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Utilizing fluid–structure interactions to improve energy efficiency of composite marine propellers in spatially varying wake

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ABSTRACT

Flexible composite marine propellers, made of fiber-reinforced plastic (FRP) composites, have a number of advantages over conventional rigid metallic propellers. In particular, composite propellers have great potential for performance improvement. In the current work, fluid–structure interaction effects are utilized to improve the performance of composite marine propellers under a wide range of operating conditions. Two important mechanisms, namely, the bending–twisting coupling effects of anisotropic composites and load-dependent self-adaptation behavior of composite blades are the primary sources for performance improvement of composite marine propellers. Systematically designed self-twisting composite propellers are evaluated under both steady and unsteady operating conditions. Response and performance curves are compared between the rigid and self-twisting propellers. Governing mechanisms and fluid–structure interaction effects are identified and analyzed. It is shown that the self-twisting propeller leads to significant improvement in energy efficiency over its rigid counterpart.

1. Introduction

1.1. Aircraft vs marine propellers

Theoretically, aircraft and marine propellers operate in a similar way, producing thrust/lift by rotating blades in a manner analogous to rotating a screw through a solid [1]. However, there are many more limits on marine propellers. In general, aircraft operate in relatively uniform flow and through a nearly inviscid, but compressible, medium when compared with marine propellers. Geometric constraints such as the proximity of the hull to the propeller and the inclined shaft, combined with environmental variables such as unsteady sea conditions or maneuvering of the ship, can create highly non-uniform flow fields through water. In addition to being much less viscous, air is also approximately 0.1–0.15% as dense as water. Hence, marine propellers are subject to much higher hydrodynamic forcing and resistance than aircraft propellers under the same RPM (revolution per minute). Thus, a propeller operating at the same speed will experience much higher stresses in water than in air, making it more difficult to move through water.

Another complication with marine propellers is fluid cavitation. Blade surface cavitation can be expected above 25 knots and a propeller can experience severe blade cavitation at 32–35 knots [2,3], which can lead to cavitation erosion and performance decay as a result of thrust breakdown. Further, a spatially varying wake creates a cyclic loading, in turn creating a cyclic generation and collapse of cavitation bubbles, which can erode the walls of the propeller, blades, hub, and rudder. For high-speed operations, cavitation damage can be offset by utilizing a fully submerged supercavitating or superventilating propeller [4,5] or partially submerged surface piercing propellers [6–10]. These are highly optimized propellers designed to operate at high-speeds by intentionally promoting long, thin, stable supercavities that collapse downstream of the blade trailing edge to reduce the fluid drag. These design requirements, however, lead to more rapid degradation at lower speeds because of increased drag caused by the typical thick blade trailing edge necessary to balance the sharp blade leading edge to satisfy the strength criteria [11]. Marine vessels are often required to operate at speeds below 25 knots for substantial periods of time. Thus, a multispeed design is necessary to maintain propeller efficiency over a range of operation, which is difficult to achieve using rigid, metallic propellers.

1.2. Metallic vs composite propellers

As advancements have been made in propeller design, the marine industry has shifted from cast iron to more corrosion-resistant

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metals to optimized alloys. Currently, Nickel–Aluminum–Bronze (NAB) and Manganese–Aluminum–Bronze (MAB) are the most commonly used metals for marine propellers due to their superior corrosion-resistance, high yield strength, reliability, and affordability. The marine industry has been studying metallic propellers for many years and their design and production has been optimized and well-referenced. For analysis and design, metallic propellers are more practical (compared with flexible composite propellers), because of their rigidity, allowing for separate computations of hydrodynamic pressures and structural response. However, metallic propellers have their limitations. It is expensive to machine metals into highly complex shapes. In addition, metallic propellers are more susceptible of corrosion, cavitation damage, and fatigue cracking. Moreover, galvanic corrosion of the aft-end hull can occur because of the cathodic properties of NAB [12]. In marine environments, perhaps most important is that metallic propellers, because of their characteristic rigidity, tend to exhibit decreased efficiencies under off-design conditions.

In recent years, there has been an increased interest in the use of composite materials in a wide variety of marine applications to improve the performance of marine structures under a range of operating conditions. The inherent material and mechanical properties of composite structures, including but not limited to strength-to-weight and stiffness-to-weight ratios, anisotropy, and life-cycle costs, makes the use of composites for marine propellers a viable alternative to the metallic propellers that are currently prevalent. However, until recently, there existed very little simulation and design tools for composite propellers due to the lack of reliable manufacturing methods and lack of a large, systematic performance database.

One of the first numerical studies of 3-D composite marine propellers was presented in the work of [13], finding that, for a composite with low material modulus, elastic tip deformations and in-plane and bending stresses were higher than in a traditional NAB propeller. Effects of stacking sequence on the hydroelastic behavior of composite propeller blades were assessed by [14]. The possibility of maximizing the efficiency of composite propellers was numerically investigated [15,16] by using a genetic algorithm to optimize the stacking sequence of fiber composites, with mixed results. An experimental study was presented by [17] for two composite elliptic hydrofoils made of carbon/epoxy skins with a syntactic foam core. Results showed that the tip deflections helped to delay cavitation inception due to reduced tip loading. However, the overall lift and drag coefficients remained unchanged. More recently, the design, fabrication, and testing of 24-inch model-scale pitch adapting composite marine propellers were presented in the work of [18]. The results confirmed that a properly designed flexible composite propeller can be more efficient, and cavitation inception in wake inflow can be significantly delayed compared to its rigid counterpart under highly loaded off-design conditions.

Composites can also provide better fatigue resistance, improve damping properties, and reduce life-cycle cost. The weight savings can also allow for the design of thicker and more flexible blades that increase cavitation inception speeds. Most importantly, composites can be hydroelastically tailored to optimize the energy efficiency of the propeller. A composite propeller can be designed to passively adapt to the changing environment (flow) by utilizing the load-dependent deformation coupling inherent in its anisotropic properties.

In particular, the bending–twisting coupling effect of anisotropic composites can be used to passively tailor the blade rake, skew, and pitch distributions of the propeller and improve performance. While traditional metallic propellers are designed to be rigid under working conditions, composite propellers are designed to bend and twist under hydrodynamic loads [19–21]. By properly designing the ply stacking sequence and fiber orientations of the laminate, the flexibility and adaptability of the composite propeller can be exploited under the variable flow field. This increased flexibility and twisting allows the blades to adjust their pitch in response to the changing hydrodynamic forces of a spatially varying wake, creating an optimal design range instead of a fixed-point optimal design and increasing the efficiency of the propeller over a range of conditions.

Another important issue for flexible composite propellers is their dynamic responses. As the flow field varies, the effective wake varies across the propeller blades as well, constantly changing the effective angle of attack and the resulting stress concentrations, thus reducing the efficiency of highly optimized rigid blades. The flexibility provided by composite blades creates a lighter, less stiff blade than its metallic counterpart. In turn, this tends to lower the natural frequency, making them more susceptible to resonance. Thus it is important to investigate the dynamic behaviors of self-twisting composite propellers subject to spatially varying wake inflow. By virtue of dynamic analysis, a composite propeller can be properly designed such that its excitation frequencies are much lower than the natural frequency of the propeller in water while also maintaining stability in a range of hydrodynamic conditions.

1.3. Objectives

The objective of this work is to numerically demonstrate that fluid–structure interaction can be used to improve the overall energy efficiency of marine propellers in a spatially varying wake in both subcavitating (fully wetted) and cavitating conditions.

2. Design strategy and analysis tools

A rigid propeller is designed to operate at its maximum efficiency under a specific flow condition. Because twisting is negligible for a rigid propeller, the geometry is, for practical purposes, fixed, and the propeller is optimized for a particular inflow. Hence, rigid propeller designs are typically expressed as functions of the advance coefficient $J = V/nD = V/2nR$. V is the mean axial inflow velocity, n is the propeller rotational frequency, $D = 2R$ and R are the propeller diameter and radius, respectively. The performance of a self-twisting propeller, on the other hand, cannot simply be expressed as a function of J due to differences in dimensional load, which will induce different blade deformations, and hence change the hydrodynamic performance. By design, the geometry of a self-twisting propeller, notably the pitch angle $\phi(r)$ at radius r, changes as a function of V and n due to hydrodynamic load-induced blade deformations. As shown in Fig. 1, the effective inflow angle for the blade section at radius r, defined $\beta(r) = tan^{-1}(V/2\pi nr) = tan^{-1}(JR/\pi r)$, is also a function of V and n. The resulting angle of attack is then $\alpha(r) = \phi(r) - \beta(r)$. Hence, there exists a single optimal angle of attack $\alpha_{opt}(r)$ for a specific V and n at each radius r. As a

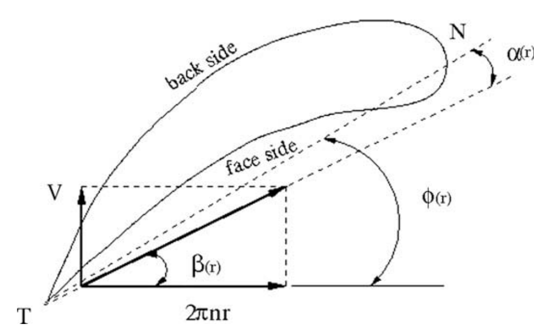

Fig. 1. Schematic drawing of flow around a blade section at radius r.