ON SUPERCAVITATING PROPELLERS

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This little paper is an attempt to answer the question as to the efficiency of a supercavitating propeller, that is, of a propeller which is intentionally designed for full cavity flow with free streamlines from the leading and trailing edges of the sections. This question arose from time to time during my stay at the David Taylor Model Basin (DTMB) in relation with the propulsion of fast ships. One advantage of such propellers was immediately seen in reduction of erosion and there were also some indications that the noise characteristics might be improved with supercavitating propellers. An open question that remained was the magnitude of the efficiency of such a propeller. It is well known that the efficiency of a conventional propeller, i.e., of a propeller designed for operation near the limit of onset of cavitation, decreases for fully developed cavitation. This reduction becomes, in general, greater the smaller the cavitation number is. The question we were mainly confronted with was, therefore, whether or not the efficiency of a propeller which is intentionally designed for supercavitating conditions might be greater than that of a conventional propeller. It might be said beforehand that the prospect for a supercavitating propeller was unfavorable on account of those theoretical considerations which could be made before the papers by Tulin (1) and Wu (2) on the free streamline theory of fully cavitating hydrofoils were available. However, this situation became different when results from the papers just cited were applied to the propeller flow. These results have made possible a successful solution of this particular propeller problem under consideration.

In the following contribution I wish first to outline briefly the statements on the efficiency of a fully cavitating propeller which were possible prior to Tulin's and Wu's work and then give a few results when their findings are applied on fully cavitating sections to a propeller.

The older papers are connected with the names of Posdunine and Baein, Betz, and Walchner. Of these the first two are of Russian origin. These two papers are related since the problem is treated in both of them by means of methods of momentum theory. To characterize the application of this method to our problem we will restrict ourselves to the paper by Baein, which is the more complete one (3). In this paper a flow model of a cavitating propeller is assumed corresponding to Fig. 1.

The essential feature of this model is that the density of the fluid behind the screw ρ_1 is assumed smaller than the density ρ_0 in front of the screw. On account of the sudden change of the density at the disc not only the pressure but also the speed will change abruptly at the disc. The results which are obtained for this model when applying the laws of energy, continuity, and momentum are interesting. For instance, when such a flow is realized, a positive thrust might be generated under certain conditions with a negative pressure jump at the disc. For the efficiency η_i, i.e., the efficiency in nonviscous flow, it follows that

$$\eta_i = \frac{2}{\left(1 - \sqrt{\frac{\rho_0}{\rho_1}}\right) + \frac{1}{2}\frac{\rho_0}{\rho_1}\left(1 + \sqrt{\frac{\rho_0}{\rho_1}}\right)\left(1 + \sqrt{1 + \frac{2c_T}{1 + \sqrt{\rho_0/\rho_1}}}\right)}$$

where $c_T = T/(\rho/2)F_p v_o^2$ is the thrust loading coefficient. It should be noted that this expression changes over into that given by the Froude-Rankine theory if $\rho_0 = \rho_1$. Further it is seen that η_i decreases if ρ_0/ρ_1 increases and that $\eta_i \rightarrow 0$ if $\rho_0/\rho_1 \rightarrow \infty$.

The answer of this theory to our problems is incomplete for two reasons. It is firstly not possible to establish a relation between ρ_0/ρ_1 and the cavitation number σ. However, one might guess that the ratio ρ_0/ρ_1 becomes great if the cavitation number becomes small. One would then conclude that the efficiency becomes small if the cavitation number is small and goes probably to zero if σ goes to zero. There are, further, no indications that a supercavitating propeller as defined at the beginning behaves differently from a conventional propeller. However, such indications might not be expected from momentum theory because of the inherent assumptions on the geometry of the propeller common to all momentum theories.

It is therefore necessary to consider a supercavitating propeller from the point of view of airfoil theory which requires the polar curves of supercavitating sections to be known. An approximate theory for the lift and drag as functions of the cavitation number σ and the angle of attack α is developed in the aforementioned paper by Betz (4). He starts out from the free streamline flow of a flat plate according to Helmholtz and Kirchhoff. From this theory the lift coefficient is approximated by $c_L \sim \pi\alpha/2$, which is only 1/4 the lift in the usual flow without free streamlines. In a cavitating flow, the lift is greater, since the pressure of the fluid between the free streamlines is assumed in the theory by Helmholtz and Kirchhoff to equal the pressure of the undisturbed flow, p_o. When the free streamlines form the boundary of a cavity the pressure is smaller than p_o and equals the cavity pressure. From this follows an additional lift of order σ so that

$$c_L \sim \frac{\pi}{2}\alpha + \sigma .$$

Then the pressure drag coefficient for a flat plate is

$$(c_d)_p = c_L \alpha$$

and the total drag coefficient is

$$c_d = (c_d)_p + c_f$$

where c_f is the frictional resistance coefficient of the pressure side of the plate. Further, the drag/lift ratio ε is represented by

$$\varepsilon = c_d/c_L = \alpha + (c_f/c_L) .$$

With these relations for a fully cavitating plate, one is able to estimate the efficiency of a fully cavitating propeller. It follows from propeller theory that the efficiency is

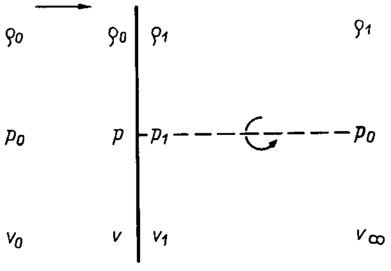

Fig. 1 - Flow model of a cavitating propeller

$$\eta = \eta_i \ \eta_\varepsilon$$

where η_i represents the losses which arise from the kinetic energy of the slipstream and η_ε those from the drag of the sections. The first factor is for optimum propellers a known function of number of blades, advance coefficient, and loading coefficient. The second factor may be written

$$\eta_\varepsilon \sim (1 - 2\bar{\varepsilon}\ \lambda_i) \Big/ \left(1 + \frac{2}{3}\ \frac{\bar{\varepsilon}}{\lambda_i}\right)$$

where $\bar{\varepsilon}$ is the effective mean of the drag/lift coefficients of the sections and $\lambda_i = \lambda/\eta_i$.

Comparison of the efficiency of two propellers, both designed for the same conditions, the one as a conventional propeller at the limit of onset of cavitation and the other one as a supercavitating propeller, amounts essentially to a comparison of η_ε. For the propeller of an MTB (motor torpedo boat) of 43.5 knots the conventional design gave the following results: $\eta_i = 0.84$, $\bar{\varepsilon} = 0.080$, $\lambda_i = 0.444$, $\eta_\varepsilon = 0.837$, and $\eta = 0.703$. Designing this propeller for equal conditions as a supercavitating propeller on a basis of Betz's theory, one obtains $\bar{\varepsilon} = 0.125$ and $\eta_\varepsilon = 0.745$. These latter figures depend somewhat on the choice of the lift coefficients and may be considered as an order of magnitude. This means then a loss of efficiency for the supercavitating design of about 12 percent. Since numerous other numerical results were in about the same range, one is led to conclude that a supercavitating propeller is, in general, connected with an appreciable loss of power input.

This conclusion, depends, of course, to a great deal on the accuracy of Betz's theory of fully cavitating hydrofoils. However, there was not much reason to consider this theory inadequate since tests by Walchner showed satisfactory agreement. Walchner conducted cavitation tests on series of both ogival (5) and modified ogival sections (6). The modified sections had a circular-arc suction surface and a flat pressure surface with rounded leading and trailing edges. With these modified sections the measurements have been recently repeated by Kermeen (7). His results for cavitating flow show poor agreement with those obtained by Walchner. There was in general more cavitation in Kermeen's tests at all cavitation numbers, so that the loss in lift in the latter tests is greater for the same cavitation number. The difference in forces amounts to a change in cavitation number of about 0.1. Because of these discrepancies between the experimental results, the approximations by Betz do not appear sufficient for a general application.

The same conclusion is reached by the work of Tulin and Wu. It is not the purpose of this paper to enter into these theories; only a few numerical results which are of interest for the propeller design will be given here. In Fig. 2 the pressure drag/lift coefficient is shown as a function of the lift coefficient for both the flat plate and a circular-arc plate as follow from Wu's theory (8). The figure is restricted to the limit $\sigma = 0$. For this limit the result for the flat plate passes over into that from Raleigh's

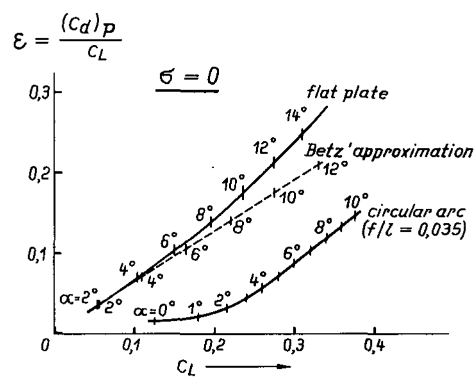

Fig. 2 - Pressure drag/lift coefficient as a function of the lift coefficient for both a flat plate and a circular-arc plate

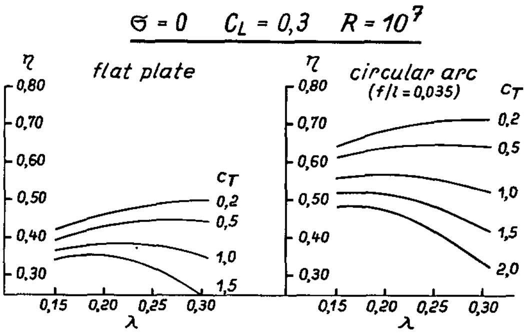

Fig. 3 - Effect of camber on propeller efficiency

theory of the oblique lamina. The figure shows clearly the considerable effect of the section camber on the drag/lift coefficient in fully cavitating flow. For a comparison, the result of Betz's approximations is included. It is seen that there is satisfactory agreement only for small angles of attack of a flat plate. This is to be expected, whereas the effect of camber does not follow from the approximation because of the inherent assumptions.

It is this latter effect, which has made it possible to successfully design a supercavitating propeller. Taking the same example of the MTB propeller as before and calculating the efficiency for equal values of both local lift coefficient and local cavitation number, one obtains for fully cavitating circular-arc plates a mean effective drag/lift ratio $\bar{\varepsilon}$ = 0.055 and correspondingly η_ε = 0.87. As compared to the conventional propeller the supercavitating propeller designed from circular arc plates shows in this particular case a gain in efficiency of about 4 percent.

The effect of the camber of fully cavitating sections on the propeller efficiency is shown in a more general way on Fig. 3 (9). On the left side of the diagram, the efficiency of 3-bladed propellers is represented for flat plate sections, on the right side for circular sections as function of the advance coefficient and the thrust loading coefficient. To simplify, the limiting case $\sigma = 0$ has been considered and also the lift coefficient has been assumed to equal 0.3. Similar diagrams have been calculated for different lift coefficients. Because of the first assumption, viz., $\sigma = 0$ the diagram gives the lower limit of the propeller efficiency which may be obtained under extreme conditions of cavitation. For cambered sections this limit is considerably greater than was formerly expected. As a consequence I think I am right in saying that the possibility is indicated for efficient propulsion of naval vessels at unlimited speed by means of a screw propeller.

Since these numerical results on the propeller efficiency depend on an experimental verification of the free streamline theories of fully cavitating sections, the papers by Parkin (10) and by Waid and Lindberg (11) are of great interest. In the first paper a flat plate and a circular-arc section are tested; in the second one a curved wedge-shaped section designed for full cavity operation by DTMB on the basis of Tulin's theory. In both of these investigations good agreement between the experimental and theoretical lift coefficients is found. The drag coefficients as measured in the latter paper, however, differ if $\sigma > 0.2$ and $\alpha > 5°$. Although the drag lift ratio and its trend are affected by the discrepancies, there is fairly satisfactory agreement for full cavity flow if the cavitation number is less than 0.2. This covers the range of cavitation numbers which is of interest for high-speed propellers. It should be mentioned that the discrepancies are not considered imperfections of the theoretical work but are attributed either to tunnel wall effect or to an incomplete evaluation of the theory.

The aforestated results for the efficiency of fully cavitating propellers, designed from proper low-drag sections, made it worth while to enter into the problem of developing such propellers. When this decision was made, the method of propeller design on a basis of circulation theory was well advanced at DTMB. This method has been applied to fully cavitating propellers. Without going into details I only wish to mention that circulation theory has reliably worked also in this case. Many difficulties arose from the necessity to satisfy both hydrodynamic and strength conditions. Since most of the work to overcome these difficulties has been done after I had left DTMB, I hope that Mr. Tachmindji and Mr. Morgan are going to report in their paper on the further progress on this problem.

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EDITOR'S NOTE:

The Symposium discussion of Dr. Lerb's paper was deferred until the next paper on the same subject had been read. The joint discussion appears after the next paper.

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