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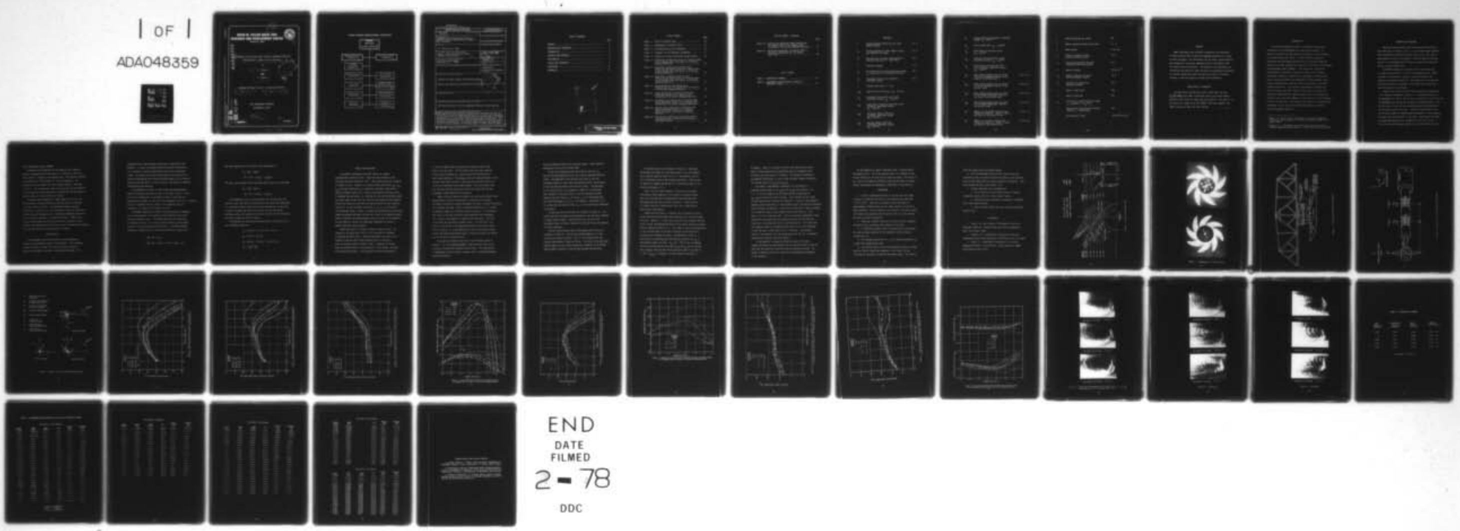

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PERFORMANCE OF AN INCLINED SHAFT PARTIALLY-SUBMERGED PROPELLER OPERATING OVER A RANGE OF SHAFT YAW ANGLES

(12)

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

AD A048359

(6) PERFORMANCE OF AN INCLINED SHAFT PARTIALLY-SUBMERGED PROPELLER OPERATING OVER A RANGE OF SHAFT YAW ANGLES

by

(10) R. S./Alder

[redacted]

D. H./Moore

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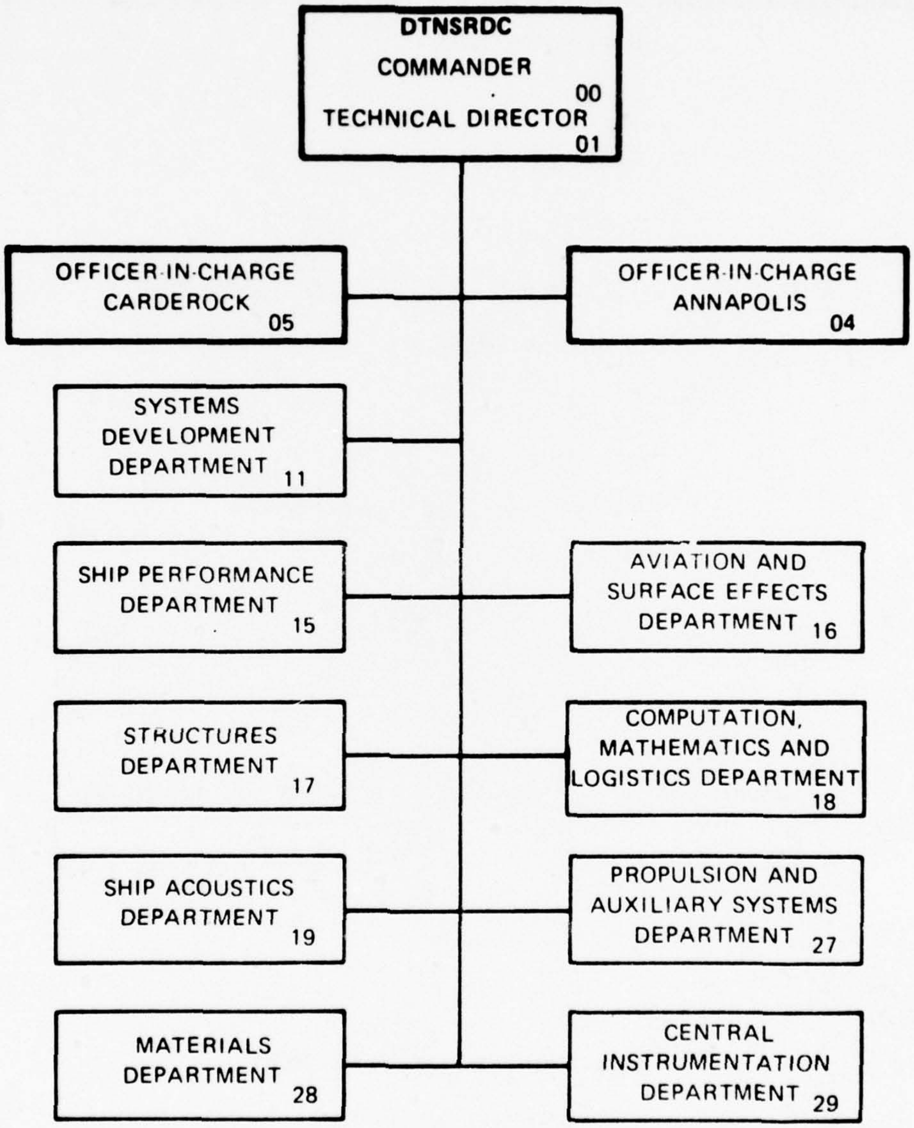

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Model experiments were conducted to determine the performance of model propeller 4407 in partially-submerged operation for a range of shaft yaw angles. All experiments with the highly skewed propeller were conducted at 30 percent submergence and at 19.5 degrees shaft inclination from the horizontal. The purpose of the experiments was to determine the effects of shaft yaw angle on the propeller performance. Test results showed that shaft yaw angle could yield a 15 percent increase in efficiency based on forward thrust production.

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NOTATION

a	Distance between forward and aft shaft moment flexures	in., m
a_1	Distance between aft shaft moment flexure and propeller hub center	in., m
BF	Bearing force, the total force acting on the shaft bearing, $BF = \sqrt{H_p^2 + V_p^2}$	lb, m
D	Propeller diameter	ft, m
H_e	Horizontal force in earth coordinate system. H_e is positive in the starboard direction	lb, N
H_p	Horizontal force (in the propeller coordinate system)	lb, N
J	Advance coefficient, $J = V/nD$	
K_{BF}	Bearing force coefficient, $K_{BF} = BF/\rho n^2 D^4$	
K_{H_e}	Horizontal force coefficient (earth coordinate system), $K_{H_e} = H_e/\rho n^2 D^4$	
K_{H_p}	Coefficient of measured horizontal force (propeller coordinate system), $K_{H_p} = H_p/\rho n^2 D^4$	
K_{MH}	Horizontal moment coefficient (propeller coordinate system) $K_{MH} = MH/\rho n^2 D^5$	
K_{MV}	Vertical moment coefficient (propeller coordinate system) $K_{MV} = MV/\rho n^2 D^5$	

K_Q	Torque coefficient (propeller coordinate system), $K_Q = Q/\rho n^2 D^5$	
K_{T_e}	Thrust coefficient, $K_{T_e} = T_e/\rho n^2 D^4$	
K_{T_p}	Coefficient of shaftline thrust, $K_{T_p} = T_p/\rho n^2 D^4$	
K_{V_e}	Vertical force coefficient (earth coordinate system), $K_{V_e} = V_e/\rho n^2 D^4$	
K_{V_p}	Coefficient of measured vertical force (propeller coordinate system), $K_{V_p} = V_p/\rho n^2 D^4$	
M_{AX}	Shaft bending moment about the center of the aft dynamometer flexure in the plane of the pitched shaft	in-lb , N.m
M_{AY}	Shaft bending moment about the center of the aft dynamometer flexure in the vertical plane	in-lb , N.m
M_{BX}	Shaft bending moment about the center of the forward dynamometer flexure in the plane of the pitched shaft	in-lb , N.m
M_{BY}	Shaft bending moment about the center of the forward dynamometer flexure in the vertical plane	in-lb , N.m
MH	Moment in a horizontal plane passing through the propeller. Moment is about the center of the propeller hub.	in-lb , N.m
MV	Moment in a vertical plane passing through the propeller. Moment is about the center of the propeller hub.	in-lb , N.m

n	Shaft revolutions per second	RPS
P	Nominal propeller blade section pitch	in., m
Q	Shaft torque	in-lb, N.m
T_e	Thrust or propulsive force (earth coordinate system)	lb, N
T_p	Thrust measured along the shaft (propeller coordinate system)	lb, N
V	Speed of advance	ft/sec, ms^{-1}
V_e	Vertical force or lift force (earth coordinate system)	lb, N
V_p	Vertical force (propeller coordinate system)	lb, N
α	Angle of shaft pitch	deg
β	Angle of shaft yaw	deg
η_e	Efficiency in earth coordinate system, $\eta_e = T_e V/2\pi Qn = J(K_{T_e})/2\pi K_Q$	
θ	Bearing force angle measured from the vertical, $\theta = \text{Arctan}\ H_p/V_p$	deg
ρ	Mass density of water	lb-sec^2/ft^4, kg m^{-3}

ABSTRACT

Model experiments were conducted to determine the performance of model propeller 4407 in partially-submerged operation for a range of shaft yaw angles. All experiments with the highly skewed propeller were conducted at 30 percent submergence and at 19.5 degrees shaft inclination from the horizontal. The purpose of the experiments was to determine the effects of shaft yaw angle on the propeller performance. Test results showed that shaft yaw angle could yield a 15 percent increase in efficiency based on forward thrust production.

ADMINISTRATIVE INFORMATION

The experiments reported herein were funded under Task Area SF 4342170408, Task 17646, Element 627N, Naval Sea Systems Command (NAVSEA) Project Order No. 40002, Work Unit 1520-110. The analysis of the results was funded by PMS 304, NAVSEA, Task Area S0308001, Task 19588, Fund Code A 7056, Work Unit 1532-304.

INTRODUCTION

The partially-submerged propeller arrangement has long been recognized as being advantageous for special applications[1]. It appears to be one of the most efficient systems for use as propulsors on Surface Effects Ships (SES)[2]. A rather extensive program to investigate the performance characteristics of partially-submerged propellers has been conducted at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC). This program has included the investigation of the effect of number of blades, type of blades, blade skew, blade rake, propeller disc submergence, and many other factors which would affect the performance of these propeller types. Large transverse forces have been found to be produced by partially submerged propellers. The results of experimental investigations seem to indicate that these transverse forces may be substantially reduced or transformed into useable forward thrust by orienting the propeller shaft such that components of the forces act in the direction of motion of the craft. The purpose of this report is to identify the advantages, if any, that can be derived from yawing a 30 percent partially-submerged propeller.

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[1] Hadler, J.B. and R. Hecker, "Performance of Partially-Submerged Propellers," Seventh Symposium on Naval Hydrodynamics, Rome, Italy (August 1968).

[2] Shields, C.F., "Performance Characteristics of Several Partially-Submerged Supercavitating Propellers," NSRDC Report 2723 (July 1968).

APPARATUS AND PROCEDURE

Experiments were conducted using the supercavitating propeller model 4407 shown in Figures 1 and 2. It is an eight-bladed propeller, highly skewed (45°) and highly pitched (pitch ratio = 1.8), with a skew-induced tip rake of 19.5 degrees. Propeller 4407 was selected because it is representative of the type of propeller that would be used on a surface effects ship.

The DTNSRDC towing tank at Langley Field, Virginia was used to conduct the experiments. A small flat-bottomed hull was rigidly attached to the carriage to provide a platform from which the propeller could operate (Figure 3). When towed by the carriage, the flat bottom of the hull generated a flat smooth water surface into which the propeller could operate.

Propeller side forces and shaft bending moments were measured by a four component dynamometer (Figure 4). The maximum side force on the dynamometer was 150 lb (667 N) with an accuracy of ± 0.8 lb (±3.6 N). The dynamometer was constructed to measure two bending moments in the vertical plane of the shaft and two bending moments were measured in the horizontal plane of the shaft. Side forces were computed using the distance between the bending moment measurements in the respective horizontal and vertical planes of the shaft. Shaft thrust and torque were measured separately by a standard 100 in-lb (± 0.5 in-lb), (11.3 N.m ± 0.06 N.m) torque and 100 lb (± 0.5 lb), (445 N ± 2.2 N) thrust dynamometer used by DTNSRDC.

Experiments were conducted with the propeller at 30 percent diameter submergence which corresponds to a condition in which the water surface is tangent to the propeller hub. The shaft was inclined 19.5 degrees from the horizontal for all yaw experiments. The propeller shaft was yawed to the five separate angles as indicated in Table 1. The yaw angle was taken to be positive with the propeller on the centerline of the barge and the upstream shaft of the propeller angled to the port side as defined in Figure 5.

Experiments were conducted at a model speed of 7.5 knots with the exception of the zero degree yaw condition which was conducted at a model speed of 10 knots. An approximate range of advance coefficient, J, from 0.6 to 2.0 was obtained for each yaw condition by varying the shaft revolution rate. Underwater photographs were taken of the cavitating propeller at selected conditions. Shaft thrust, torque, bending moment and side force data were collected for each yaw angle and advance condition with the aid of an Interdata mini-computer which averaged the data for approximately 15 seconds.

DATA ANALYSIS

The experimental data were obtained by using dynamometers aligned to the coordinate system of the propeller. This coordinate system as defined in Figure 5 has the thrust vector along the propeller shaft which is positive in the forward direction. The measured vertical and horizontal forces were in the plane of the propeller. In order to determine effective propeller performance, it is necessary to resolve these forces into an earth coordinate system. The analysis was further complicated by the design of the side force dynamometer which measured bending moments at two separate stations along the shaft. In order to obtain side forces an algebraic transformation was necessary.

The dynamometer as shown in Figure 4 measured bending moments about the horizontal and vertical axes in the planes A and B. Planes A and B are perpendicular to the shaft at points A and B and are separated by a distance "a" which for this dynamometer was 2.16 in. (5.49 cm) Point A is separated from the center of the propeller disc by a distance of "a_1" equal to 4.0 inches (10.16 cm).

The moment produced on a propeller operating partially submerged can be represented by a pure moment and force applied to the shaft about the propeller center. This moment and force can be measured as a moment and force in the vertical plane (MV and V_p) and a moment and force in the horizontal plane (MH and H_p). The bending moments generated at Planes A and B in the vertical plane are, respectively:

$$- M_{AY} = MV - V_p \, a_1$$

$$- M_{BY} = MV - V_p \, (a_1 + a) = MV - V_p \, a_1 - V_p \, a$$

From these equations, the "vertical" force and moment are

$$V_P = (M_{BY} - M_{AY})/a$$

$$- MV = [(a + a_1)\ M_{AY} - a_1\ M_{BY}]/a$$

Similarly, the horizontal force and moment coefficients can be obtained:

$$H_P = (M_{BX} - M_{AX})/a$$

$$- MH = [(a + a_1)\ M_{AX} - a_1\ M_{BY}]/a$$

The dynamometers used in the experiments were mounted along the propeller shaft, the thrust was measured and side forces were determined in a coordinate system aligned parallel and perpendicular to the shaft. In order to present the results in an earth or (ship referenced) coordinate system, the measured forces were resolved into the horizontal and vertical planes as shown in Figure 5.

The formulae for resolving the measured forces into forces of the ship coordinate system are:

$$T_e = (T_P \cos\alpha - V_P \sin\alpha) \cos\beta + H_P \sin\beta$$

$$V_e = T_P \sin\alpha + V_P \cos\alpha$$

$$H_e = H_P \cos\beta - (T_P \cos\alpha - V_P \sin\alpha) \sin\beta$$

$$BF = \sqrt{V_p^2 + H_P^2}$$

RESULTS AND DISCUSSION

The propeller performance data were reduced to standard nondimensional coefficient form. Force data were divided by $\rho n^2 D^4$ and moment data were divided by $\rho n^2 D^5$. These coefficients are presented in Figures 6 to 14. Figures 6 to 9 present force coefficients K_{T_p}, K_{H_p}, K_{V_p} and torque coefficient K_Q in propeller coordinate system versus propeller advance coefficient. Figure 9 also presents efficiency which is computed from the thrust, T_e, resolved into the ship coordinate system. The torque data for the 9.75° yaw condition were defective and therefore neither the torque nor efficiency has been presented for that condition. Figures 10, 11, and 12 present the forces T_e, H_e, V_e, in the earth or ship coordinate system. Figure 13 presents the bearing force coefficients (based on measured horizontal and vertical forces in the propeller plane). Figure 14 presents the bending moments about the center of the propeller hub and Figure 15 presents the underwater photographs (at various advance conditions and yaw angles).

Trends were noted in the data as shown in Figures 6 and 7. An increase in yaw angle from -9.75° to 19.5° resulted in a decrease in measured shaftline thrust. Measured horizontal side force in the propeller plane and shaft torque decreased with an increase in shaft yaw angle as shown in Figures 7 and 9. Propeller efficiency, based on resultant thrust in the direction of craft motion, increased with increasing yaw angle. Peak propeller efficiencies observed at

5.0 and 19.5 degree shaft yaw angle were 15 percent higher than that at zero yaw angle. The 19.5 degree shaft yaw angle condition achieves peak efficiency at a lower advance coefficient than for other yawed conditions. There appear to be no pronounced trends in the vertical force data of Figure 8 indicating that vertical forces are relatively insensitive to yaw angle changes. This may be due to the fact that the vertical forces are of such small magnitude that the dynamometer cannot measure them accurately.

Figures 10 and 11 present resultant (ship coordinate system) thrust and horizontal side force coefficients as functions of yaw angle. Horizontal side force is reduced throughout the range of advance coefficient for increasing yaw angle. Below an advance coefficient of 1.2, thrust is generally higher for increasing positive yaw angle. The horizontal side force in the ship coordinate system approaches zero throughout the J range as the propeller is yawed to positive angles. The 19.5° yaw position has the lowest horizontal force. This decline is the result of the decline in the measured horizontal side force as noted earlier; however, it is more emphasized in the ship coordinate system because the measured horizontal vector is directed forward contributing less to the ship's horizontal force.

The results of yawing can be seen in the efficiency curves of Figure 9. It is the added component of the horizontal force in the direction of motion that improves the efficiency. This observation is emphasized by the fact that a constant ratio is maintained between measured horizontal force and shaftline thrust with yaw angle change. A more detailed explanation of this will be given later.

In the ship coordinate system the vertical side force is derived from the measured vertical force and the measured shaftline thrust. The magnitude of the vertical side force in the ship coordinate system is larger than the measured vertical force because of the contributions made by the shaftline thrust. The magnitude of the vertical force, V_e, presented in Figure 12 is significant when compared to the other forces in the ship coordinate system. Comparing vertical force, V_e, to thrust, T_e, on a percentage basis the lowest percentage of V_e to T_e is 40 percent. From Figure 12 it is evident that the vertical force, V_e, is not significantly influenced by yaw angle.

The bearing force coefficients are presented in Figure 13. The curves show that the bearing force decreased as the yaw angle increased to higher positive angles. Bearing forces are similar to the horizontal forces of Figure 7 because the vertical forces are generally of smaller magnitude.

Vertical and horizontal shaft bending moment coefficients are presented in Figure 14. The vertical bending moment has no clear trend with yaw angle variation. This is to be expected from the previous observations of vertical forces. The trends of the horizontal bending moment are not clearly defined but in general the horizontal bending moment increases as the yaw angle becomes more positive.

Cavitation results are displayed in Figure 15. Underwater photographs were taken for a yaw angle range of 0 to 19.5 degrees and an advance condition from 0.6 to 1.6. The propeller was not fully ventilated at two of the displayed conditions. They are the yaw angle of 5 degrees and advance of 1.4 and the yaw angle of 19.5 degrees and advance of 1.6.

Table 2 of this report contains a listing of the unfaired experimental values measured in the propeller coordinate system. These are the actual data collected during the experiment with adjustment made for zero (no load) conditions. A water density of 1.9905 $lb\text{-}sec^2/ft^4$ (1025.86 Kg/m^3) was used in computing the dimensionless coefficients.

Summarizing the results, it appears that the shaftline thrust, torque, and measured horizontal forces decrease with increasing shaft yaw angle. However, it is also noted that the ratios between shaftline thrust, torque, and measured horizontal force remain relatively constant below an advance condition of 1.4. The result of these two observations is that the efficiency in the earth coordinate system necessarily increases with increasing yaw angle. Mathematically stated η_e is proportional to $(J/2\pi)/(K_{T_e}/K_Q)$ (assuming K_{V_p} constant) and K_{T_e} is approximately equal to $K_T \cos\beta + K_{H_p} \sin\beta$. Solving for the maximum efficiency and applying the fact that K_{T_p}/K_Q and K_{H_p}/K_Q are constant with yaw angle, then the peak efficiency occurs when a yaw angle of $\beta = \mathrm{Tan}^{-1} K_{H_p}/K_{T_p}$ is achieved. For this propeller the angle is

37 degrees. There is no reason to believe that these results would apply to other propellers and experiments were not conducted at the relatively large yaw angle of 37 degrees. The propeller performance may degrade significantly at such a large yaw angle thereby eliminating the constant ratios of K_{H_p}/K_Q and K_{T_p}/K_Q.

The change in hydrodynamic performance of the propeller is evidenced by the change in the K_{H_p}/K_Q and K_{T_p}/K_Q ratios above a J of 1.4. It is also evidenced by the steady decline in magnitude of K_{T_p}, K_{H_p} and K_Q with yaw angle increase. These changes are the result of many factors which influence the propeller. A review of the propeller geometry would be beneficial in understanding some of the physical mechanisms which influence the propeller. Definition of rake angle is made by running a line from the center of the propeller hub to the blade tip. This angle is 19.5° for propeller 4407. With the 30 percent submergence a more appropriate rake angle would be defined by the line running from the blade root to the blade tip which is approximately 30°. This means that the propeller radius as defined from hub center is not fully presented to the flow until a shaft angle of 30° is achieved. The effective radius of the propeller over the wetted portion of the disc is therefore changing with yaw angle (and pitch angle).

As the propeller is yawed the effective pitch of the blade changes and because of the propeller rake the effective pitch is not the same over the entire disc area with even the smallest yaw angle. The change in effective pitch will influence the hydrodynamic performance of the propeller.

As the propeller is yawed a transverse flow is created across the propeller disc. This flow velocity vector is a function of the forward velocity of the craft and the shaft yaw angle. The result of this flow is to change the effective blade section angles of attack, thereby influencing the hydrodynamic performance of the propeller.

CONCLUSIONS

1. The most enlightening results of the data were the steady increases in propeller efficiency as the propeller was yawed from -9.75° to 19.5°. There was an increase in peak efficiency of approximately 15 percent from the zero yawed condition to the 19.5° yawed condition. For this propeller the increase is the direct result of orienting the propeller plane horizontal force to a more forward position by yawing the propeller.

2. There was a general reduction of shaftline thrust, measured horizontal force, and torque with increase in yaw angle.

3. A relatively constant ratio of T_P/Q and H_P/Q was maintained for each yaw angle condition of this propeller below an advance condition of 1.4.

4. The resultant horizontal force H_e was reduced throughout the J range with increasing yaw angle.

5. The vertical force in the ship coordinate system was a large positive force of significant magnitude. Its minimum size was 40 percent of the thrust in the ship coordinate system. The vertical

force was insensitive to yaw angle changes.

6. With the magnitude of the vertical force in the ship coordinate system, consideration should be given to utilizing this force in high speed craft by midship placement of propellers. This could improve the total craft dynamic lift.

7. Further experiments are recommended to:

a. Fully explore yaw angle change effects of smaller incremental changes and over a wider range of angles.

b. Generate detailed underwater photography to determine fully ventilated conditions.

c. More accurately define the water surface entering the propeller disc.

REFERENCES

1. Hadler, J.B. and R. Hecker, "Performance of Partially Submerged Propellers," Seventh Symposium on Naval Hydrodynamics, Rome, Italy (August 1968).

2. Shields, C.F., "Experimental Performance of Partially Submerged Supercavitating Propellers," NSRDC Report 2723 (July 1968).

3. Hecker, R., "Experimental Performance of a Partially Submerged Propeller in Inclined Flow," Paper presented at SNAME Spring Meeting (April 1973).

PITCH RATIO AT 0.7R	1.800
EXPANDED AREA RATIO	0.502
BLADE THICKNESS FRACTION	0.029

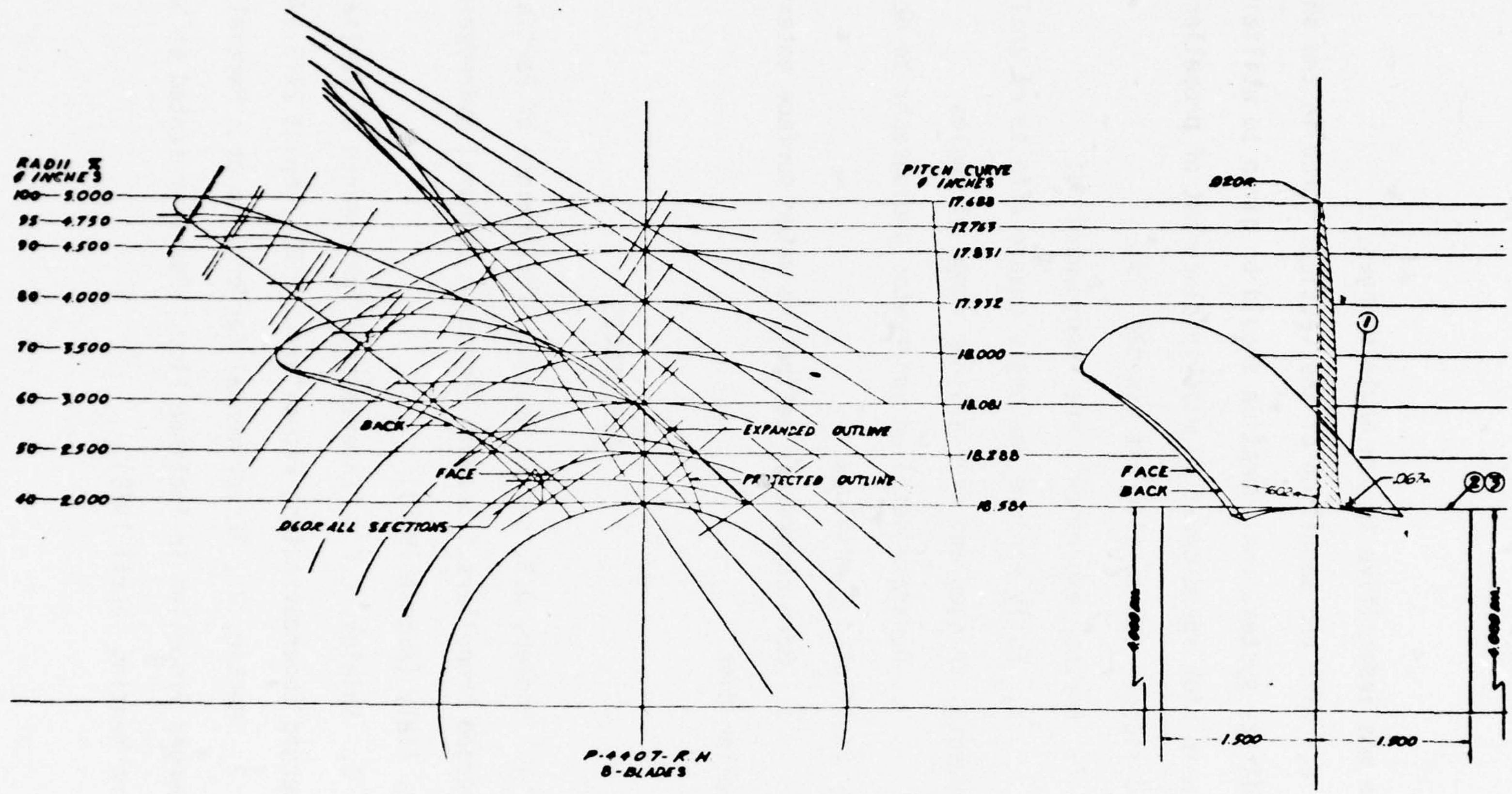


Figure 1 - Plans of Propeller 4407

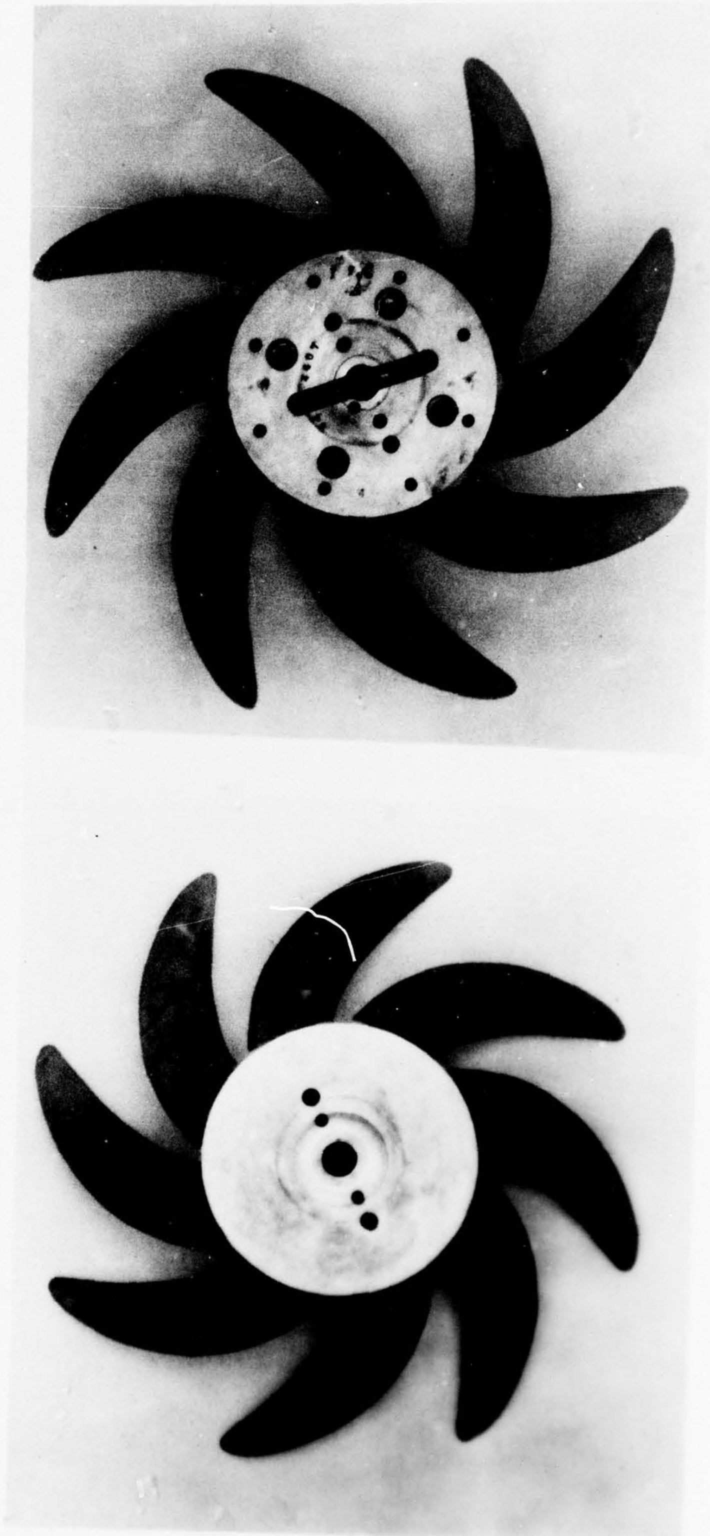


Figure 2 - Photographs of Propeller 4407

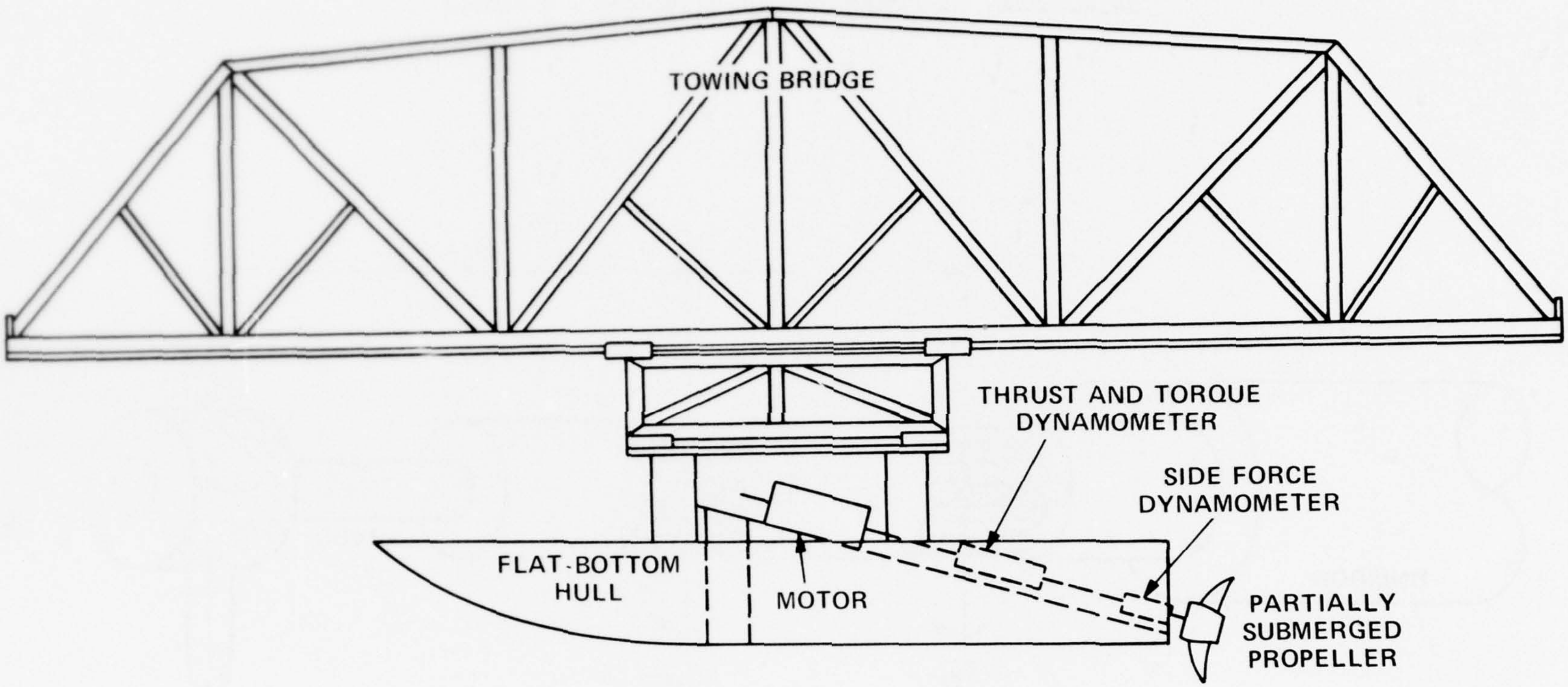


Figure 3 - Flat-Bottom Barge with Dynamometry

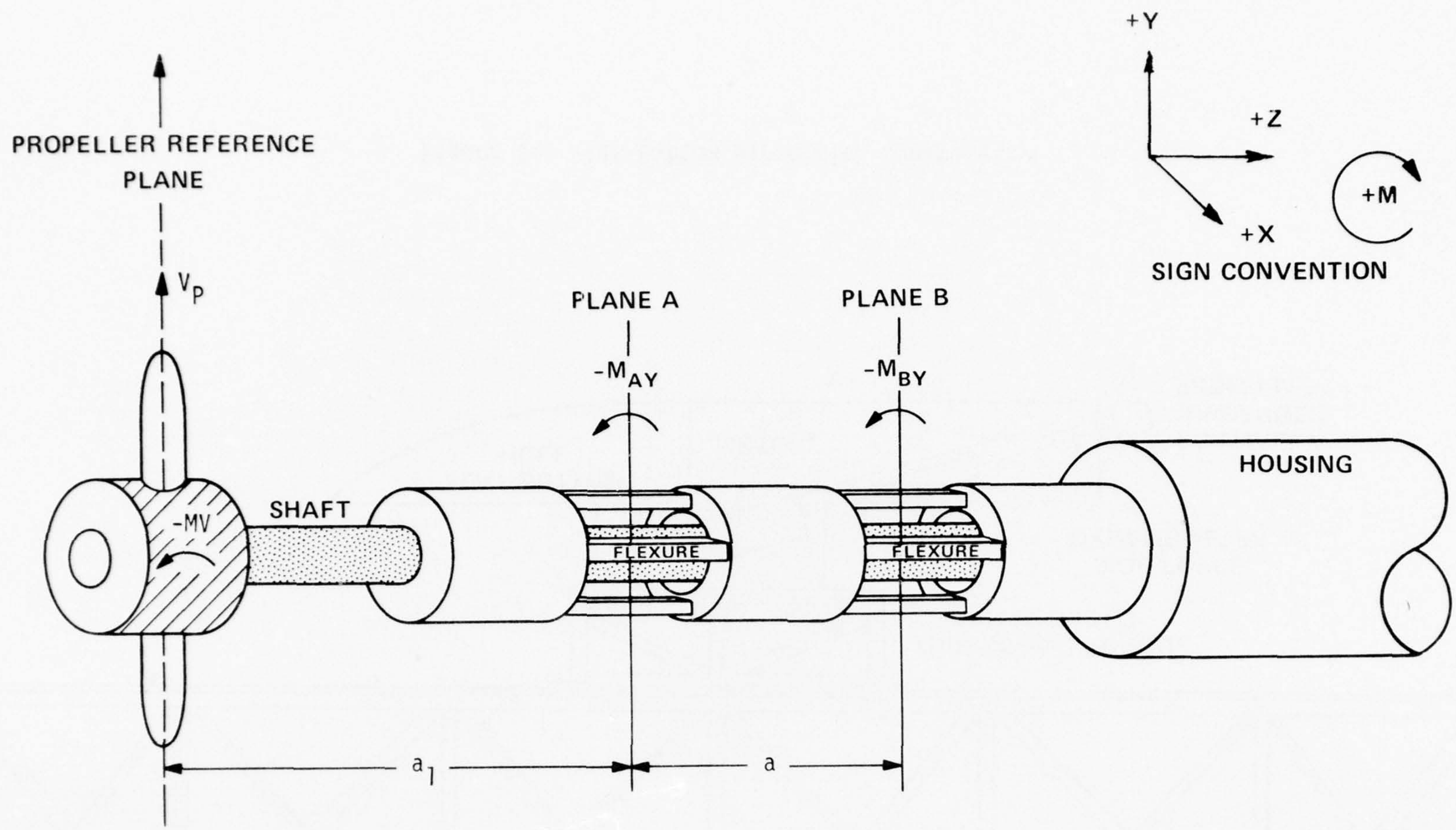


Figure 4 - Schematic of Four-Component Dynamometer

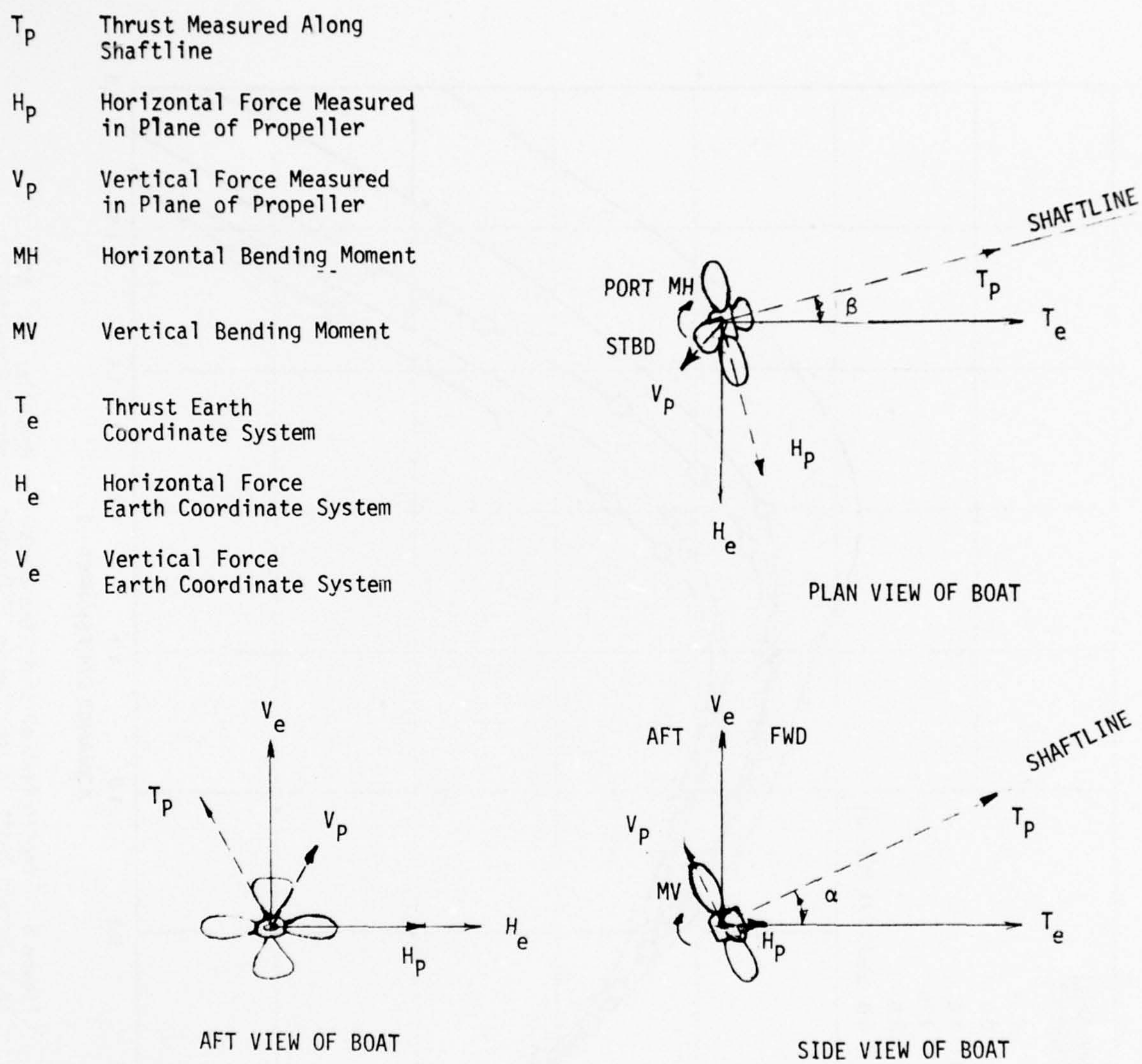


Figure 5 - Propeller and Earth Coordinate Systems Diagram

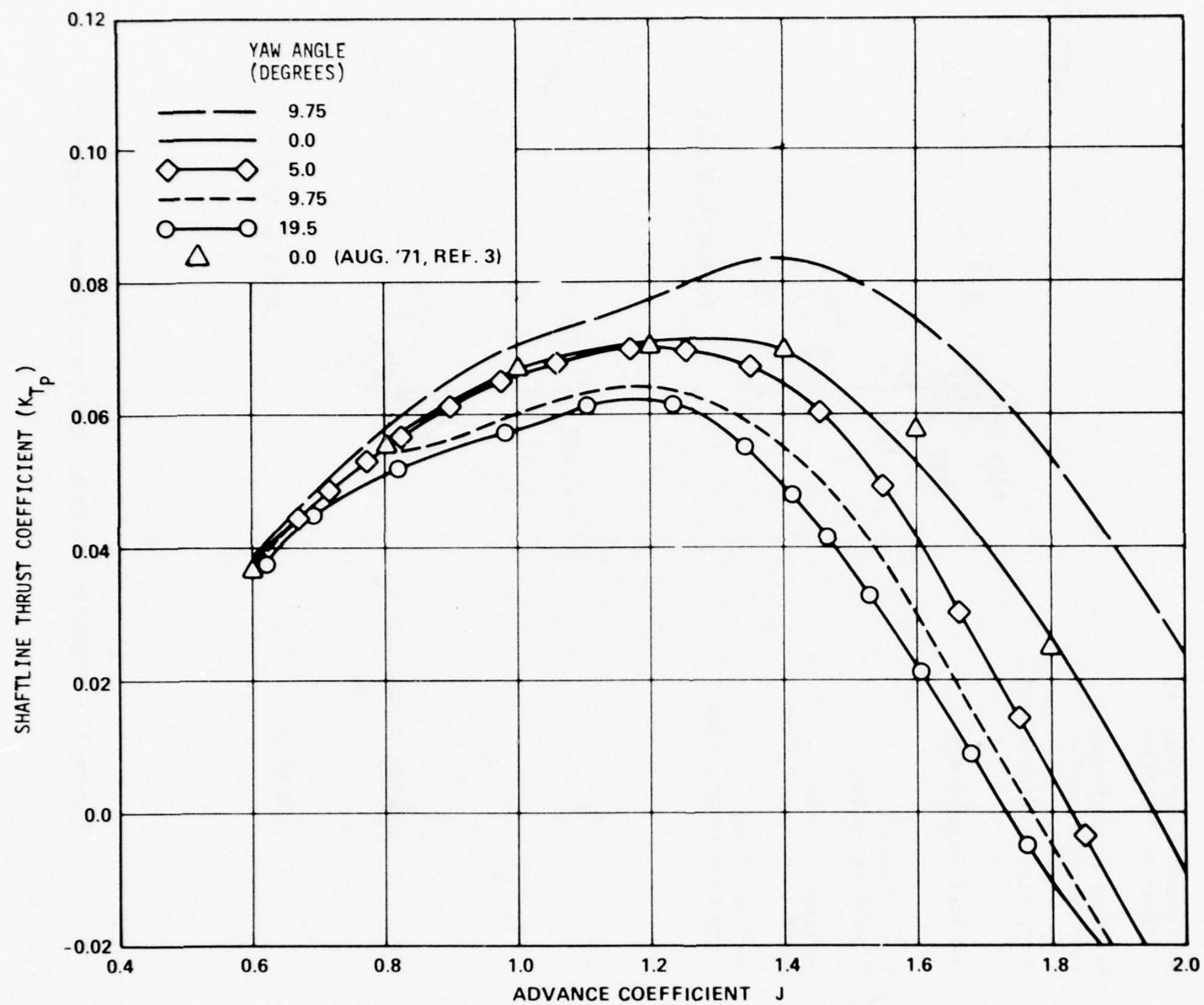


Figure 6 - Coefficient of Shaftline Thrust For Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

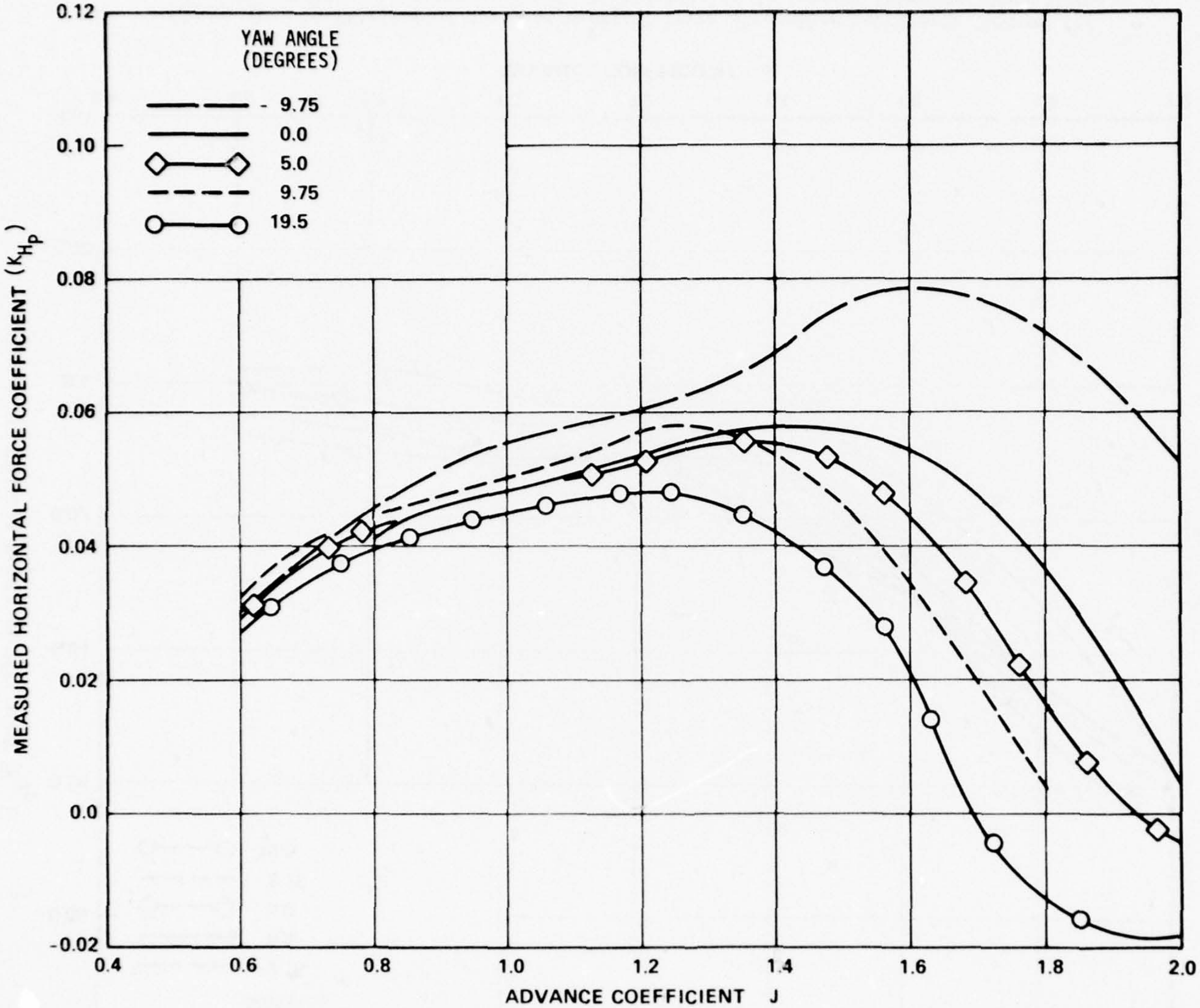


Figure 7 - Coefficient of Measured Horizontal Force (Propeller Coordinate System) for Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

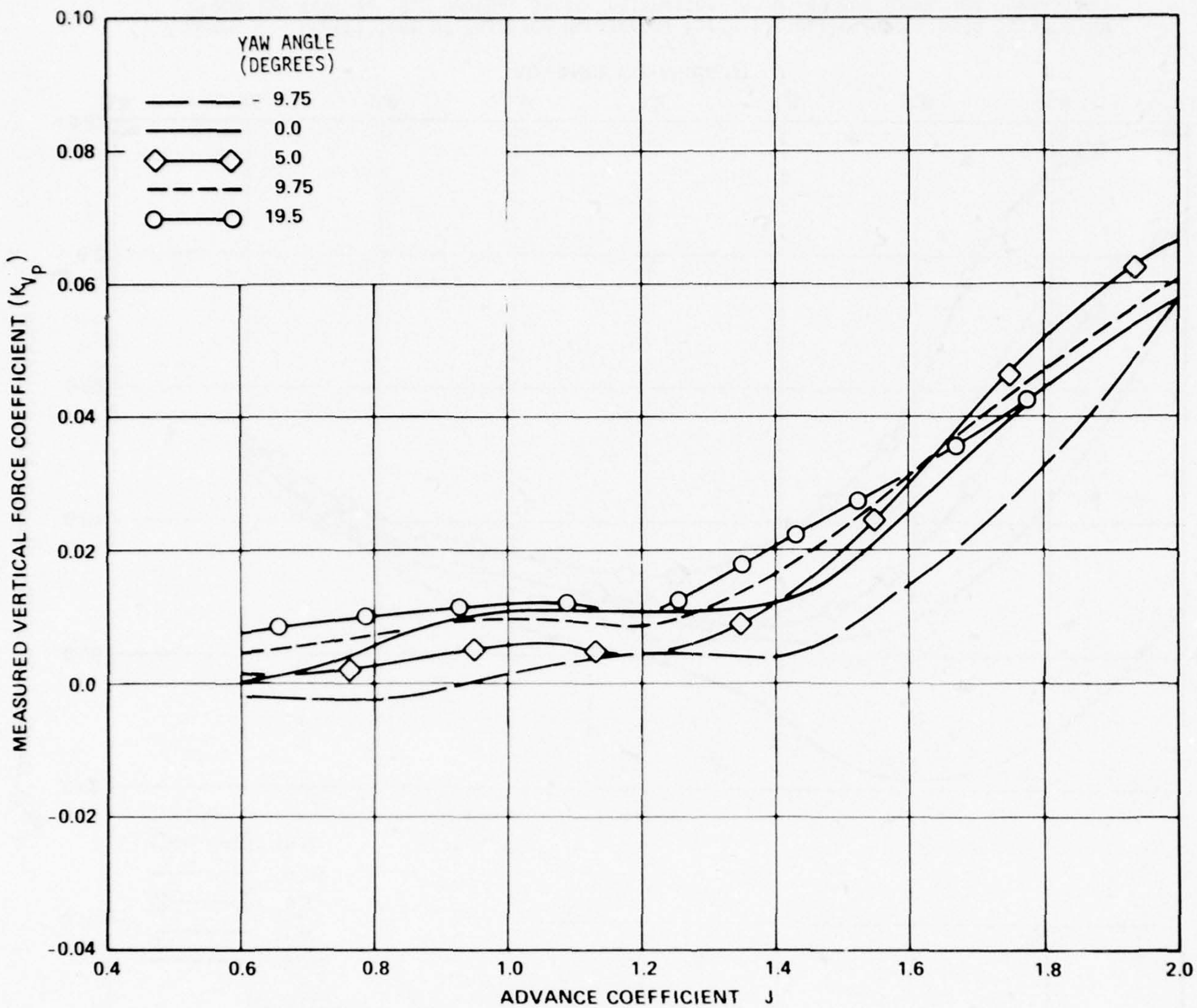


Figure 8 - Coefficient of Measured Vertical Force (Propeller Coordinate System) for Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

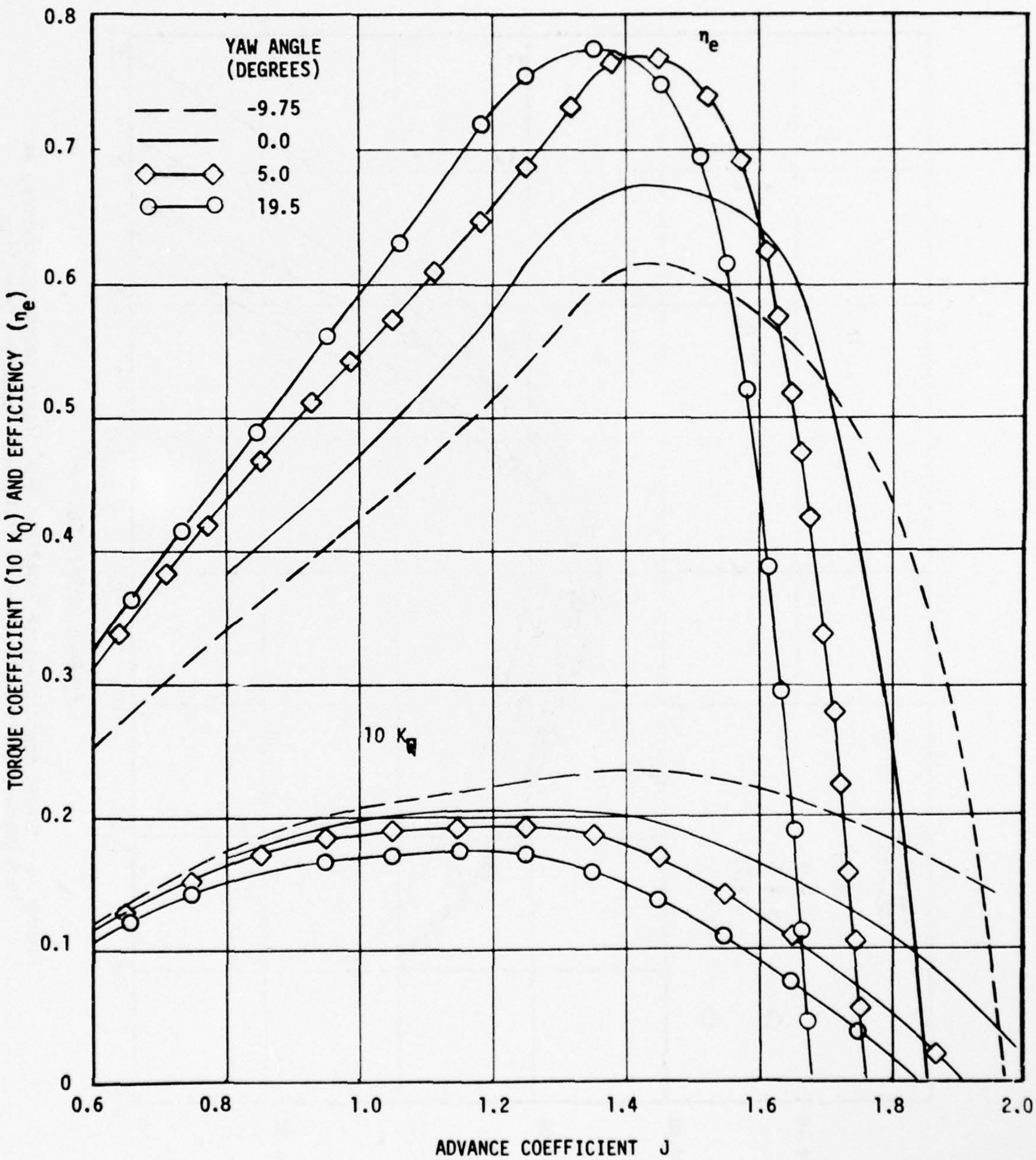


Figure 9 - Torque Coefficient and Efficiency of Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

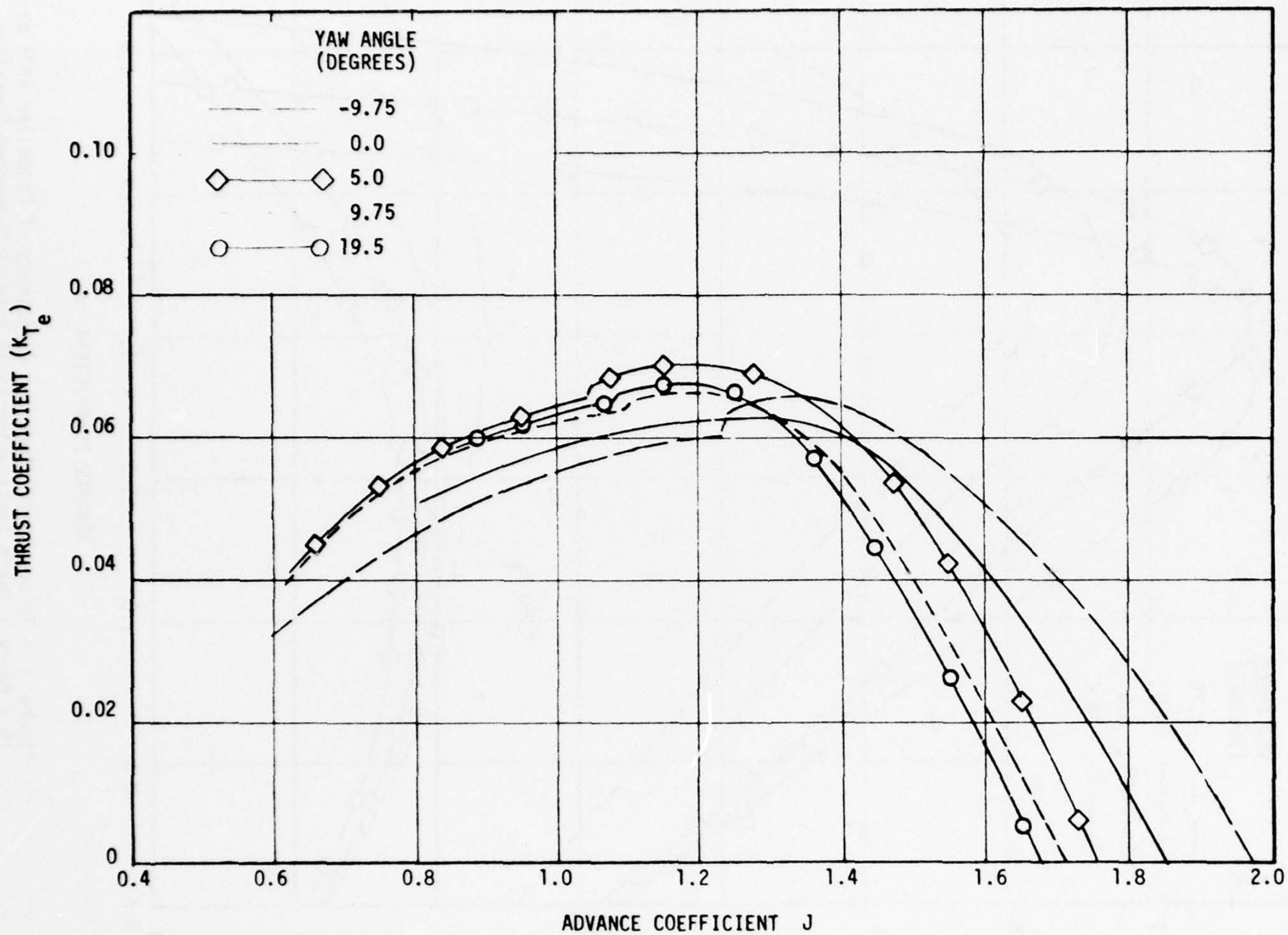


Figure 10 - Thrust Coefficient of Propeller 4407 (Earth Coordinate System) at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

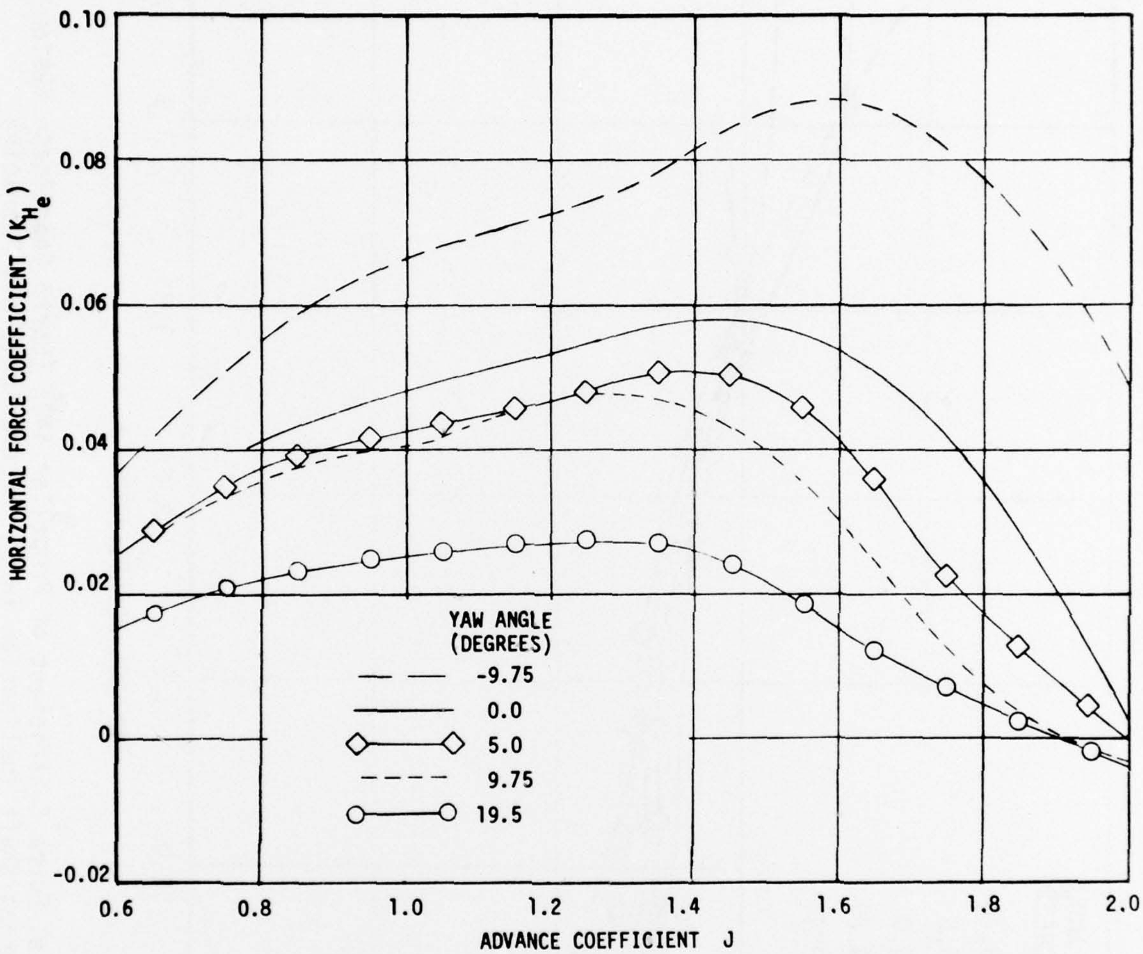


Figure 11 - Horizontal Force Coefficient of Propeller 4407 (Earth Coordinate System) at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

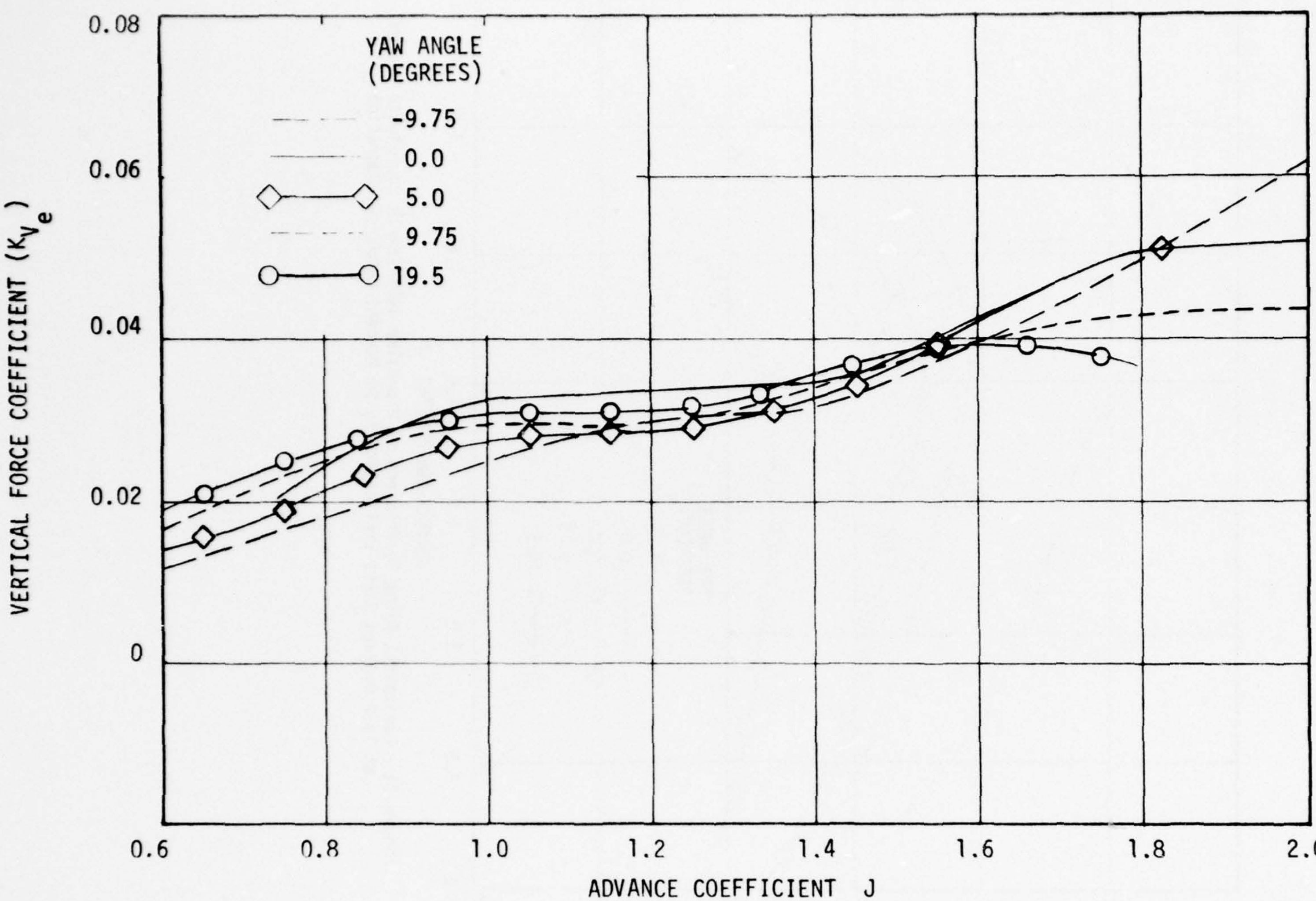


Figure 12 - Vertical Force Coefficient of Propeller 4407 (Earth Coordinate System) at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

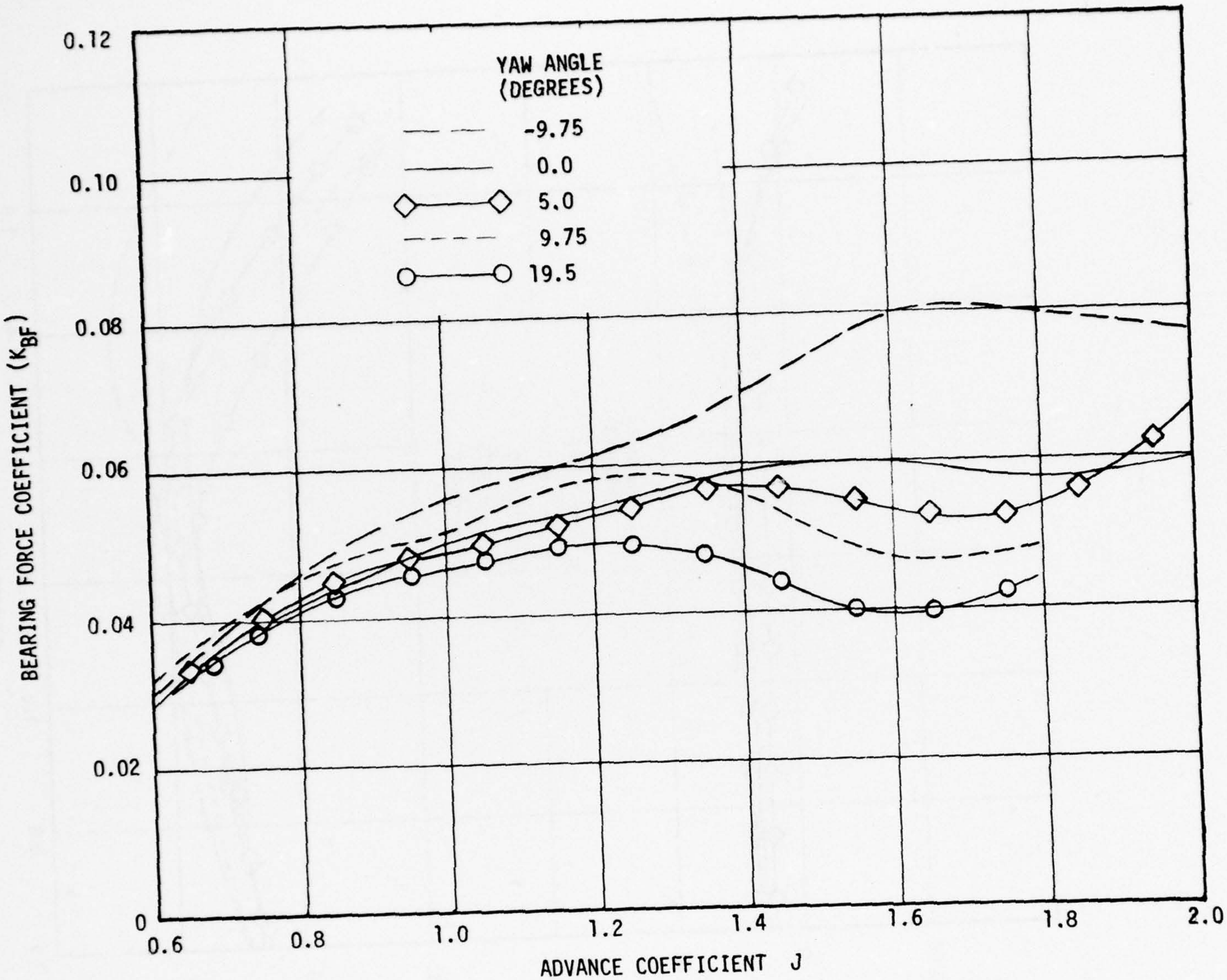


Figure 13 - Bearing Force Coefficient of Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

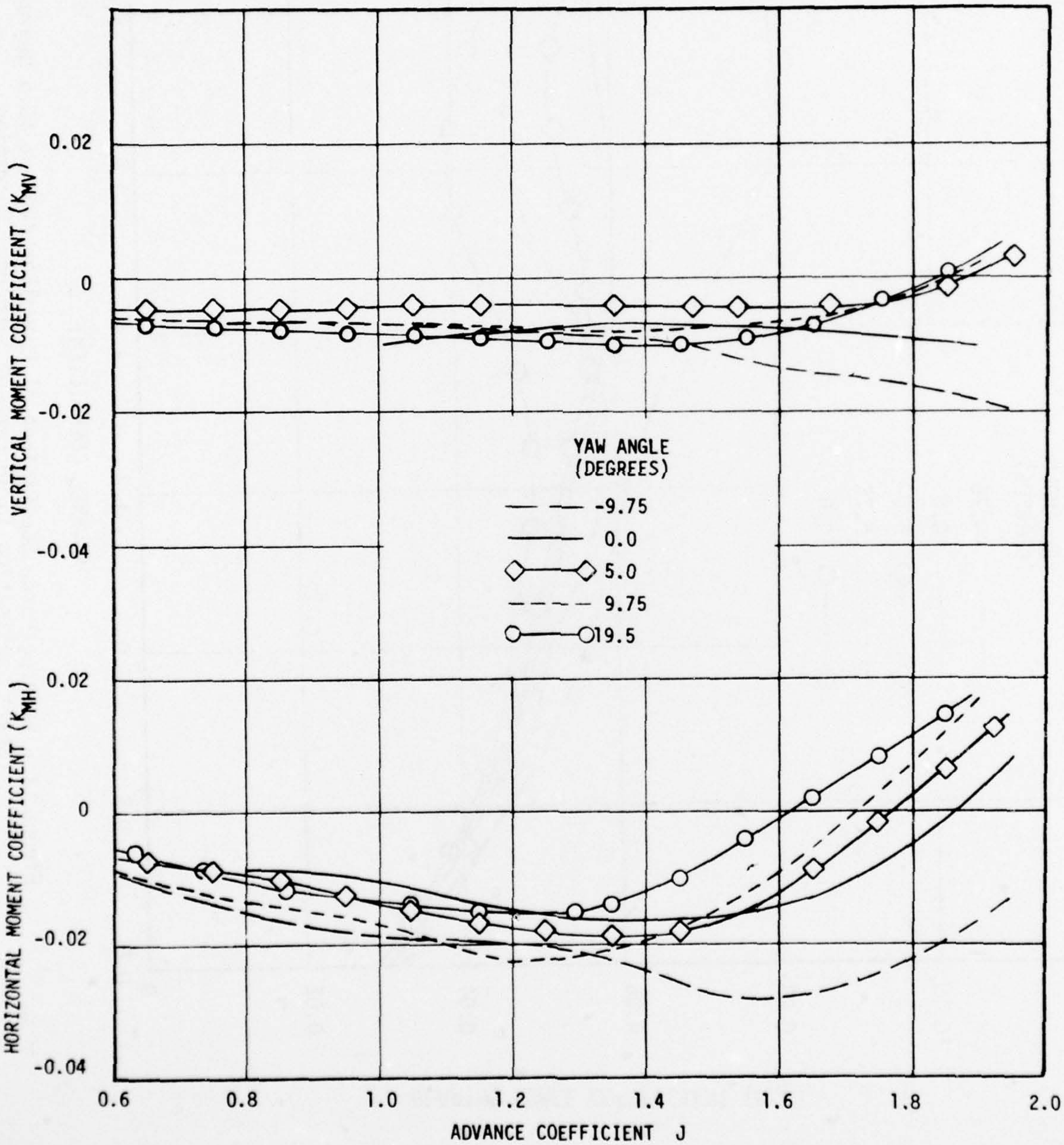
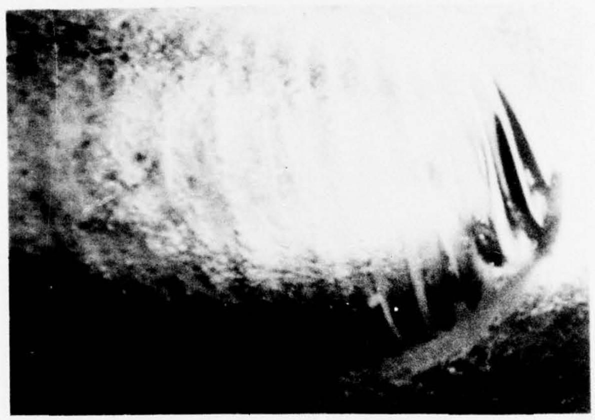
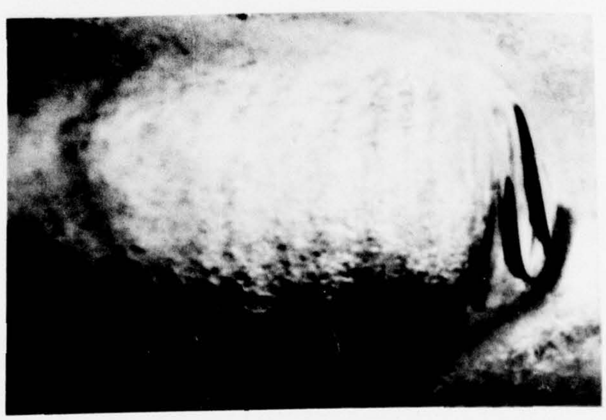


Figure 14 - Vertical and Horizontal Moment Coefficients of Propeller 4407 at 19.5 Degrees Shaft Inclination in 30 Percent Submerged Operation

Yaw Angle = 5.0 Deg J = 0.6

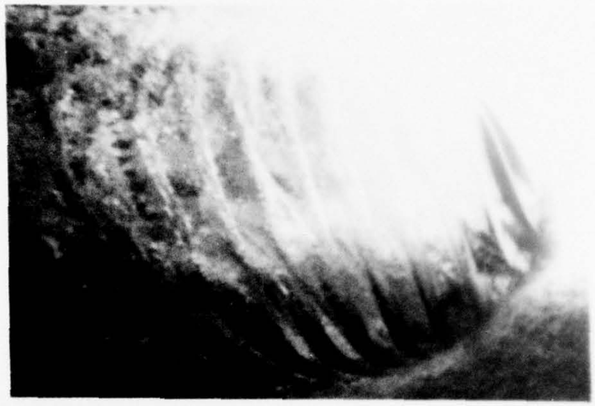


Yaw Angle = 9.75 Deg J = 0.6

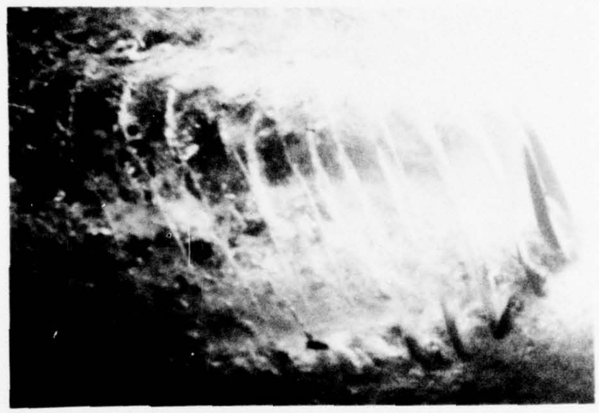


Yaw Angle = 19.5 Deg J = 0.6

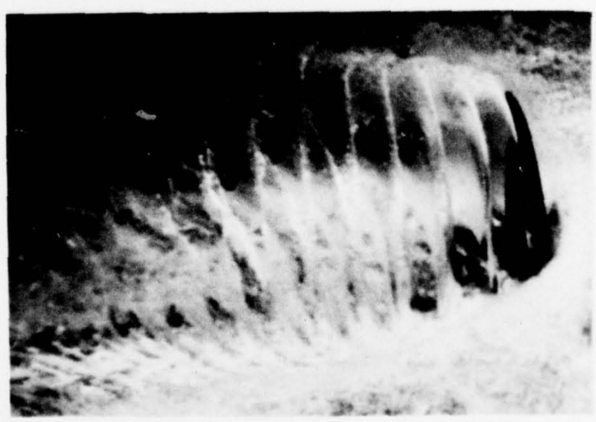
Figure 15 - Cavitation Photographs of Propeller 4407 at 30 Percent Submergence and 19.5 Degrees Shaft Pitch



Yaw Angle = 5.0 Deg   J = 1.0



Yaw Angle = 9.75 Deg   J = 0.8



Yaw Angle = 19.5 Deg   J = 1.0

Figure 15 - Continued

Yaw Angle = 0 Deg J = 1.2

Yaw Angle = 5.0 Deg J = 1.4

Yaw Angle = 19.5 Deg J = 1.6

Figure 15 - Concluded

TABLE 1 - EXPERIMENTAL PROGRAM

Yaw Angle, β (Degrees)	Inclination Angle, α (Degrees)	Model Speed, V (ft/sec)	Advance Coefficient, J
-9.75	19.5	12.66	0.55 - 2.2
0	19.5	16.88	0.80 - 2.0
5.00	19.5	12.66	0.45 - 2.0
9.75	19.5	12.66	0.60 - 1.9
19.50	19.5	12.66	0.60 - 1.9

1.0 ft/sec = 0.3048 m/s

TABLE 2 - EXPERIMENTAL DATA MEASURED IN PROPELLER COORDINATE SYSTEM

Yaw Angle = -9.75 Degrees

SPEED (FT/SEC)	THRUST (LB)	TORQUE (IN-LB)	RPM	VERTICAL FORCE (LB)	HORIZONTAL FORCE (LB)
12.353	-.407525E-01	4.16387	412.843	3.42178	1.37012
12.402[illegible]	.906323E-01	3.936[illegible]	414.675	3.474[illegible]2	1.38815
13.0616	-.924149E-0[illegible]	3.60712	431.159	3.82538	1.2619
12.6925	1.07394	6.98334	450.2[illegible]8	3.29[illegible]95	2.59603
12.6694	1.14297	6.83260	449.109	3.2814	2.59603
12.6[illegible]6[illegible]	1.09966	6.87269	449.[illegible]75	3.24631	2.63208
12.6958	3.78025	12.591[illegible]	504.79	2.29873	4.86755
12.6167	3.70938	12.7801	502.2[illegible]	2.26364	4.8315
12.5903	3.7445[illegible]	13.1558	502.958	2.2[illegible]854	4.8[illegible]952
12.3859	6.33889	19.9736	559.738	1.2[illegible]078	6.59824
12.5837	6.25302	19.[illegible]322	561.936	1.33362	6.61627
12.6364	6.35868	19.[illegible]678	564.5	1.3[illegible]607	6.6343
12.5604	9.3[illegible]893	26.6033	647.289	.386047	7.69795
12.5738	9.2[illegible]49	26.6735	646.922	.386047	7.69795
12.5936	9.3651[illegible]	26.7426	646.19	.421143	7.71598
12.7452	11.8806	34.236	752.789	.719452	9.24836
12.6101	11.813[illegible]	34.0369	756.086	.737	9.30244
12.6727	11.8225	34.2305	756.086	.772695	9.30244
12.6892	15.4379	45.[illegible]708	903.713	.386047	12.241
12.643	15.4211	45.0915	901.14[illegible]	.3685	12.[illegible]869
12.6529	15.4203	45.3797	904.4[illegible]5	.3685	12.241
12.4486	19.8027	59.7233	1144.75	-.789643	15.7204
12.6364	20.1839	60.1848	1136.[illegible]2	-.666809	15.8465
12.4321	19.8193	59.138[illegible]	1140.35	-.789643	15.6362
12.6397	23.7803	72.8963	1512.53	-1.12304	18.695
12.676	23.9014	73.295[illegible]	1505.58	-1.0528	18.[illegible]031
12.649[illegible]	23.8576	73.1229	1501.18	-1.03531	18.7671
12.6068	24.3617	76.8236	1705.9	-.859[illegible]33	19.2178
12.514[illegible]	24.1704	76.314	1707.42	-.859[illegible]33	19.3195
12.6167	24.4[illegible]87	76.[illegible]523	1696.8	-.789643	19.2178

1 ft/sec = 0.3048 m/s
1 lb = 4.4482 N
1 in-lb = 0.1129 N.m

Yaw Angle = 0 Degrees

SPEED (FT/SEC)	THRUST (LB)	TORQUE (IN-LB)	RPM	VERTICAL FORCE (LB)	HORIZONTAL FORCE (LB)
16.940	-1.52218	.204038	602.231	5.8[illegible]2[illegible]	-.721119E-01
16.7299	-1.47109	.181474	596.37	5.73297	-.1382[illegible]E-01
16.8321	-1.45329	.100597	598.202	5.77316	-.721119E-01
16.7[illegible]29	3.07312	12.0819	670.[illegible]33	5.36957	4.3[illegible]47[illegible]
16.5552	3.378[illegible]9	12.7024	668.169	5.1239	4.56108
16.7893	3.21252	11.8777	670.0	5.33447	4.30869
16.8881	7.76992	23.6501	754.254	4.0535	8.1[illegible]47
17.343	7.73295	23.8707	758.65	4.15878	8.16668
16.8717	7.944[illegible]6	23.979	756.086	3.9833	8.22076
16.9508	13.6048	38.4992	865.982	2.5[illegible]685	11.5739
16.7761	13.683[illegible]	38.9083	863.418	2.351[illegible]8	11.5559
16.9145	13.7009	38.4291	863.784	2.4[illegible]157	11.5559
16.7365	19.5662	55.4[illegible]23	1023.86	2.96554	14.7[illegible]69
16.7332	19.261	55.0895	1020.[illegible]	2.98309	14.602[illegible]
16.6885	19.4	54.813	1019.47	2.96554	14.602[illegible]
16.8486	25.831[illegible]	75.8013	1203.7[illegible]	4.3869	18.8753
16.786	25.735[illegible]	75.2[illegible]27	1204.82	4.071[illegible]	18.8212
16.9013	25.7[illegible]28	75.6369	1202.99	4.22897	18.8031
16.5388	34.8352	101.395	1520.96	3.29894	25.0949
16.9[illegible]72	34.4935	102.904	1503.01	3.70254	25.347[illegible]
16.514[illegible]	34.0168	101.1	1514.37	3.36913	25.131

Yaw Angle = 5.0 Degrees

SPEED (FT/SEC)	THRUST (LB)	TORQUE (IN-LB)	RPM	VERTICAL FORCE (LB)	HORIZONTAL FORCE (LB)
12.5343	-1.78371	-2.32885	451.307	3.63235	-.234364
12.5507	-1.70535	-2.36068	452.406	3.61481	-.252392
12.62	-1.87918	-2.27103	454.237	3.66745	-.270419
12.6958	.542401	3.52808	508.453	3.52707	1.15379
12.6793	.551099	3.52808	508.453	3.50952	1.17182
12.7386	.438131	3.54679	509.918	3.59726	1.13576
12.6035	3.42505	10.2021	564.134	2.63214	3.6777
12.5403	3.18115	10.351	558.639	2.63214	3.56954
12.5408	3.27687	10.0036	559.372	2.61459	3.587[illegible]7
12.9667	7.34653	20.3628	657.912	1.50909	6.39993
12.5969	7.54616	20.5955	653.15	1.22833	6.41796
12.5963	7.34596	20.3462	651.318	1.24588	6.38191
12.6694	11.2498	28.[illegible]104	760.482	.7019[illegible]4	8.13062
12.6496	11.1716	28.5697	759.383	.684356	8.14865
12.6[illegible]98	11.1194	28.4993	759.016	.7019[illegible]4	8.13062
12.8704	14.7816	39.9235	907.743	1.42135	10.7[illegible]86
12.9397	14.7991	39.814	909.208	1.40381	10.690[illegible]
12.9[illegible]98	14.8077	39.8719	907.377	1.36871	10.6725
12.6793	20.0493	55.8881	1145.12	.842285	14.8911
12.6[illegible]32	20.0145	55.868[illegible]	1144.38	.772695	14.855
12.7551	19.979[illegible]	55.6478	1140.35	.859[illegible]33	14.855
12.6331	23.798	69.2075	1516.5[illegible]	.684357	17.7936
12.7287	23.9986	69.7405	1508.14	.754547	17.9017
12.6991	23.9723	69.5989	1511.44	.754547	17.8657
12.6958	27.9016	90.3699	2211.84	1.52664	19.7586
12.6826	27.8659	90.3088	2211.11	1.45645	19.7767
12.6694	27.7537	90.0132	2207.81	1.55173	19.7226

Yaw Angle = 9.75 Degrees

SPEED (FT/SEC)	THRUST (LB)	RPM	VERTICAL FORCE (LB)	HORIZONTAL FORCE (LB)
12.7056	-1.75239	474.609	3.43933	-.504783
12.8474	-1.76199	480.102	3.36914	-.486755
12.7782	-1.54413	477.539	3.38669	-.534783
12.7683	-1.55301	478.637	3.36914	-.540839
12.5507	-.469125	498.779	3.22876	.10328
12.6266	-.534215	500.61	3.24631	.144223
12.3728	-.233093	491.455	3.12347	.21633
12.7685	-.574395	504.272	3.29895	.144223
12.4653	2.66894	562.5	2.59704	2.99264
12.4521	2.6342	562.133	2.5795	2.99264
12.412	2.68615	563.593	2.5795	3.04673
12.5576	2.71106	566.528	2.64967	3.01067
12.6529	6.21661	649.202	1.89514	5.90529
12.4815	6.20641	645.263	1.77231	6.12951
12.6463	6.19065	649.658	1.86004	6.07543
12.676	6.21742	651.489	1.84249	6.12951
12.5277	9.82127	759.887	1.29852	8.77963
12.5174	10.0387	760.253	1.28097	8.92385
12.498	10.0299	759.521	1.22831	8.8878
12.5771	9.9516	759.155	1.28097	8.83371
12.3659	9.97796	760.62	1.26343	8.97794
12.5507	13.369	907.836	2.19345	11.0511
12.6595	13.4293	909.301	2.1759	11.1052
12.7122	13.3785	905.639	2.15835	11.0692
12.5474	13.4391	906.372	2.19345	11.0672
12.6958	16.598	1130.12	2.52685	15.2156
12.6531	16.5202	1132.32	2.52685	15.3959
12.5604	16.4761	1129.39	2.49176	15.486
12.6266	16.4845	1127.93	2.52685	15.4499
12.6791	22.6488	1510.25	2.93045	19.7586
12.587	22.3184	1515.38	2.87781	19.5603
12.676	22.5094	1502.92	2.9129	19.7406
12.6134	22.588	1512.08	2.87781	19.38

Yaw Angle = 19.5 Degrees

SPEED (FT/SEC)	THRUST (LB)	TORQUE (IN-LB)	RPM	VERTICAL FORCE (LB)	HORIZONTAL FORCE (LB)
12.6298	-1.93346	-1.35071	477.905	3.03573	-1.00956
12.6232	-1.93366	-1.87915	477.539	3.05328	-.991539
12.7353	-1.93107	-1.87938	482.299	3.12347	-1.00956
12.877	-1.98066	-1.4719	487.06	3.15857	-1.00956
12.8639	-1.02204	.492794	506.469	2.96554	-1.00956
12.7847	-1.10172	.544668	503.906	2.948	-.955483
12.6628	-1.1482	.28306	498.413	2.89535	-.937455
12.7979	-1.04063	.339225	504.272	2.948	-.919427
12.6298	1.84549	7.984	565.429	2.9129	1.60449
12.7155	1.83739	7.84674	566.528	2.98309	1.56843
12.5211	1.88598	7.51854	559.936	2.86026	1.58646
12.5376	1.86129	7.79283	562.5	2.86026	1.64054
12.4782	5.56281	16.9187	644.531	2.19345	4.74126
12.5573	5.60522	17.0095	646.362	2.22854	4.7053
12.6496	5.47302	16.8816	649.292	2.2811	4.7053
12.6496	5.57804	16.4582	648.193	2.31628	4.63319
12.6331	9.59002	27.1694	757.324	1.63192	7.42753
12.6628	9.44996	26.8066	756.225	1.68457	7.37345
12.6101	9.40707	26.7529	756.958	1.68457	7.37345
12.5474	9.49405	27.1606	756.958	1.64947	7.39147
12.4083	12.7098	37.4574	911.865	2.63214	9.93342
12.6628	12.7799	37.4451	910.766	2.70233	9.89737
12.5705	12.8231	37.4363	911.499	2.68478	9.93342
12.5178	12.8067	37.1468	909.301	2.70233	9.89737
12.7518	17.6206	53.0894	1130.12	3.43933	13.7193
12.8012	17.6284	52.7657	1127.93	3.45688	13.7012
12.6661	17.6204	52.6923	1129.76	3.50952	13.7193
12.7419	21.4932	66.7616	1514.28	4.7554	16.8381
12.6892	21.3798	66.3645	1512.45	4.77295	16.8201
12.7584	21.5265	66.6	1506.22	4.82559	16.9462

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