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MODEL FLOW STUDIES TO INVESTIGATE PROPELLER-EXCITED VIBRATIONS  
ON U.S. ARMY SHIP LT. COL. JOHN U.D. PAGE (BDL-1X)  
EQUIPPED WITH VERTICAL-AXIS PROPELLERS

by

N.L. Ficken and S.G. Gawlik

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RESEARCH AND DEVELOPMENT REPORT

March 1960

DTMB Report 1412



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## ABSTRACT

A model of U.S. Army Ship "LT. COL. JOHN U.D. PAGE" (BDL-1X) fitted with twin vertical-axis propellers was run in the Circulating Water Channel to investigate visually the source of blade-frequency vibrations. Tests were conducted with sinusoidal, Rotor "A" and cycloidal blade motions. The observations indicated that a vortex system exists on the propeller that might be a vibration source. The strength of the vortex system seems to depend on the blade angles in the fourth quadrant of the blade orbit.

## INTRODUCTION

A vibration survey was conducted on U.S. Army ship "LT. COL. JOHN U.D. PAGE" (BDL-1X),<sup>1</sup> to ascertain the cause of excessive vibration of after ballast tank bulkheads. Large amplitudes at blade frequency and twice blade frequency were observed on some panels. The amplitudes were observed to increase with the increase of pitch setting of the vertical-axis propellers. Although the large amplitudes apparently result from panel resonance, the results indicated the existence of propeller-induced, blade frequency exciting forces.

It was recommended that a wake survey be conducted to investigate their source.<sup>1</sup> However, since the source of vibration was not known, and since velocity is probably of much smaller importance than direction of flows in a problem of this type, the David Taylor Model Basin recommended that flow studies be conducted in the Circulating Water Channel.<sup>2</sup>

Model 4571, representing BDL-1X was fitted with vertical-axis propellers, brass tubes for injection of dye and wool yarn tufts to indicate direction of flow (see Figures 1, 2, and 3). For some of the test runs, air was injected through the tubes or the propeller housing to better visualize vortex motions.

The tests were conducted at the "ocean condition," 4126 tons displacement, with no trim (from the baseline) and calculative draft of 13' 4" forward and aft.

## PROPELLERS

The blade angles of a vertical-axis propeller are normally controlled by a set of cranks and arms (a brief explanation of the theory of operation of vertical-axis propellers is given in the Appendix). A particular linkage will produce a specific pattern of blade angle as a

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<sup>1</sup>References are listed on page 8.

function of position, with the amplitude and direction of thrust continuously variable. The blade motion of the model propeller was controlled by cams, each set of cams producing a particular motion at a single amplitude. The tests were conducted with three types of blade motion, with variations of pitch and compensation as shown in Table 1 (see Appendix for definition of terms).

TABLE 1  
Blade Motions used in Tests

Type of Motion	Nominal Pitch	Compensation (deg.)	Steering Angle (deg.)	Rotation
Sinusoidal	.58 $\pi$	9	4	Outward
Sinusoidal	.65 $\pi$	10	4	Outward
Sinusoidal	.65 $\pi$	10	4	Inward
Sinusoidal	.65 $\pi$	5	4	Outward
Rotor A	3.15 in. ecc.	7	2.5	Outward
Rotor A	3.15 in. ecc.	2	2.5	Outward
Mod. Cyclo- idal	.65 $\pi$	2.5	-6	Outward

In 1955, powering tests were conducted with sinusoidal and Rotor "A" blade motions,<sup>4</sup> which were developed by Pacific Car and Foundry Co. for possible installation in BDL-1X. The sinusoidal motion specified at that time had 5 degrees compensation at a nominal pitch ratio of .65  $\pi$ . During the vibration trials, the propellers were fitted with a sinusoidal linkage, for which the blade angle curve measured on the ship with a nominal pitch setting of 0.65 $\pi$  is shown in Figure 4a.<sup>3</sup> The compensation measured from the curve is 10 degrees. To achieve a 10 degree compensation for a pitch of 0.65 $\pi$  on the model sinusoidal motions, the blades were shifted in the negative direction (leading edge inward) 2 1/2 degrees with respect to their normal reference. The locations of the peak blade angles of the full-scale curve indicated that an initial steering angle of 4 degrees was used as determined from the 1955 model powering tests.

For all the motions tested, the steering angle used was that determined from the powering tests using that motion.

#### DISCUSSION

To simulate the full-scale trial operation, the first tests were conducted with sinusoidal motion, outward rotating (see Appendix),  $0.58 \pi$  and  $0.65 \pi$  nominal pitch ratio with 5 degrees additional compensation achieved by shifting the cam followers  $2 \frac{1}{2}$  degrees inward from the trailing edges of the blades (see Figures 4a and Figures 7 through 10). The appearance of the flow was similar for all speeds tested (6, 8, and 10 knots full-scale).

Since the photographs do not adequately show all the details of the flow, an artist's representation of the visual observations is included (Figure 6). It was observed that in the outboard quadrants of each propeller the flow was accelerated in an outward and aft direction, and approached a fore-and-aft direction near the centerline of the propeller. In the after, inboard quadrant of each propeller, the flow direction changed sharply so that, at about 60 degrees beyond the after centerline, the flow was directed nearly perpendicular to the direction of motion. Observation from the side of the model showed that the flow passing between the propellers was forced down away from the hull by this cross-flow. A vortex filament was seen to extend from each propeller into the downwash. Inside the propeller blade circle, a large vortex was observed almost directly inboard of the axis of each propeller. The vortex strength apparently decreased with vertical distance from the rotor housing.

It is not known to what extent the vortex system acts as a vibration generator, but it is conceivable that as each propeller blade passes through the region it would undergo a severe change in lift and drag forces. Since no other phenomena were observed which seemed likely to produce significant blade-frequency vibratory forces, tests were conducted to investigate the vortex system further.

To investigate whether the downwash and vortices might be influenced by the wake of the large centerline skeg, the propeller rotation was

reversed so that the formation of vortices would be shifted outboard of the propeller and out of the influence of the skeg (Figures 11 and 12). The downwash was reduced, since the cross-flow was not acting against the cross-flow from the other propeller. However, the vortex filaments and interval vortices were at least as strong as, or stronger than, previously observed.

The most probable cause of the vortex system appeared to be that the angles of attack were too large in the fourth (inboard, aft for outward rotation) quadrant. Figure 4b shows the blade-angle curves and curves of "local pitch ratio" for the sinusoidal motion with 5 and 10 degrees compensation. Except near zero and 180 degrees orbit angle, the local pitch ratio gives a measure of the local angle of attack.  $V_x$  in the ratio  $V_x/ND$  is the inflow velocity required to produce zero angle of attack. The infinite values near zero and 180 degrees occur where the chord of the blade is directed fore-and-aft, so that the angles of attack will be small in any case. However, within about 60 degrees of the centerline (30 to 150 degrees and 210 to 330 degrees) high values of the ratio are indicative of large angles of attack, as is the case in the fourth quadrant of the sinusoidal motion. In this region, the blade experiences a large angle of attack. The lift of the blade in this region is directed generally perpendicular to the direction of motion, and large angles of attack will produce excessive cross-flow.

At the end of the first scheduled test period, a test was conducted with the Rotor "A" cams associated with the maximum 3.15 inches eccentricity of the control point, and 2.5 degrees steering angle as previously determined (Figure 5a). The compensation was 7 degrees instead of the normal 2 degrees for this motion. No photographs were made, but observation indicated that the cross-flow and vortex system were weaker than observed with the sinusoidal motion. The vortex filament and the vortex within the blade circle were further aft on the propeller rotor. It will be noted that the local pitch curve for Rotor "A" is more uniform and lower in magnitude than for the sinusoidal motion.

The cam followers were then shifted to their normal angle with respect to the blades, and the remainder of the tests conducted with the normal compensation for each of the motions used. Tests were conducted with the sinusoidal motion (Figures 4, and 13 through 16), Rotor "A" motion (Figures 5a and 17 through 19), and a modified cycloidal motion tested previously on a BuShips hull<sup>6</sup> and used here because of its very flat pitch curve (Figures 5b and 20-23).

For the sinusoidal motion, with reduced compensation, the vortices appeared to be slightly weaker and were moved aft slightly. The vortices observed for the Rotor "A" and cycloidal motions were respectively progressively weaker, although not eliminated. The vortices can probably not be eliminated entirely, if any thrust is to be developed in the fourth quadrant. However, minimizing the angles of attack in this region should minimize the strength of the vortex system.

#### CONCLUSIONS

The rotary motion of a vertical-axis propeller produces a vortex system comprising a vortex filament extending aft from near zero orbit angle and a vortex within the blade circle, also near zero orbit angle. This vortex system was the only phenomenon observed which might conceivably be a source of blade-frequency vibratory forces. The strength of the system depends on the magnitude of the angles of attack in the fourth quadrant of the rotor orbit circle, and may be minimized by minimizing these angles of attack. Of the two motions available for use on BDL-1X, Rotor "A" is superior to the sinusoidal motion in this respect.

## APPENDIX

BDL-1X is fitted with variable-pitch, vertical-axis propellers (also referred to as Voith-Schneider or cycloidal propellers), comprising a horizontal rotor disc with blades which project vertically downward from the disc. As the disc rotates, the blades oscillate about their own vertical axes so that, for practically all angular positions, the blade contributes some portion of its lift to the total thrust. The blade motion of a full-scale vertical-axis propeller is controlled by a mechanism composed of some combination of cranks and (sometimes) sliding links. Some examples are shown in Reference 4.

In this report, the orbit angle of a blade is defined as the angular position of a radius of the rotor disc through the axis of rotation of the blade in question, and is measured in the direction of rotation, with 90 degrees in the direction of motion. The angular references are shown in Figure 24, as well as identification of the quadrants mentioned in the text. Blade angles are measured from the tangent to the orbit circle at the blade axis, and are taken as positive when the leading edge is rotated away from the rotor centerline.

When the ship moves in a straight path, the path of each blade (or any point on the rotating disc) is a cycloid. No thrust is developed on the blades, if at all orbit angles each blade is tangent to its cycloidal path. To achieve this motion, called the cycloidal blade motion, the perpendicular to the chord of each blade must, for all orbit angles, pass through the same point (for example, N or N1 in Figure 22), called the steering center, since angular displacement of the point changes the direction of the thrust. With the steering center at N, the advance of the cycloid per revolution of the rotor, for no-load or zero slip operation, is  $\pi$  times the diameter of the blade circle, and the pitch ratio is  $\pi \times \overline{ON} / \overline{OP}$ . Under very light load, the slip is relatively constant throughout the orbit.

The mechanism required to produce the cycloidal blade motion is complex, and several different motions have been developed which permit

cheaper construction and maintenance. These other motions, of course, deviate from the constant slip condition under light loads, and may, depending on the degree of deviation, affect the propeller efficiency. Discussion of the efficiencies, however, is beyond the scope of this report, although some measure of comparison of various motions is available in the literature.<sup>5,6</sup>

For a vertical-axis propeller under moderate loads, whether the motion is cycloidal or a variant, two adjustments are made to the motion. One adjustment, called compensation, is made to account for the non-uniformity of the flow over the blade circle. Under load, the blades in the forward (first and second) quadrants accelerate the flow and also induce a transverse component directed from the first to second, or fourth to third quadrants. To achieve angles of attack in the after quadrants of similar magnitude, as those in the forward quadrants, the blade angles in the after quadrants must be greater in magnitude than in the forward quadrants. A numerical value is assigned to the compensation by taking difference in magnitude between the maximum blade angles in the forward and after quadrants. No attempt has been made here to evaluate the magnitude of compensation required from the standpoint of efficiency. The evaluation would require a detailed analysis, or an extensive test program, involving the type of motion, loading and perhaps other variables.

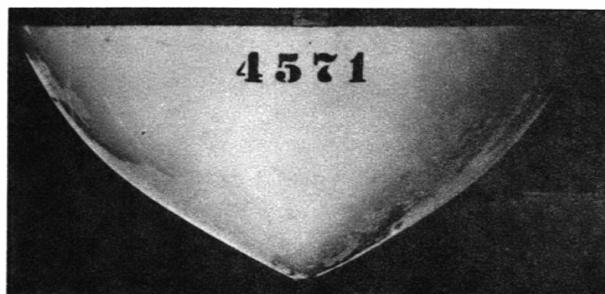
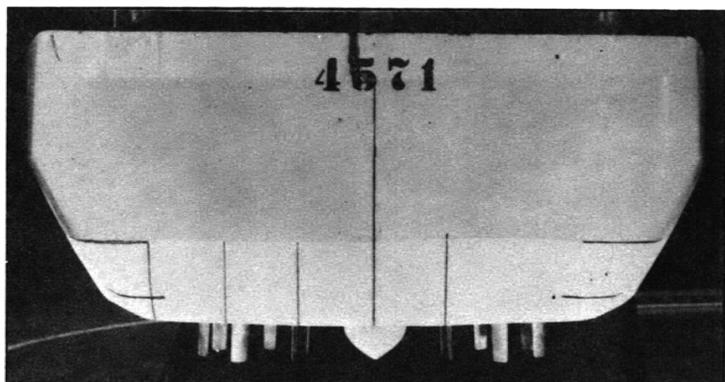
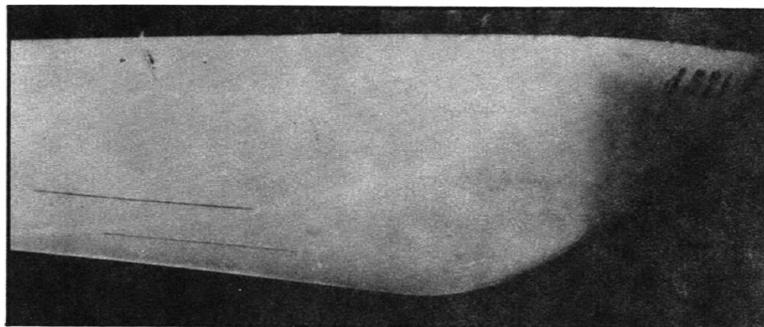
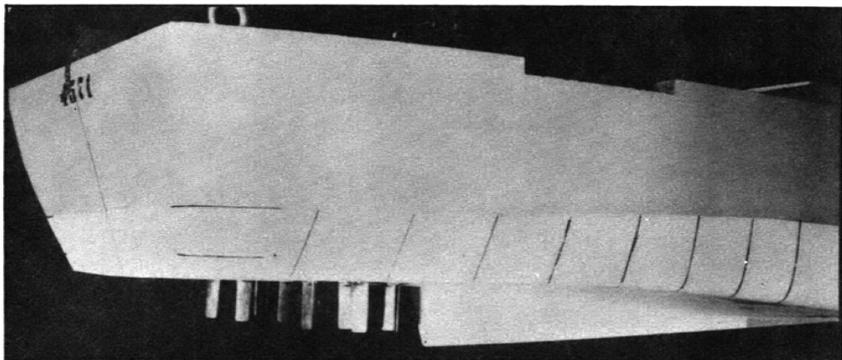
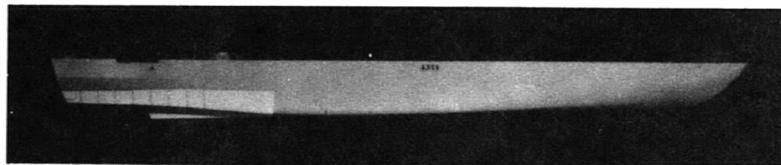
The other adjustment, also related to the lack of uniformity of the flow field, is called the steering angle (initial steering angle might be a better term). Operation of a single vertical-axis propeller driven ship would show that, in order to maintain a straight course, an angular displacement of the steering center would be required (similar to the rudder angle required to hold a single-screw ship on course). This would be accomplished either by the helmsman or by displacement of the steering linkage, and on a single propeller system is the only criterion. With a twin propeller system, since the two propellers would produce equal and opposite transverse forces with similar setting

of their steering centers, the problem of holding a straight course is not significant. However, there is a loss in efficiency associated with the angularity of the thrusts. It is standard practice at the Model Basin, when conducting powering tests with twin vertical-axis propellers, to determine the steering angle which requires minimum shaft horsepower at design speed (similar to the method of determining the optimum initial rudder angle for twin-screw, twin-rudder ships). This angle will be close to but not necessarily exactly that which produces directly fore and aft thrust. The steering angle, on either the full-scale or model propellers, may be set by rotating the propeller housings in opposite directions.

#### REFERENCES

1. Buchmann, E. and Birmingham, J.T., "Vibration Survey on U.S. Army Ship LT. COL. JOHN U.D. PAGE (BDL-1X)," David Taylor Model Basin Report 1343 (June 1959).
2. Telcon between Mr. Hundley of TRECOM and Mr. Stuntz of the Taylor Model Basin (11 Aug 1959).
3. TRECOM letter TRECOM-DS-MA 9-57-03-000 TK109M of 26 Aug 1959 to the Model Basin.
4. Taylor Model Basin letter S1/2, S44 (523NLF:or) of 27 Feb 1956 to TRADCOM.
5. Dr. Hans F. Mueller, "Recent Developments in the Design and Application of the Vertical-Axis Propeller," The Society of Naval Architects and Marine Engineers Transactions, Vol. 63, May 19-20 1955.
6. Hinterthan, W.B. and Yeh, H.Y., "Powering Predictions for Bureau of Ships Design LCU(A), Project 149, Fitted with Vertical-Axis Propellers from Tests with Models 4585, 4586, and 4631," David Taylor Model Basin Report C-776-4 (1960)

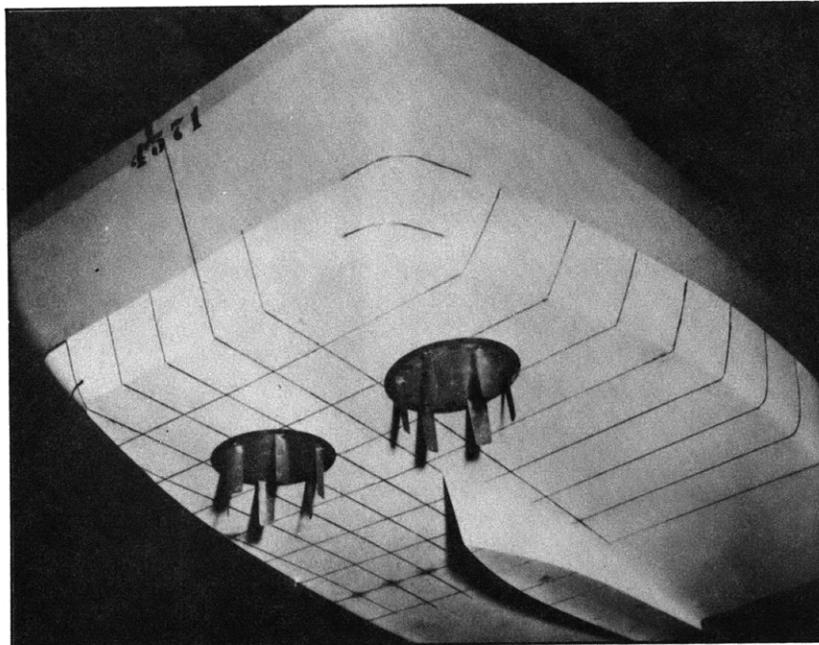
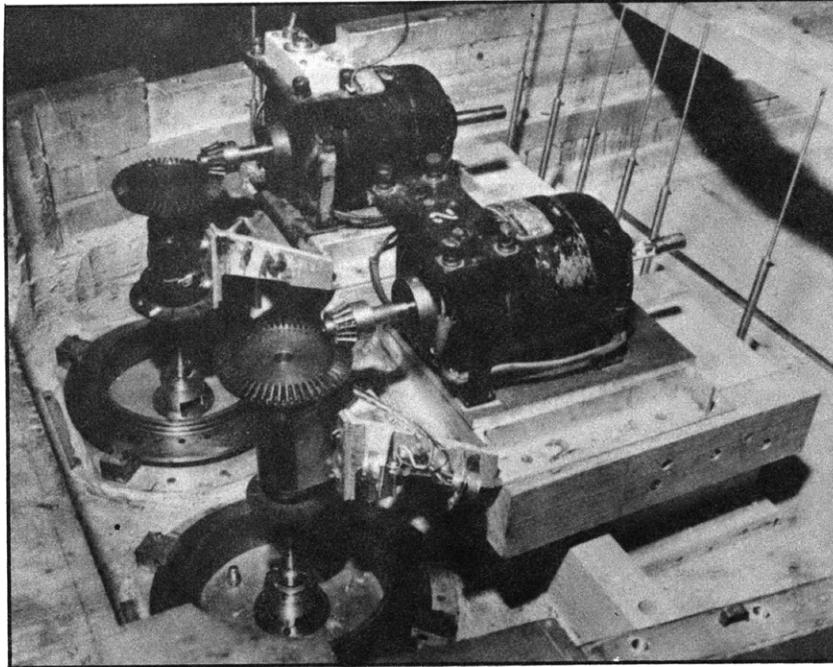
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MODEL 4571  
U. S. ARMY SHIP  
"LT. COL. JOHN U. D. PAGE"

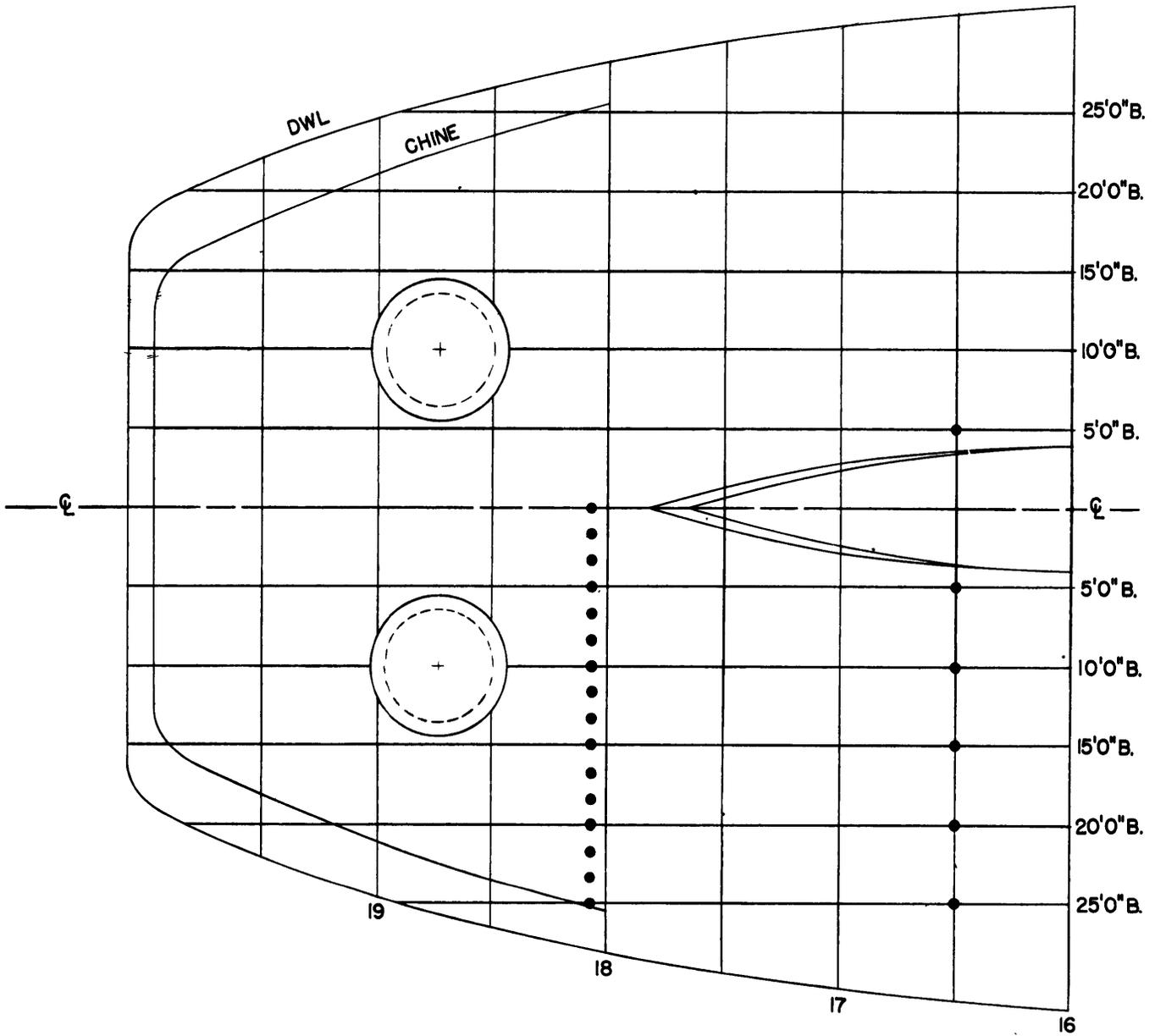
FIGURE 1

FIGURE 2



MODEL 4571  
INSTALLATION OF VERTICAL - AXIS  
PROPELLERS AND DRIVING MOTORS.

FIGURE 3



MODEL 4571  
ARRANGEMENT OF DYE TUBES  
FOR FLOW VISUALIZATION

FIGURE 4

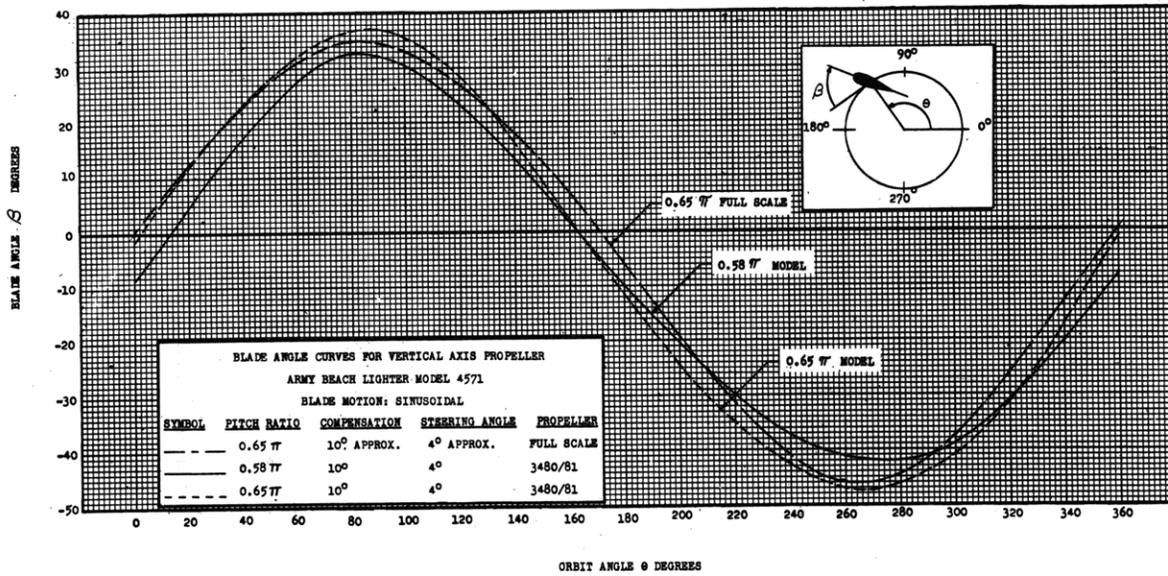


FIGURE 4a

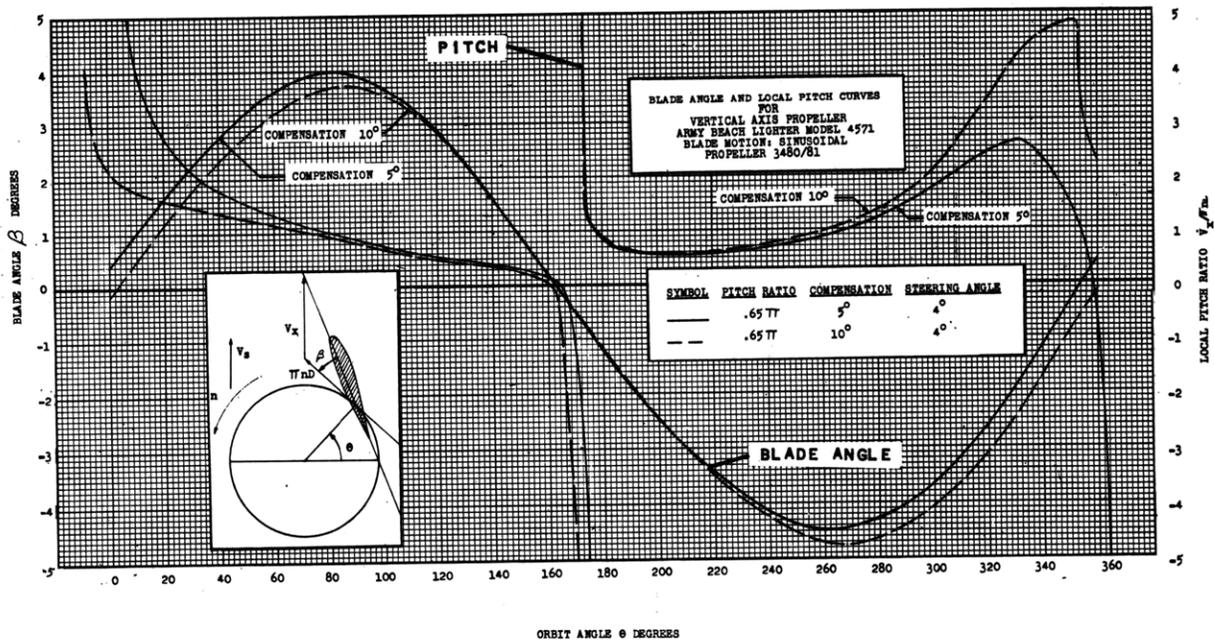


FIGURE 4b

FIGURE 5

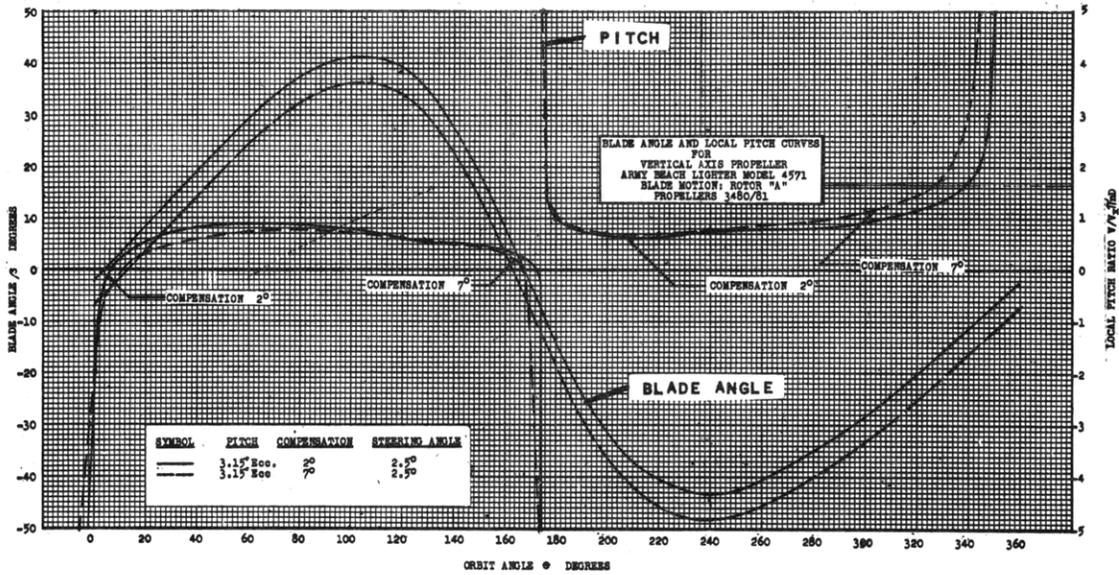


FIGURE 5a

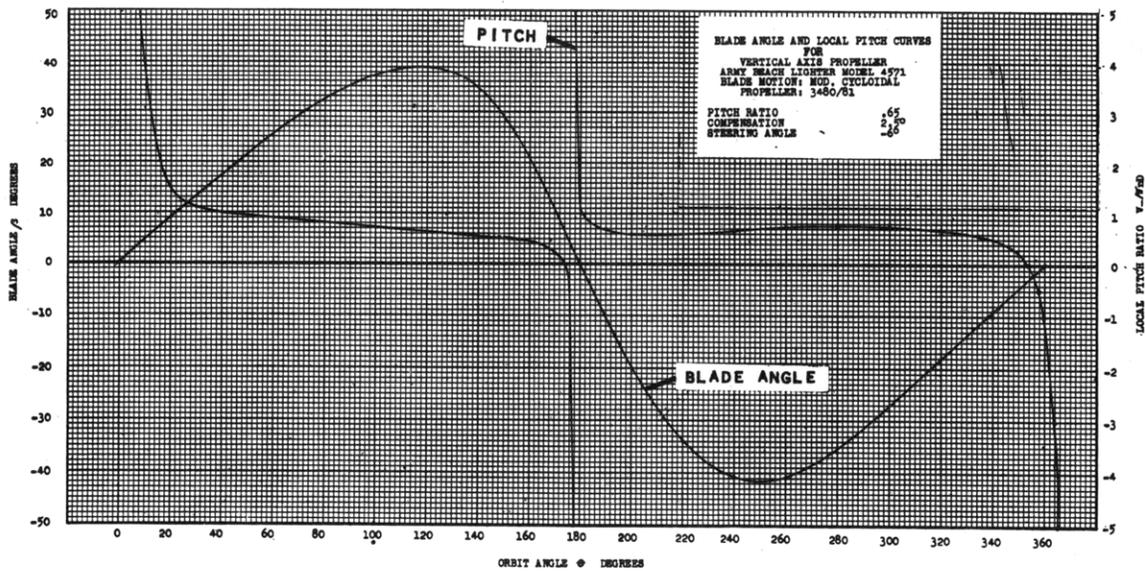


FIGURE 5b

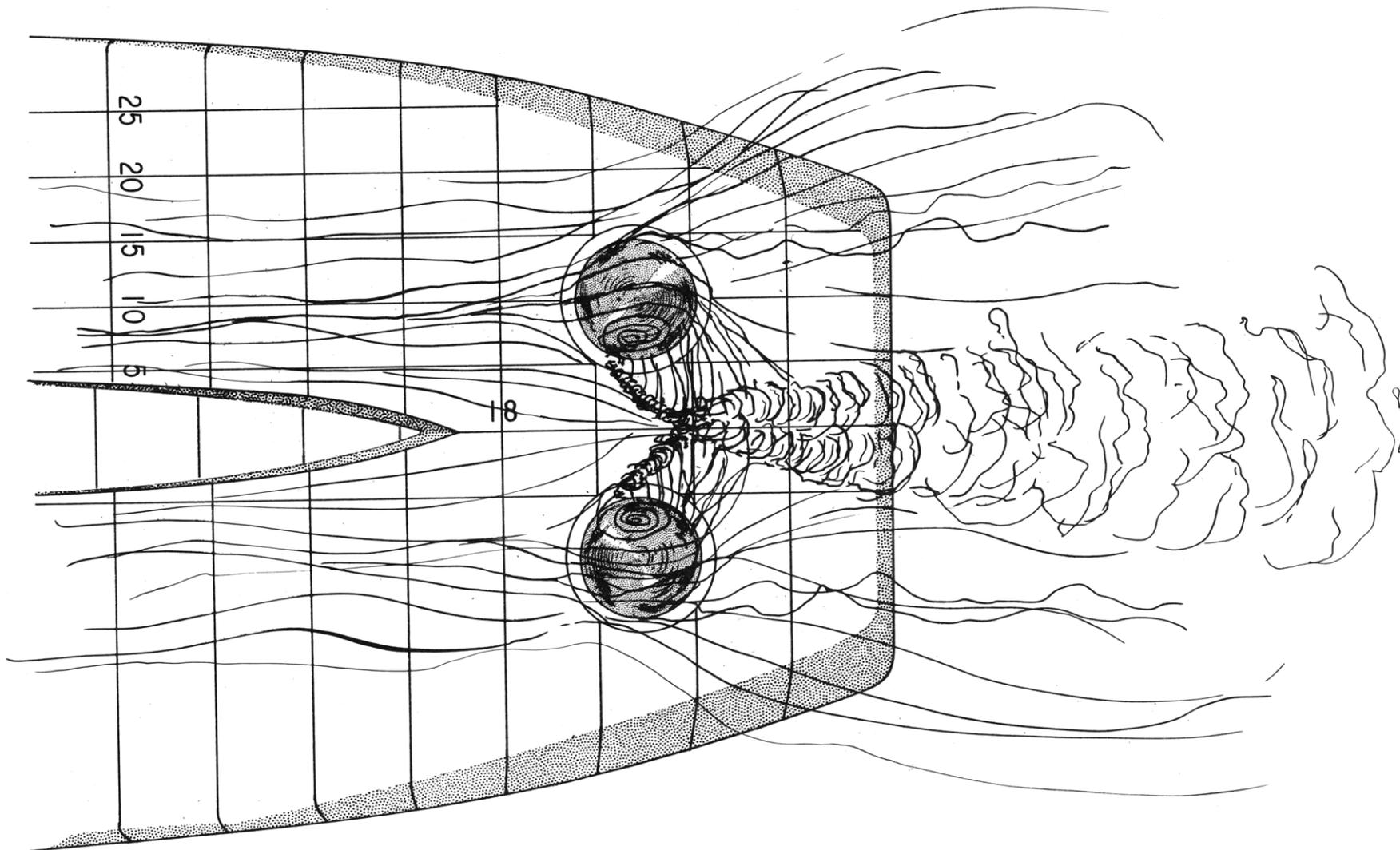
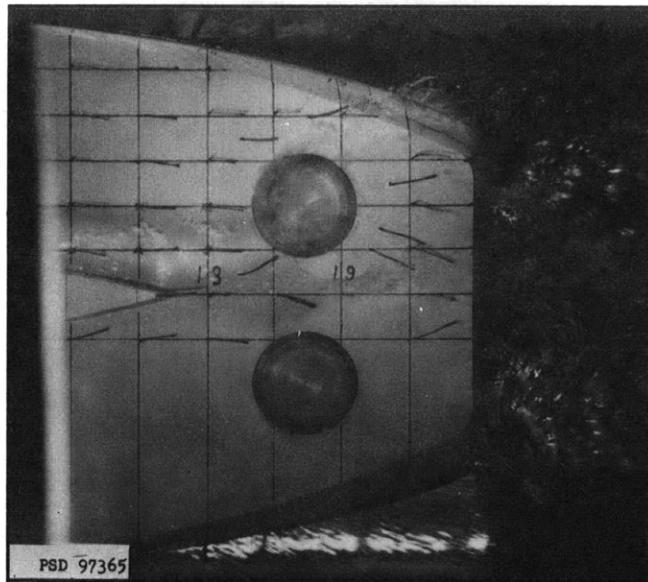
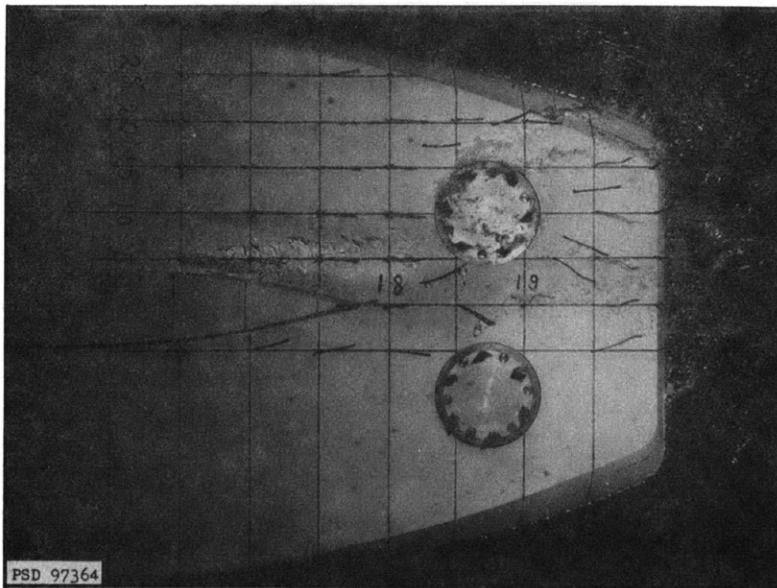


FIGURE 6

ARTIST CONCEPTION OF FLOW IN WAY  
OF VERTICAL - AXIS PROPELLER

FIGURE 7

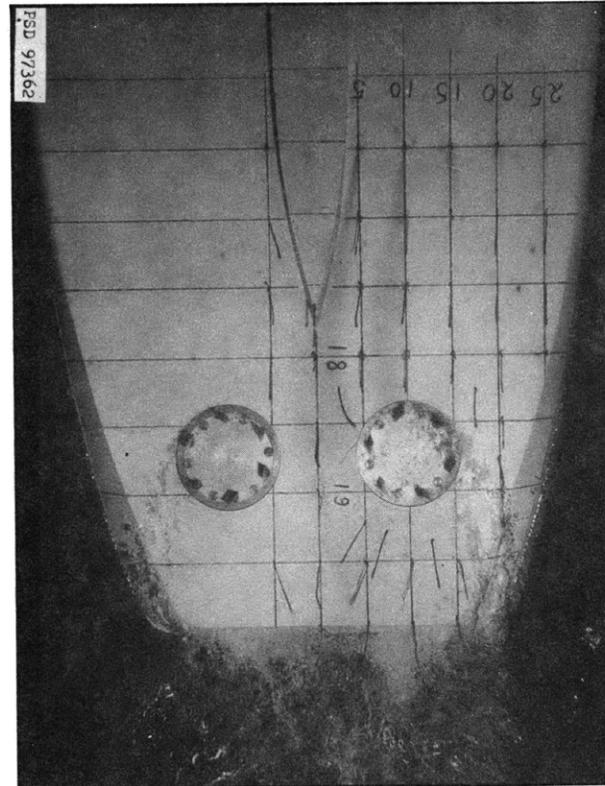
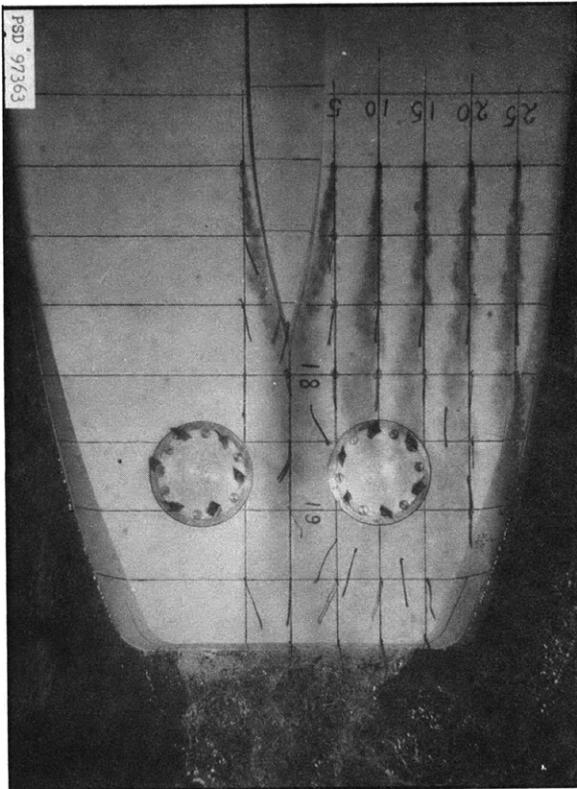
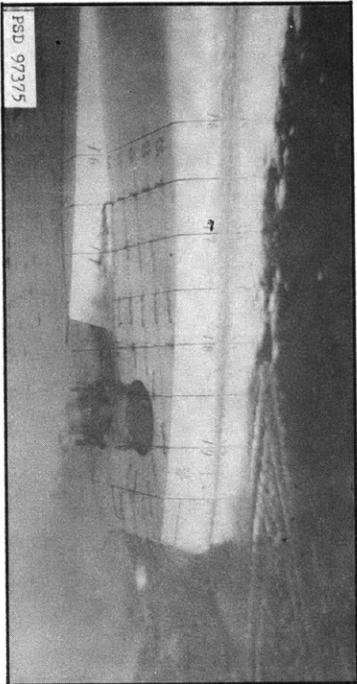


MOTION: SINUSOIDAL  
PITCH  $.58\pi$

MODEL 4571  
SPEED 6 KNOTS  
RPM 66.9

COMPENSATION  $10^\circ$

OUTWARD ROTATION  
STEERING ANGLE  $4^\circ$

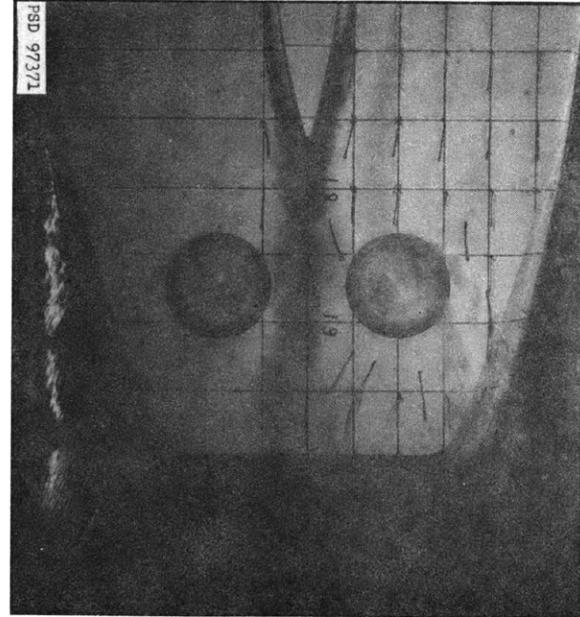
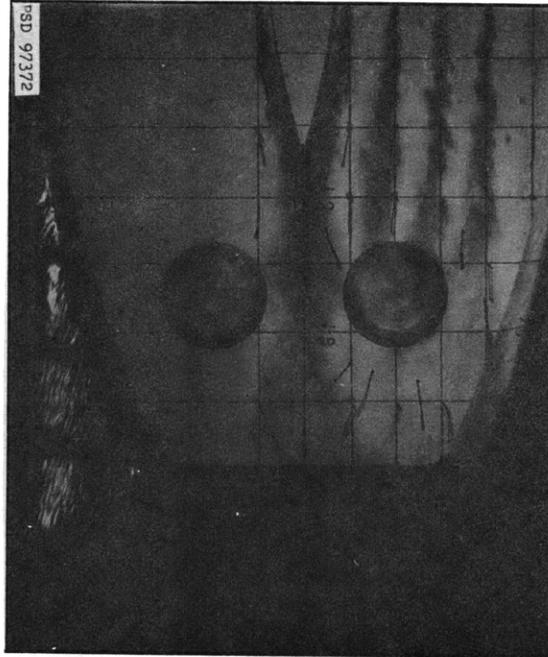
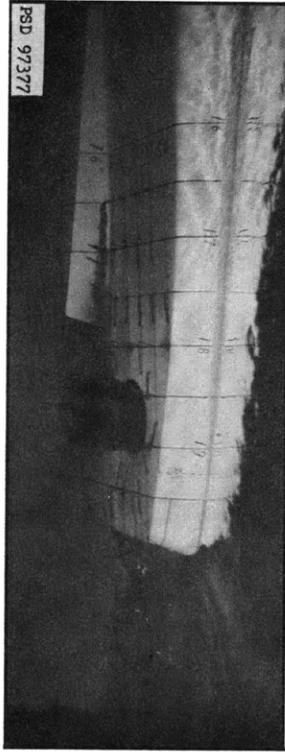


MOTION: SINUSOIDAL  
 PITCH  $.58\pi$

MODEL 4571  
 SPEED 8 KNOTS  
 RPM 91.8  
 COMPENSATION  $10^\circ$

OUTWARD ROTATION  
 STEERING ANGLE  $4^\circ$

FIGURE 8



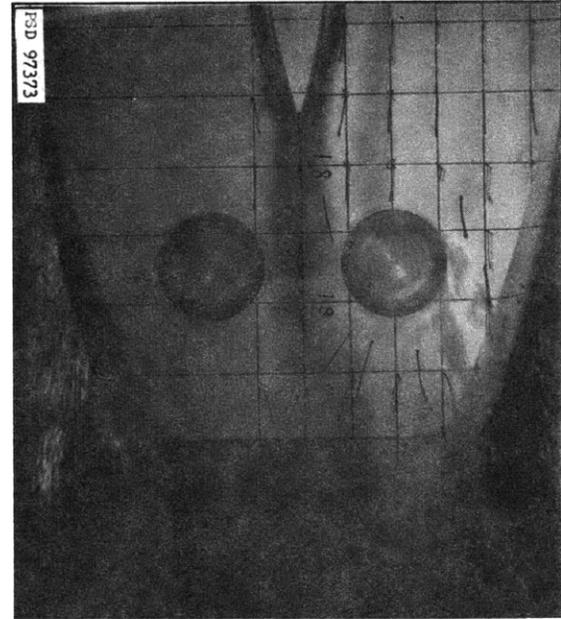
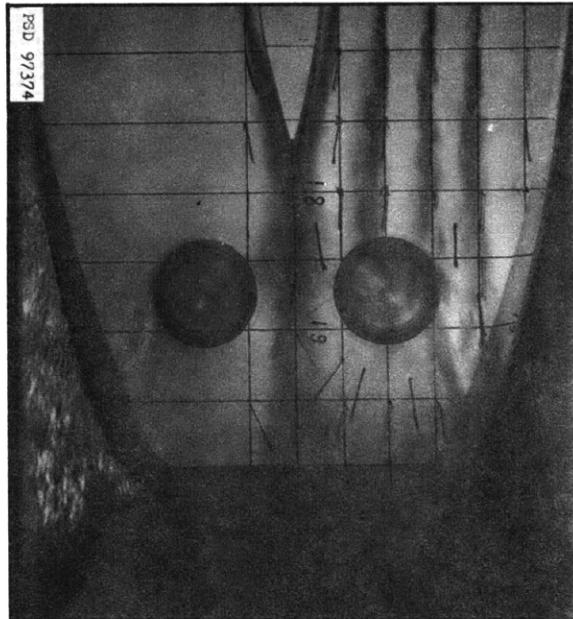
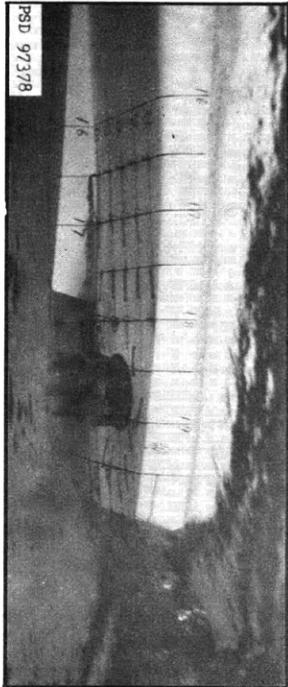
MOTION: SINUSOIDAL  
PITCH  $.65\pi$

MODEL 4571  
SPEED 6 KNOTS  
RPM 65.9

COMPENSATION  $10^\circ$

CUTWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 9



MOTION: SINUSOIDAL  
PITCH  $.65\pi$

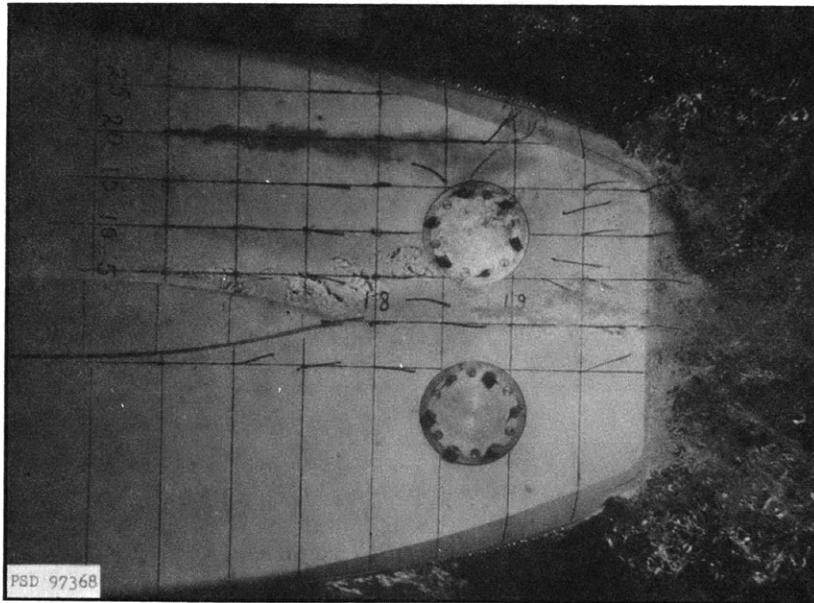
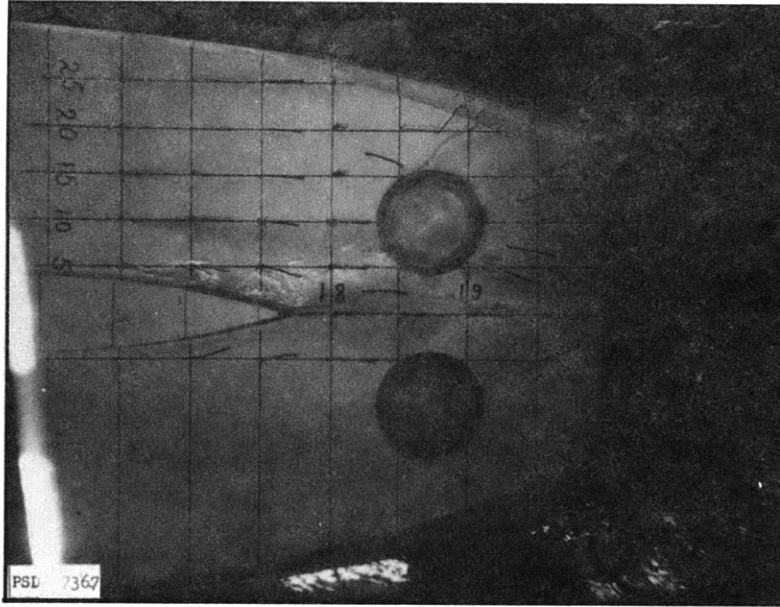
MODEL 4571  
SPEED 10 KNOTS  
RPM 101.2

COMPENSATION  $10^\circ$

OUTWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 10

FIGURE 11

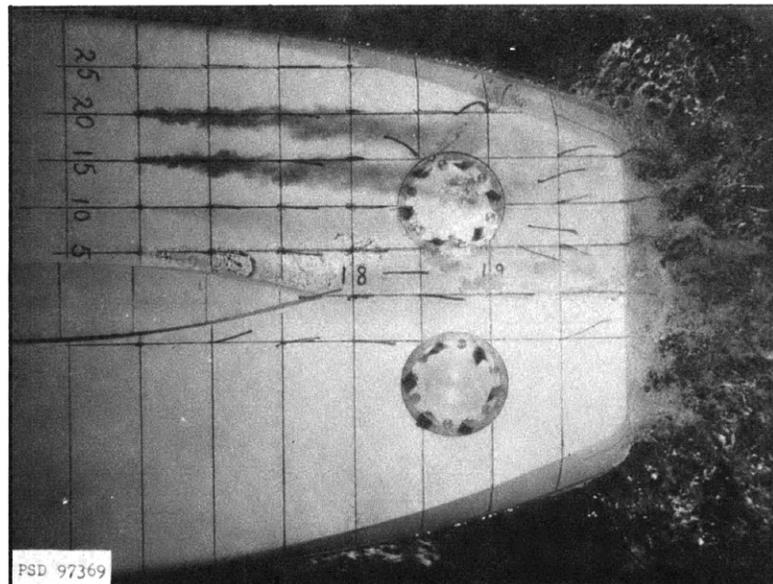
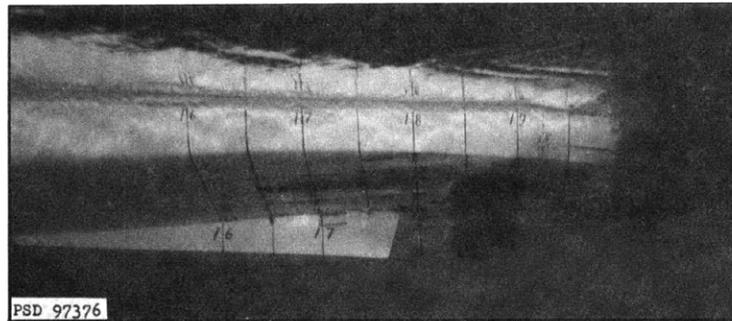


MOTION: SINUSOIDAL  
PITCH  $.58\pi$

MODEL 4571  
SPEED 8 KNOTS  
RPM 98.3  
COMPENSATION  $10^\circ$

INWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 12



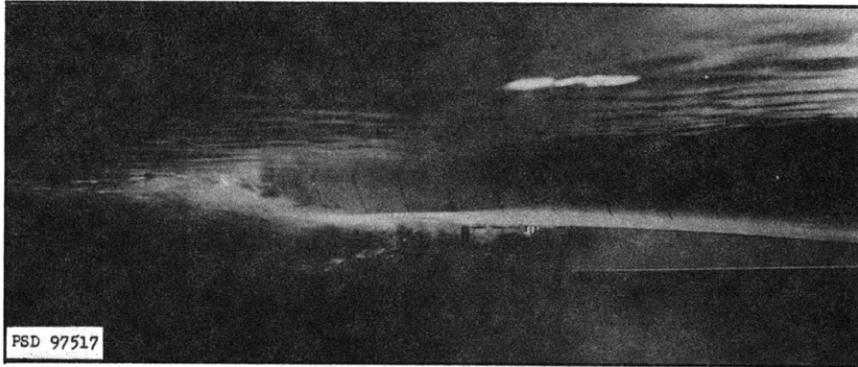
MOTION: SINUSOIDAL  
PITCH  $.58\pi$

MODEL 4571  
SPEED 8 KNOTS  
RPM 98.3

COMPENSATION  $10^\circ$

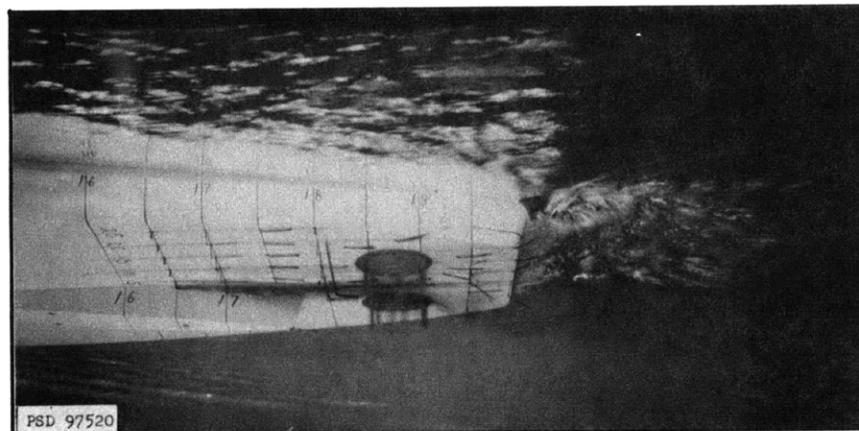
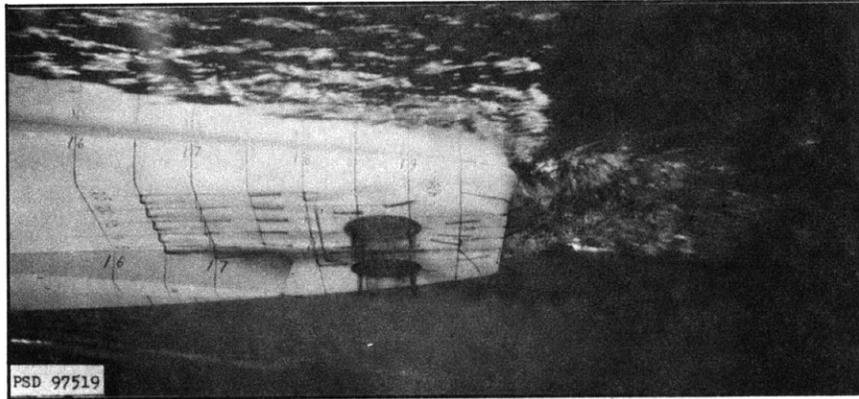
INWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 13



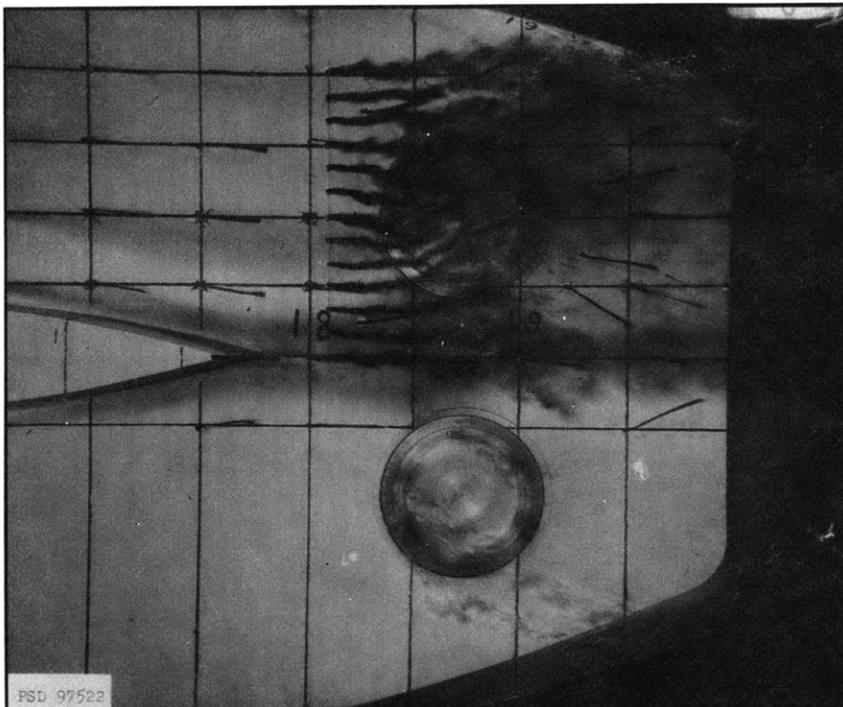
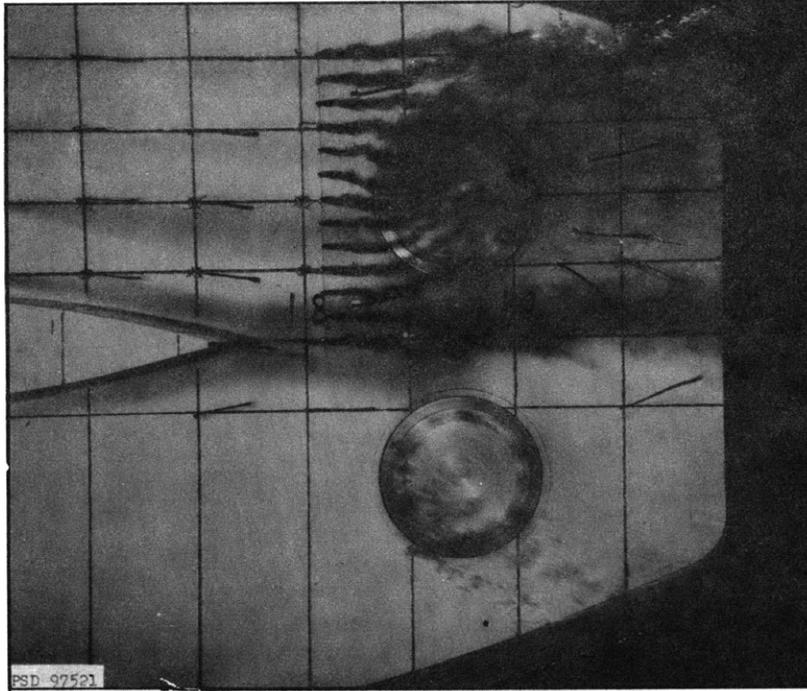
MOTION:	SINUSOIDAL	MODEL 4571	
PITCH $.65\pi$		SPEED 8 KNOTS	
		RPM 71.5	
		COMPENSATION $5^\circ$	OUTWARD ROTATION
			STEERING ANGLE $4^\circ$

FIGURE 14



MOTION:	SINUSOIDAL	MODEL 4571	OUTWARD ROTATION
PITCH $.65\pi$		SPEED 8 KNOTS	STEERING ANGLE $4^\circ$
		RPM 71.5	
		COMPENSATION $5^\circ$	

FIGURE 15

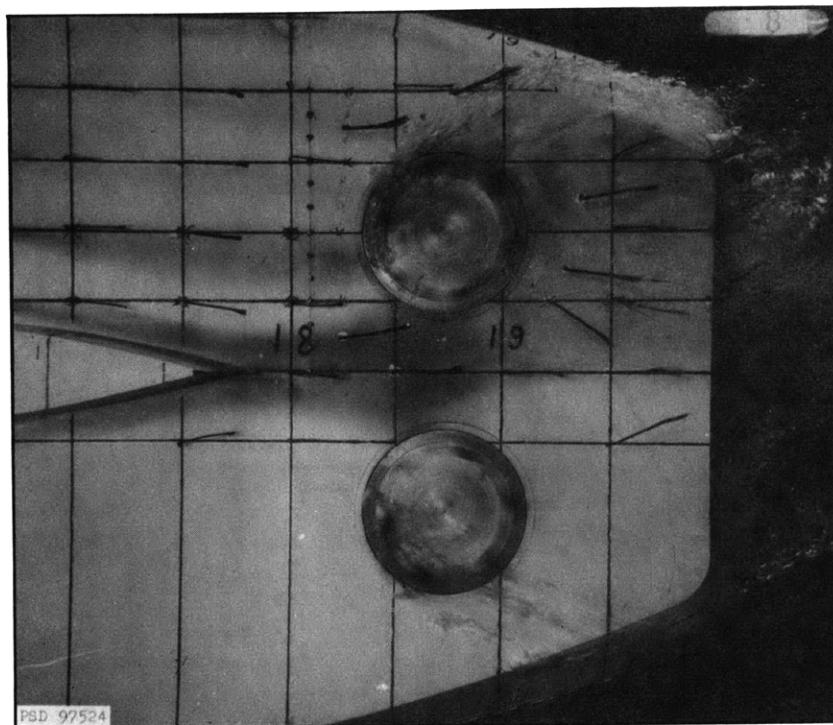
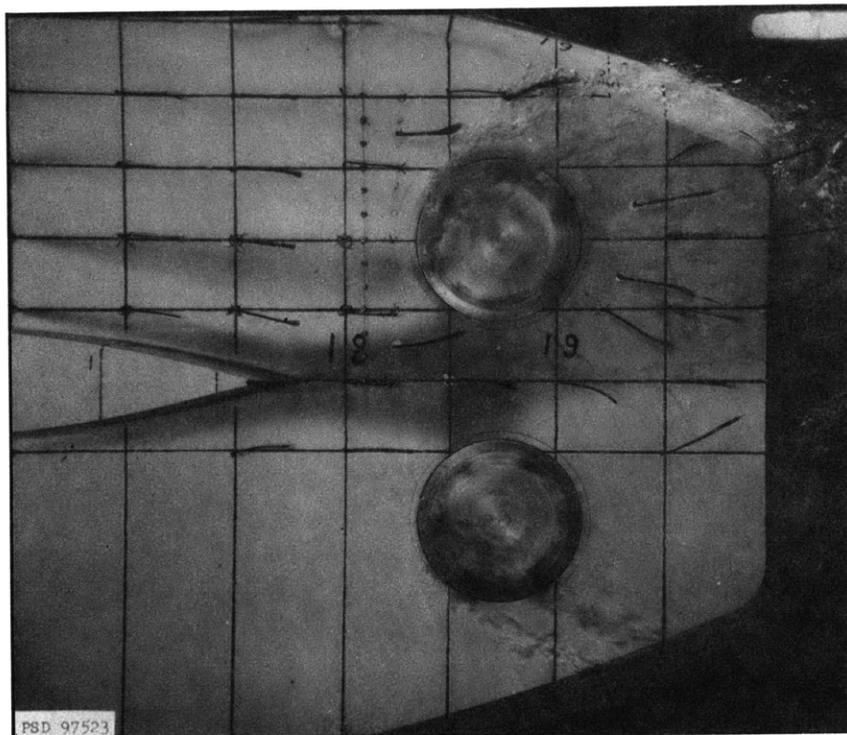


MOTION: SINUSOIDAL  
PITCH  $.65\pi$

MODEL 4571  
SPEED 8 KNOTS  
RPM 71.5  
COMPENSATION  $5^\circ$

OUTWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 16



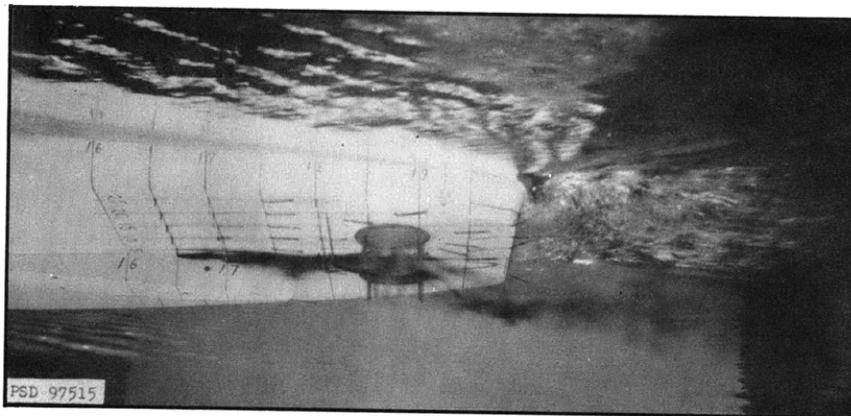
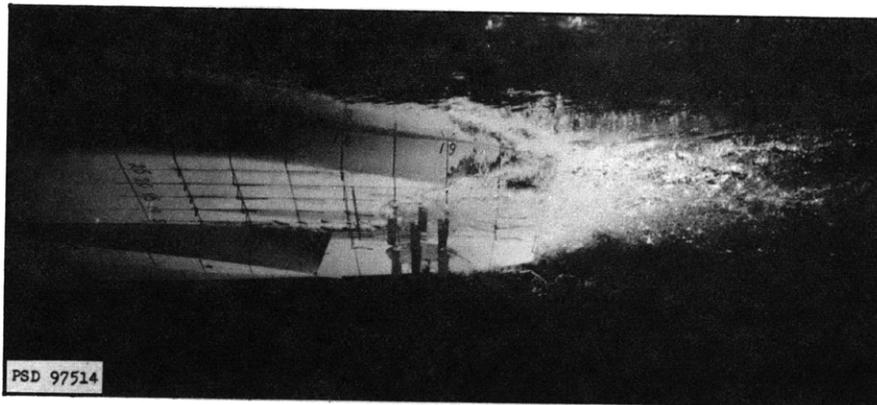
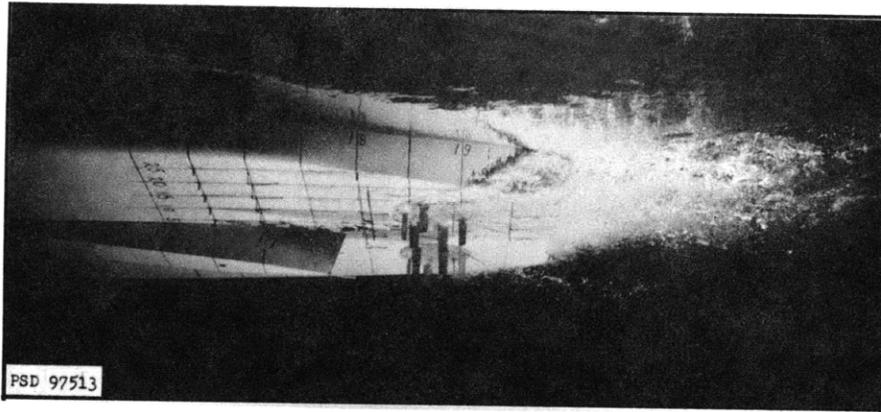
MOTION: SINUSOIDAL  
PITCH  $.65\pi$

MODEL 4571  
SPEED 8 KNOTS  
RPM 71.5

COMPENSATION  $5^\circ$

OUTWARD ROTATION  
STEERING ANGLE  $4^\circ$

FIGURE 17

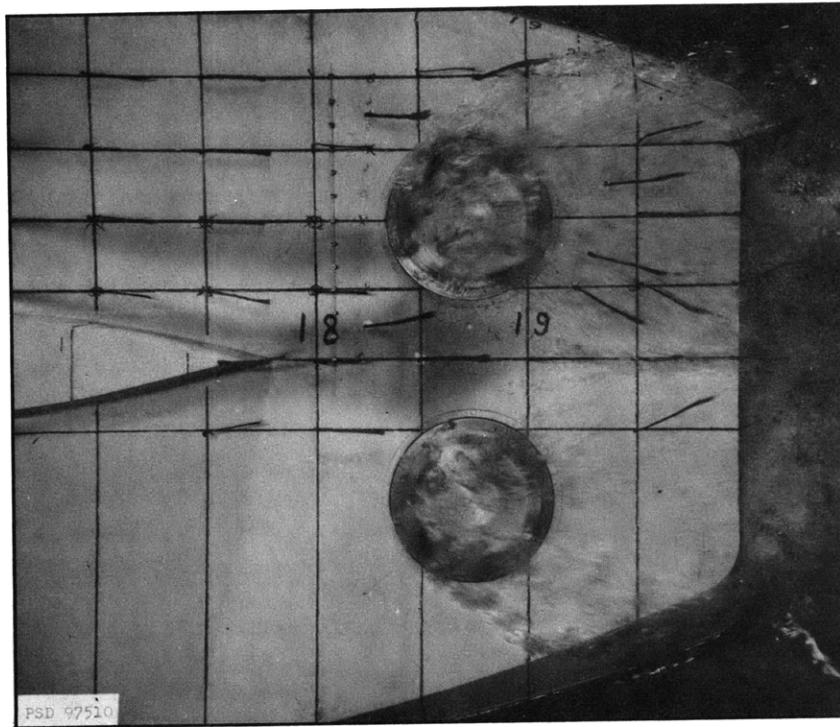
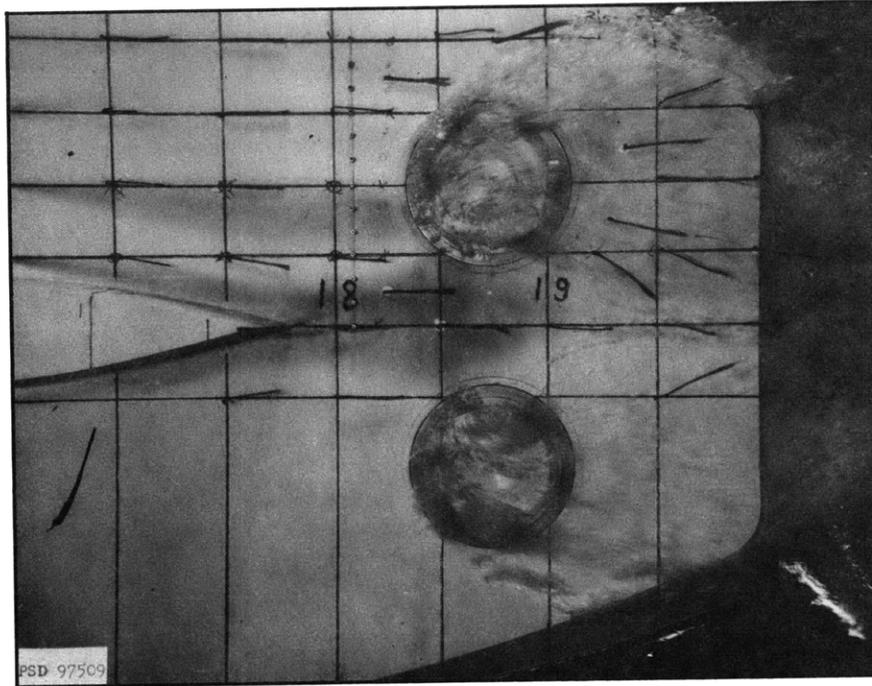


MOTION: ROTOR "A"  
PITCH  $.65\pi$  (3.15"e.)

MODEL 4571  
SPEED 8 KNOTS  
RPM 78.7  
COMPENSATION  $2^\circ$

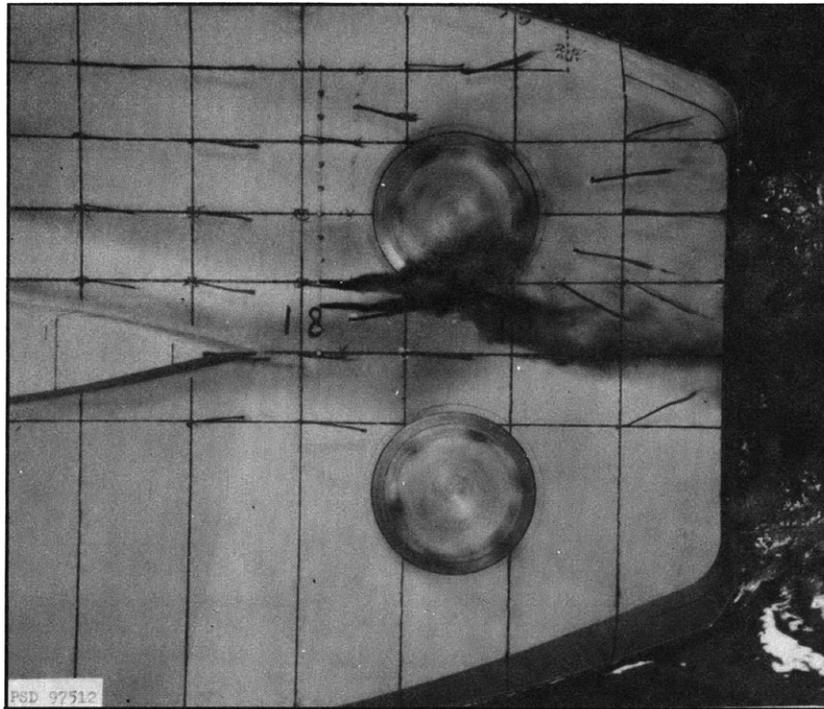
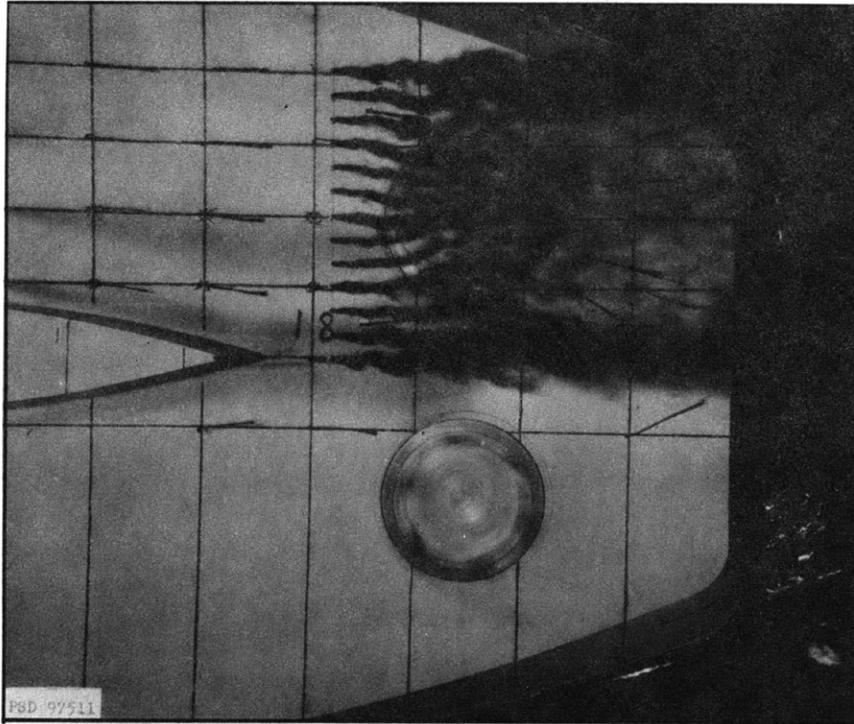
OUTWARD ROTATION  
STEERING ANGLE  $2.5^\circ$

FIGURE 18



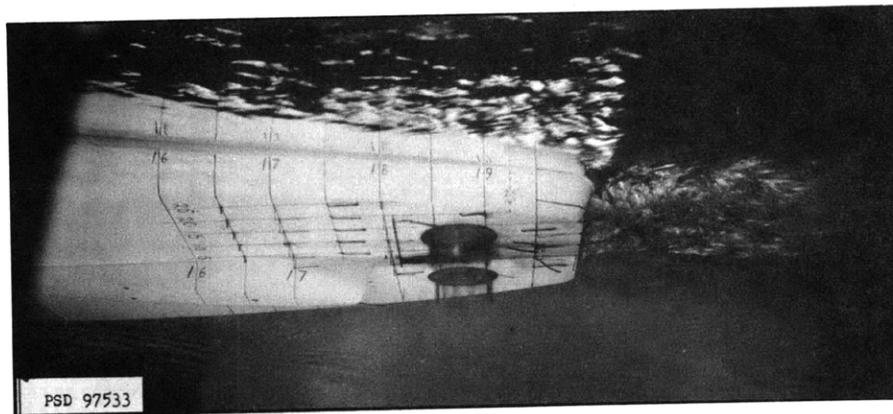
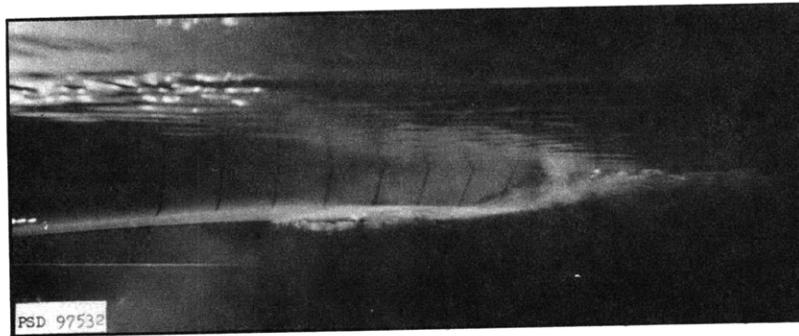
MOTION:	ROTOR "A"	MODEL 4571	
PITCH $.65\pi$ (3.15"e.)		SPEED 8 KNOTS	
		RPM 78.7	
		COMPENSATION $2^\circ$	OUTWARD ROTATION
			STEERING ANGLE $2.5^\circ$

FIGURE 19



MOTION:	ROTOR "A"	MODEL 4571	
PITCH	$.65\pi$ (3.15"e.)	SPEED	8 KNOTS
		RPM	78.7
		COMPENSATION	$20^\circ$
		OUTWARD ROTATION	
		STEERING ANGLE	$2.5^\circ$

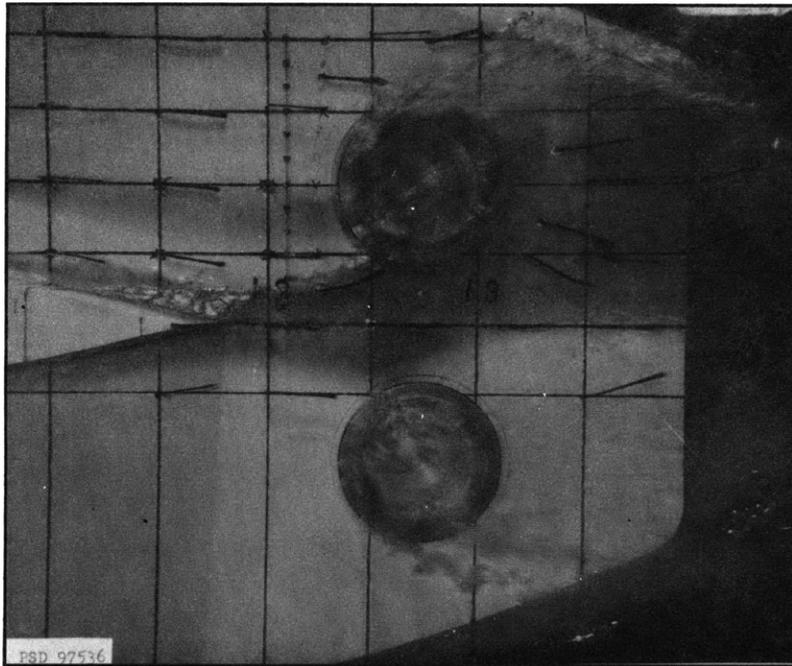
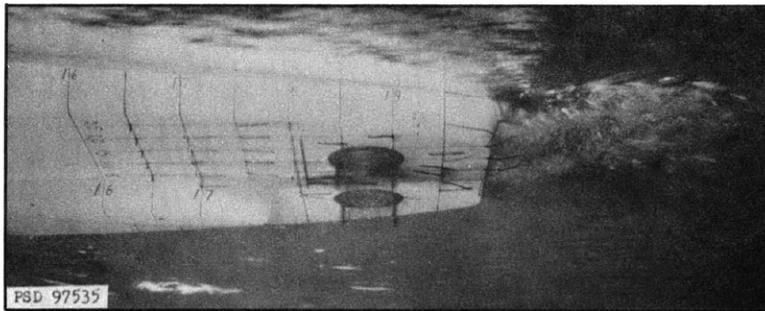
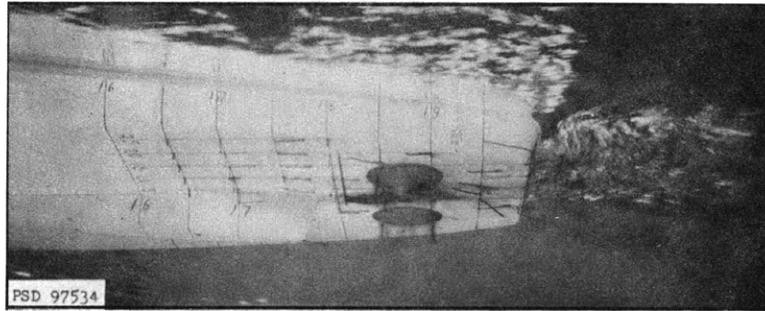
FIGURE 20



MODEL 4571  
SPEED 8 KNOTS  
RPM 74.6  
MOTION: MODIFIED CYCLOIDAL  
PITCH  $.65\pi$  COMPENSATION  $2.5^\circ$

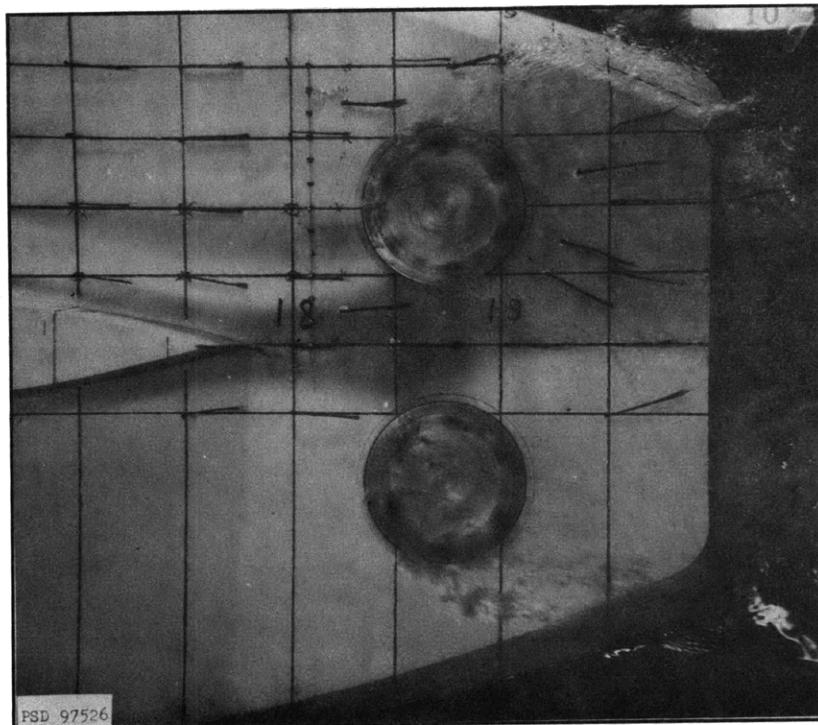
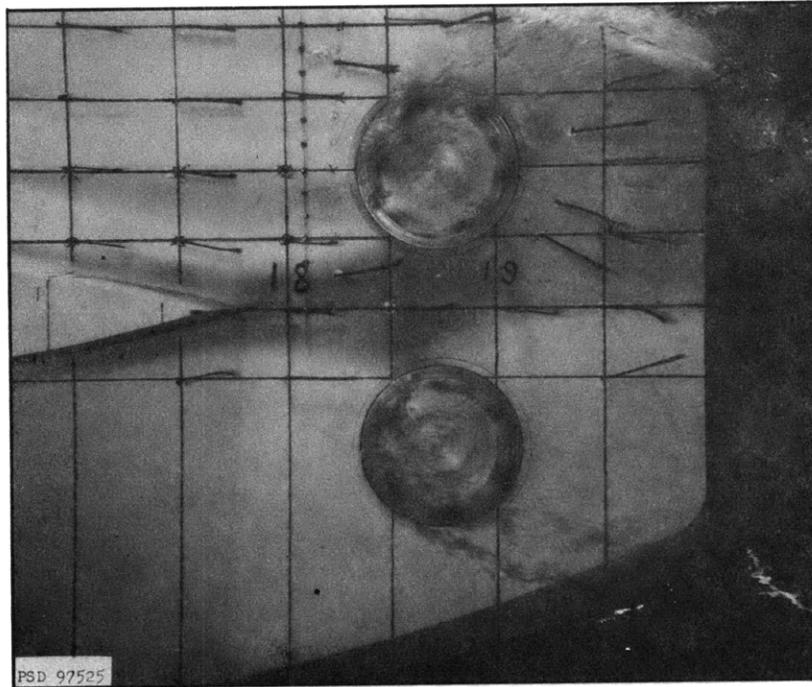
OUTWARD ROTATION  
STEERING ANGLE  $-6^\circ$

FIGURE 21



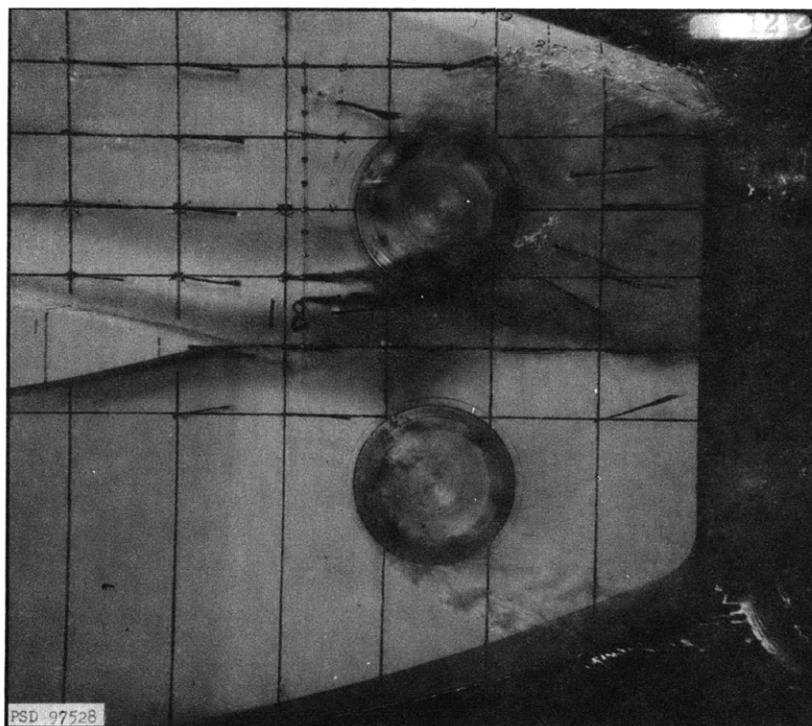
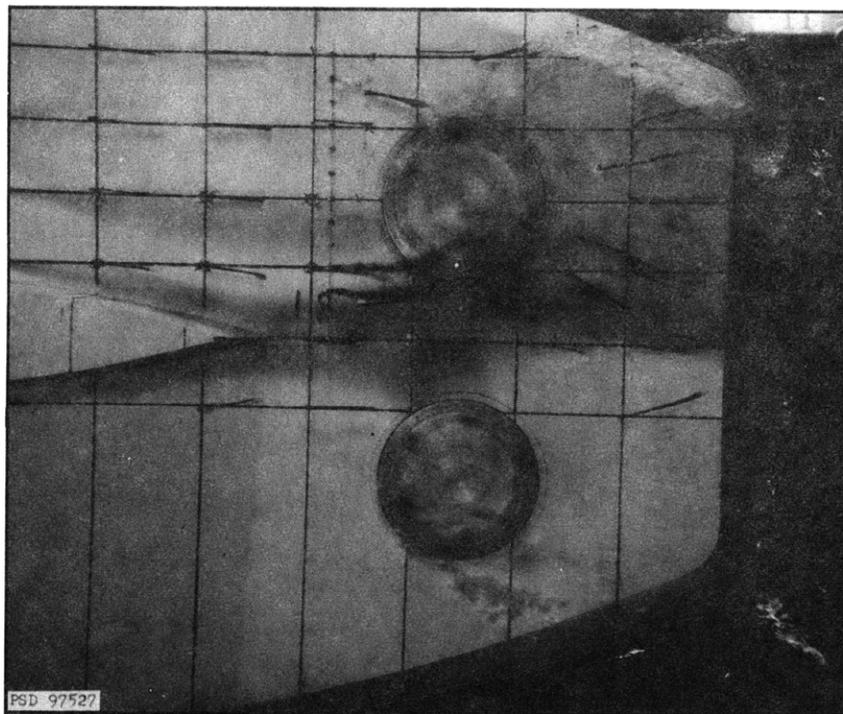
	MODEL 4571	
	SPEED 8 KNOTS	
	RPM 74.6	
MOTION: MODIFIED CYCLOIDAL		OUTWARD ROTATION
PITCH $.65\pi$	COMPENSATION $2.5^\circ$	STEERING ANGLE $-6^\circ$

FIGURE 22



	MODEL 4571	
	SPEED 8 KNOTS	
	RPM 74.6	
MOTION: MODIFIED CYCLOIDAL	COMPENSATION 2.5°	OUTWARD ROTATION
PITCH $.65\pi$		STEERING ANGLE $-6^\circ$

FIGURE 23



	MODEL 4571	
	SPEED 8 KNOTS	
	RPM 74.6	
MOTION: MODIFIED CYCLOIDAL	COMPENSATION 2.5°	OUTWARD ROTATION
PITCH .65π		STEERING ANGLE -6°



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