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Review of Marine Propellers and Ducted Propeller Propulsive Devices

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This paper reviews the present state-of-the-art of marine propellers and related propulsive devices. These devices are described in terms of the physical flow processes and simple energy and momentum considerations. The objective of the paper is to provide a component-level understanding of propellers and ducted propellers through a brief and idealized treatment. Although it is not intended to determine the optimum region of performance for any specific type of propeller or ducted propeller, the general regions where they perform best are presented on a comparative basis, and the operating characteristics and potentials of some types of ducted propellers which have not received serious attention heretofore are pointed out.

Nomenclature

A_d = cross-sectional area of the propeller flow streamtube at the propeller disk
A_o = cross-sectional area of the propeller flow streamtube well upstream of the propeller (at freestream conditions)
C_p = relative minimum pressure coefficient
D = maximum diameter of propeller
g = acceleration due to gravity, 32.2 ft/sec^2
J = freestream advance ratio, V_0/nD
K_d = diffusion coefficient
P_H = hydraulic power added to fluid by propeller
P_T = thrust power obtained from fluid accelerated by propeller
q = dynamic pressure
T = propeller thrust
V = flow velocity
W = weight flow rate of fluid accelerated by propeller
β = prewhirl (or postwhirl) angle, deg
η = ideal efficiency
$\eta_{hydraulic}$ = propeller hydraulic efficiency
$\eta_{propulsive}$ = propulsive efficiency
ρ = mass density of fluid, slugs/ft^3
σ = cavitation index

Subscripts

r = relative to the propeller blade
o = ambient or freestream conditions
j = conditions downstream at ultimate wake
v = vapor pressure
L = local on blade surface
1 = station 1, just upstream of propeller
2 = station 2, just downstream of propeller
d = at propeller disk

Introduction

IN the past 25 years, scientific and technological achievement has progressed at an incredible pace. In the aerospace and aeronautical sciences, progress has been dynamic, keynoted by advances in propulsion. Space engines have grown from low-impulse, small-rocket engines to multi-million-pound thrust engines which permit orbiting of large spacecraft and which ultimately will send man to the moon and beyond. Positive-displacement powered propeller-driven aircraft have been almost entirely superseded by high subsonic and soon-to-be supersonic jet engine-driven airliners. Unfortunately, progress in the marine sciences has not kept pace with aerospace achievement; new developments have been very slow in emerging, and in some areas are virtually nonexistent. It has been only recently that any significant attention has been given to the science of marine propulsion.

In the chronological progression of marine propulsion devices, sailing ships were displaced by paddle wheels, which in turn were displaced by screw propellers. The early patent literature shows reference to screw-type propellers in the early 1800's. By the turn of the century, the screw-type propeller was the accepted thrust producer but, until recently, has remained virtually untouched in its development.

This paper reviews the present state-of-the-art of marine propellers and ducted propeller propulsive devices, using Ref. 1 as a basis. These devices are described in terms of the physical flow processes and simple energy and momentum considerations. Many of the devices that are discussed are still in the early development stage, and considerable time will pass before they will be exploited in practice. However, pictures of models and/or experimental installations are shown where available. Even though there has been very little progress in marine propulsion, it is, nevertheless, hardly possible to review the field adequately in a paper of this type. Above all, it is realized that major advances in the state-of-the art of marine systems will be made only when the entire system is considered. The detailed hydrodynamics and the interactions of the hull, appendages, and control surfaces, as well as the power plant characteristics and mission requirements, must all receive serious attention. Before considering the entire system on a knowledgeable basis, however, it is necessary that an understanding be obtained of the components. This component-level understanding of propeller and ducted propeller types of marine propulsive devices is the objective of this paper.

Hydrofoil Sections

It is of interest to discuss briefly the types of hydrofoil or vane sections which the hydrodynamicist or naval architect has available at this time to use for designing the thrust producer or propeller. Hydrofoil sections are the building

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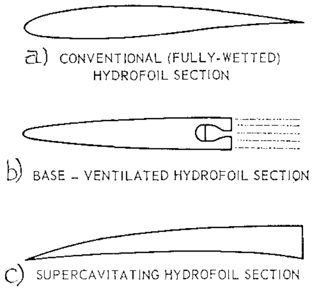

Fig. 1 Types of hydrofoil sections.

blocks of the propeller designer. There are three basic types: 1) conventional subcavitating (fully-wetted) hydrofoil, 2) base-ventilated hydrofoil, and 3) supercavitating hydrofoil. The basic type, the conventional or fully-wetted hydrofoil (Fig. 1a), is analogous to the subsonic airfoil or wing section. In fact, conventional low-drag airfoil sections often are used for propellers and ducted propellers. In order to avoid blade surface cavitation, the minimum local static pressure on the suction surface of this hydrofoil must be greater than the vapor pressure of water. Cavitation results in erosion, noise, and a loss in performance, all of which are undesirable.

When it is necessary to increase the total work or lift that a typical section can produce and still maintain a given cavitation performance, the size or chord of the section must be increased. Otherwise, the number of vanes or blades must be increased. Increased work or lift from a hydrofoil section is needed when the propeller must propel a ship faster and transmit more power into the water. As the chord becomes larger and larger, with consequent increases in friction drag, a point is reached beyond which it is impractical to increase the size of the hydrofoil.

One method of extending the operating range of the subcavitating hydrofoil is to eliminate the trailing-edge pressure-recovery region, leaving a blunt end as shown in Fig. 1b. In order to eliminate the otherwise high base drag, this region is ventilated by a suitable gas, so that the pressure approaches ambient.[2] In this manner, the overvelocity due to thickness is reduced significantly, and furthermore, the freedom to use larger section leading-edge radii ensures better off-design performance. In addition, the long, thin trailing edge is eliminated. This type of hydrofoil is referred to as a base-ventilated section. The extent to which this technique extends the operating range of a propeller is discussed later in this paper.

As the flow conditions become increasingly critical, with respect to cavitation because of high blade loading and/or high relative velocities and low ambient pressures, conditions ultimately are reached where cavitation can be avoided no longer. At this point, the hydrofoil sections must be designed for cavitating flow. A hydrofoil section designed

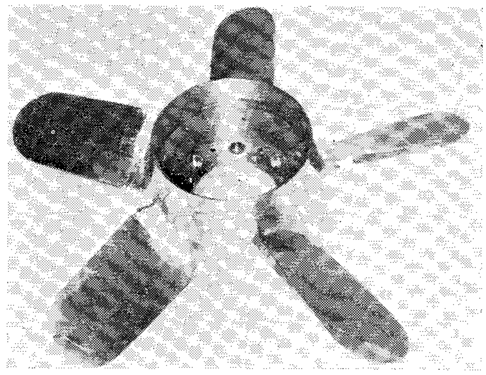

Fig. 3 Base-ventilated propeller.[4]

for cavitating flow (supercavitating hydrofoil) has a general shape represented by the sketch shown in Fig. 1c. This type of section is characterized by a relatively sharp leading edge and a blunt trailing edge, and is analogous in many respects to a supersonic airfoil. The cavity is formed at the leading edge of the foil and collapses downstream of the trailing edge. The foil is designed to be within the cavity.[3] In order to minimize drag, the cavity usually is ventilated.[4]

Types of Propellers

The conventional (fully-wetted) single blade row propeller is the simplest type of propulsive device and, for many years, has been the only propulsor of any major consequence. However, there are three types of propellers which are of interest, based on utilizing the basic types of hydrofoil sections or building blocks: 1) conventional propeller (Fig. 2), 2) base-ventilated propeller (Fig. 3), and 3) supercavitating propeller (Fig. 4). Any of these propellers, in turn, can be incorporated within a duct. The propeller or rotating blade row imparts the energy to the water; the duct provides a physical mechanism to control the flow before it reaches the plane of the propeller.[5,6] The duct can either accelerate or diffuse the flow to a considerable extent independent of the forward velocity. Any of the three basic hydrofoil sections can be used for the duct as well as for the propeller. Therefore, the various types of ducts around the propeller can be categorized as 1) conventional (fully-wetted) duct a) accelerating (Kort nozzle), b) diffusing; 2) base-ventilated duct a) accelerating, b) diffusing, and 3) supercavitating duct a) accelerating, b) diffusing.

With the basic types of propellers and with 6 different types of ducts, 18 different ducted propeller combinations and three free propellers are possible. Therefore, 21 different configurations are available. In addition, stationary prewhirl vanes in front of the rotating blade row and/or straightening vanes behind the rotating blade row also can be considered, or dual or counter-rotating blade rows can be

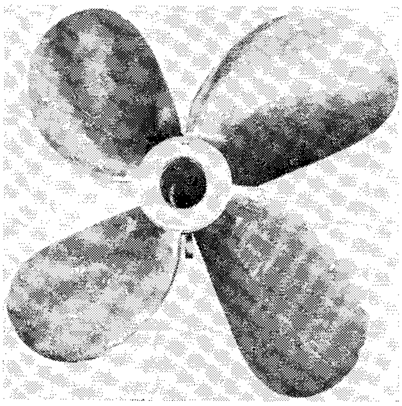

Fig. 2 Conventional propeller.

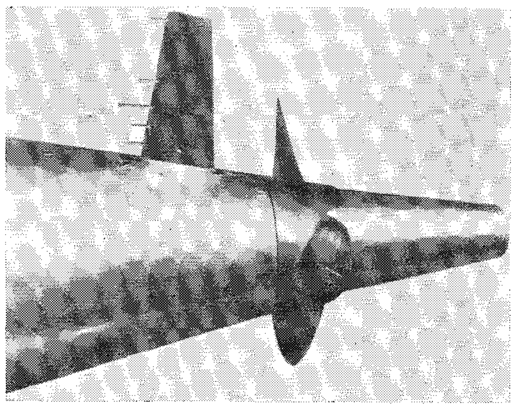

Fig. 4 Ventilated supercavitating propeller.[4]

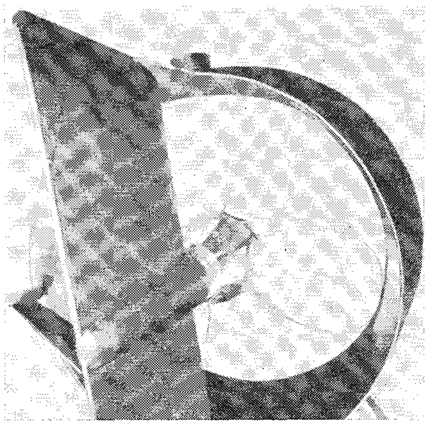

Fig. 5 Kort nozzle.

used. These probably would be limited to conventional subcavitating sections. Therefore, considerably more than 21 configurations are possible. Of these, only the Kort nozzle type of ducted propeller (Fig. 5) has been used to any extent in practice, although several experimental ducted propellers of the diffusing variety have been operating. Figure 6 shows the ducted propellers or pumpjets on the destroyer "Witek"; the flow-straightening vanes downstream of the propeller can be noted. Figure 7 shows a model of a pumpjet for a submarine using prewhirl vanes upstream of the rotor; this unit is equipped with a transparent shroud for test purposes.

It is not the intent to imply that all of these configurations should receive serious attention or have unique advantages. The significant point is that there are many configurations of propeller and propeller-related devices. A number of them are obviously of very little interest. The role and importance of others, however, are yet to be identified and explored in depth.

In order to provide a logical first step for an understanding of marine propulsive devices, the analysis presented herein will consider only ideal propellers and/or ducted propellers with single rotating blade rows. The performance features will be examined, based on cavitation as a limiting condition, and only diffusing-type ducts will be considered. The next step is to extend the present work into detailed design considerations of actual propulsors with their losses, to evaluate the over-all propulsive efficiency as well as cavitation limited conditions, and to establish the operating regions where accelerating ducts contribute to increased propulsive efficiency. This, however, must remain the subject of future papers.

Free Propellers

The conventional propeller is the simplest of the various thrust-producing devices and utilizes a single rotating blade row to transmit energy into the water. Simple momentum theory provides a convenient tool for examining the characteristics of the flow.

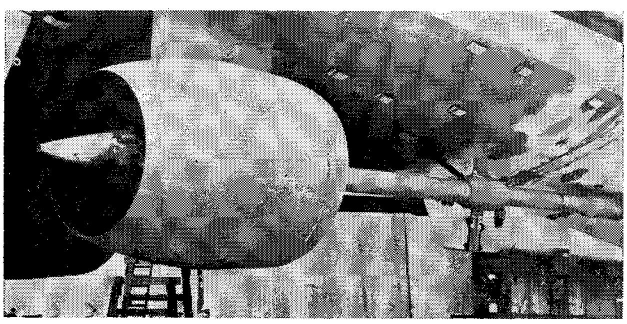

Fig. 6 Pumpjet installation on destroyer "Witek."

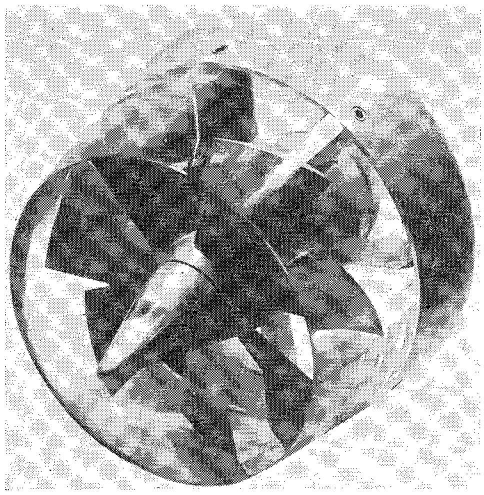

Fig. 7 Model of pumpjet for submarine.

The propeller increases the rate of axial momentum of the working fluid to produce propulsive thrust. When the momentum equation is applied to the fluid between stations 0 and j within the slipstream boundary (see Fig. 8), the force acting on the fluid in the direction of flow is:

$$\left.\begin{aligned} T &= W/g(V_j - V_o) = (p_2 - p_1)A_d \\ W/g &= \rho A_d V_d \\ p_2 - p_1 &= \rho V_d(V_j - V_o) \end{aligned}\right\} \quad (1)$$

Writing Bernoulli's equation between stations 0 and 1 and between stations 2 and j, with $p_j = p_o$ and $V_1 = V_2 = V_d$, and $p_2 - p_1 = \frac{1}{2}\rho(V_j^2 - V_o^2)$, then by combining and simplifying

$$V_d = \tfrac{1}{2}(V_j + V_o) \quad (2)$$

which shows that the velocity at the propeller disk is the average of the jet and freestream velocities, one-half of the

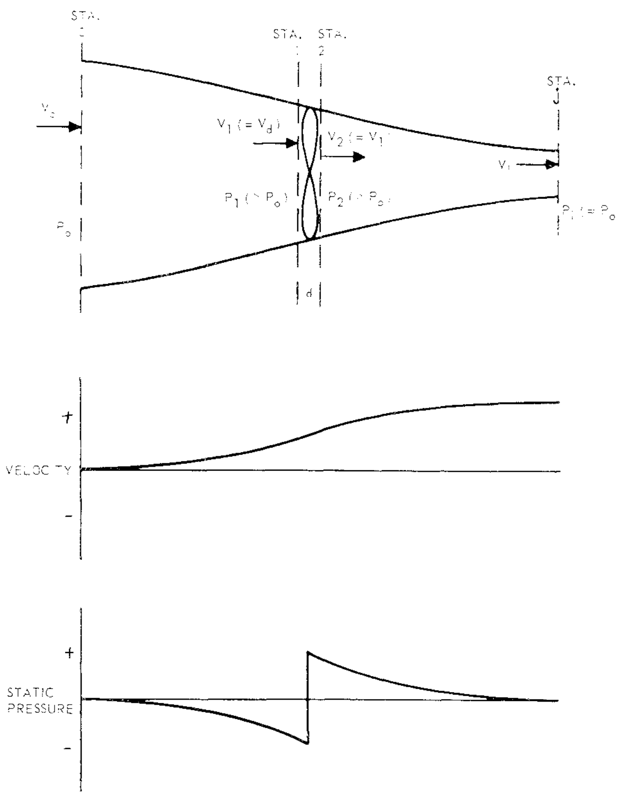

Fig. 8 Schematic showing pressure and velocity changes in an ideal conventional propeller.

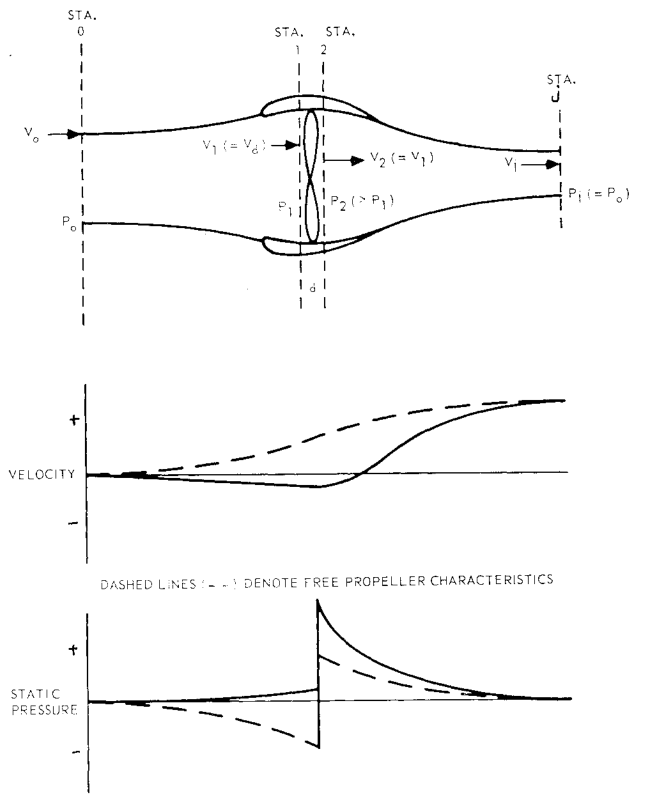

Fig. 9 Schematic showing pressure and velocity changes in an ideal diffusing ducted propeller.

velocity increase that is imparted to the flow occurs before the propeller disk is reached. After progressing through the propeller, the velocity continues to increase until the well-downstream station j is reached, where the static pressure becomes ambient.

It is of interest to follow the local pressure changes that occur. As energy is not added to the flow until the propeller disk is reached, and as the total energy within each stream tube remains a constant, the increase in local flow velocity must manifest itself as a reduction in the local static pressure. The static pressure increases across the propeller disk when energy is added. The ambient static pressure is reached again when the ultimate jet velocity is attained far downstream. Thus, the conditions at the propeller are such that the propeller sees a flow with a velocity higher than the forward velocity of the craft it is propelling and a static pressure lower than ambient. A generalized representation of the pressure and velocity changes in the free propeller system is shown in Fig. 8. The quantitative implications of these conditions merit examination.

Ideal Efficiency

Consider an ideal propeller that does not have any friction, induced or whirl losses. The thrust power obtained from the fluid accelerated by the propeller is:

$$P_T = T \times V_o = W/g(V_j - V_o)V_o \tag{3}$$

The hydraulic power added to the fluid by the propeller is:

$$P_H = W/2g(V_j^2 - V_o^2) \tag{4}$$

Thus, the ideal efficiency becomes:

$$\eta = \frac{P_T}{P_H} = \frac{W/g(V_j - V_o)V_o}{W/2g(V_j^2 - V_o^2)} = \frac{2V_o}{V_j + V_o} = \frac{2}{(V_j/V_o) + 1} \tag{5}$$

As the jet velocity approaches freestream velocity, the ideal efficiency approaches 100%. This is related to the propulsive efficiency by:

$$\eta_{\text{propulsive}} = \frac{\text{hydraulic power}}{\text{shaft power}} \times \frac{\text{thrust power}}{\text{hydraulic power}} = \eta_{\text{hydraulic}} \times \eta$$

When hydraulic efficiency equals 100%, then propulsive efficiency equals the ideal efficiency. The ideal efficiency also is referred to as the jet or Froude efficiency.

Cavitation

Cavitation occurs on the surface of a rotating propeller blade when $p_L = p_v$. Therefore, based on relative conditions, the minimum pressure coefficient is defined as:

$$C_{p_r} = (p_r - p_L)/q_r = (V_L/V_r)^2 - 1 \tag{6}$$

and the cavitation index is defined as

$$\sigma_r = (p_L - p_v)/q_r \tag{7}$$

When $p_L = p_v$, cavitation occurs on the blade surface; this corresponds to the condition of $\sigma_r = 0$,

$$V_r = [(V_1)^2 + (\pi n D)^2]^{1/2} = V_o[(1/\eta)^2 + (\pi/J)^2]^{1/2} \tag{8}$$

The corresponding dynamic pressure is:

$$q_r = (\rho/2)V_r^2 = q_0 \cdot [(1/\eta)^2 + (\pi/J)^2] \tag{9}$$

and

$$\sigma_r = \frac{\sigma_o - [(1/\eta)^2 - 1]}{(1/\eta)^2 + (\pi/J)^2} - C_{p_r} \tag{10}$$

By the use of base-ventilated sections, lower values of minimum pressure coefficient on the blade surface can be attained with a consequent increase in the cavitation-limited forward velocity. However, as the velocity increases further, and as the amount of energy added to the water increases, the pressure upstream of the propeller becomes lower and lower, until a point is reached where the propeller will cavitate regardless of the type of blade section used. In fact, theoretical considerations lead to the result that conditions can be reached where the flow in front of the propeller will cavitate before the propeller is reached, although such a flow situation actually cannot be realized.

Some improvement in the cavitation-limited speed can be attained by using prewhirl vanes to impart a rotation to the incoming flow in the direction of propeller rotation, thereby decreasing the relative velocity. However, the whirl in the existing flow is amplified, thus making a more pressing requirement for straightening or stator vanes. A more promising approach is to use a diffusing duct that increases the static pressure and reduces the relative velocity at the plane of the propeller to produce more substantial improvement. The alternate approach is to accept the limitations of operating with cavitation conditions, and to utilize supercavitating propeller blade sections that are specifically designed to operate in a cavity. The implications of these various alternatives are discussed in a subsequent section of this paper.

Diffusing Ducted Propeller

A diffusing duct provides a mechanism to delay the onset of cavitation on the propeller blades. By varying the amount of diffusion, the flow entering the propeller can be controlled to a considerable extent independent of the ambient operating conditions. The generalized characteristics of a diffusing-type ducted propeller (see Fig. 9) are presented in a manner similar to that employed for the free propeller. With this type of duct, the flow velocity is reduced before the plane of the propeller is reached. As the total energy within each stream tube is constant, the decrease in velocity upstream of the propeller must manifest itself by an increase in static pressure. The propeller then adds energy to the flow, and the velocity increases as the flow progresses further downstream until the ambient pressure is reached.

Therefore, in addition to the local velocity at the plane of the propeller being reduced to a value lower than the forward velocity, the local pressure is greater than the ambient pressure. This represents favorable flow conditions with regard to extending the cavitation-limited operation of the propeller.

Of equal or even greater significance in many applications is the effect on the cavitation-limited rotative speed or the advance ratio. Diffusion allows operation at a lower advance ratio for the same cavitation-limited forward velocity, which can become important in the design of the power plant.

Ideal Efficiency

When an ideal ducted propeller is considered, the drag of both the propeller and the duct is neglected, and the ideal efficiency is determined from conditions far upstream and far downstream. Therefore, it remains the same as for the free propeller. However, for equal thrust output with increasing diffusion, the ducted-propeller diameter must be increased over the free propeller to attain the same ideal efficiency.

Cavitation

Following the same approach as for the free propeller, the diffusion coefficient is introduced. The flow velocity relative to the propeller blade is:

$$V_r = (V_1)^2 + (\pi nD)^2 = V_o[(1 - K_d) + (\pi/J)^2]^{1/2} \quad (11)$$

The corresponding dynamic pressure is:

$$q_r = (\rho/2)V_r^2 = q_o[(1 - K_d) + (\pi/J)^2] \quad (12)$$

By again applying Bernoulli's equation between freestream conditions and the station just upstream of the propeller:

$$C_{p_o} = C_{p_r}[(1 - K_d) + (\pi/J)^2] - K_d \quad (13)$$

and

$$\sigma_r = \frac{\sigma_o + K_d}{(1 - K_d) + (\pi/J)^2} - C_{p_r} \quad (14)$$

so that cavitation occurs when

$$\sigma_o = C_{p_r} \cdot [(1 - K_d) + (\pi/J)^2] - K_d \quad (15)$$

Prerotation Vanes

The use of prerotation vanes located upstream of the propeller offers a means whereby the relative flow direction entering the propeller can be controlled. These vanes can prerotate the flow: 1) in the direction of propeller rotation decreasing the relative velocity and thereby improving cavitation performance with an increase in whirl losses; or 2) against the direction of propeller rotation, which results in a decrease in whirl losses. In the latter case, the propeller straightens the flow while adding energy with some compromise in cavitation performance.

For the case of prerotation vanes upstream of a free propeller imparting an initial flow direction to the propeller,

$$\sigma_r = \frac{\sigma_o - [(1/\eta)^2 - 1]}{(1/\eta)^2 + [(\pi/J) - (\tan\beta/\eta)]^2} - C_{p_r} \quad (16)$$

Cavitation occurs when

$$\sigma_o = C_{p_r}\left[\left(\frac{1}{\eta}\right)^2 + \left(\frac{\pi}{J} - \frac{\tan\beta}{\eta}\right)^2\right] + \left[\left(\frac{1}{\eta}\right)^2 - 1\right] \quad (17)$$

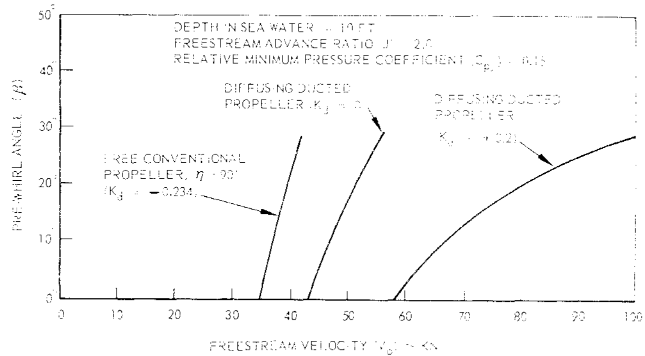

Fig. 10 Variation of prewhirl angle with cavitation-limited freestream velocity.

For a ducted propeller or pumpjet, the flow can be accelerated or diffused before reaching the propeller; then

$$\sigma_r = \frac{\sigma_o + K_d}{(1 - K_d) + [(\pi/J) - (1 - K_d)^{1/2}\tan\beta]^2} - C_{p_r} \quad (18)$$

It should be pointed out that the free propeller can be considered to have a negative K_d because of the induced velocity.

The effect of prewhirl on the cavitation-limited freestream velocity for a free propeller and ducted propellers with various diffusion factors is shown in Fig. 10. The free propeller shows relatively small improvement with prewhirl as compared with the diffusing ducted propeller.

These results show that prewhirl offers some gains in cavitation performance, but, again, the extent to which it actually can be attained in practice is not known with any degree of certainty. Prewhirl to delay the onset of cavitation on the rotor results in increased whirl losses in the exiting flow, which makes a more pressing requirement for straightening or postrotation vanes to minimize or eliminate whirl losses.

Another use of prewhirl vanes is to prerotate the flow against the direction of propeller rotation to eliminate whirl losses and accept a compromise in cavitation performance. To eliminate the whirl losses,

$$\beta = \arctan\{-2J/\pi[(1/\eta) - 1]\} \quad (19)$$

Straightening Vanes

Straightening or postrotation vanes are located downstream of the rotating blade row and remove the whirl from the exiting flow. The postwhirl angle, or the angle through which the flow must be turned to emerge without whirl, is the same as for prewhirl.

Operating Regions

The preceding discussions described the principles of operation of free and ducted propellers and the role of prewhirl and postwhirl straightening vanes. Now, the important question arises with regard to the operating range of free and ducted propellers and their relative performance with respect to each other. In order to establish rigorous operating boundaries, considerably more effort and analysis than presented herein is needed. It is necessary to analyze the details of the flow as it progresses through the propeller and, in particular, the blade element, duct design parameters and practical limitations which may be encountered. However, approximate quantitative results can be derived readily in terms of cavitation-limiting conditions, which provide a good basis for preliminary evaluations and for a component level understanding.

Figures 11, 12 and 13 were prepared to present a spectrum of performance of various propulsors based on the relationships presented herein and on reasonable design values of c_{p_r}, η, and K_d. The propeller types considered are 1) conventional

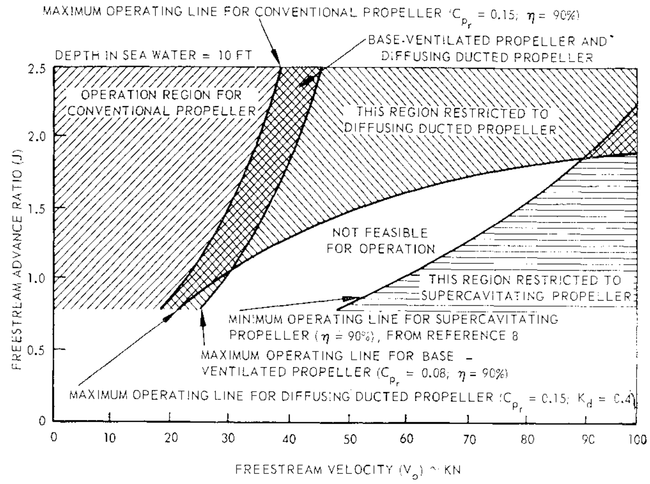

Fig. 11 Cavitation-limited operating regions for various types of propellers in terms of advance ratio.

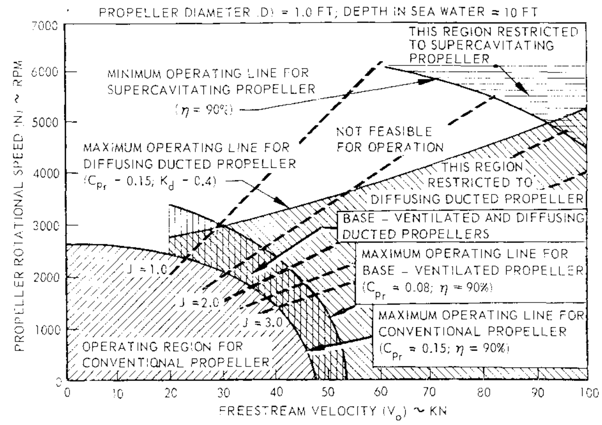

Fig. 13 Cavitation-limited operating regions for various types of propellers in terms of propeller rotational speed.

propeller, 2) base-ventilated propeller, 3) conventional propeller in a diffusing duct (for $K_d = 0.4$), and 4) supercavitating propeller. For comparison, an ideal efficiency of 90% was used for all free propellers. For the ducted propeller, the cavitation-limited performance is a function of K_d and independent of ideal efficiency. A relative minimum-pressure coefficient of 0.15 was used for both ducted and free conventional propellers, and a coefficient of 0.08 for the base-ventilated propeller. These are not intended to be exact values but are reasonable for the present purposes. The supercavitating propeller is designed to cavitate under normal operating conditions; its minimum freestream velocity boundaries for practical operation were obtained from Ref. 3.

Figure 11 presents freestream advance ratio as a function of cavitation-limited freestream velocity for various selected propeller types for a sea water depth of 10 ft. The conventional propeller is forced to increase rapidly the advance ratio for cavitation-free operation as the freestream velocity is increased, thus making reasonable propeller efficiencies increasingly difficult to attain. It tends to approach an asymptote in the region of 40 knots when the advance ratio exceeds 2.5. For an advance ratio of 1, which is a reasonable design value, the limiting speed is approximately 23 knots. For a lower value of η, the limiting speed is even less. Thus, the operating range of this type of propeller is extremely limited.

The use of a base-ventilated section increases the range of the free propeller, so that at an advance ratio of 1, the limiting speed is 29 knots. A completely different effect is shown by the diffusing ducted propeller. The limiting speed curve is asymptotic to an advance ratio of approximately 2, extending out beyond the range of the graph. This result clearly illustrates that the diffusing ducted propeller or pumpjet can be designed for almost any practical forward velocity. However, as the velocity increases, the shroud or duct can cavitate, and the limiting condition then must be based on the duct cavitation performance. Unfortunately this limit again is not known with any degree of certainty. However, as the duct is stationary, velocities upwards of 50–60 knots are expected. When cavitation on the duct cannot be avoided, the use of a ventilated duct can raise the cavitation-limited speed further. Finally, a supercavitating duct can be used. With a supercavitating duct, there would not be any limitations on the attainable forward speed.

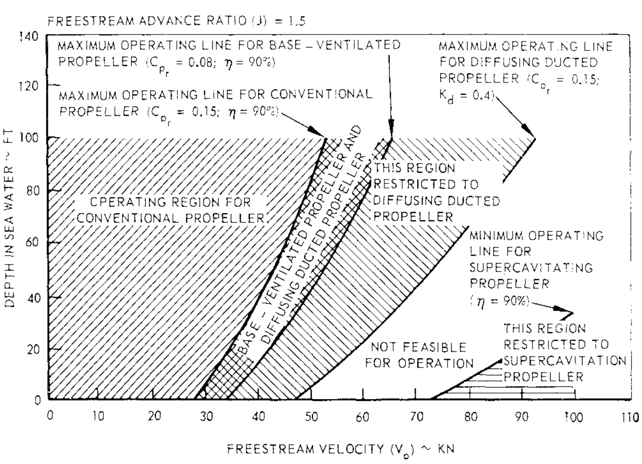

Fig. 12 Cavitation-limited operating regions for various types of propellers in terms of depth.

The lower limit of operation of the supercavitating propeller[3] results in an operating range that is considerably higher than that of the diffusing ducted propeller at advance ratios below approximately 1.5. There is a region between the two which is not feasible for operation. This region could be eliminated either by utilizing an accelerating duct around the supercavitating propeller to extend its operating range to lower speeds[7] or by increasing the diffusion coefficient for the diffusing, ducted, subcavitating propeller to extend its operating range to higher speeds. The effect of depth adds another dimension to the performance evaluation criteria for the various propellers (Fig. 12). These results were determined for a freestream advance ratio of 1.5.

A final consideration is presented as a basis for a relative evaluation of the various propellers. Many times, the absolute rotational speed is fixed by the power plant. Therefore, Fig. 13 presents characteristics of the various propellers to illustrate the effect on rotational speed. The limiting rotational speed falls rapidly for the subcavitating free propellers; however, the limiting rotational speed rises for the ducted propeller. The highest allowable rotational speeds result with the supercavitating propeller.

It is realized that the simplified theory upon which these results are based considers only idealized propellers and ducted propellers which have no drag. However, in the actual case, the propeller and the ducts have drag. The duct is an integral part of the propulsor system, and its interaction with the propeller has an important influence on performance. In order to represent the flow through a ducted propeller realistically, all the forces acting on the duct must be considered, and the mutual effects of the duct and propeller cannot be dissociated from each other. The analysis presented herein is intended only to illustrate the pertinent performance features of the various types of ducted systems and not to give detailed design values.

Conclusion

The foregoing discussion reviews the present state-of-the-art of marine propeller and ducted propeller propulsive devices on a fundamental basis. The general regions of performance are presented on a comparative basis, and the operating characteristics and potentials are pointed out of some types of ducted propellers that have not received serious attention heretofore. It is now the challenge of naval architects and marine system designers to fulfill better the missions of advanced marine craft and to demonstrate ultimately the same dynamic development within the marine propulsion field that has been occurring in space and aircraft propulsion.

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