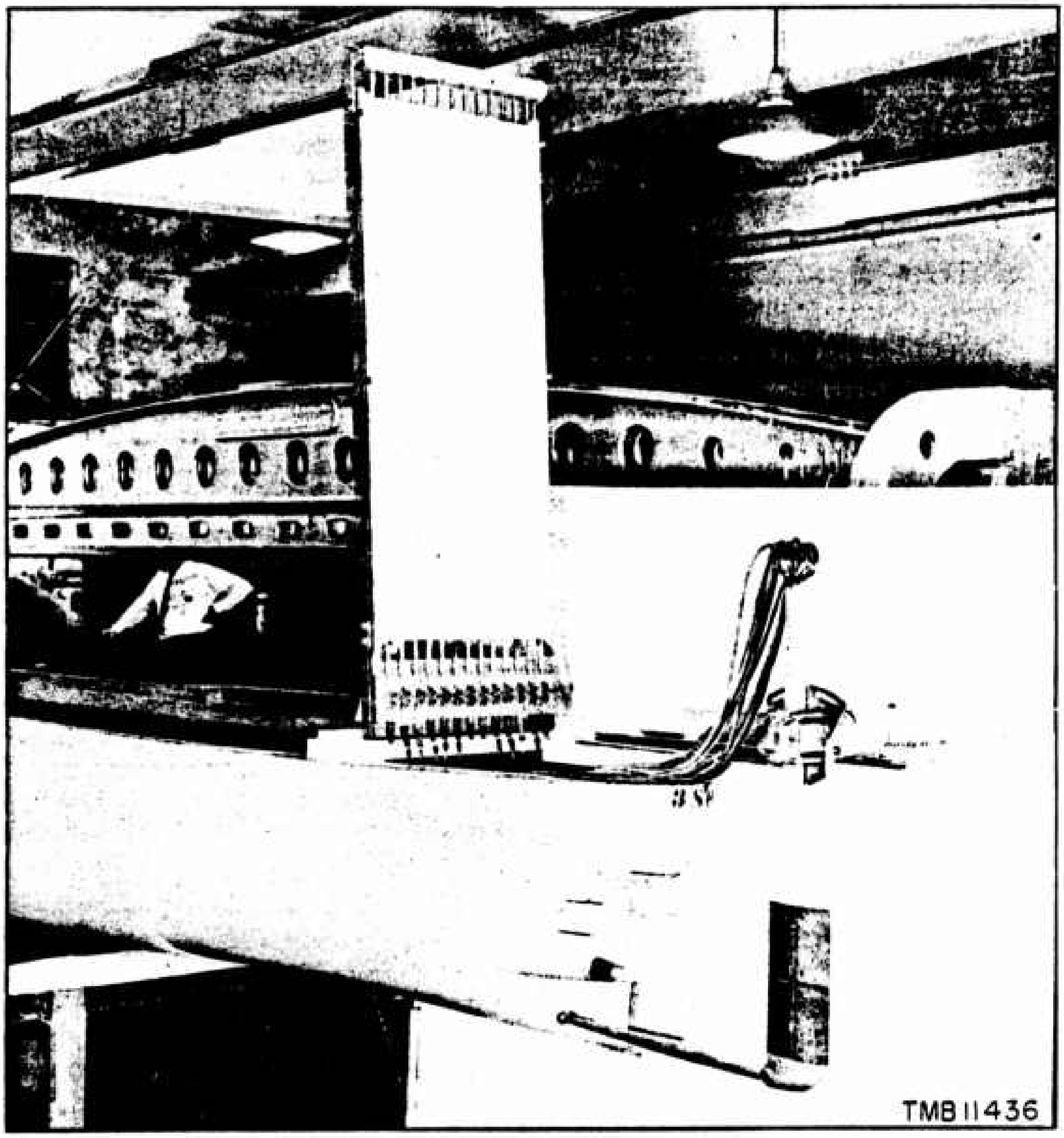


Figure 9 - Spherical Pitot Tube and Manometer Mounted on Model

The position of the sphere relative to the model may be varied by working from above the surface, changing the adjustments on the clamping mechanism attached to the stern of the model. A fairing is fitted to the vertical leg of the pitot-tube assembly to prevent lateral vibration of the apparatus at high towing speeds.

manometer is very satisfactory for speeds up to 12 knots. The tubes are connected to a manifold at the top from which a tube leads to a vacuum tank. A partial vacuum in the tank is used to bring the water into contact with the mercury.

These manometers are fitted with stopcocks by means of which the columns are closed off before the end of a run and read while the carriage is making its return trip. Readings are considered correct when they check from one run to the next within 0.1 inch of water.

Appendix 1 explains the method of operation of the spherical pitot tube, and Appendix 2 shows how the data obtained with this tube are used to determine the angle of inclination of strut arms which produces the least interference with flow.

The method of calibrating this tube is similar to the method of calibrating the original spherical pitot tube described on page 10. A sample calibration chart is shown in Figure 8.

There are some problems in propeller design for the solution of which a complete and detailed knowledge of the wake in way of a propeller is necessary. The spread between the maximum and minimum values may have a serious effect on vibration, and the direction of the flow may determine the relative efficiencies of outboard- and inboard-turning propellers. Exploration of the wake by the spherical pitot tube is of great value in such tests. The pitot tube and manometer are set up on the model as illustrated in Figure 9. A wake diagram measured by this tube is shown in Figure 10. The variation of wake over the area tested is clearly shown and the effect of the shaft and bosses may be seen.

The advantage of the spherical pitot tube over other instruments used to measure the flow of water around a model is that by its use a complete measurement of both the speed and the direction of flow is obtained. With these tubes, angles of flow up to 25 degrees can be measured directly with an accuracy of less than 1 degree.

Since the sphere containing the pressure orifices is relatively large in size, interaction between the tube and the adjacent surface of a model may be expected to introduce an error when the tube is near the surface of the model. To investigate this effect, tests were made with the pitot tube alongside a friction plane and also abreast the parallel middle body of a model of a Great Lakes freighter. It was found that the measurement of longitudinal flow was practically unaffected but that the measurement of transverse flow required correction both as to angle and as to magnitude when the space between the sphere and the model surface was less than the diameter of the sphere.

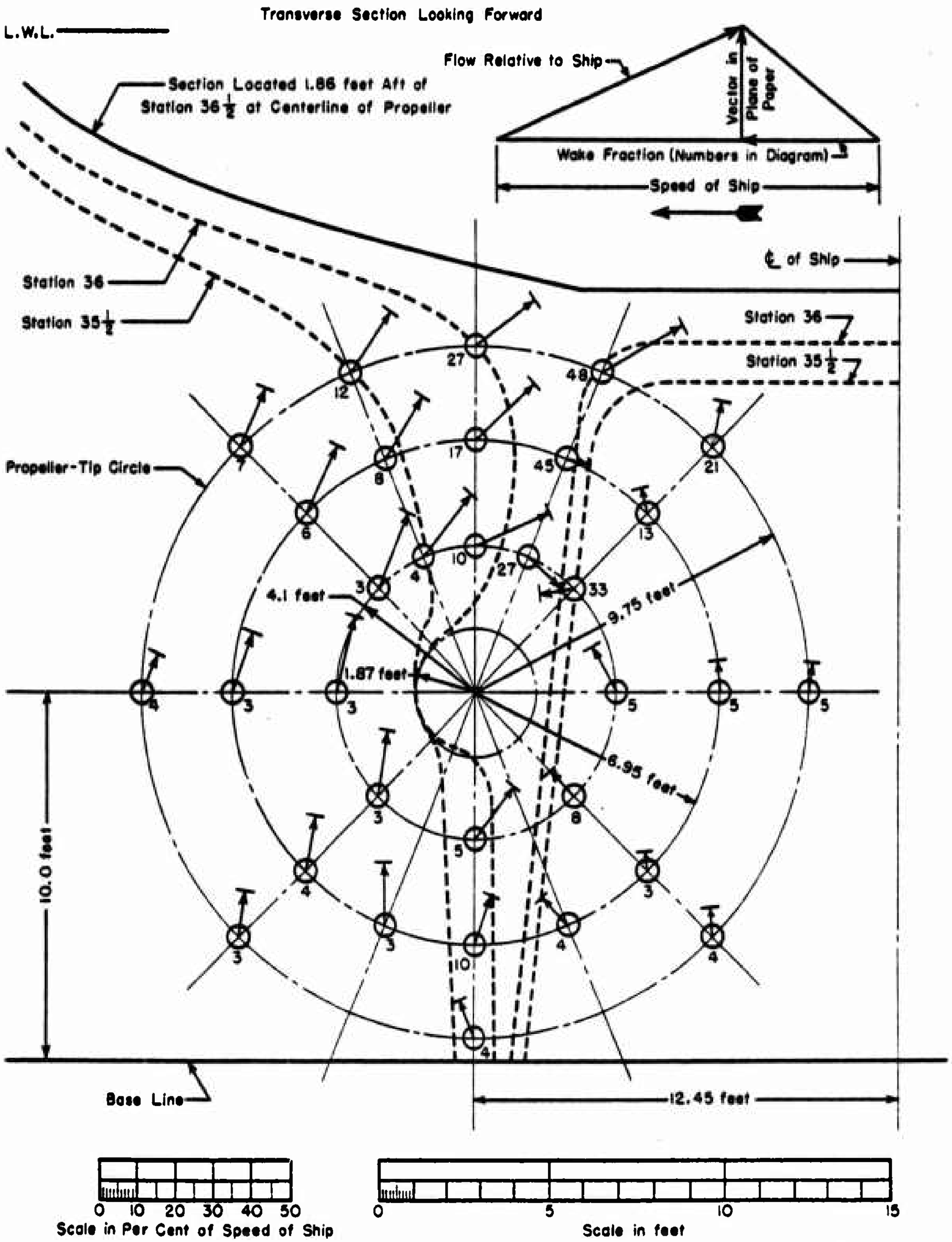


Figure 10 - Wake Diagram from Measurements by Spherical Pitot Tube

The bilge keels, dummy hubs, fairwaters, shaft, and bosses were in place when this test was made. The arrows are vectors showing the transverse components of wake in fractions of the speed of the ship. The numbers indicate fore-and-aft components of the wake in per cent of ship speed. These data were obtained from tests on Model 3738.

ROTATING WAKE METER

To design a propeller it is necessary to know its speed of advance through the water and hence the wake. Model-basin tests show that the wake varies over the disk of the propeller through a wide range of speed, especially for single-screw installations, and that the average wake in way of the tips of the blades is different from that near the hub. The pitch of the blades between the hubs and the tips can be varied to adapt each part of the average speed of the water in which it operates. The rotating wake meter was designed to measure the *average* speed of the wake and its radial variation. From these data an analysis of the wake can be developed and studied, and pitch variations may be designed to suit the propeller more accurately to this wake and thus increase the efficiency of the propeller. Thus, if the average wake is measured in a series of rings of increasing diameters, the pitch at a number of radii may be correspondingly designed, and a curve determined for radial pitch variation.

The rotating wake meter used at the Taylor Model Basin has a brass body on which vane wheels of various sizes can be mounted, as shown in Figure 11. The meter body is 3 inches long and can be attached to a brass tube of sufficient length to fit into the propeller-shaft tube of the model to be tested. The vane wheels are mounted on the meter body in the position of the propellers. A wooden fairwater and bushing similar to the propeller hub are fitted around the meter.

There are 16 vane wheels whose diameters increase from 1 1/4 inch to 12 1/2 inches in 3/4-inch increments. Two of these vane wheels are shown in Figure 12. The chromium-plated brass blades are 3/8 inch wide and are screwed onto nickel-plated tool-steel spokes so that their leading edges are at an angle of 45 degrees with the direction of travel. The spokes are in turn screwed into a brass hub.

The vane wheels are mounted, one at a time, on the wake-meter body and turn as a windmill with the flow of water as the model is towed. The wheels drive a worm gear which operates an electric contact maker, and the revolutions and the speed are recorded. Each vane wheel averages the speed of flow in a ring 3/8 inch wide.

To determine the speed of flow from the number of revolutions of the vane wheels, each vane wheel must be calibrated by running it in open water on a frame similar to that of the spherical pitot tube except that the vane wheel replaces the sphere. The frame is attached to the towing carriage, and runs are made throughout the required range of speed. This calibration must be made for each test.

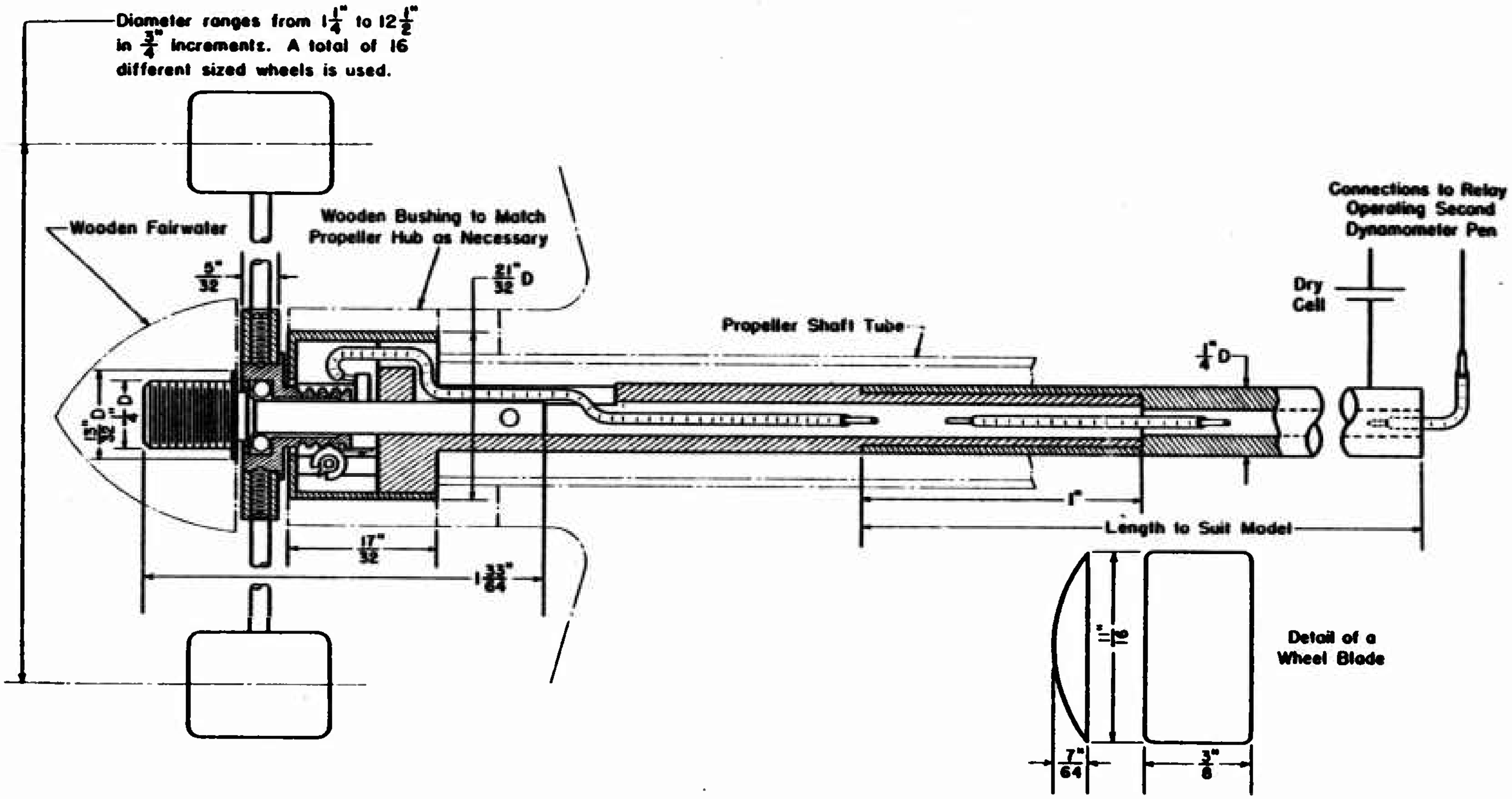


Figure 11 - Sketch of the Rotating Wake Meter

The vanes are set at angles similar to those of propeller blades so that the flow of the water causes the vane wheel to rotate like a windmill.

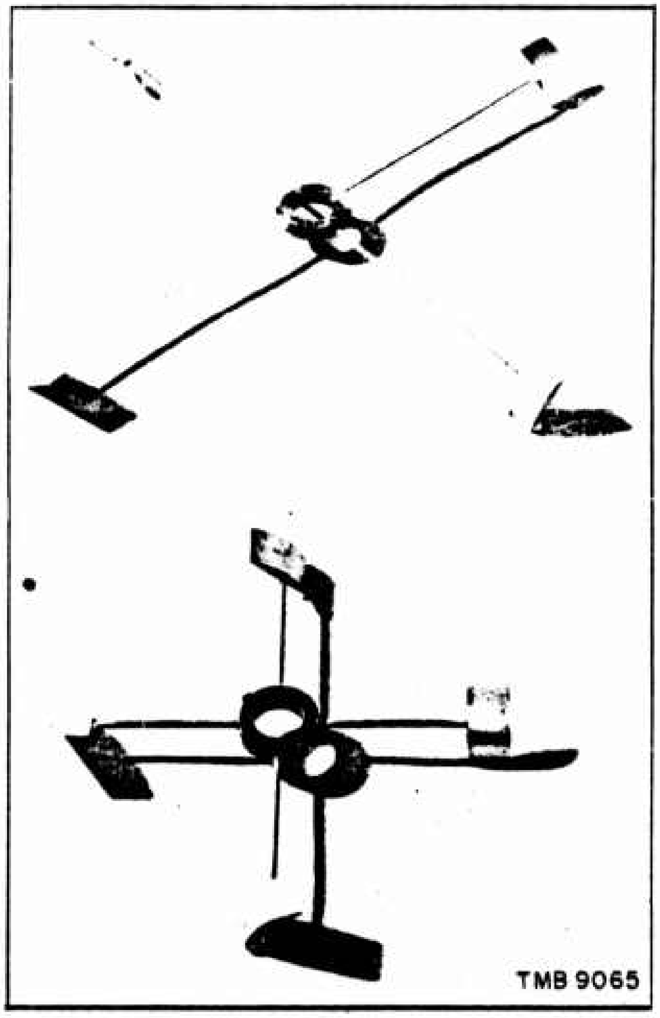


Figure 12 - Two of the Vane Wheels Used with the Rotating Wake Meter

The rotating wake meter was used in an extensive series of tests on 12 ship models over a period of 3 years. The results obtained in these tests were very satisfactory and agreed well with results obtained with pitot tubes.

BOW LOG

A pressure speed log, called a bow log, was developed by the U.S. Experimental Model Basin about 1930. The bow log is based on the pitot-tube principle. It is mounted on the stem of a ship or model and has a single orifice in the center of the head. The size of the bow log depends on the size of the ship or model on which it is to be used. This apparatus measures static head at the bow plus velocity head due to the speed of the ship. The static head is determined when the ship or model is at rest and is substracted from the average total head to give the net head. The speed of the vessel through the water is found from a special calibration curve obtained in tests of a self-propelled model in a model basin with an impact tube and orifice the same as those on the ship.

In June 1931 the Experimental Model Basin used the bow log in tests of the destroyer HAMILTON.

The bow log used on the HAMILTON consisted essentially of a hemispherical head about 6 inches in diameter mounted in a special fitting on the stem of the ship well below the waterline; see Figure 13. In the center of this head, pointing directly forward, was a single orifice about 1/4 inch in diameter which was connected by a small pipe to an indicating gage and a recording gage in the forecastle. Its operation was so successful that it was used for the measurement of the ship speed during all the subsequent investigations of the boundary layer.

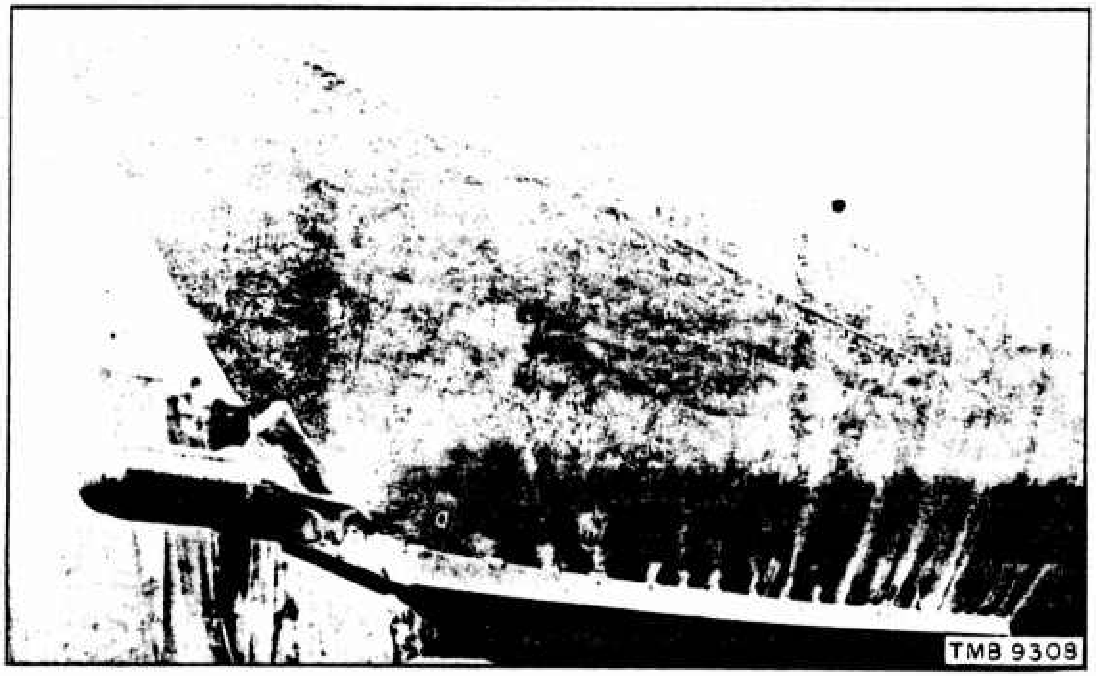


Figure 13 - Bow Log Installed on the USS HAMILTON (DD141)

It is considered a serious disadvantage of the bow log that the ship must be brought to rest to determine the static head. This disadvantage can be readily overcome by the use of a hole in the side of the ship or in the side of the impact tube. Early model tests showed that the head from such a hole when a ship is underway is not (as in a pitot tube) an accurate measure of the static head; therefore, it is called a quasi-static head. The quasi-static head can be used in place of the static head, and a calibration curve of ship speed against total head minus quasi-static head can be used in place of the ordinary calibration curve previously described. The new calibration curve is just as good as the old one for accurately determining ship speed and it eliminates the disadvantage of stopping the ship to determine the static head. The quasi-static head varies for different speeds and can be determined only from a model test. When it was finally realized that a model test was necessary anyway in order to calibrate the log, it became apparent that it would be better to use quasi-static head instead of static head in all calibration curves.

INSTRUMENTS USED BY OTHER MODEL BASINS

To investigate the flow in the vicinity of the side of a ship, G.S. Baker of the Froude Tank in Teddington, England, developed two types of pitot tube (10). The instrument used for measurements close to the hull is a single-orifice pitot tube of the basic type; it is shown in Figure 14. For measurements at greater distance from the hull an adaptation of the pitot-static tube, shown in Figure 15, is used.

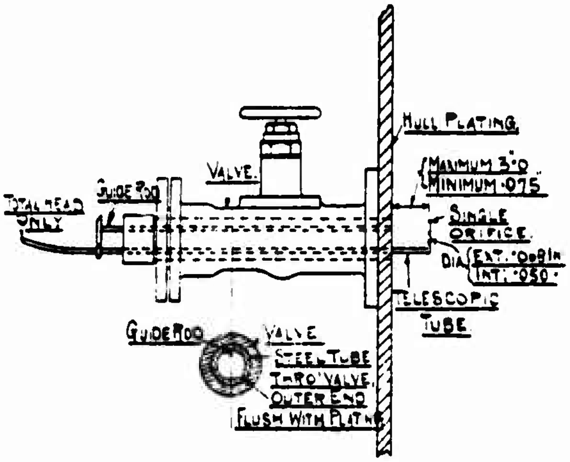


Figure 14 - Pitot Tube of the Basic Type with Single Orifice

This is Figure 8 of Reference (10).

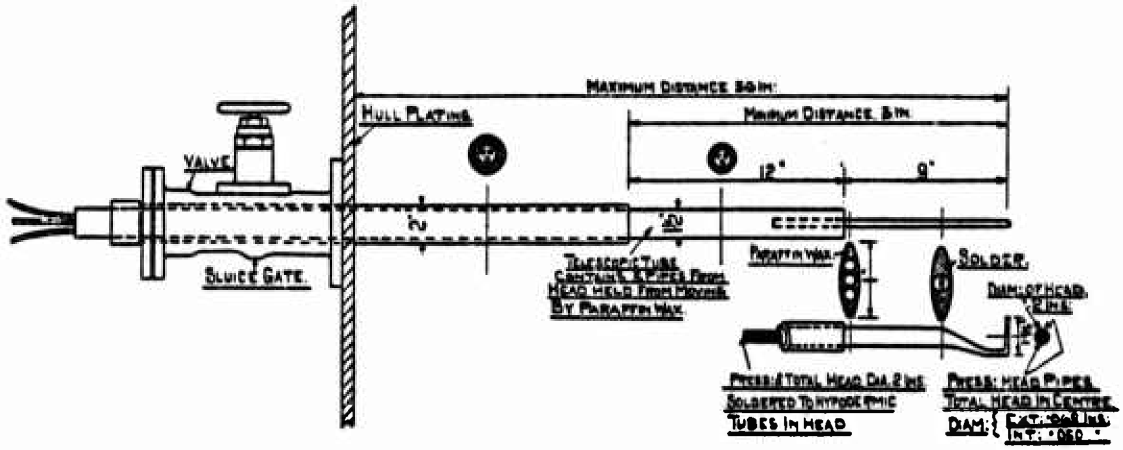


Figure 15 - Baker's Variation of the Pitot-Static Tube

This is Figure 7 of Reference (10).

For similar purposes a cylindrical pitot tube was developed at the Berlin Tank. This tube is shown in Figures 16 and 17 and is described in detail by Wilmar Laute in Reference (11). The tube has an opening at the front for measuring total pressure and openings at 40 degrees on either side for measuring static pressure. The inside of the tube is divided into three parts by a Y-shaped partition, so that the pressure of each opening can be read separately on a manometer.

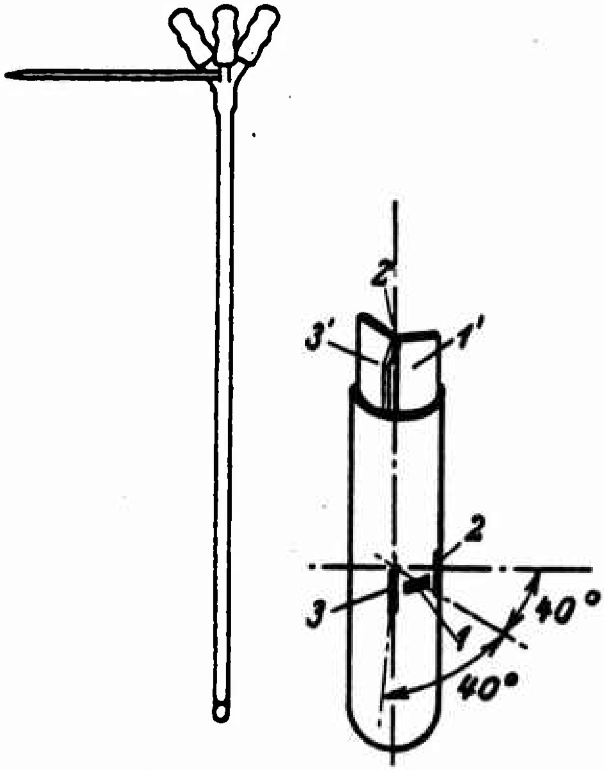


Figure 16 - Sketch Showing Details of Cylindrical Pitot Tube Used by Laute

This is Figure 6 of Reference (11).

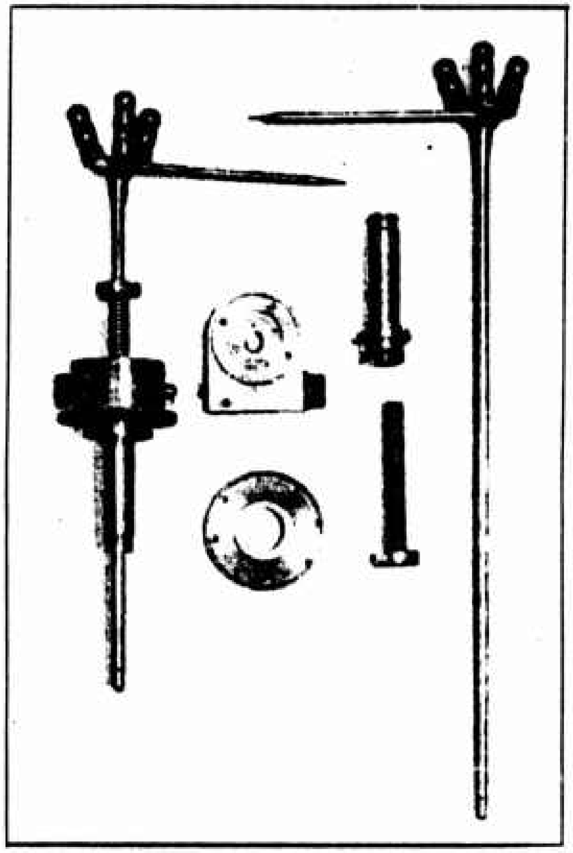


Figure 17 - Cylindrical Pitot Tube Used by Laute in the Berlin Tank

This is Figure 8 of Reference (11).

The Dutch have a spherical pitot tube with five orifices; this tube is described in Reference (12). One orifice is situated on the axis of the tube, two lie on a meridian 45 degrees from the central orifice, and the other two on the appertaining equator 50 degrees from the central orifice. This pitot tube must be rotated about its vertical axis during measurement until the pressures at the orifices on the equator become equal. Under such conditions the angle formed with the equatorial plane, the velocity and prevailing static pressure, and the angle described with respect to a vertical reference plane, determined by rotation, can be found successfully from the pressure data for the remaining orifices.

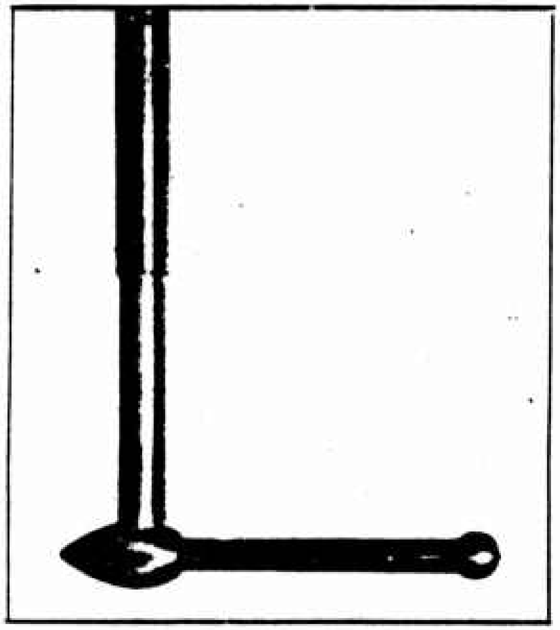


Figure 18 - Spherical Pitot Tube Designed by Gutsche

This is Figure 11 of Reference (13).

F. Gutsche of the Berlin Tank designed a spherical pitot tube with five orifices, similar to the spherical pitot tube described in this report. Gutsche's pitot tube is shown in Figure 18 and is described in Reference (13).

The Berlin Tank uses vane wheels for wake measurements (14). These bladed wheels give the mean wake velocity over the circumferences of concentric circles.

At the Netherlands Model Basin in Wageningen another method of determining wake has been used. The resistances of stationary pressure rings of various diameters are measured. The rings are installed in place of the propeller. By means of the resistance curve thus determined, the mean velocities corresponding to the ring resistance measured with the model can be determined. This method is described in detail in Reference (15).

In the Froude Tank at Teddington, England, wake measurements are made with propellers (16).

ACKNOWLEDGMENTS

These investigations of flow were conducted by various members of the U.S. Experimental Model Basin Staff. A.V. Curtis worked out the design of the original spherical-ended pitot tube under the direction of Rear Admiral D.W. Taylor. The 13-hole tube in use at present by the Hydromechanics Division of the David Taylor Model Basin was a further development made by the author in 1940.

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[redacted]

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APPENDIX 1

METHOD OF OPERATION OF SPHERICAL PITOT TUBE

With the spherical pitot tube installed on a model at the position to be explored, the model is run at the desired speed and the heights of the water columns in the manometer are recorded.

These manometer readings are plotted, and two curves are drawn, one for the readings along the horizontal circle and the other for those along the vertical circle. The horizontal curve is symmetrical about a vertical plane which contains the stagnation point. Thus the angle between the "zero" or polar orifice and the axis of symmetry of the "horizontal" curve is the horizontal component of the angle of flow relative to the fore-and-aft axis of the pitot tube. The vertical component is found in a like manner. Then, if θ is the angle of flow relative to the axis of the pitot tube and h and v are its horizontal and vertical components respectively,

$$\theta = \sqrt{v^2 + h^2}$$

within limits well below the experimental limits of error for angles up to 25 degrees.

To find the velocity of the flow it is necessary to determine the angle of latitude on the sphere at which the change of pressure due to speed is zero, since the static pressure underway is usually different from the static pressure at rest. This is done by calibration. The pitot tube is run in open water with the axis of the lower arm in the line of advance at speeds ranging from 3 knots to 7 knots. The horizontal and vertical curves of pressure readings are plotted for each condition; then the velocity heads corresponding to the speeds as measured by the basin carriage are laid off on the appropriate curves at zero angle from the maximum point downward; see Figure 19.

Since the variation of this angle throughout the range of speed is irregular and small, the average is used for all speeds. For Pitot Tube 1 this angle was 47.3 degrees. This angle of 47.3 degrees was found with the stagnation point at the pole and applied only to that condition, so further calibration was necessary to find the reduction in the angle as the direction of flow is changed. For this purpose the pitot tube was run with its axis at angles with the direction of advance varying from 0 degree up to 25 degrees

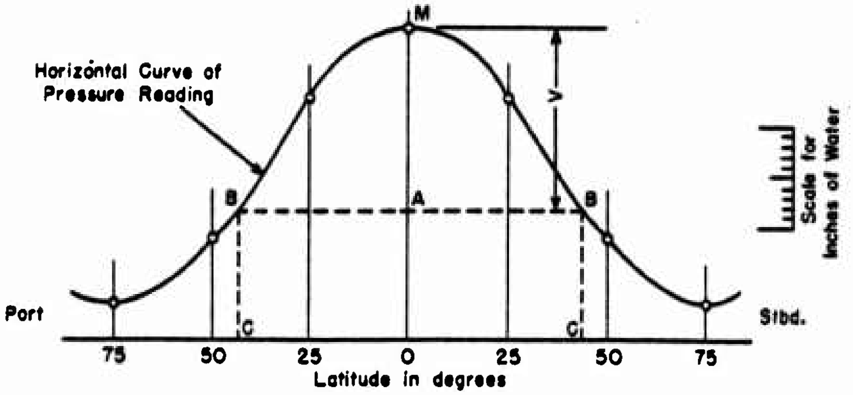

Figure 19 - Horizontal Curve of Pressure Reading

In the diagram *V* is the velocity head. *V* laid down from *M* determines the point *A*. *B*, *B* are points on the curve which have the same pressure reading as *A* and hence are points of zero change of pressure. *C*, *C* are the readings of *B*, *B* on the angle scale and determine the angle at which the change of pressure due to speed is zero.

in both horizontal and vertical planes. From the results of this calibration a curve of angles was obtained from which the static pressure underway could be found. Thus, if the vertical component of the angle of flow is 10 degrees and the horizontal component is 0 degree, the angle of zero pressure change is 46.4 degrees for the horizontal curve and 47.3 degrees for the vertical curve. Note that the vertical angle of flow determines the angle of latitude for the "static" on the horizontal curve and vice versa.

With the tube thus calibrated, the angular reading for zero pressure change may be found for any curve of pressure readings for a position behind a model. In this way a base line is fixed for each curve, from which the net pressure may be read.

For each experimental position two determinations of the net pressure are thus measured at the central orifice, one from the horizontal curve and one from the vertical curve. It has been found in practice that for a model speed of 5 knots these values should check within about 0.1 inch of water except when the flow is rendered irregular by model appendages such as skegs or struts ahead of the pitot tube.

With the static pressure underway determined, the wake values are found as follows:

1. The angle of flow θ is found from its components as previously described:

$$\theta = \sqrt{v^2 + h^2}$$

2. From the net head at the central orifice and the angle θ, the velocity head is found by use of the calibration curve, which is plotted in fractions of maximum. This measures the velocity of the water relative to the

pitot tube and thus to the model to which the pitot tube is secured.

3. From the velocity and the angle θ, the longitudinal wake and the wake in a transverse plane are computed.

4. A transverse section of the ship is then laid off in way of the test positions. At each test position a vector is laid off to represent the transverse motion of the wake. The longitudinal wake is indicated by numbers which give its value in per cent of the model speed; these values of wake are then ready for use in the design of propellers or in aligning the strut sections with the flow.

APPENDIX 2

DETERMINATION OF ANGLE OF TWIST OF STRUT ARMS FOR LEAST INTERFERENCE WITH FLOW FROM RESULTS OF TESTS WITH SPHERICAL PITOT TUBE

SOLUTION FOR STRUT ARM WITH NO RAKE

In Figures 20 and 21 the point O is a test position on the centerline of the strut arm XY. The flow at this position with the strut removed is measured by the pitot tube. In Figure 21, OG is the vector representing the transverse velocity of flow.

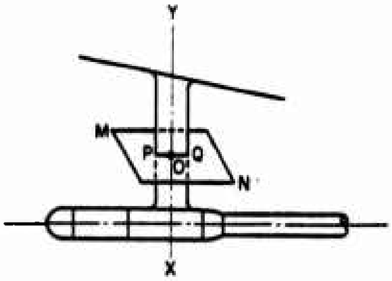

Figure 20

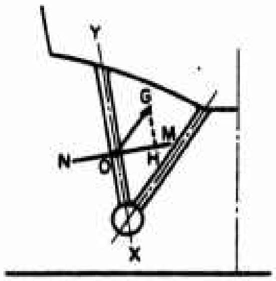

Figure 21

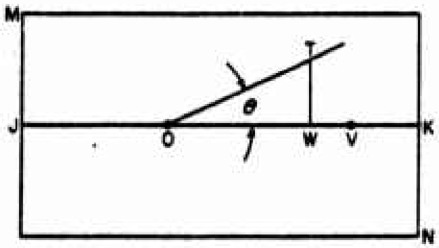

Figure 22

Pass a plane (M,N) through O normal to XY. In Figure 21, project OG on the plane (M,N); the projection OH represents the velocity of the transverse flow in the plane (M,N).

In Figure 20, PQ is the centerline of the section of the strut arm as cut by the plane (M,N). Then, for minimum interference with flow, PQ should lie in the direction of flow.

In Figure 22, (M,N) represents the plane normal to the centerline of the strut arm, JK is a line in the plane parallel to the centerline of the model through the test point O, OV represents the speed of the model, and VW represents the longitudinal wake. Then OW represents the resultant longitudinal velocity of the water in the plane (M,N).

From W lay off WT normal to JK and corresponding in length to OH in Figure 21. Then WT represents the transverse velocity of the water in the plane (M,N), and the direction of flow in the plane (M,N) is along the line OT at angle θ with JK.

For the centerline of the strut section, PQ in Figure 20, to lie in the line of flow it must therefore make the angle θ with JK. Therefore the section of the strut at the test position must make the angle θ with the model centerline.

SOLUTION FOR STRUT ARM WITH RAKE

In Figures 23 and 24, (M,N) is a plane normal to XY at the test point O and parallel to the centerline of the model.

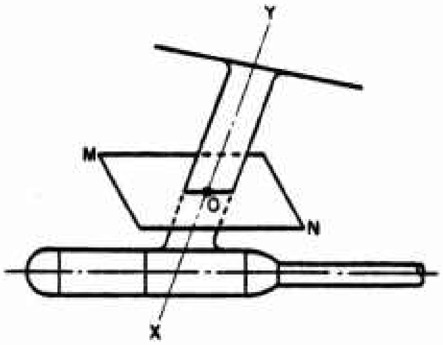

Figure 23

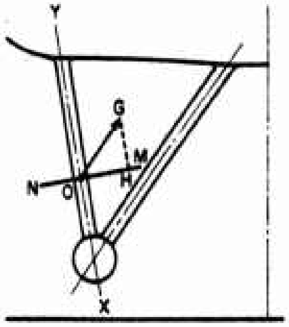

Figure 24

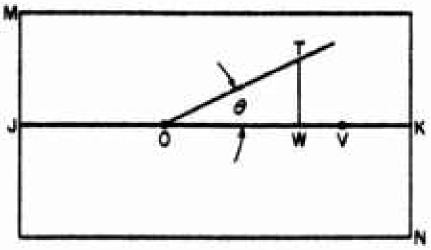

Figure 25

In Figure 24, OG represents the velocity of the transverse flow and OH the velocity of the transverse flow in the plane (M,N). In Figure 25, (M,N) represents the plane which is parallel to the centerline of the model and normal to XY at O in Figure 24. JK is a line through the test point O parallel to the centerline of the model.

From O on JK lay off OV to represent the speed of the model, and from V lay off VW to represent the velocity of the longitudinal wake. Then OW represents the velocity of the longitudinal flow. From W lay off WT equal to OH in Figure 24 to represent the velocity of the transverse wake in the plane (M,N). Then OT represents the velocity of flow in the plane (M,N), and θ is the angle in the plane (M,N) between the direction of flow and the fore-and-aft line JK.

In Figure 26, (M,N) is the plane described before, and (R,S) is a plane normal to (M,N), parallel to the centerline of the model, and intersecting (M,N) along a line which includes the test point O. Then, if the strut arm has no twist, the plane (R,S) contains the centerplane of the strut arm ABCD. XY is the centerline of the strut arm; it lies in the plane (R,S) and intersects (M,N) at O. Draw OF perpendicular to XY, then EOF, or ϕ, is the angle of rake.

To align the strut arm with the flow, the arm is rotated about the line XY until OE, the centerline of the horizontal section through the strut arm, makes the angle θ with the plane (R,S).

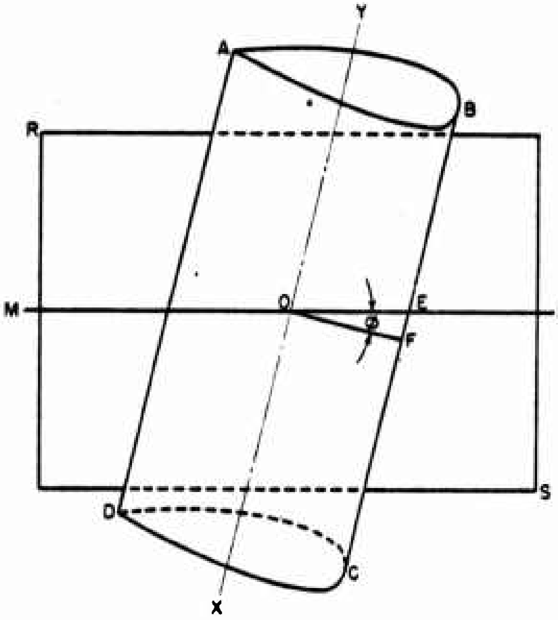

Figure 26

Now, when the strut arm is rotated to lie in the line of flow, every point on the line BC describes the same radius about the line XY. Thus E and F move equal distances from the plane (R,S), and both OE and OF will lie in a plane which contains the line XY and is set at an angle with it such that OE makes the angle θ with the plane (R,S).

To find the angle through which the strut arm has been rotated, let D be the distance between the point E as rotated and the plane (R,S). The distance of F from the plane is also D.

Then if α is the required angle

$$\sin\alpha = \frac{D}{OF}; \qquad \sin\theta = \frac{D}{OE}$$

$$\cos\phi = \frac{OF}{OE}$$

$$\sin\alpha = \frac{OE\sin\theta}{OF} = \frac{\sin\theta}{\cos\phi}$$

Or, for small angles, the angle of twist for a strut arm with rake is the angle of twist for no rake divided by the cosine of the angle of rake.

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