Blade Section Design of Marine Propellers with Minimum Cavitation Induced Pressure Fluctuations

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Abstract. To minimize cavitation induced pressure fluctuations by marine propellers with minimum efficiency loss, the paper presents a new design and optimization method using a blade section design method. The sheet cavity volume variation on a two-dimensional blade section in quasi-steady condition has been simplified to a relation with only a limited number of non-dimensional parameters. This results in a fast prediction method of the cavity volume of a blade section passing a wake peak, using a pre-calculated database. This makes optimization feasible. The optimization method was applied to the propeller of a container ship. Extensive tests in a towing tank and a cavitation channel validated the reduction of pressure fluctuations: 33% reduction in the first blade frequency amplitude and 18% reduction in the second blade frequency amplitude, with the same open water efficiency.

1. Introduction
Traditionally the objective of propeller design was to obtain maximum efficiency with a more or less shock-free pressure distribution on the blade sections in the tangentially averaged wake distribution. Nowadays we are able to calculate the pressure distribution on propeller blades in unsteady condition. However it has to be related to effects that are relevant, such as cavitation inception, induced pressure fluctuations or erosion. These phenomena are essentially unsteady and thus the wake has to be taken into account. And these also require that the cavitation can be calculated.

In case of cavitation inception calculation of the cavity can be avoided and an objective of the non-cavitating pressure distribution can be formulated: the minimum pressure on the blades during one revolution remains above the vapor pressure. This requires that all blade sections operate within the cavitation bucket of the section. This is essentially a two-dimensional method and the section designs have to be modified for three dimensional effects. Such a design method using the Eppler method was already developed by Kuiper and Jessup in 1993 [1]. This method was recently updated and automated by Zeng [2].

However, in most operating conditions of commercial ships it is not possible to avoid cavitation. One detrimental effect of cavitation is induced pressure fluctuations, resulting in hull vibrations. Then the design objective becomes: minimum cavitation induced pressure fluctuations. Efforts have been made to relate the cavitation induced pressures directly with properties of the pressure distribution on the blades. Johnsson [3] used a new type of section thickness distribution with two ellipses at the

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leading edge to obtain a favorable pressure distribution from cavitation point of view. Yamaguchi et al [4] tried to relate the type of pressure distribution in steady condition with the cavitation induced pressure fluctuations. Wang et al [5] showed that a shift of the locations of maximum camber and thickness towards the trailing edge decreased calculated induced pressure fluctuations, but this improvement was not confirmed by experiments. Dang [6] used much wider cavitation buckets than that of a NACA section to reduce the total cavity volume. So the efforts to replace the criterion of minimum pressure fluctuations by pressure distributions have not been successful. A pressure source is proportional to acceleration of the cavity volume, and the cavity acceleration is very sensitive to the (unsteady) pressure distribution in the wake. This relation is strongly non-linear, so a prediction independent of the wake distribution and without cavitation might not be possible.

The design method in this paper includes the cavitation behavior in a wake. The objective of minimum induced pressure fluctuations was obtained using an optimization procedure. This approach is a continuation of the optimization procedure of the authors for maximum inception speed, so some elements are re-used.

2. Cavity volume prediction
The prediction of the cavity volume on a propeller blade is simplified by considering two dimensional cavitation on each blade section. The propeller blade sections are transformed in a linearized way by replacing the geometrical camber line with the effective camberline from the chordwise loading distribution [1]. When a section passes a wake peak the cavity on the section will experience inception, development and disappearance with the rotating propeller blade position $\theta$. The cavity area: $V_c$ on a section can be calculated using CFD as proposed by Singhal [7]. But to carry out such a calculation on each section in a range of blade positions requires considerable computing time and this makes optimization impossible. Therefore an approximate method was developed.

The cavity volume on such blade section is directly related with the fully wetted pressure distribution at the leading part of the suction side which is now related with parameters from the Eppler method. Figure 1 shows typical pressure distributions from the Eppler method at two angles of attack. There is a constant pressure distribution $-C_{p1}$ in the middle segment at angle of attack $\alpha_1$ and another constant pressure distribution $-C_{p2}$ on the first segment at another angle of attack $\alpha_2$. The difference $\Delta C_p = -C_{p2} - (-C_{p1})$ and the location $\chi$ between the two segments are the dominant parameters controlling this change in pressure distribution.

To make optimization possible a range of sections were generated using the Eppler parameters and varying the parameters $\chi$ and $\Delta C_p$. For each case, the cavity area $V_c$ was calculated using Singhal full cavitation model [7] with a 10% volume fraction of vapor phase as cavity boundary. First the cavitation number $\sigma$ was varied with fixed angle of attack $\alpha$ and then $\alpha$ was varied with fixed $\sigma$. When $V_c/(\alpha - \alpha_i)$ is plotted versus the non-dimensional condition parameter $\sigma^* = (\sigma + C_{p1})/(\alpha - \alpha_i)$ a unique relationship between $V_c$ and ($\sigma$, $\alpha$) is found, as shown in figure 2. Here $\alpha_i(\sigma)$ is the inception angle of attack at $\sigma$, a parameter originally proposed by Le, Franc & Michel [8]. The unique relationship for each case can be fitted by a power function also shown in the figure.
Blade section optimization and validation

The induced pressure fluctuations are periodical with blade passages and section optimization is therefore done in the frequency domain. The cavitation induced pressure fluctuations amplitude of a certain blade frequency \( [p_r] \) (m is blade frequency, Z is blade number) thus can be derived as,

\[
[p_r]_{z=m} \equiv \frac{\pi \rho n^2}{r_c} \left[ \frac{\partial^2 V}{\partial \theta^2} \right]_{z=1} = \frac{\pi \rho n^2}{r_c} Z^2 m^2 |J_{z=1}|, \quad \text{when} \quad V_e = V_{c1} + \sum_{n=m} (a_n \cos m\theta + b_n \sin m\theta)
\]

where water density \( \rho \), propeller rotation speed \( n \), and the distance of the field point \( r_c \). The focus in this paper is on the first three blade frequency harmonics, the objectives can be formulated as \( \min [C_1(X), C_2(X), C_3(X)] \), where \( X \) is combination of design parameters in Eppler method, \( \Omega \) is a design space of these parameters, and \( c_1 = |J_{z=1}|, c_2 = 4|J_{z=2}|, c_3 = 9|J_{z=3}| \) by neglecting the influence of the change of \( r_c \). The optimization procedure follows a similar path as used in the section optimization for maximum inception speed [2].

The method was applied for the propeller of a container ship, where only one section was optimized. Figure 3 shows the objectives of an optimized section at \( r/R=0.8 \) in behind condition. It can be seen that the amplitudes of the first and second blade frequency of induced pressure fluctuations are significantly reduced compared with the conventional NACA section; the third one increases, however both of them are small. Figure 4 shows that the optimized section has much smaller acceleration of the cavity area with the blade position \( \theta \), which is responsible for the much lower blade frequency amplitudes.

With the optimized two-dimensional section, a propeller blade has been redesigned in a similar
way as was done for the optimization of the maximum inception speed[2]. The open water performance test and the cavitation test in behind condition for both the optimized propeller and the NACA propeller were carried out in the towing tank and in the large cavitation channel of CSSSRC in Wuxi, China. The test results show that the loads and efficiency are very close. The first blade frequency amplitude of the pressure fluctuations of the optimized propeller has a reduction of 33%, and 18% for the second one, and the third one is close to each other. Figure 5 shows the cavity extent of the optimized propeller model is much smaller which indicates that the optimization also significantly reduced the cavity extent (the volume can only be calculated).

![Figure 3. The optimized objectives](image)

![Figure 4. The variation of cavity area acceleration](image)

![Figure 5. Comparison of cavity extent: (a)the NACA propeller model, (b) the optimized propeller model (at the 12 o’clock position in behind condition)](image)

### 4. Conclusion

A design technique using blade sections optimized for minimizing cavitation induced pressure fluctuations is shown to be effective. The developed method has the following main features: 1) A non-dimensional parameter \( \sigma' = (\sigma + C_{\rho l})/(\alpha - \alpha_c) \) is used to represent the working condition of two-dimensional blade sections beyond inception. 2) The calculation of two-dimensional cavity area on a blade section during a revolution was made so efficient that it could be used in an optimization program. This was done by making a database of pre-calculated cases. 3) It was shown that the amplitude of the blade frequencies of the pressure fluctuations was proportional to the amplitude of the cavity volume variations. This omitted the calculation of higher derivatives of the cavity volume and made the calculation stable. It also reduced the calculation time.

There are many simplifications in the method. Experimental and numerical validation of the optimized cavity volume variation is recommendable. After engineering practice, the method proposed can be further developed to be a design tool to improve propeller with favorable ship vibration.

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