Performance of an Inclined Shaft Partially-Submerged Propeller Operating Over a Range of Shaft Yaw Angles

by

R. S. Alder
D. H. Moore

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NOTATION

a  Distance between forward and aft shaft moment flexures  in., m

a₁  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, \( J = \frac{V}{nD} \)

\( K_{BF} \)  Bearing force coefficient, \( K_{BF} = \frac{BF}{\rho n^2 D^4} \)

\( K_{H_{e}} \)  Horizontal force coefficient (earth coordinate system), \( K_{H_{e}} = \frac{H_{e}}{\rho n^2 D^4} \)

\( K_{H_{p}} \)  Coefficient of measured horizontal force (propeller coordinate system), \( K_{H_{p}} = \frac{H_{p}}{\rho n^2 D^4} \)

\( K_{MH} \)  Horizontal moment coefficient (propeller coordinate system) \( K_{MH} = \frac{MH}{\rho n^2 D^5} \)

\( K_{MV} \)  Vertical moment coefficient (propeller coordinate system) \( K_{MV} = \frac{MV}{\rho n^2 D^5} \)
$K_Q$ Torque coefficient (propeller coordinate system), $K_Q = Q/\rho n^2 D^5$

$K_{Te}$ Thrust coefficient, $K_{Te} = T_e/\rho n^2 D^4$

$K_{Tp}$ Coefficient of shaftline thrust, $K_{Tp} = T_p/\rho n^2 D^4$

$K_{Ve}$ Vertical force coefficient (earth coordinate system), $K_{Ve} = V_e/\rho n^2 D^4$

$K_{Vp}$ Coefficient of measured vertical force (propeller coordinate system), $K_{Vp} = V_p/\rho n^2 D^4$

$M_{Ax}$ Shaft bending moment about the center of the aft dynamometer flexure in the plane of the pitched shaft

$M_{Ay}$ Shaft bending moment about the center of the aft dynamometer flexure in the vertical plane

$M_{Bx}$ Shaft bending moment about the center of the forward dynamometer flexure in the plane of the pitched shaft

$M_{By}$ Shaft bending moment about the center of the forward dynamometer flexure in the vertical plane

$M_H$ Moment in a horizontal plane passing through the propeller. Moment is about the center of the propeller hub.

$M_V$ Moment in a vertical plane passing through the propeller. Moment is about the center of the propeller hub.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>( n )</td>
<td>Shaft revolutions per second</td>
<td>RPS</td>
</tr>
<tr>
<td>( P )</td>
<td>Nominal propeller blade section pitch</td>
<td>in., m</td>
</tr>
<tr>
<td>( Q )</td>
<td>Shaft torque</td>
<td>in-lb, N.m</td>
</tr>
<tr>
<td>( T_e )</td>
<td>Thrust or propulsive force (earth coordinate system)</td>
<td>lb, N</td>
</tr>
<tr>
<td>( T_p )</td>
<td>Thrust measured along the shaft (propeller coordinate system)</td>
<td>lb, N</td>
</tr>
<tr>
<td>( V )</td>
<td>Speed of advance</td>
<td>ft/sec, ms^{-1}</td>
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<tr>
<td>( V_e )</td>
<td>Vertical force or lift force (earth coordinate system)</td>
<td>lb, N</td>
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<td>( V_p )</td>
<td>Vertical force (propeller coordinate system)</td>
<td>lb, N</td>
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<tr>
<td>( \alpha )</td>
<td>Angle of shaft pitch</td>
<td>deg</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Angle of shaft yaw</td>
<td>deg</td>
</tr>
<tr>
<td>( \eta_e )</td>
<td>Efficiency in earth coordinate system, ( \eta_e = \frac{T_e V}{2\pi Qn} = \frac{J(K_{T_e})}{2\pi K_Q} )</td>
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<tr>
<td>( \theta )</td>
<td>Bearing force angle measured from the vertical, ( \theta = \arctan \frac{H_p}{V_p} )</td>
<td>deg</td>
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<tr>
<td>( \rho )</td>
<td>Mass density of water</td>
<td>lb·sec^2/ft^4, kg·m^{-3}</td>
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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.


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 \( K_T, K_H, K_Y \) 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-sec²/ft⁴ (1025.86 Kg/m³) 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 $\eta_e$ is proportional to $(J/2\pi)/(K_T/K_Q)$ (assuming $K_{vp}$ constant) and $K_T$ is approximately equal to $K_T \cos \theta + K_{hp} \sin \theta$. Solving for the maximum efficiency and applying the fact that $K_T / K_Q$ and $K_{hp} / K_Q$ are constant with yaw angle, then the peak efficiency occurs when a yaw angle of $\beta = \tan^{-1} \frac{K_{hp}}{K_T}$ 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 \( \frac{K_H}{K_Q} \) and \( \frac{K_T}{K_Q} \).

The change in hydrodynamic performance of the propeller is evidenced by the change in the \( \frac{K_H}{K_Q} \) and \( \frac{K_T}{K_Q} \) ratios above a \( \gamma \) of 1.4. It is also evidenced by the steady decline in magnitude of \( K_T \), \( K_H \), 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


Figure 1 - Plans of Propeller 4407
Figure 2 - Photographs of Propeller 4407
**Figure 5 - Propeller and Earth Coordinate Systems Diagram**

- $T_p$: Thrust Measured Along Shaftline
- $H_p$: Horizontal Force Measured in Plane of Propeller
- $V_p$: Vertical Force Measured in Plane of Propeller
- $MH$: Horizontal Bending Moment
- $MV$: Vertical Bending Moment
- $T_e$: Thrust Earth Coordinate System
- $H_e$: Horizontal Force Earth Coordinate System
- $V_e$: Vertical Force Earth Coordinate System
Figure 6 - Coefficient of Shaftline Thrust 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
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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
Figure 15 - Cavitation Photographs of Propeller 4407 at 30 Percent Submergence and 19.5 Degrees Shaft Pitch
Figure 15 - Continued

- 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 - Concluded
<table>
<thead>
<tr>
<th>Yaw Angle, $\beta$ (Degrees)</th>
<th>Inclination Angle, $\alpha$ (Degrees)</th>
<th>Model Speed, $V$ (ft/sec)</th>
<th>Advance Coefficient, $J$</th>
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<tr>
<td>-9.75</td>
<td>19.5</td>
<td>12.66</td>
<td>0.55 - 2.2</td>
</tr>
<tr>
<td>0</td>
<td>19.5</td>
<td>16.88</td>
<td>0.80 - 2.0</td>
</tr>
<tr>
<td>5.00</td>
<td>19.5</td>
<td>12.66</td>
<td>0.45 - 2.0</td>
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<tr>
<td>9.75</td>
<td>19.5</td>
<td>12.66</td>
<td>0.60 - 1.9</td>
</tr>
<tr>
<td>19.50</td>
<td>19.5</td>
<td>12.66</td>
<td>0.60 - 1.9</td>
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1.0 ft/sec = 0.3048 m/s
## TABLE 2 - EXPERIMENTAL DATA MEASURED IN PROPELLER COORDINATE SYSTEM

<table>
<thead>
<tr>
<th>Yaw Angle = -9.75 Degrees</th>
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<tr>
<td><strong>SPEED (FT/SEC)</strong></td>
</tr>
<tr>
<td>12.5163</td>
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1 ft/sec = 0.3048 m/s
1 lb = 4.4482 N
1 in-lb = 0.1129 N.m
### Yaw Angle = 0 Degrees

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35
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