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Optimization and experiment of composite marine propellers

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ABSTRACT

This paper demonstrates the experimental result of changeable pitch propellers in composite material. The use of this composite material is to apply its characteristic of bend-twist coupling; this characteristic is applied to better performance design requirements of the propeller. Two stacking sequences are considered: the first one is a quasi isotropic sequence, while the second one is an optimum sequence obtained using a genetic algorithm. Experiments are designed considering two original propellers manufactured by the first and the second stacking sequence, respectively, and a pre-deformed propeller with the second sequence. Experimental results correspond to the same trend as the calculations and confirm the method of optimization.

1. Introduction

Fiber-reinforced plastic (FRP) is extensively applied in various structures, because of its light weight, high strength and corrosion resistance. Bend-twist coupling effect is another unique characteristics of composite material. Structures can be stiffened or deformed in a certain direction by arranging the orientation of the fibers.

Most marine propellers are made of metal material such as bronze or steel. The advantages of replacing metal with an FRP composite are that the latter is lighter and corrosion-resistant. Another important advantage is that the deformation of the composite propeller can be controlled to improve its performance. Fig. 1 schematically depicts inflow angles at different ship speed. Propellers always rotate at a constant velocity that maximizes the efficiency of the engine. When the ship sails at the designed speed, the inflow angle is close to its pitch angle. When the ship sails at a lower speed, the inflow angle is smaller. Hence, the pressure on the propeller increases as the ship speed decreases. The propulsion efficiency is also low when the inflow angle is far from the pitch angle. If the pitch angle can be reduced when the inflow angle is low, then the efficiency of the propeller can be improved.

Bend-twist coupling is a unique characteristic of FRP composite: structures twist when they are bended. This effect appears when the laminating sequence is unbalanced, meaning that the number of positive angle plies is not equal to the number of negative angle plies [1]. This effect has been exploited in aerodynamics to solve the problems of fluttering and divergence ([2,3] for example). It has also been applied in forward swept wings [4] and propellers ([5,6]) to control deformation. The same effect can be employed in the marine propeller. The water pressure results in bending and twisting, which, combined with the arranged ply angles, changes the pitch of the propeller and thus changes its performance.

Our previous study employed the bend-twist effect and 'pre-deformed' design to produce a changeable-pitch-propeller [7]. The optimum stacking sequence has been obtained using a genetic algorithm [8,9]. The deformation and performance of the propeller are calculated iteratively. The calculation is performed using the finite element software ABAQUS and the propeller calculation program PSF2 [10,11]. The thrust, torque, efficiency and pressure distribution are determined using the program PSF2 (developed by the Massachusetts Institute of Technology), which applied numerical lifting-surface theory for marine propellers as a practical tool in the solution of both steady and unsteady flow problems. When the pressure that acts on the blade is obtained, it is then input to the finite element software ABAQUS to calculate the deformation of the blade. Then, the deformed blade geometry is input to the PSF2 again. After several iterations, a converged pressure and deformation are obtained [7]. This paper introduces the optimization method and performs experiments to verify the optimization design of the composite propeller.

2. Optimum propeller

2.1. Definition of optimum propeller

The machinery that propels a ship must be selected to yield an optimal solution for deadweight, storage and several other factors.

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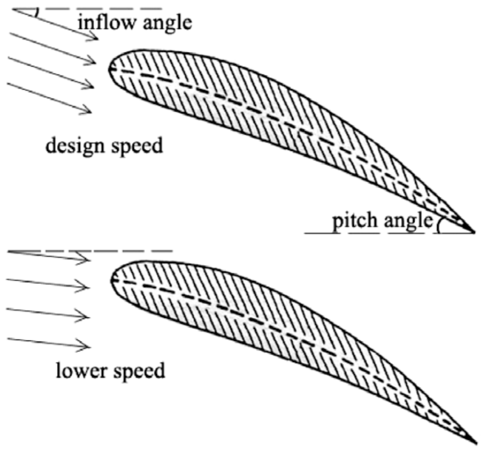

Fig. 1. Inflow angle at various ship speeds.

The machinery is selected such that the necessary propulsion power is produced as efficiently as possible. Any change in one of the part systems may seriously reduces the efficiency of the propulsion systems. Therefore, the characteristic curves of the optimum propeller must match the operating area of the main engine.

The diesel engine has a general characteristic of the type presented in Fig. 2, on which a propeller demand curve is superimposed, and in this instance passes through the maximum continuous rating (MCR) of the engine (the point of 100% power and 100% revolution in Fig. 2). If the pitch of the propeller is selected incorrectly, then the propeller will be either over-pitched (curve A) or under-pitched (curve B). In either case, the maximum power of the engine is not reached, because, in the case of over-pitching, the maximum power attainable will be point *X* at a reduced RPM, which result is governed by the engine torque limit. In the alternative under-pitching case, the maximum power that can be reached is point *Y* at 100% RPM, since the engine speed limit is the governing factor. In practice, the derated engine power is used as the basis for propeller design, to prevent excessive maintenance costs in keeping the engine at peak performance throughout its life. Therefore, the propeller is generally based on a normal continuous rating (NCR) of between 85% and 90% of the MCR condition; Fig. 2 shows a typical propeller design point.

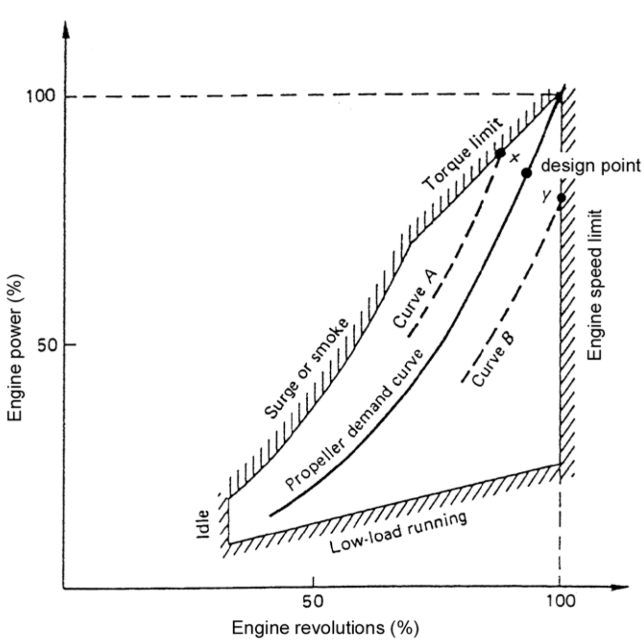

Fig. 2. Engine characteristic curve.

Propellers are designed to operate at a constant ratio of axial to rotational velocity, at which point the torque, thrust and efficiency are optimal for the propulsion system. Hence, the first limitation on the design of a composite propeller is to maintain the originally designed torque, thrust and efficiency at the designed axial velocity.

When the propeller operates at a low axial velocity, it is in an over-pitched condition, and the torque exceeds the tolerance of the engine. Accordingly, the second rule that governs the design of an optimum composite propeller is that the pitch must decrease as much as possible as the inflow angle is reduced, to keep the torque within the narrowest possible range.

The characteristics of the propeller are generally presented using the following coefficients:

$$\begin{aligned} &\text{advance coefficient} \quad J = \frac{V_a}{nD} \\ &\text{torque coefficient} \quad K_Q = \frac{Q}{\rho n^2 D^5} \\ &\text{thrust coefficient} \quad K_T = \frac{T}{\rho n^2 D^4} \\ &\text{efficiency} \quad \eta = \frac{TV_a}{2\pi nQ} = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \end{aligned} \tag{1}$$

where D = diameter of the propeller; V_a = axial velocity; n = rotational velocity (rps); ρ = fluid density; T = thrust and Q = torque.

Herein, the propeller DTNSRDC 4498 [12] is chosen as the design target; Table 1 presents its geometric parameters. The design advance coefficient is $J = 0.889$ and the corresponding torque coefficient is $K_Q = 0.05204$. These values represent the design point at which a composite propeller should optimally function. The other point considered is $J = 0.6$, with a corresponding K_Q of 0.07311. The K_Q of the optimally functioning propeller should be as close as possible to the designed value of 0.05204.

Therefore, the performance of the optimum propeller is defined as follows:

(1) K_Q at $J = 0.889$ must be equal to the designed K_Q (0.05204).
(2) K_Q at $J = 0.6$ must be as close as possible to the designed K_Q (0.05204).

The goal is to design a propeller with the same pitch as that originally designed at $J = 0.889$, and with the smallest pitch at

Table 1
Geometric parameters of propeller DTNSRDC 4498 [11]

r/R	Pitch P/D	Rake Rake/D	Skew Degree	Chord C/D	Camber Camber/Ci	Thickness Thickness/D
0.2	1.566	0	0.	0.174	0.0402	0.0434
0.25	1.539	0	4.647	0.202	0.0408	0.0396
0.3	1.512	0	9.293	0.229	0.0407	0.0358
0.4	1.459	0	18.816	0.275	0.0385	0.0294
0.5	1.386	0	27.991	0.312	0.0342	0.0240
0.6	1.296	0	36.770	0.337	0.0281	0.0191
0.7	1.198	0	45.453	0.347	0.0230	0.0146
0.8	1.096	0	54.245	0.334	0.0189	0.0105
0.9	0.996	0	63.102	0.280	0.0159	0.0067
0.95	0.945	0	67.531	0.210	0.0168	0.0048
1.0	0.895	0	72.000	0.000	0.0000	0.0029

Number of blades: 5; diameter: 0.305 m; hub-diameter ratio: 0.2; expanded area ratio: 0.725; section meanline: NACA $a = 0.8$ and section thickness distribution: NACA 66.