sign and development of ocean-going hydrofoil ships. With the exception of having demonstrated full design capability in rough water, the craft has met or exceeded all of her design goals, including a verification of the concept of the turbine-powered, fully submerged foil ship being routinely operated by the "white hat" Navy.

Sporadic leakage of salt water into the transmission oil sumps has been the principal reason for limited reliability to date. This and other problems evaluated during the test program can be corrected, as presently envisioned, without major alteration of the craft. In contrast, much operational experience and test data have been obtained that commend many of the more gross aspects of the craft design. Sea-keeping characteristics while hullborne, takeoff performance foilborne comfort, and safety have been found to be most satisfactory. The high vehicular efficiency of the full-scale craft was accurately predicted by model work done prior to construction of the ship.

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Selection of a Propulsor for a Submersible System

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The problem of propulsor selection is discussed as it might arise when conducting a preliminary performance estimate on an underwater vehicle. To this end, the methods of determining the performance characteristics of a single open propeller and a single rotor pumpjet for operation on a given vehicle are presented. Included are propulsor efficiency, cavitation, and noise produced as affected by propulsor size, rotational shaft speed, and vehicle forward velocity. A comparison of these characteristics is made to allow the selection of the best suited propulsor configuration. The predicted performance is obtained employing average velocity ratios and actuator disk theory. Although this approach is not as accurate as the more detailed design procedures, it is sufficient when employed as a preliminary design tool for predicting over-all performance characteristics. An example is presented to illustrate the use of the procedure.

Nomenclature

A_B = frontal area of body, ft²
A_D = disk area, ft²
A_i = inlet flow area [defined by Eq. (2)], ft²
C_b = blade pressure coefficient [defined by Eq. (22)]
C_D = drag coefficient $(\text{drag}/1/2\rho V_\infty^2 A_B)$
C_T = thrust coefficient $(\text{thrust}/1/2\rho V_\infty^2 A_B)$
D_m = maximum body diameter, ft
d_t = blade tip diameter, ft
F = force, lb
h_s = submergence depth, ft
J_m = advance ratio, V_∞/nD_m
k = energy loss coefficient [defined by Eq. (13)]
L = body length, ft
m = mass flow, slugs/sec
n = shaft speed, rev/sec
P_∞ = freestream static pressure, psf
P_D = static pressure immediately upstream of blade leading edge, psf
$P_{\min}$ = minimum pressure on blade surface, psf
P_v = vapor pressure of fluid, psf
ΔP = pressure rise across propeller, psf
Q = volumetric rate of flow, cfs
r_h = body radius at any specific station, ft
r_t = blade tip radius, ft
R_L = Reynolds number, $V_\infty L/\nu$
shp = shaft horsepower
t = time, sec
U = average rotor velocity, $U_t/2^{1/2}$
U_t = rotor tip velocity, fps
V_∞ = freestream velocity, fps
$\bar{V}_D$ = average fluid velocity at disk, fps
V_i = velocity upstream of inlet, fps
$\bar{V}_i$ = average velocity upstream of inlet, fps
$\bar{V}_e$ = average propulsor exit velocity, fps
ΔV = change in average fluid velocity between the inlet and discharge of propulsion unit in the direction of thrust, fps
V_θ = average fluid peripherial velocity, fps
W = relative fluid velocity at blade leading edge, fps
W_t = relative fluid velocity at blade tip leading edge, fps
y = normal distance from body, ft
β = angle between relative inlet velocity to blade and axial direction, deg
δ = boundary-layer thickness, ft
η_t = over-all efficiency [defined by Eq. (11)]
η_p = propulsive efficiency [defined by Eq. (12)]
η_h = hydraulic efficiency [defined by Eq. (11)]
η_p' = propeller propulsive efficiency [defined by Eq. (14)]
η_p'' = pumpjet propulsive efficiency [defined by Eq. (15)]
θ = convergence angle of hull, deg
ρ = mass density, slugs/cf
σ_{cr} = critical cavitation index, $P_\infty - P_{\min}/1/2\rho V_\infty^2$
ν = kinematic viscosity, ft²/sec

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Introduction

WITH the advent of more sophisticated and diversified submersible vehicle systems, it is becoming increasingly important to be able to understand the general performance of individual system components and how each affects the over-all performance of the vehicle. Depending upon the specified performance characteristics of the vehicle, certain variations in the configuration of the individual components will occur. These variations are determined by tradeoffs of various performance characteristics to obtain a primary vehicle performance goal.

In a submersible vehicle system, one system component that must be considered is the propulsor. It is the purpose of the propulsor, as considered here, to convert rotational shaft energy into a propelling action on the vehicle. Ideally, this conversion is to be accomplished in the most efficient, quietest, and least complicated manner. However, the performance requirements of current underwater vehicles sometimes require outstanding performance in one area although sacrificing performance in another area. It is therefore necessary to optimize the over-all performance characteristics of the propulsor as dictated by the system requirements.

Any rotating propulsor has certain propulsion characteristics that can affect the over-all performance of the vehicle. These characteristics are 1) efficiency, 2) cavitation performance, 3) physical size, 4) noise production, 5) effect on system dynamics and control, and 6) simplicity of manufacture and operation. Although these characteristics are general, the tolerable absolute level and relative importance of each is dictated by the goals of the system under consideration. On this basis a performance analysis must be made to determine what sacrifices can be tolerated in various performance areas in order to obtain outstanding performance in a specific area. For example, it may be possible to sacrifice efficiency in order to decrease the possibility of cavitation occurring in the propulsor.

Since the discussion presented here is limited to rotating propulsors, the resulting configurations can be included in one of two general categories: propellers or pumpjets. Figure 1 depicts the major differences between these two types of propulsors. The amount of and the velocity of flow through the propeller is dependent upon the forward velocity of the vehicle. The pumpjet by virtue of the shroud enclosing the rotating blades permits, within certain limits, the amount of flow and its velocity to be controlled and made essentially independent of the vehicle velocity. Several variations of these basic configurations can be employed. A discussion of these variations will be presented.

It is the purpose of this paper to compare the performance of the propeller and the pumpjet and their different configurations and to discuss the advantages and disadvantages of each. These comparisons will be of the forementioned propulsion characteristics. With this information it will be possible to select the particular rotating propulsor configuration best suited to perform the desired vehicle system goals. It must be emphasized that these data will be of a preliminary form only and are within 5 to 10% of the characteristics that would be determined in a detailed design analysis. The detailed design of the propellers and pumpjets are discussed in Refs. 1 and 2 and Refs. 3 and 4, respectively.

In the preliminary development of a submersible vehicle system, certain performance characteristics are known which specify the over-all goals and purpose of the system. These characteristic values affect the selection of the propulsor to

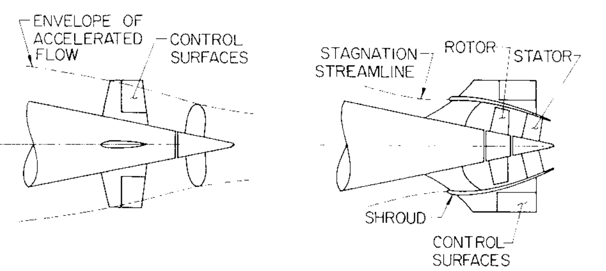

Fig. 1 General arrangement of a propeller and a pumpjet on the after end of a body of revolution.

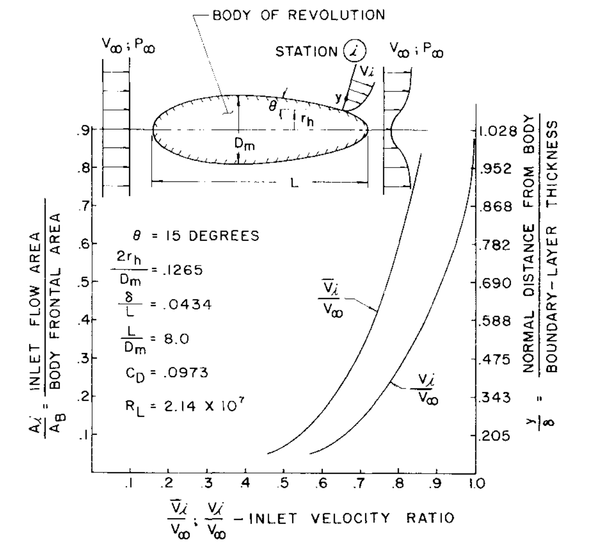

Fig. 2 A typical streamlined body of revolution and its velocity distributions.

be employed and include 1) vehicle forward velocity, 2) available power for propulsion, 3) propulsor shaft speed, 4) vehicle size and shape, and 5) required submergence depth below which no cavitation is tolerable. If all of these characteristics are known, the selection of a propulsor is greatly simplified. However, in many instances several of these characteristics are not known, and it is desirable to determine such variables while optimizing the over-all performance.

The design or performance analysis of a propulsor is a study of fluid flow or hydrodynamics. It is therefore necessary to have a knowledge of how the vehicle, exclusive of the propulsor, affects the fluid through which it passes. This basic knowledge must include the forward velocity of the vehicle, the characteristics of the flow that enter the propulsor, i.e., the velocity distribution, and the drag or resistance of the vehicle. Figure 2 presents a sketch of a typical streamlined body with typical velocity distributions in front of, behind, and on the body near the location of the propulsor.

Prior to the selection of a propulsor for operation on a particular body these data must be measured or estimated. The accurate experimental determination of body resistance and the necessary velocity distributions are required for the detailed design of a propulsor, and their availability represent a definite advantage to the analysis discussed here. If experimental data cannot be obtained, an estimate must somehow be made. One method of estimation is to examine experimental measurements conducted with similar bodies. Since these data show a marked variation for different body shapes, no attempt will be made in this paper to discuss the manner of obtaining such estimations. The reader is directed to Refs. 5 and 6, which present such information.

Figure 2 represents the data required prior to the selection of a propulsor for a particular underwater vehicle system. These presented data were determined experimentally using the depicted vehicle configuration exclusive of the propulsor. The nondimensional velocity distribution V_i/V_∞ is presented as a function of y/δ. As shown in Fig. 2, the term y/δ expresses the portion of the velocity profile that enters the propulsor. The quantity y is the normal distance from the body and from δ the boundary-layer thickness defined as the normal distance from the body to the location where the velocity in the boundary layer equals the freestream velocity. These data are presented in a nondimensional form to allow their use with any other geometrically similar conditions.

The propulsor for this body is located at the aft end of the body. Such a position represents a general application, since the employment of a freestream propulsor, i.e., with a uni-

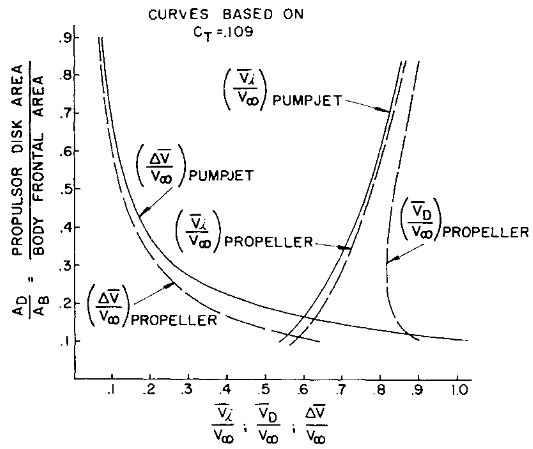

Fig. 3 Nondimensional propulsor disk area as a function of different characteristic propeller and pumpjet velocity ratios.

form inflow, simplifies the problem by eliminating the need of the velocity distribution on the body. The resistance or drag of the body in Fig. 2 is specified in the form of a drag coefficient

$$\text{drag} = C_D \tfrac{1}{2}\rho V_\infty{}^2 A_B$$

The drag coefficient C_D is constant for similar bodies operating at geometrically similar flow conditions and Reynolds number.

If the drag of the vehicle without the propulsor operating is known, the net step is to determine the force or thrust that the propulsor must produce to propel the body. This value of thrust produced is identically equal to the drag of the vehicle-propulsor combination. Thus the over-all system will experience zero acceleration at the propulsor design point.

When the propulsor is operating on the vehicle, it has the effect of increasing the drag of the vehicle, since the pressure distribution over the aft end of the body is adversely altered and additional resistance is added by the surface area of the propulsor. Methods for the estimation of this additional drag are presented in Refs. 2–4. However, for the analysis presented here, it is assumed sufficient to consider this additional drag as being approximately 12% of the drag without the propulsor operating. Therefore, at the condition of vehicle self-propulsion, the required thrust is

$$C_T = C_D + 0.12C_D$$

This estimation of required thrust or thrust coefficient, together with the nondimensional velocity profile on the body in the area of the propulsor, represent the preliminary data that must be determined prior to the selection of the propulsor. It must be emphasized that the more accurate the information is, the more accurate will be the following analysis. Employing these data as presented in Fig. 2, one can determine the propulsor characteristics listed previously for a propeller and a pumpjet. For both the propeller and the pumpjet the example configuration is assumed to have only one set of rotating blades.

Comparison of Propeller and Pumpjet Characteristics

Practically all known means of hydrodynamic propulsion depend upon the principle of reaction, i.e., a mass of fluid is accelerated in a direction opposite to the motion of the propelled body so that the force of reaction can act to propel the body.

The simplest expression for this relationship is that the "impulse" (product of force and time of action) is equal to the change in the momentum of the masses involved, i.e., for a constant mass m,

$$F \cdot t = m\Delta V$$

where ΔV is the change in fluid velocity in the direction of F between the inlet and discharge of the propulsion device. Dividing by the time interval t one can express the force F as

$$F = \rho Q \Delta V \tag{1}$$

where ρ is the mass per unit volume, and Q is the volume flow per unit time.

It is evident from this relationship that the required propulsive force or thrust F may be produced by imparting a large change in the velocity ΔV to a relatively small quantity of fluid per unit time or, conversely, by imparting a small change in velocity to a rather large quantity of fluid. As will be seen, this choice is reflected in the efficiency of the propulsor, and to a large extent provides the distinction between a propeller and a pumpjet, though both propulsors employ the principle of reaction to produce the required thrust.

Prior to the calculation of efficiency, the quantity of fluid per unit time passing through the propulsor and the corresponding increase in velocity ΔV required to produce the desired thrust must be determined. The quantity of flow Q is dependent upon the amount of the velocity profile ingested by the propulsor through the inlet flow area A_i. This inlet flow area can be related to the normal distance from the body y as follows:

$$A_i/A_B = 4[(y/D_m)^2 \cos\theta + 2(r_h/D_m)y/D_m] \tag{2}$$

The terms y/D_m, r_h/D_m, and θ are depicted in Fig. 2.

The quantity of flow per unit time is

$$\frac{Q}{A_B V_\infty} = 8 \int_{r_h/D_m}^{r_h/D_m + y/D_m \cos\theta} \left(\frac{r/D_m}{\cos\theta}\right) \frac{V_i}{V_\infty} \frac{dr}{D_m} \tag{3}$$

and the average inlet velocity is

$$\bar{V}_i/V_\infty = (Q/V_\infty A_B)(A_B/A_i) \tag{4}$$

These relationships allow the average inlet velocity to be plotted as a function of A_i/A_∞ (Fig. 2). The use of average values is necessary in the following presentation in order to provide a straightforward and simplified analysis.

It is more convenient to express the propulsor's action in terms of the flow area of the rotating blades or propulsor disk A_D than of the inlet area to the propulsor. The pumpjet by virtue of its shroud allows control of the amount of fluid and velocity passing through the pumpjet. As discussed in Ref. 3, the ability to control this flow, i.e., either accelerating or diffusing, allows the designer to control, to a certain extent, the cavitation performance of the pumpjet. For the analysis presented here the assumption will be made that there is neither acceleration nor diffusion into the rotor. Therefore, the average velocity into the pumpjet rotor equals the average velocity at the inlet, and A_i equals A_D for the pumpjet. Figure 3 presents the variation of $\bar{V}_i/V_\infty$ with the ratio A_D/A_B as determined from Fig. 2 and Eq. (4) for the pumpjet.

If a propeller is considered, the relationship between the propeller disk area and the inlet area is different and more complicated than for a pumpjet. As in any propulsor, the quantity of flow through the inlet area A_i and the disk area A_D must be equal, i.e.,

$$A_i\bar{V}_i = A_D\bar{V}_D \tag{5}$$

Based on actuator disk theory,[7] the average velocity at the propeller disk $\bar{V}_D$ is

$$A_i\bar{V}_i = A_D(\bar{V}_i + \Delta V/2) \tag{6}$$

Since ΔV is related to the amount of thrust produced by the propulsor, Eq. (6) can be written to give a relation between the disk area and the inlet area

$$A_D/A_i = 1/[1 + (C_T/4)(V_\infty/\bar{V}_i)^2 \cdot A_B/A_i] \qquad (7)$$

With the use of this expression, the variation of $\bar{V}_i/V_\infty$ with the ratio A_D/A_B for the propeller can be determined as shown in Fig. 3, using the data presented in Fig. 2.

If both a propeller and a pumpjet are considered as a means of propelling the same body, both propulsors must produce the same net or propulsive thrust. From Eq. (1) this is written as

$$(A_i\bar{V}_i\Delta V)_{\text{pumpjet}} = (A_i\bar{V}_i\Delta V)_{\text{propeller}} \qquad (8)$$

The variation of ΔV with A_D/A_B for the pumpjet is straightforward since A_i is assumed to equal A_D. The determination of such a variation for the propeller involves Eq. (7), which relates the propeller disk area and inlet area. Applying this relationship for the body shown in Fig. 2 gives the variation of ΔV with respect to A_D/A_B for the propeller, Fig. 3. The variation of velocity at the propeller disk as calculated from Eq. (6) is also shown. The disk velocity for the pumpjet is the same as $\bar{V}_i/V_\infty$ since inlet area and disk area have been assumed equal.

Propulsor Efficiency

The over-all efficiency of a propulsor is defined as the ratio of useful propulsive energy output to energy input. This efficiency can therefore be defined to relate the required shaft horsepower and the amount of thrust produced by the propulsor as

$$\text{shp} = (C_T/\eta_t)\cdot\rho/2\cdot(V_\infty^3/550)\cdot A_B \qquad (9)$$

The over-all efficiency η_t is the product of two efficiencies, η_p and η_h. The propulsive efficiency η_p is a measure of the effectiveness of the propulsor in converting the energy of the fluid passing through the propulsor into thrust. The hydraulic efficiency η_h measures the effectiveness of the rotating blades in converting shaft energy into fluid energy and includes friction losses in the propulsor. The over-all efficiency can be defined as

$$\eta_t = \eta_p\,\eta_h = [\text{thrust } V_\infty/\text{energy input to fluid}] \qquad (10)$$
$$= [\text{energy input to fluid/available shaft energy}]$$

This definition of efficiency complies with the usual definition as the useful energy output is expressed as the product of propulsor thrust and vehicle forward velocity. For the purpose of the discussion presented here, the hydraulic efficiency will be assumed to be a constant for both the propeller and the pumpjet and to be equal to 0.9.

If the average fluid velocities entering and leaving the propulsor, $\bar{V}_i$ and $\bar{V}_e$, respectively, are both referred to the freestream static pressure P_∞, then η_p can be written as

$$\eta_p = \text{thrust } V_\infty/[\tfrac{1}{2}\rho Q(\bar{V}_e^2 - \bar{V}_i^2) + \text{loss}] \qquad (11)$$

Employing Eq. (1) and expressing the loss as some fraction k of the inlet energy, one can write Eq. (11) as

$$\eta_p = 2\Delta V\, V_\infty/(\bar{V}_e^2 - \bar{V}_i^2) + k\bar{V}_i^2 \qquad (12)$$

where ΔV equals the change in velocity from the inlet to the exit of the propulsor in the direction of thrust. In order to obtain simplified expressions that are easily applicable in this analysis, the assumption is made that the difference between the averaged exit and inlet velocities $\bar{V}_e$ and $\bar{V}_i$ equals ΔV. Actually, ΔV equals $\bar{V}_e - \bar{V}_i\cos\theta$ for the propulsors shown in Fig. 1. In this analysis such an assumption is justified since θ rarely exceeds 15° to 20° in order to prevent flow separation on the body.

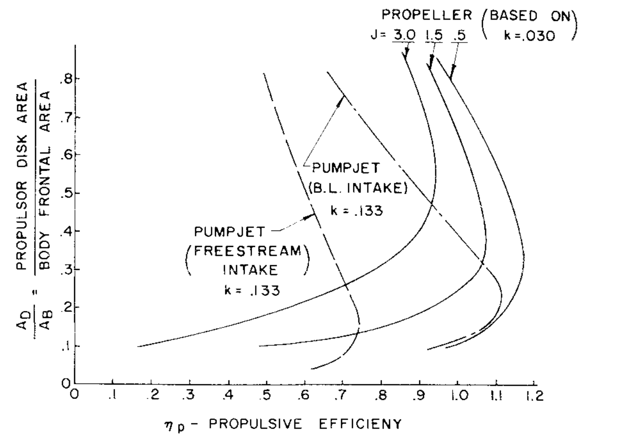

Fig. 4 Nondimensional propulsor disk area as a function of propeller and pumpjet propulsive efficiency.

As shown in Fig. 1 the pumpjet has a vane system aft of the rotating blades designed to force the exit flow to leave the propulsor in the axial direction. The single propeller, Fig. 1, does not permit such control, and therefore its exit velocity contains some fluid rotation. Thus, the propulsive efficiency of a propeller η_p' and that of a pumpjet η_p'' can be written by employing Eq. (12) as

$$\eta_p' = 1\bigg/\left\{\frac{\bar{V}_i}{V_i} + \frac{1}{2}\frac{\Delta V}{V_\infty}\left[1 + \left(\frac{\bar{V}_\theta}{\Delta V}\right)^2\right] + \frac{k}{2}\left(\frac{\bar{V}_i}{V_\infty}\right)^2\frac{V_\infty}{\Delta V}\right\} \qquad (13)$$

$$\eta_p'' = 1/[\bar{V}_i/V_\infty + \tfrac{1}{2}\,\Delta V/V_\infty - k/2(\bar{V}_i/V_\infty)^2 V_\infty/\Delta V] \qquad (14)$$

where $\bar{V}_\theta$ is the average rotational velocity in the exit fluid.

The thrust produced by the propeller is related to the static pressure or head increase across the propeller disk of area A_D as

$$\text{thrust} = \Delta P\, A_D = \rho A_D \bar{V}_D \Delta V \qquad (15)$$

If Euler's turbomachinery equation is employed,[8] the average velocity at the disk $\bar{V}_D$ can be related to $\bar{V}_\theta$ as

$$\bar{V}_\theta/\Delta V = \bar{V}_D/\bar{U} \qquad (16)$$

where $\bar{U}$ is an average rotational speed defined as $\bar{U} = U_t/2^{1/2}$, the subscript t representing conditions at the blade tips. Equation (16) therefore becomes

$$\bar{V}_\theta/\Delta V = \bar{V}_D/U = 2^{1/2}J_m(A_B/A_D)(\bar{V}_i/V_\infty + \tfrac{1}{2}\,\Delta V/V_\infty) \qquad (17)$$

The quantity $J_m = V_\infty/nD_m$ is the advance ratio that relates the vehicle forward velocity V_∞ to the shaft speed n.

The propulsive efficiency η_p' of a propeller is therefore dependent upon its design advance ratio J_m. On the other hand, the pumpjet propulsive efficiency η_p'' is independent of advance ratio. Figure 4 shows the variations of both η_p' and η_p'' using the velocity characteristics presented in Fig. 3. For the propeller, three advance ratios, $J_m = 0.5$, 1.5, and 3.0, are shown demonstrating that the lower the advance ratio (i.e., the larger the rotational shaft speed for a given vehicle forward velocity) the greater will be the propulsive efficiency. There is also an optimum propulsor disk area or amount of flow taken through the propulsor from an efficiency standpoint. Since both of these factors affect the cavitation performance of the propulsor, as will be discussed in the following, a comparison between propulsive efficiency and cavitation must be made prior to the selection of propulsor size and advance ratio. The values of k employed to estimate the losses through these propulsors are presented in Fig. 4 and are intended to represent typical values. Ref. 9 presents a detailed discussion of expected losses.

Values of propulsive efficiency greater than 1.0 are shown for certain values of A_D/A_B. These values are the result of the

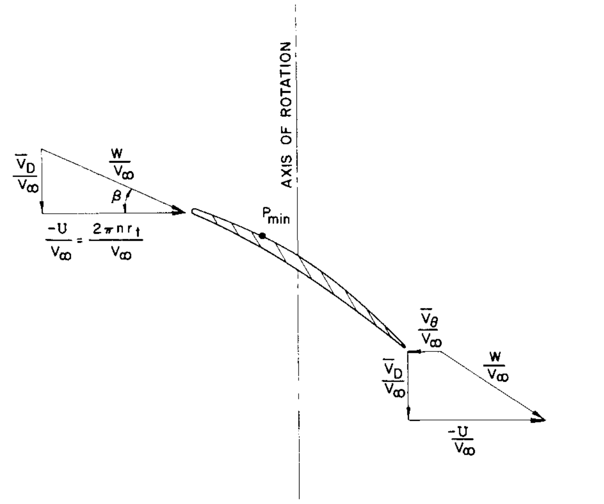

Fig. 5 Typical velocity diagrams at the inlet and discharge of a propulsor blade.

manner by which the propulsive efficiency is defined [Eq. (10)]. To eliminate any confusion resulting from efficiencies greater than 1.0, it is an accepted practice to term this definition as a propulsive coefficient rather than propulsive efficiency.

Cavitation

The occurrence of cavitation in a propulsor results in a degradation of the propulsor operating characteristics if extensive amounts of cavitation exist, and in significant noise when minute amounts occur. As a result, the performance requirements of a submersible weapon system specify that the occurrence or inception of cavitation be avoided below certain operating depths.

Reference (10) discusses the inception of cavitation and states its dependence upon local static pressure, which is in turn dependent upon local flow velocities. It is obvious therefore that the rotating blades of a propulsor usually represents the most critical component of a propulsor with respect to cavitation since the local velocities are usually greater over the blades.

Cavitation occurs in a fluid when the local static pressure is approximately equal to the vapor pressure of the fluid P_v. A means of describing the cavitation characteristics of a hydrofoil, for example, is by the use of its pressure coefficient. This coefficient is defined as the greatest reduction in static pressure experienced by the flow passing over the foil divided by the relative dynamic pressure of the flow, i.e.,

$$C_b = P_D - P_{\min}/(\rho W^2/2) \tag{18}$$

The terms contained in this definition are shown in Fig. 5. For the type of foils usually employed in propulsor blades,[3] values of C_b between 0.2 and 0.3 are obtainable. As noted previously, cavitation will occur when $P_{min} = P_v$.

Although the blade pressure coefficient describes the cavitation characteristics of the blades, it does not represent these characteristics in terms of the usual operating parameters of forward velocity and submergence depth. For this purpose a quantity similar to C_b is defined and termed σ, the cavitation index,

$$\sigma = P_\infty - P_v/\tfrac{1}{2}\rho V_\infty^2 \tag{19}$$

The pressure P_∞ is the static pressure of the free or undisturbed stream and is related to the depth of submergence h_s. Considering the fluid to be water yields

$$\sigma = h_s + 3.10/(V_\infty^2/2g) \tag{20}$$

Referring to Fig. 1, one can write the flow energy between the propulsor inlet and disk as

$$P_\infty + \tfrac{1}{2}\rho\bar{V}_i^2 = P_D + \tfrac{1}{2}\rho\bar{V}_D^2 \tag{21}$$

Solving for P_D and substituting into Eq. (18) with $P_{min} = P_v$, one can obtain the following expression for σ_{cr}:

$$\sigma_{\text{cr}} = C_b(W/V_\infty)^2 + (\bar{V}_D/V_\infty)^2 - (\bar{V}_i/V_\infty)^2 \tag{22}$$

The difference in values of σ and σ_{cr} is clarified when it is observed that σ_{cr} occurs only when the minimum pressure at some point on the foil reaches the vapor pressure of the fluid. Conversely, σ does not represent a unique point in the relation between submergence depth and forward velocity. If this value of σ_{cr} is known, the corresponding submergence depth at which cavitation will occur can be determined from Eq. (20). The greater the value of σ_{cr}, the greater the depth at which cavitation will first occur for a given forward velocity.

The cavitation index as defined in Eq. (22) is a direct function of the relative velocity W over the blades, indicating that the blade tips represent the most critical region with respect to cavitation inception. Figure 5 shows that the relative velocity at the blade tip can be expressed as

$$W_t^2 = \bar{V}_D^2 + U_t^2 = \bar{V}_D^2 + (2\pi n r_t)^2 \tag{23}$$

Therefore, Eq. (22) can be written as

$$\sigma_{\text{cr}} = C_b\left\{\left(\frac{\bar{V}_D}{V_\infty}\right)^2 + \left(\frac{\pi}{J_m}\right)^2\left[\frac{A_D}{A_B} + \left(\frac{D_h}{D_m}\right)^2\right]\right\} + \left(\frac{\bar{V}_D}{V_\infty}\right)^2 - \left(\frac{\bar{V}_i}{V_\infty}\right) \tag{24}$$

where D_h/D_m represents the ratio of body diameter at the propulsor to the maximum body diameter.

This expression for critical cavitation index applies to any rotating propulsor. For the propeller, the value of $\bar{V}_D$ is obtained from Eq. (6). For the pumpjet, under the assumption of no acceleration or deceleration of the flow from the inlet to the rotating blades, the expression reduces to

$$\sigma_{\text{cr}} = C_b\{(\bar{V}_i/V_\infty)^2 + (\pi/J_m)^2[A_D/A_B + (D_h/D_m)^2]\} \tag{25}$$

Figure 6 presents the variation in σ_{cr} with propulsor size A_D/A_B for both a propeller and a pumpjet operating at different advance ratios on the body shown in Fig. 2, which indicates that cavitation is less likely to occur at high values of advance ratio. This contradicts the requirement of low advance ratios in a propeller to obtain maximum propulsive efficiency and emphasizes the necessity of compromise in specific performance areas in order to optimize the system.

The cavitation characteristics predicted by Eq. (24) and Fig. 6 are for the design advance ratio representing the condition of self-propulsion. In performing its mission, a submerged vehicle may at various times, accelerate or decelerate.

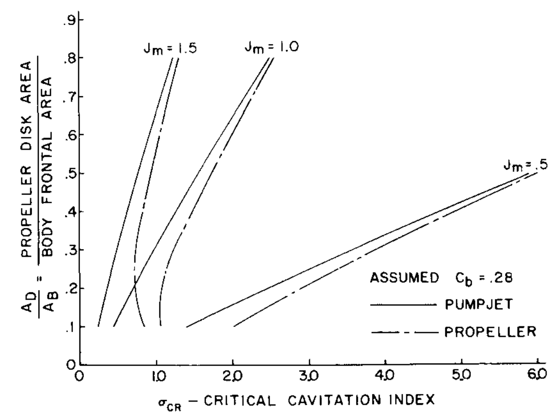

Fig. 6 Nondimensional propulsor disk area as a function of propeller and pumpjet critical cavitation index and advance ratio.

During such phases, the advance ratio must change as the propulsor produces either an excess or deficency of thrust in off-design conditions. Since minute amounts of cavitation result in significant noise, it is important to examine the off-design cavitation characteristics of the vehicle. Such a consideration reveals a major difference between a propeller and a pumpjet. A change in advance ratio implies a corresponding change in the inlet flow angle β to the blades, if the velocity $\bar{V}_D$ and $\bar{U}$ do not change proportionally.

Figure 7 presents the cavitation performance of a typical propeller as a function of advance ratio. It is seen that as the advance ratio is varied over the range shown, the inlet angle to the blades is changed as evidenced by the existence of cavitation on the suction side of the blade at advance ratios below self-propulsion and on the pressure side above self-propulsion. Such behavior can only be produced by changes in the inlet angle.

Also shown in Fig. 7 is the experimentally determined cavitation performance of a pumpjet operating on the same vehicle. At advance ratios greater than self-propulsion, the pumpjet, like the propeller, exhibits pressure-face cavitation. However, as the advance ratio is lowered the blades continue to exhibit pressure-face cavitation and do not experience as great an increase in critical cavitation index from the self-propulsion value as does the propeller. This characteristic is caused by the presence of the shroud, which allows a corresponding change in velocity at the disk of the pumpjet when the rotational speed of the blades is varied. As a result the pumpjet blades exhibit nearly a constant inlet angle with varying advance ratio. The critical cavitation index does increase, however, since the relative velocity over the blades increases with decreasing advance ratio. It has been observed that this behavior exists in the pumpjet for advance ratios approximately 20% above and below the self-propulsion value. The pumpjet, therefore, exhibits cavitation performance, which is superior to that of a propeller at off-design advance ratios.

Propulsor Rotational Speed

The forementioned discussion of propulsor efficiency and cavitation demonstrates the dependence of these characteristics for a constant forward velocity upon the rotational speed of the propulsor blades. The efficiency of a propulsor that does not act to cancel rotation in the flow leaving the blades, i.e., a single propeller, is increased with increasing rotational speed or decreasing advance ratio V_∞/nD_m. On the other hand, the cavitation resistance of any rotating propulsor is degraded by increases in rotational speed. There exists therefore an optimum rotational speed when both efficiency and cavitation are considered.

There are advantages to operating at high rotational speeds. Such operation implies the possibility of direct coupling between the powerplant and the propulsor, thereby eliminating the speed reducing gears, a possible noise source and contributor to the over-all weight. Assuming that operation at high rotational speeds does not alter the amount of shaft power that must be transmitted and that the same over-all efficiency can be realized, the weight of the power-transmitting machinery can be reduced since the torques on such machinery are reduced. A complete discussion of this concept is presented in Refs. 3 and 10.

For a given operating forward velocity V_∞, increased rotational speeds mean a reduction in operating advance ratio. As shown in Fig. 6, decreases in advance ratio lead to increases in critical cavitation index for a given value of A_D/A_B. However, at a constant advance ratio, an improvement in cavitation performance can be realized by reducing the propulsor disk area. If the propulsor is operating in the boundary layer of the body, acceptable values of propulsive efficiency can be maintained over a large range of values of A_D/A_B, thus allowing improved cavitation performance without sacrifices in efficiency by employing lower values of A_D/A_B. However, at very low values of A_D/A_B a sacrifice in efficiency must be accepted if cavitation free operation is to be realized at low advance ratios.

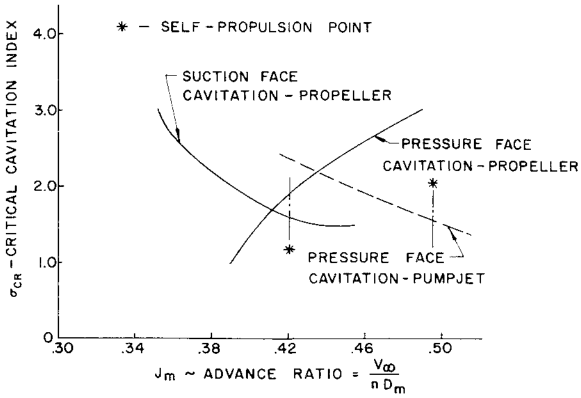

Fig. 7 Experimentally observed critical cavitation index as a function of propeller and pumpjet advance ratio.

The propeller has a limitation in minimum disk area not shared by the pumpjet. Since the propeller has no shroud to control the flow about it, the distribution of loading on the blades must be gradually reduced to zero at the tips. If not, the propeller will generate strong tip vortices, which degrade both its efficiency and cavitation performance. The pumpjet, by virtue of its shroud, can be loaded to the ends of the blades. For the same disk area this means that the loading near the middle of the propeller blades is greater than for the pumpjet. If this loading is too high, degradation of efficiency and cavitation performance will result. This implies the existence of an upper limit to the amount of thrust that can be practically produced by a propeller having a given disk area.

This limit is usually specified in terms of the nondimensional increase in velocity $\Delta V/V_\infty$ through the propeller. Based on information presented in Refs. 9 and 10, it may be assumed that the maximum value of $\Delta V/V_\infty$ that can practically be obtained with a propeller is 0.4. When Fig. 3 is referred to, this implies that, if a ratio of A_D/A_B less than 0.165 is desired to obtain a required cavitation performance, a pumpjet should be employed.

Going to the small, high rotational speed pumpjet to realize the advantages of direct coupling with the powerplant results in a marked change in the configuration of the propulsor from that shown in Fig. 1. As discussed in detail in Ref. 10, this type of pumpjet has the advantage of allowing a body having a greater internal volume than does the pumpjet depicted in Fig. 1. The slope and curvature of the afterbody are governed by the requirement that the flow will not separate before entering the propulsor. It is possible to employ the shroud inlet as a boundary-layer control device since a smaller percentage of the boundary layer is injected thus delaying separation and allowing the more blunt afterbody.

Propulsor Noise Characteristics

The total radiated noise produced by an underwater vehicle is usually of primary concern to the system designer. As discussed previously, a major contributor to propulsor-originated noise is the occurrence of cavitation within the propulsor. If a quiet vehicle is desired the propulsor must be selected with stringent requirements regarding cavitation-free operation. The realization of cavitation-free operation does not insure a quiet system, however.

In the absence of cavitation there are several known or suspected contributors to hydrodynamically generated noise.[11] These contributors are usually associated with irregularities or fluctuations occurring in the flow through the propulsor. Such irregularities can result from turbulence in the boundary layer of the body and from disturbances upstream of the propulsor, such as control surfaces that cause the forces produced by the blades to be time dependent and varying. These unsteady forces act as a time-varying forcing function, which can drive other components into vibration causing additional sources of radiated noise.

At the present time there is not sufficient knowledge regarding the mechanism of the interaction of the blades with the flow fluctuations to establish any concrete criteria that can aid in the selection of a propulsor having a minimum radiated noise characteristic. By eliminating any upstream control surfaces or appendages the problem is certainly aided. It may also be possible to minimize the fluctuations entering the propulsor by making the inlet small, thereby reducing the energy of the incoming flow and its level of fluctuation. This small propulsor size is in line with the use of high rotational speeds discussed previously that would permit direct coupling with the powerplant and reduction of the mechanical noise produced by speed-reducing gears. Future studies are in progress to shed more light on this problem area and provide data to aid in the selection of the propulsor.

Another source of hydrodynamic noise is that of "singing" blades or appendages. This phenomenon occurs when resonance exists between one of the natural frequencies of blade vibration and the unsteady fluctuations caused by vortex shedding. By altering the thickness of the trailing edges of the blades and changing the shedding frequency, one can usually avoid this state of resonance. It is usually desirable to operate with blades having sharply pointed trailing edges thereby minimizing the possibility of singing.

Propulsor Effect on Vehicle Control

The propulsor and hydrodynamic control system are usually located on the aft end of a body of revolution relatively near to each other. As a result the propulsive action of the propulsor can strongly affect the control characteristics of the vehicle. However, the degree of propulsor control surface interaction varies depending upon the propulsor configuration under consideration.

The single open propeller affects vehicle control since the propeller imparts a net rotation to the fluid passing through it, thereby producing net rolling moment about the body longitudinal axis. This characteristic is termed roll unbalance and can be overcome by employing the control surfaces to counteract the propulsor moment. This means that the control surfaces are deflected in straight and level flight and, as a result, their maximum available effectiveness for maneuvering is reduced.

The problem of roll unbalance can also be eliminated by the use of counterrotating open propellers that impart no net rotation to the fluid. Such a system, although mechanically more complicated, is slightly more efficient than the single propeller.[4] The pumpjet, because of its stator vanes, does not produce a roll unbalance with a single rotating shaft. Therefore, the single rotor pumpjet has a marked advantage over a single open propeller because of roll unbalance and over a set of counterrotating propellers because of its simplicity.

Illustrative Example

To demonstrate the use of the procedure described in this paper, the following example is presented. It will be assumed that the body under consideration and its flow characteristics are those described in Figs. 2–4. The use of these characteristics, together with the following specified system performance, permits the selection of an acceptable propulsor: 1) forward speed, $V_\infty = 35$ knots, 2) cavitation free depth = 128 ft or $\sigma_{cr} = 3.0$, 3) minimum of noise generation, 4) minimum propulsor system weight, and 5) propulsor driven by a direct current motor that produces a relatively constant torque output of 52.5 ft-lb over a 40–70 hp range.

When Fig. 4 is referred to, the peak propulsive efficiency of the pumpjet is $\eta_p' = 1.12$ at a ratio of $A_D/A_B = 0.22$. If the hydraulic efficiency η_h is assumed to be 0.90, the required shaft horsepower, Eq. (9), can be calculated as

$$\text{shp} = C_T(1/\eta_p\eta_h)\rho[(V_\infty{}^3A_B)/2(550)] = 53.6$$

Using this horsepower and the given motor characteristics indicates that a shaft rpm of 5380 will be required. Substitution of this value into the equation for advance ratio indicates $J_m = 0.500$. Figure 4 indicates a peak propeller propulsive efficiency of 1.17 for an advance ratio of 0.5 at $A_D/A_B = 0.30$. This results in a shaft rpm of 5130 and an advance ratio $J_m = 0.52$. Rather than calculate a new curve in Fig. 4 for $J = 0.52$, it will be assumed that the existing one for $J_m = 0.50$ is applicable. It should be pointed out however that if a large difference exists, a new plot of A_D/A_B vs σ_{cr} should be constructed from Eq. (13).

Referring now to Fig. 6, it is evident that, for the forementioned values of A_D/A_B for propeller and pumpjet, the pumpjet satisfies the cavitation requirements whereas the propeller does not. The propeller shows a $\sigma_{cr} = 3.85$, and the pumpjet $\sigma_{cr} = 2.85$. A propeller could be used if a speed reducing unit were incorporated between the prime mover and propulsor to reduce the rotational speed and increase the advance ratio, but this would add to the weight and possibly increase the noise of the vehicle. Again it must be emphasized that considerations relating to the mission of the vehicle will also tend to dictate the choice of a propulsor. If the employment of the system involves acceleration and deceleration of the vehicle, use of a pumpjet is suggested which permits the blades to operate at a constant inlet angle and improve cavitation performance and noise characteristics at advance ratios other than self-propulsion. In this example, since the operating characteristics of the pumpjet and propeller are nearly equivalent, manufacturing and simplicity considerations could dictate the use of a propeller.

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