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PENNSYLVANIA STATE UNIV UNIVERSITY PARK APPLIED RESE--ETC F/G 13/10
SURFACE SHIP TESTING AT THE GARFIELD THOMAS WATER TUNNEL.(U)
JUN 77 A L TREASTER, J J EISENHUTH N00017-73-C-1418

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 TM-77-212	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 SURFACE SHIP TESTING AT THE GARFIELD THOMAS WATER TUNNEL	5. TYPE OF REPORT & PERIOD COVERED 9 Technical Memorandum	
7. AUTHOR(s) 10 A. L. Treaster and J. J. Eisenhuth	6. PERFORMING ORG. REPORT NUMBER	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Research Laboratory Post Office Box 30 State College, PA 16801	8. CONTRACT OR GRANT NUMBER(s) 15 N00017-73-C-1418	
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Washington, DC 20362	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS	
12. REPORT DATE 11 30 June 1977	13. NUMBER OF PAGES 30	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 33p.	15. SECURITY CLASS. (of this report) UNCLASSIFIED	
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE		
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release. Distribution unlimited. Per NAVSEA - 19 September 1977. 16 SAS 38		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) 17 SAS 38012		
18. SUPPLEMENTARY NOTES Submitted to the Society of Naval Architects and Marine Engineers for publication in the <u>Journal of Ship Research</u> or <u>Marine Technology</u> .		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) propeller hull cavitation wakes water tunnel surface ship		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The 48-inch (121.92 cm) diameter Garfield Thomas Water Tunnel of the Applied Research Laboratory was recently used to compare the relative cavitation characteristics of propellers operating on a surface ship hull. A basic objective of the investigation was to develop a method of using this facility for surface ship propeller evaluations. Evaluation of a propeller operated with a model hull in a water tunnel so that the three-dimensionality of the flow is maintained is one of several techniques		

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Subject: Surface Ship Testing at the Garfield Thomas Water Tunnel

References: See Page 17.

Abstract: The 48-inch (121.92 cm) diameter Garfield Thomas Water Tunnel of the Applied Research Laboratory was recently used to compare the relative cavitation characteristics of propellers operating on a surface ship hull. A basic objective of the investigation was to develop a method of using this facility for surface ship propeller evaluations.

Evaluation of a propeller operated with a model hull in a water tunnel so that the three-dimensionality of the flow is maintained is one of several techniques of testing surface ship propellers. Although neither Froude nor Reynolds number scaling was applicable, it was demonstrated that meaningful cavitation results could be obtained if the flow conditions in the plane of the propeller matched those measured in towing tank tests where the effect of the free surface was present.

Acknowledgment: The work described in this paper was sponsored by the Naval Sea Systems Command, Code 037, Subproject SAS 38012, Task 17730, U. S. Navy. This manuscript was prepared for submission to the Society of Naval Architects and Marine Engineers for publication in the Journal of Ship Research or Marine Technology.

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NOMENCLATURE

D_p	- the propeller diameter
J	- the advance ratio
K_Q	- the torque coefficient
K_T	- the thrust coefficient
n	- the shaft rotational speed
$P_{T.S.}$	- the uncorrected test section static pressure
P_v	- the vapor pressure of water at its average temperature
P_∞	- the desinent free stream static pressure
V_r	- the radial velocity component
$V_{T.S.}$	- the uncorrected test section velocity
V_x	- the longitudinal or axial velocity component
V_θ	- the peripheral velocity component
V_∞	- the nominal ship speed or the equivalent free stream test section velocity corrected for model blockage
ρ	- the fluid mass density
σ	- the cavitation index

1. INTRODUCTION

The Fluids Engineering Department of the Applied Research Laboratory (ARL) participated in a program to develop a reliable procedure for documenting the relative cavitation characteristics of a series of surface ship propellers using the ARL's 48-inch (121.92 cm) diameter water tunnel. This experimental facility, the Garfield Thomas Water Tunnel, is shown in Figure (1) and is described in Reference (1). The model propellers employed in the current programs had been previously evaluated in towing tank tests; whereas, the model hulls, auxiliary hardware, and instrumentation were fabricated especially for the water tunnel test programs.

The subject of testing propellers to be used on surface ships and in particular the simulation of the ship's wake is a very complicated one. The best method of performing laboratory tests of such propellers is a subject of continuing investigation. Some techniques presently used by various laboratories include: (1) flow regulation in a water tunnel by screens or metering devices in which only the axial velocity component of the ship's wake is simulated; (2) use of a complete ship model in an evacuated towing tank which enables the ship's wake, free surface effects and cavitation to be simulated; (3) mounting the propeller relative to a model hull shape in a water tunnel so that the three-dimensionality of the flow is maintained.

The first technique can be extended in some cases to include the simulation of radial and tangential components of velocity in the plane of the propeller by inclining the axis of the propeller by an appropriate amount. Generally, such an installation requires powering the model from behind, which negates any chance of observing the cavitating hub vortex.

The second technique is, of course, limited to a laboratory like the Netherlands Ship Model Basin (NSMB) at Wageningen, Reference (2), which has such a unique facility. Potentially it offers a means of scaling Froude number and cavitation number. However, the model size limitations to which experimentation is usually restricted makes Reynolds number scaling nearly impossible.

The third technique which has also been employed at NSMB offers another alternative for water tunnel facilities. It is this technique which has been applied in the ARL's 48-inch (121.92 cm) diameter water tunnel. The dimensions of this water tunnel's test section permits

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the installation of a model of reasonable size. This experimental technique does not permit complete Reynolds number scaling or, because there is no free surface, Froude number scaling. In effect zero Froude number or a rigid water surface is assumed. Reynolds number based on ship length does not appear to be a critical scaling parameter for this kind of test because the propeller is located outside of the expected hull boundary layer.

These considerations led to the conclusion that significant propeller cavitation testing could be conducted in the ARL's large water tunnel using a model hull of appropriate size. One of the objectives of this study was to determine the validity of this conclusion. While the effects of tunnel wall interference and the inability to scale Reynolds and Froude number were of great concern, it was felt that, if the flow conditions in the plane of the propeller could be demonstrated to accurately match those previously measured in towing tank tests, the cavitation test results would be meaningful. If a model hull alone proved inadequate in producing the correct flow field in the vicinity of the propeller, devices such as screens or judiciously placed inserts could be used to further alter the flow.

The ARL conducted test programs to evaluate the cavitation characteristics of a series of propellers for two surface ships. The validity of the ARL installations were verified by the close agreement of the propeller-plane wake surveys with those measured in towing tank tests. Comparison of the thrust and torque measurements with predicted full-scale data provided additional credibility to the water tunnel installation. These thrust and torque data provided the means for documenting the propeller cavitation characteristics on either a thrust or torque identity basis.

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Due to the limited amount of full-scale cavitation data, the cavitation scaling laws from model to full-scale are not well defined. However, it is possible to evaluate propeller cavitation characteristics on a relative basis using model propellers. This relative performance is dependent upon having the best possible modeling of the ship's wake, which means that the peripheral and radial components should be present. It is concluded, therefore, that the use of a model hull in the ARL 48-inch (121.92 cm) water tunnel, though not as good a simulation as is possible in a vacuum towing tank, is better than that which can be attained with a flow regulator or screens which simulate only the axial wake velocity.

This installation also provides an opportunity to compare, on a relative basis, the effects of such parameters as rudder throw, upstream appendage and strut geometry on the propeller cavitation. With proper instrumentation, the measurement of the unsteady hull pressure forces and the relative noise levels is also possible.

Although the question of data-scaling is always present, the prospects of obtaining significant scaling information between model-scale and full-scale data in future programs are very promising.

Described in the remainder of this document is the development of the method employed to utilize the 48-inch (121.92 cm) diameter water tunnel for surface ship propeller evaluations. Where required, data or figures from either or both of the test programs will be used for illustrative purposes.

2. MODEL DESIGN AND FABRICATION

For the test programs described herein the model-scale was chosen to correspond to existing wooden towing tank models which were used as forms for fabrication of the fiberglass water tunnel hulls. The results of powering calculations based on full-scale data, indicated that a sufficient range of propeller advance ratios could be obtained at test section velocities of 25.0 ft/sec (7.62 m/sec). The required model power was provided by using two 20-horsepower (14.92 kw) motors operated either in tandem or in parallel.

In each case the water tunnel model hull was designed so that the overall length was decreased to permit the model to fit the test section. This was accomplished by blending a shortened, streamlined nose to the aft portion of the full model. The shortened hulls were constructed in three pieces from a fiberglass-resin composition with a minimum thickness of 1/4 inch (0.635 cm). Appropriate parting lines were made so that assembly of the hull over the model motors and strut arrangement could be accomplished. An assembled model is shown in Figure (2) and a schematic of the water tunnel installation is presented in Figure (3).

To reduce installation problems the model was mounted in an inverted position on a one-inch (2.54 cm) thick flat plate located in the lower portion of the tunnel test section such that the center of the propeller hub was located at the centerline of the water tunnel working section. The model is longer than the hatch cover and, therefore, could not be attached to it. If the model were to be attached right side up to a plate in the upper portion of the working section, the model would be

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relatively inaccessible for installation and adjustment once these supporting plates were in place. The weight of such a large model also imposes many problems when being positioned with reference to all auxiliary hardware.

With the model mounted in an inverted position an error in the static pressure occurs due to the reversal of the hydrostatic pressure gradient. For the model propellers used in the subject programs this error was approximately two percent of the minimum measured cavitation indices. In general, this is within the accepted limits of the data scatter. However, for larger propellers a simple correction could be included in the data reduction program.

The model motors were mounted in watertight containers which were installed inside the model hull. Because the motor casings were watertight and the required electrical and cooling water lines were installed through a strut-tube arrangement the model hull could be flooded. The propeller shafts were attached to strain-gaged cells within the casings for measurements of thrust and torque.

The propeller shaft supporting struts for the first model were initially made as flat plates with semicircular leading and trailing edges and were installed parallel to the model's centerline. It was learned after testing began that, on the prototype, the struts were airfoil shaped and were oriented at a specified angle relative to the centerline of the model. This change in strut design was made later but was not instituted until after the completion of the initial test program. The rudders were fabricated from aluminum stock. Provision was made for the deflection of the rudder up to 25° in both port and starboard directions. This provision was made to determine the effect of rudder deflection on the cavitation characteristics of the propeller.

Finally, provision was made to allow a wake survey to be conducted in the plane of the propeller. A description of the mechanism used and the results of the survey follow in the next section.

3. WAKE SURVEYS

To verify the accuracy of the model installation and to evaluate the blockage characteristics inherent with the installation of large models in the test section of the 48-inch (121.92 cm) diameter water tunnel, velocity surveys were conducted in the propeller-disk plane of both models. The rotating wake rake which was composed of six, five-hole, angle-tube probes and is shown in Figures (4) and (5) was used to measure the three velocity components. The design, calibration, and application of these probes are discussed in detail in Reference (3).

The wake rake, which is shown installed in Figure (6), was rotated through 360° in 3.6° increments. At each of these angular positions, data were recorded from each of the six probes located at their prescribed radial positions. The data were automatically punched on paper tape and processed on the IBM 1130 computer system which simultaneously calculated and plotted the resulting velocity surveys. All wake surveys were conducted at a nominal ship speed of 16.0 ft/sec (4.88 m/sec).

A representative wake is presented graphically in Figure (8). The wake data previously measured during towing tank tests have been represented by the piecewise continuous curves with linear segments between data points; whereas, the ARL data are presented as individual data points. These ARL data are presented as velocity ratios, namely, (V_x/V_∞) , (V_r/V_∞) , and (V_θ/V_∞) where

V_x/V_∞ = the longitudinal, or axial, velocity ratio,
 V_r/V_∞ = the radial velocity ratio,
 V_θ/V_∞ = the peripheral velocity ratio,
and V_∞ = the nominal ship speed or the equivalent free
stream velocity corrected for model blockage.

The data were initially calculated in the form $(V_x/V_{T.S.})$, $(V_r/V_{T.S.})$
and $(V_\theta/V_{T.S.})$ where $V_{T.S.}$ is the test section velocity measured by a
wall mounted pitot-static probe in the propeller plane. The ARL data
were adjusted on a mass flow rate basis to account for the model blockage
and the growth of the boundary layers on the model hull and the test
section wall.

The wake data presented here were remeasured several times showing
excellent repeatability. In an attempt to determine the influence of
the shortened hulls, the hull boundary layer of the first model was
altered by adding a 12-inch (30.54 cm) section of 1/4-inch (0.635 cm)
mesh screen 33 inches (83.82 cm) aft of the bow. A wake survey conducted
with the screen in place showed no appreciable change from that measured
with the bare hull, thus, reaffirming the fact that the propeller was
operating outside of the hull boundary layer.

In general, it was felt that the agreement between the ARL and towing
tank wake data was excellent and warranted continuation of the test program
with no modification to the model installation.

4. THRUST AND TORQUE

Once the overall model installation had been verified by the results
of the wake surveys, propeller shaft thrust and torque measurements were
conducted. The thrust and torque data were automatically punched on
paper tape for each of the subject propellers at selected advance ratios

spanning a range 20.0 percent above and below the assumed operating advance ratio. The customary coefficients defined by the following equations:

$$\text{Advance Ratio} = J = \frac{V_{\infty}}{nD_p}, \quad (1)$$

$$\text{Thrust Coefficient} = K_T = \frac{\text{THRUST}}{\rho n^2 D_p^4}, \quad (2)$$

and

$$\text{Torque Coefficient} = K_Q = \frac{\text{TORQUE}}{\rho n^2 D_p^5}, \quad (3)$$

where

n = the rotational speed of the propeller,

D_p = the propeller diameter

ρ = the fluid mass density,

were calculated and plotted via the IBM 1130 computer system.

Data were measured for nominal free stream velocities of 20.0 and 25.0 ft/sec (6.096 and 7.62 m/sec) with no measurable effect on the powering data due to the variation in Reynolds number. A characteristic graph of K_T and K_Q versus J is presented in Figure (8). These data have not been adjusted to reflect full-scale ship performance. However, a onepoint comparison with predicted full-scale powering data was completed. At a given full-scale velocity, K_T was computed from the predicted full-scale data. At this value of K_T , the corresponding value of J was determined from the ARL model K_T vs J curve to given model/full-scale thrust identity. At this same value of J , K_Q was determined from the ARL K_Q versus J curve. This value of K_Q was then compared with the K_Q computed from the predicted full-scale data. The process is diagrammed on Figure (8). For all propellers the agreement between the predicted full-scale and the measured model-scale values of K_Q was within five percent.

Thus, for identical values of K_T , this relative comparison demonstrated that the ARL model produced essentially the same torque (K_Q) characteristics as predicted from towing tank model data. This was not surprising when the agreement between the ARL and towing tank wakes is considered.

Once the modeling technique has been validated by the successful wake surveys and powering tests, attention was focused on the cavitation characteristics of the subject propellers.

5. CAVITATION CHARACTERISTICS

The primary concern of this test program was the documentation of the cavitation characteristics of the subject propellers. The cavitation characteristics were recorded by visually determining the desinent cavitation condition for the various forms of cavitation as a function of advance ratio and by sketching the cavitation patterns characteristic of certain prescribed operating conditions. Typical cavitation forms are shown in Figure (9) with the propellers operating in the water tunnel environment.

At a given velocity, the cavitation observations were made by synchronizing a stroboscopic light source with the rotational speed of the propeller and then reducing the tunnel pressure level until a particular type of cavitation had formed. The pressure was then increased until the desinent condition was reached, at which time the pertinent parameters were recorded and supplied as card input to the cavitation data reduction program. The static pressure $P_{T.S.}$ and the velocity $V_{T.S.}$ measured by the wall mounted pitot-static probe in the propeller plane were corrected to free-stream conditions (P_∞ and V_∞) by the previously discussed blockage effects. The cavitation index, σ , was computed from

$$\sigma = \frac{P_\infty - P_v}{1/2\rho V_\infty^2} \quad (4)$$

where

P_{∞} = the desinent free-stream static pressure,
 P_v = the vapor pressure of the water at its average
temperature.

The cavitation data for each of the propellers were presented as curves of σ versus J . A typical graph is presented in Figure (10) where the curves representing the various cavitation forms have been identified.

Also included on the cavitation figure is the "ship's operating curve" and the corresponding inception speeds for the various cavitation forms. The development of this curve for these cavitation data is discussed in detail in the following section. It should be noted that the cavitation characteristics of an individual blade were a function of its angular position. This effect results from the unsymmetric flow field produced by the various upstream struts, shafts and appendages. The desinent cavitation data documented in these progrms corresponded to the "all-clean" condition for the particular cavitation form.

6. SHIP'S OPERATING CURVES

The cavitation characteristics of the model propellers were compared with that of the full-scale propellers on the basis of "thrust identity," i.e., at the same thrust coefficient. Predicted data on the thrusting characteristics of the full-scale propellers in the self-propelling state were obtained from towing tank tests. These thrust data were derived from model tests in the towing tank for a series of ship speeds, V_{∞} , with the rpm adjusted to permit self-propulsion at each speed. The thrust values furnished were not the simple self-propulsion values that would be derived from the model run in the towing tank but rather reflected an expected change in resistance of the full-scale ship over the model at each speed.

The predicted, full-scale thrust values were then computed in coefficient form using uncorrected, full-scale rpm values, which were also determined from towing tank model measurements. On the basis of thrust identity, these thrust coefficient values were used to enter the ARL model K_T vs J curves to obtain a water tunnel model J for each V_∞ . Knowing the operating depth of the propeller hub permitted the V_∞ values to be converted into cavitation indices. Therefore, a σ vs J curve was generated for each model propeller. Each of these curves (ship's operating curves) was superimposed on the appropriate model cavitation inception plot and its intersection with a desinent cavitation curve determined a critical cavitation index for a particular kind of cavitation.

A critical or so-called inception speed was calculated from the corresponding critical cavitation index.

7. DISCUSSION OF RESULTS

The data presented in Figure (7) show the excellent agreement between the wake data measured in the water tunnel and that measured in the towing tank. Also demonstrated is the fact that the radial and peripheral components of wake velocity can be as great as 20 percent of the free-stream or ship velocity. Therefore, in the employment of screens or flow regulators which simulate only the axial component of the wake velocity this peripheral velocity component will be absent. For propellers typical of the ones tested in this program, the absence of the peripheral velocity can lead to an error in the flow incidence to the blade tip of approximately ± 0.5 degree. For blade sections with low values of thickness-to-chord ratio such as employed at propeller blade tips, this error is enough to cause increased susceptibility to cavitation.

The relative cavitation characteristics of the individual propellers were obtained by comparing the inception speeds. The usual pressure face and suction face forms of cavitation, as well as tip and hub vortex cavitation, were observed. The characteristics of these forms of cavitation were a function of the circumferential position with the area behind the struts and in the "shaft shadow" being most critical.

The cavitation patterns such as those shown in Figure (12) that were sketched at specific points on the ships operating curve supported the measured cavitation data. These patterns were usually recorded at the most critical circumferential blade location. In addition, cavitation patterns at several angular positions, as in Reference (c), should be recorded to illustrate the asymmetric nature of the cavitation.

During a second test program involving the first model installation, the revised, streamlined barrel support struts were available. This provided an opportunity to assess the effect of strut geometry on the propeller cavitation characteristics. The resulting data are presented in Figure (13) where a sketch of the comparative strut geometry is also shown. In general, the blade forms of cavitation exhibited an improved resistance to cavitation while operating in the presence of streamlined strut.

A limited amount of testing was performed with the rudder deflected. The thrust and torque of the propeller were measured with the rudder deflected 25° in both the port and starboard directions. No significant differences were measured in the K_T and K_Q versus J relationship from that measured with no rudder deflection. However, with the rudder deflected 25° to the port, the desinent cavitation indices characteristic of the hub vortex and the leading edge pressure face cavitation were reduced.

Whereas, the critical indices for the leading edge suction face and tip vortex cavitation, showed little change. The results are displayed graphically in Figure (13) where it can be seen that the suction surface of the rudder exhibited the critical cavitation characteristics for this rudder position. With these limited observations, it is apparent that the cavitation characteristics can be affected by rudder throw.

Thus, on the basis of the desinent cavitation results it was possible to recommend a propeller design for the full-scale ship. This conclusion was based on the concept of "maximum speed for no cavitation" and was supported by the powering data and the observed cavitation patterns.

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- 3 Treaster, A. L., "The Calibration of Six Probes for Sensing Three-Dimensional Fluid Flow Properties," ARL TM 74-282, October 8, 1974.
- 4 van Oossanen, P., "Methods for the Assessment of the Cavitation Performance of Marine Propellers," International Shipbuilding Progress, Volume 22, January 1975, No. 245.

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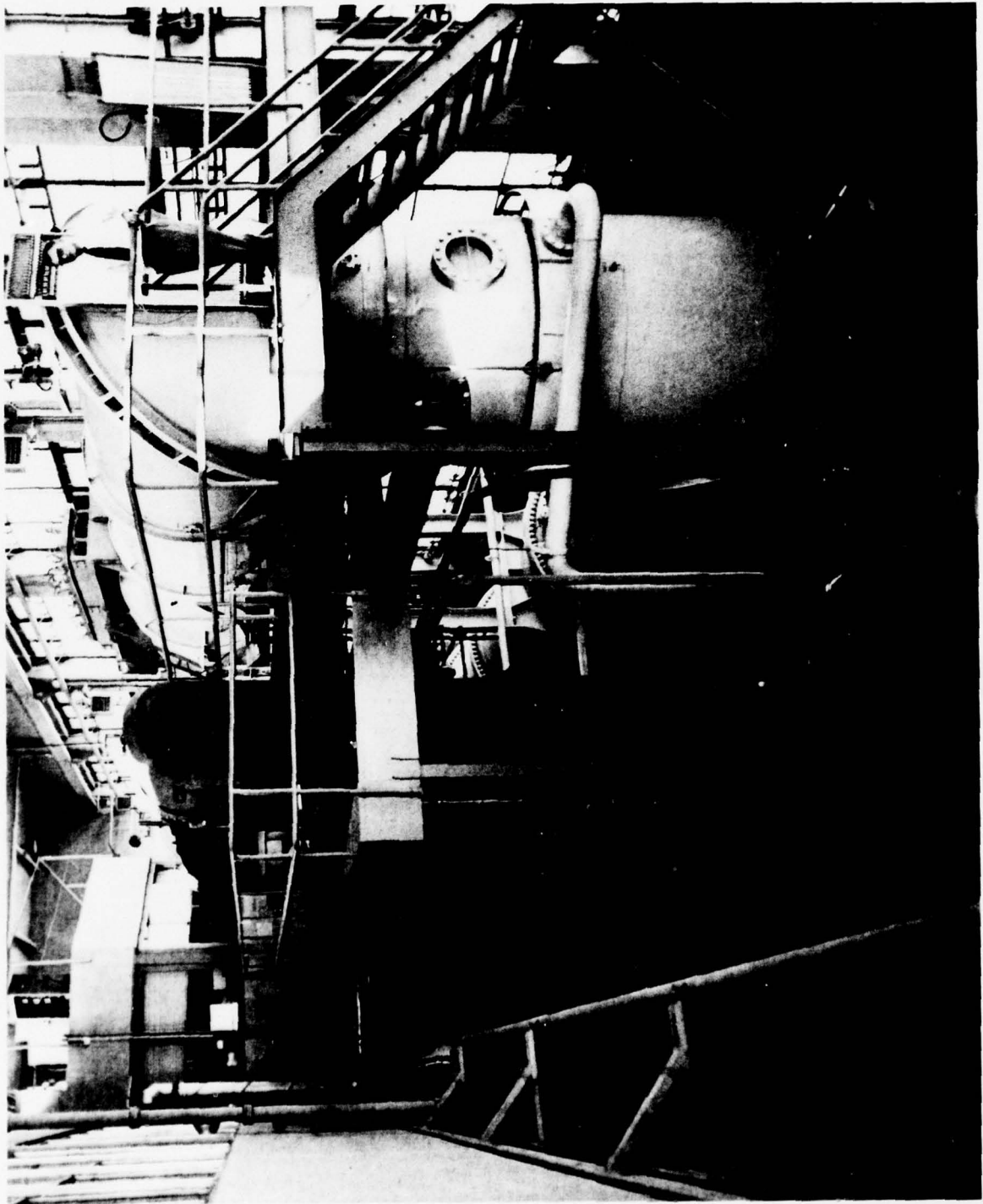


Figure 1 - The 48-inch (121.92 cm) Diameter Garfield Thomas Water Tunnel

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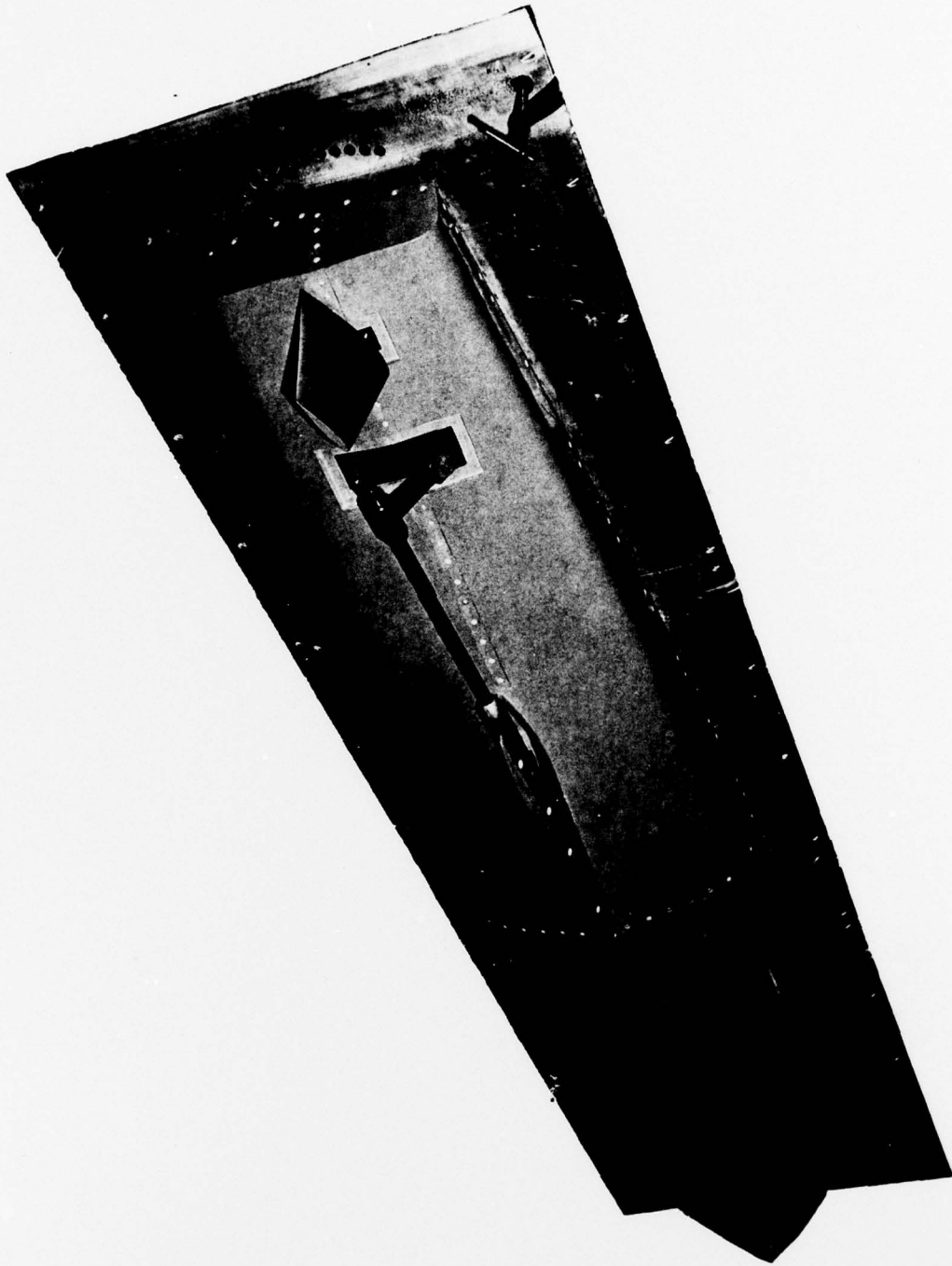


Figure 2 - ARL Surface Ship Model

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ARL WATER TUNNEL SURFACE SHIP INSTALLATION

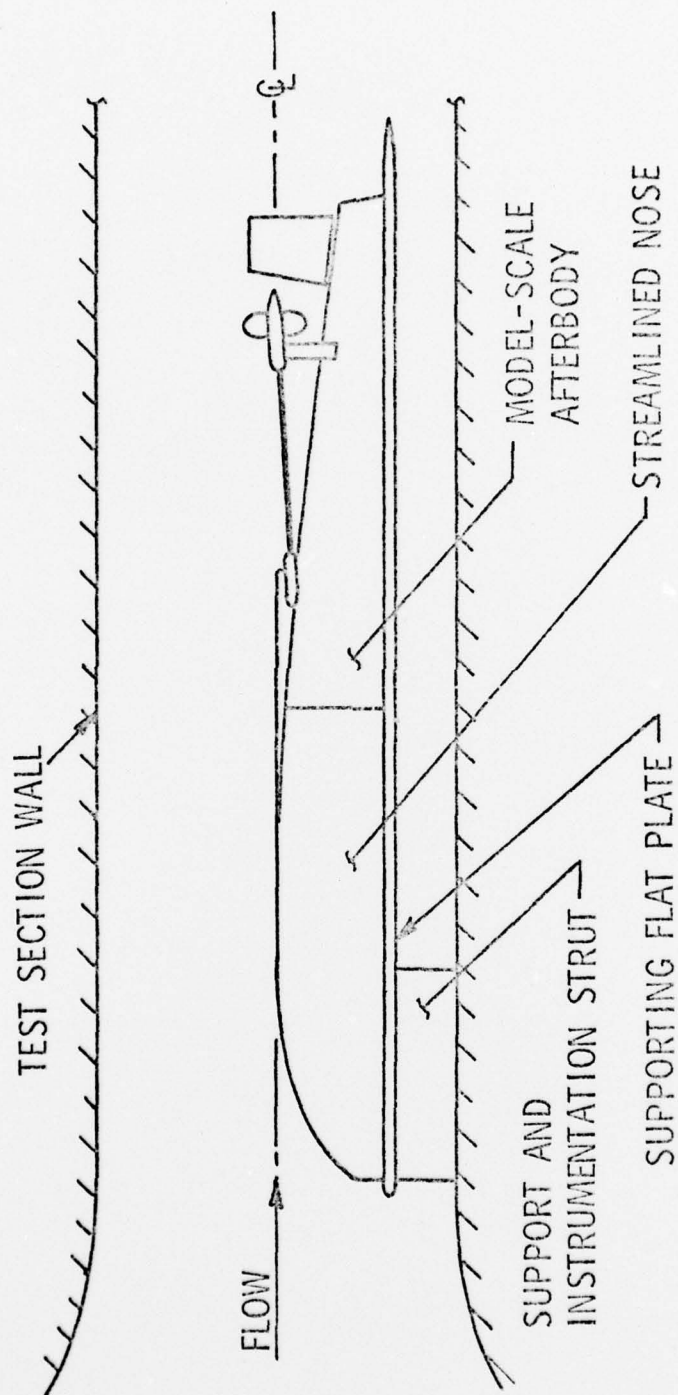


Figure 3 - Schematic of the Water Tunnel Surface Ship Installation

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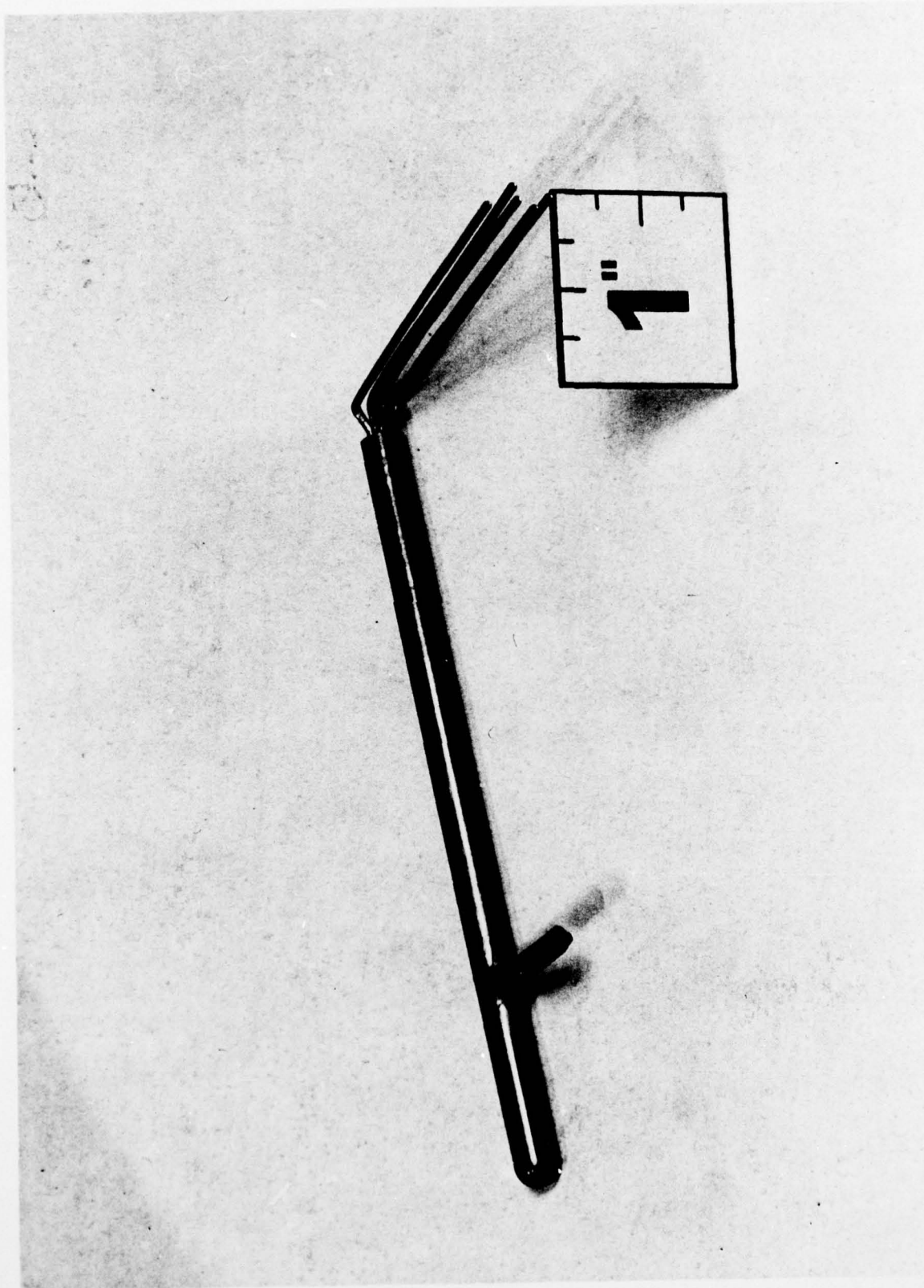


Figure 4 - Five Hole Probe for Measuring Three-Dimensional Flow Properties

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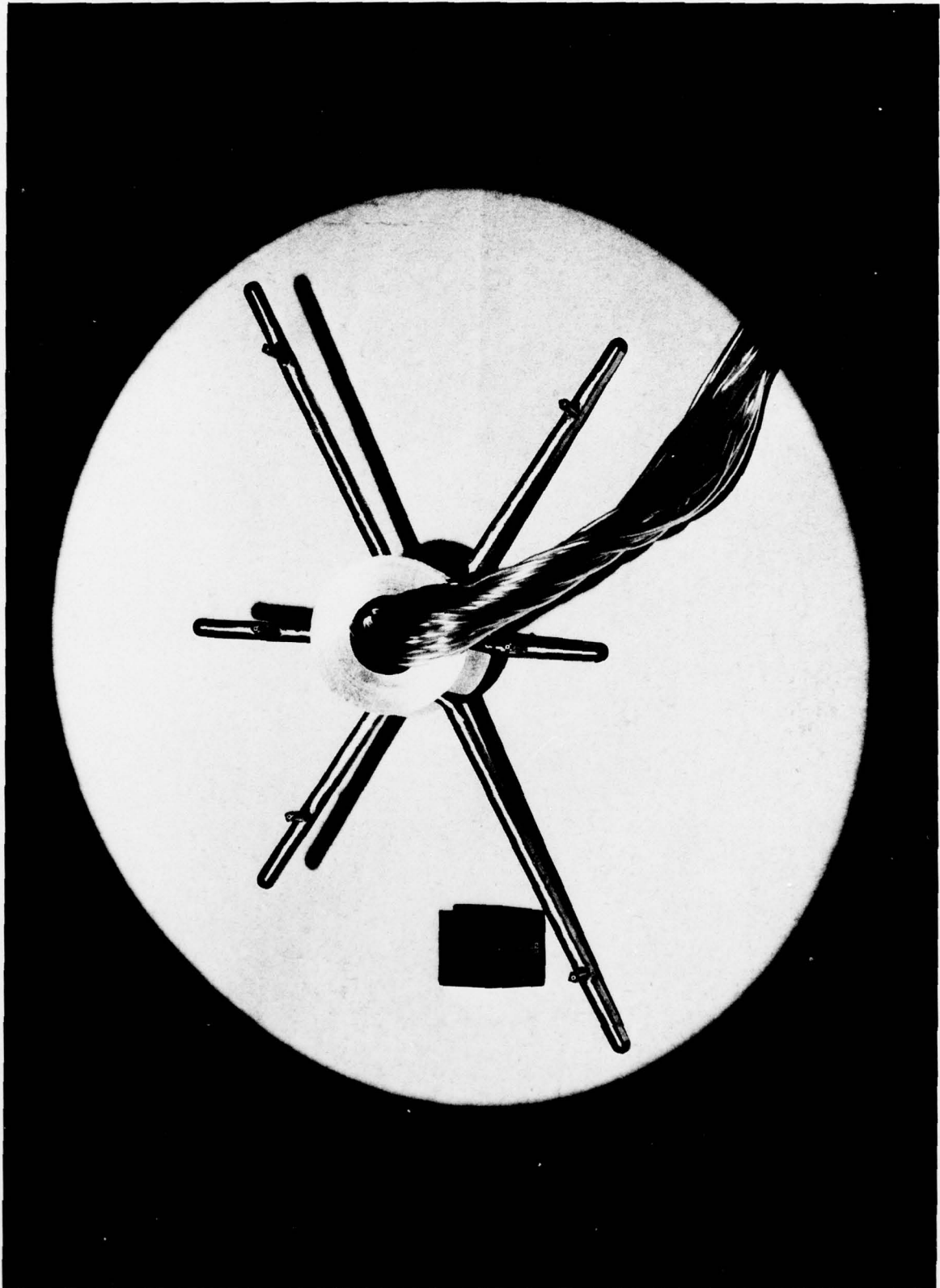


Figure 5 - Five Hole Probe Rotating Wake Rake

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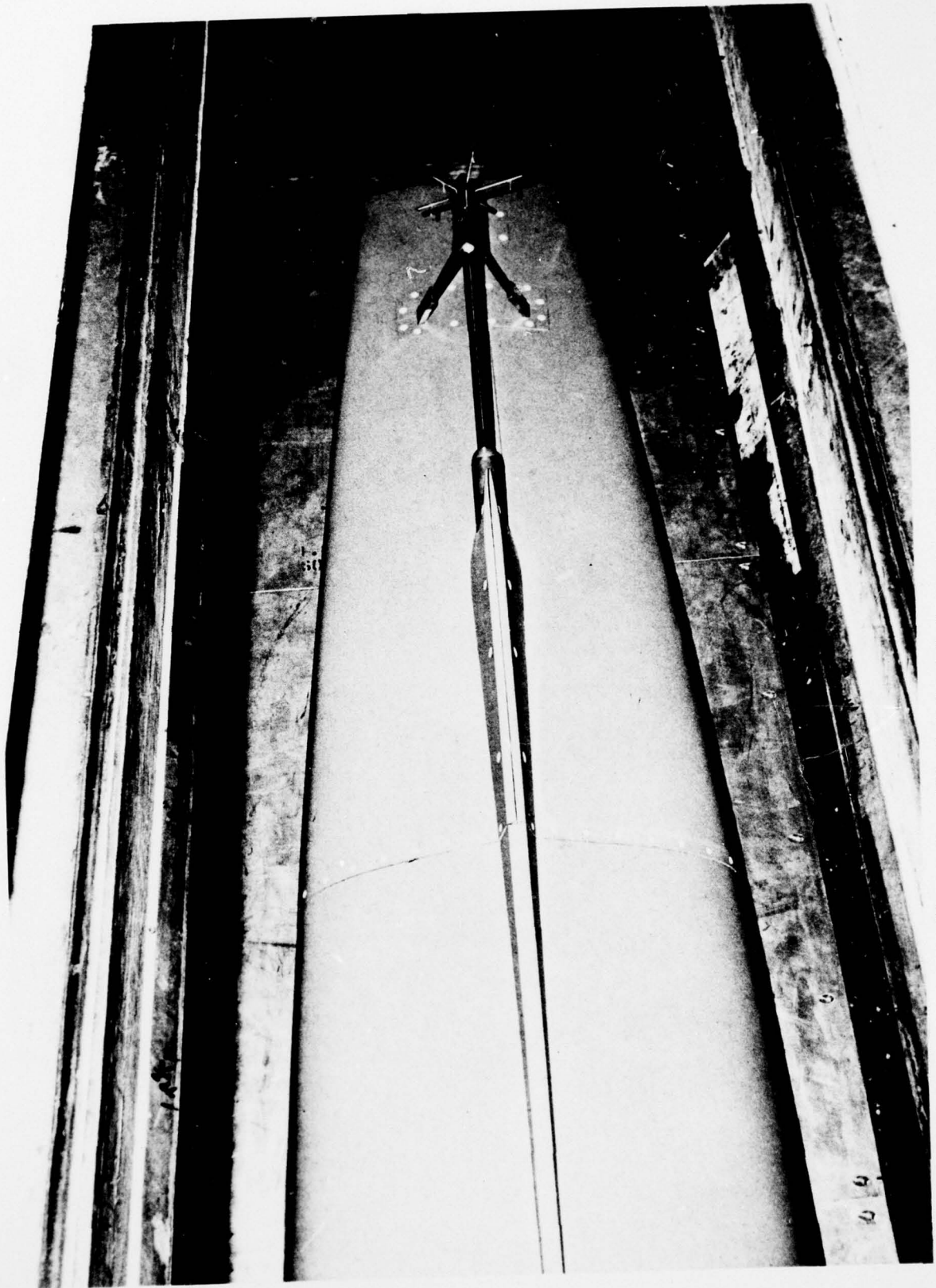


Figure 6 - ARL Model with Rotating Wake Rake Installed in
the Propeller Plane

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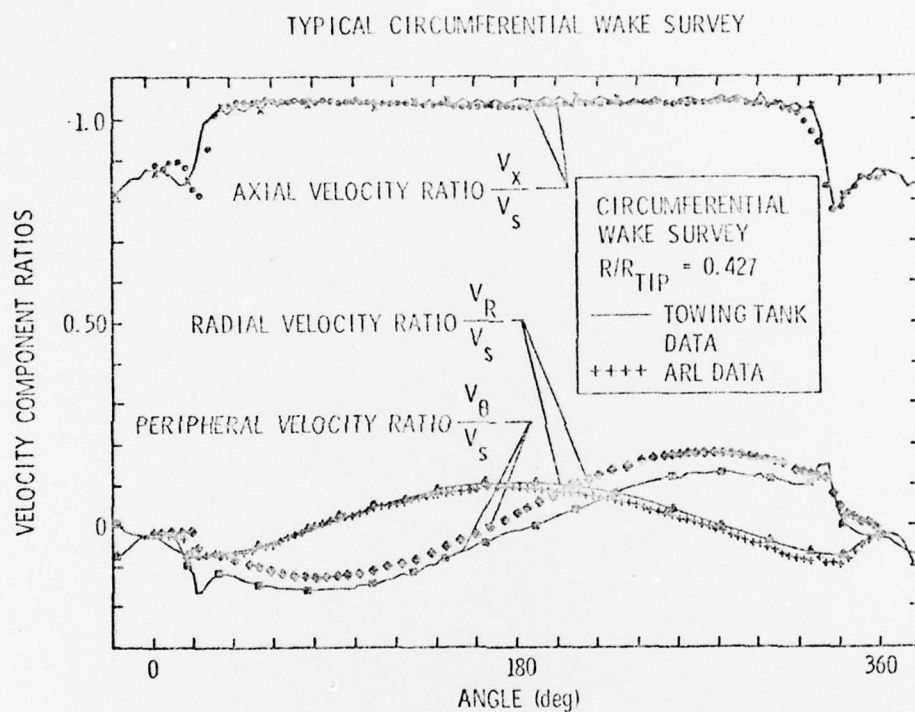


Figure 7 - Typical Circumferential Wake Survey

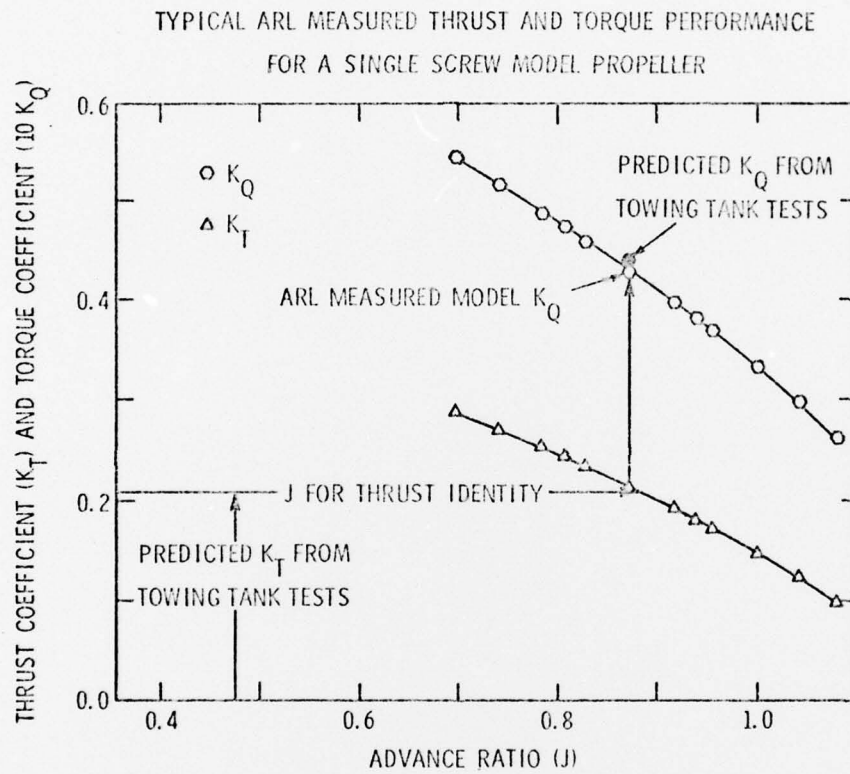


Figure 8 - Typical ARL Measured Thrust and Torque Data for a Model Propeller

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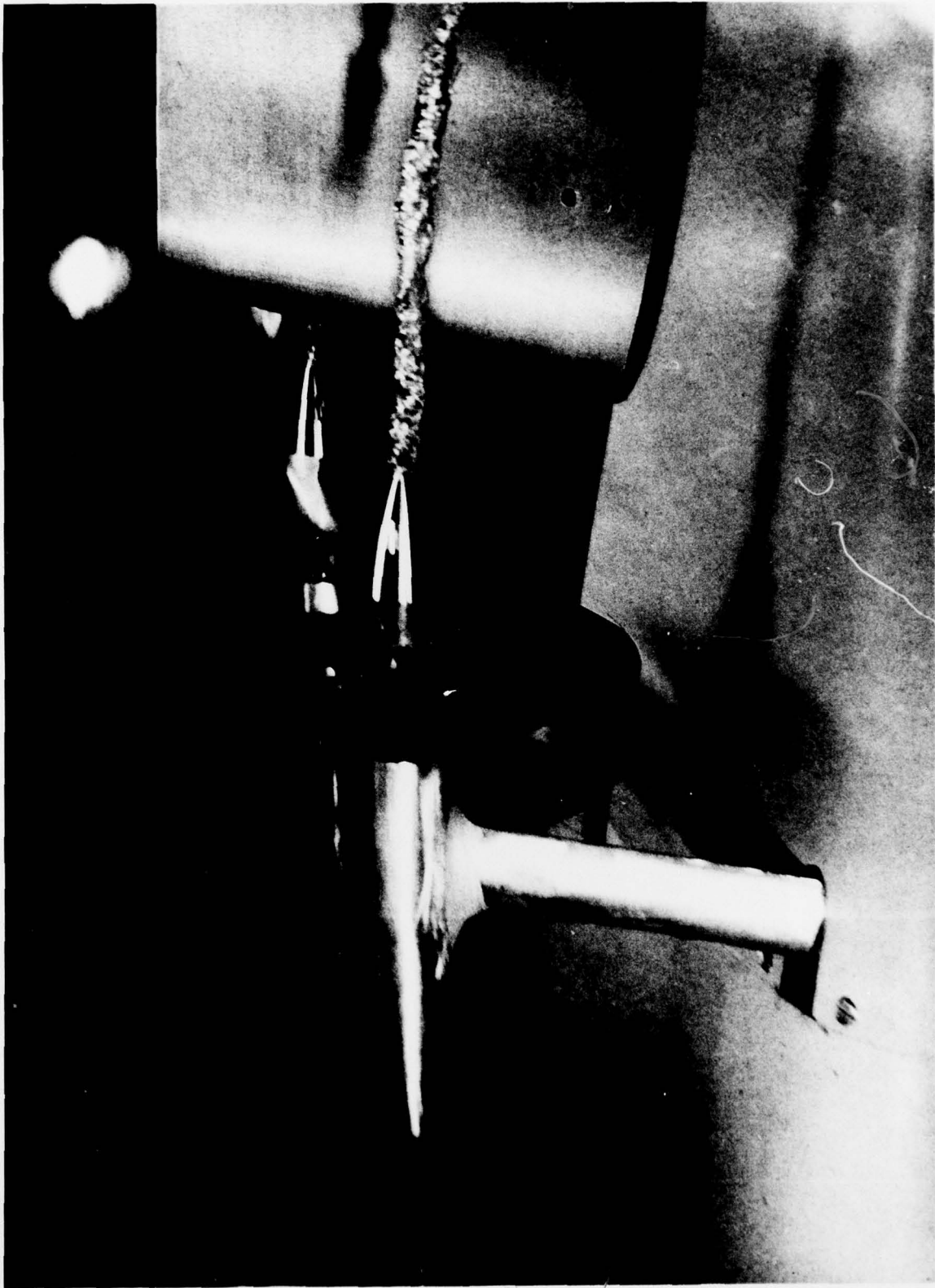


Figure 9 - Cavitation on Model Propellers

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TYPICAL CAVITATION DATA FOR A MODEL PROPELLER

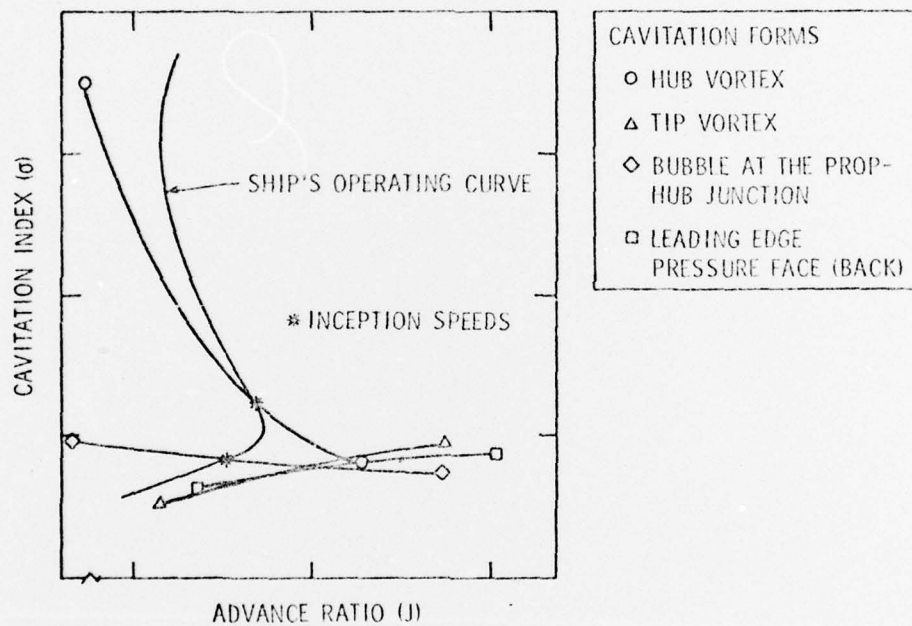


Figure 10 - Typical Cavitation Data for a Model Propeller

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CAVITATION DATA SHOWING THE EFFECT OF STRUT GEOMETRY

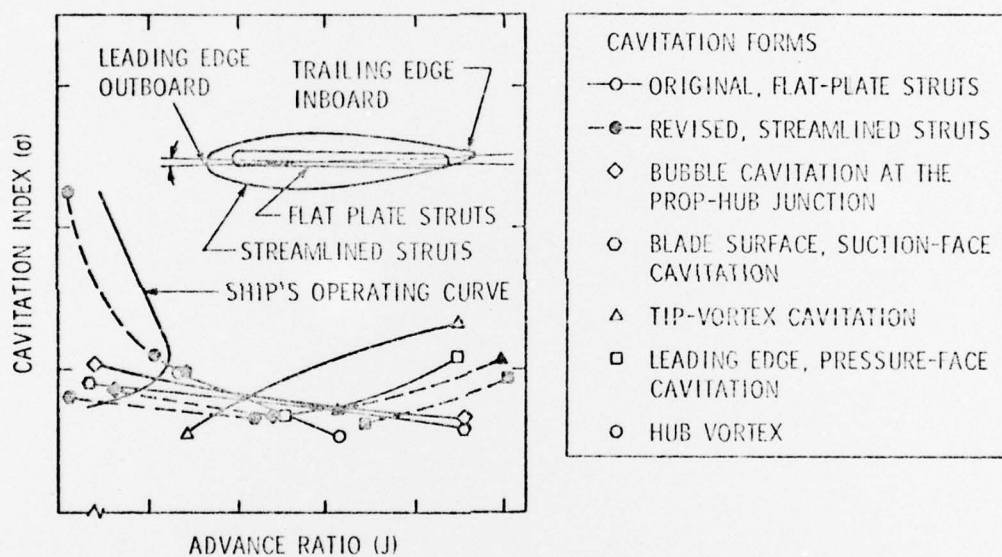


Figure 11 - Cavitation Data Showing the Effect of Support Strut Geometry

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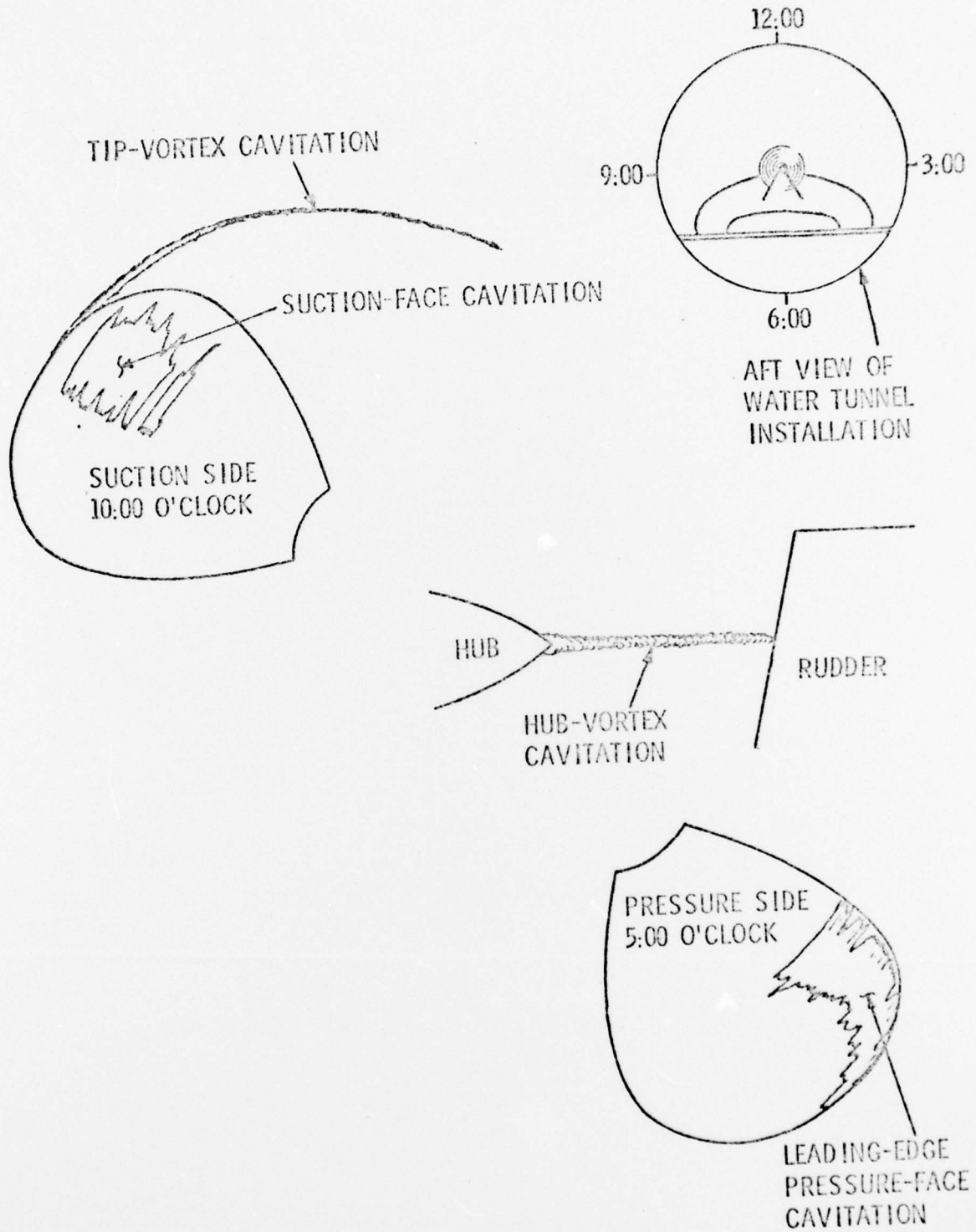


Figure 12 - Typical Cavitation Patterns

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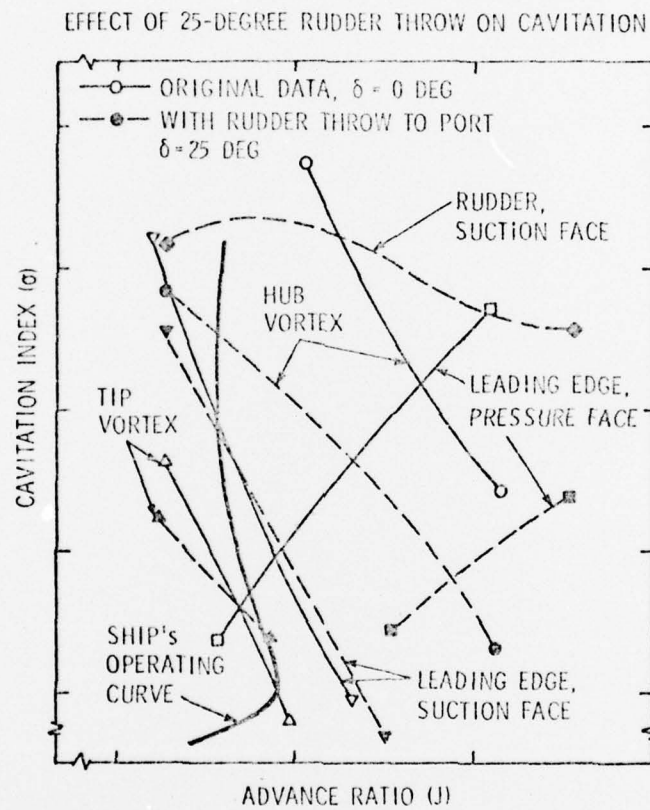


Figure 13 - Cavitation Data Showing the Effect of Rudder Throw

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