UTILIZATION OF DEFORMATION COUPLING IN SELF-TWISTING COMPOSITE PROPELLERS

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Abstract

Composites can be used as alternative materials to improve propeller performance over a wide range of operating conditions. The main source of performance enhancement is deformation coupling due to the anisotropic characteristics of composites. An analytical model is proposed based on the classical lamination theory to investigate deformation coupling effects on the hydroelastic behavior of composite marine propellers. The analytical model can be used to study the influence of material properties and fiber orientations on the parasitic twisting deformation. A strong correlation is identified between the parasitic twisting deformation, the pitch alteration, and performance enhancement. A design strategy is proposed for the proper design of composite propellers, which guarantees that the performance of the flexible composite propeller to be the same as its rigid counterpart under the design condition, and to be better than its rigid counterpart in off-design conditions. An integrated BEM-FEM solver is used to calculate the deformation and efficiencies of realistic composite propellers. A sample design is given to demonstrate the feasibility of performance enhancement from self-twisting composite propellers.

1 Introduction

Nickel-aluminum-bronze has been the dominating material to construct rigid marine propellers due to its excellent stiffness, yield strength, corrosion resistance, and anti-biofouling characteristics. However, the efficiencies of rigid propellers tend to degrade under off-design conditions and under asymmetric flows. Composites can be used as alternative materials to improve propeller performance over a wide range of operating conditions. Composite propellers are designed to not only bend, but also twist, when subject to hydrodynamic loading, and thus achieve an instantaneous change in twist (pitch angle). This is the so-called self-twisting composite propellers.

For a review of previous experimental and numerical studies involving composite propellers, readers are referred to a related paper [14] in this conference. Although numerical models seem powerful in many aspects, they are too expensive in the preliminary design phase. To obtain insights to aid the conceptual design, a reduced analytical model is highly desired. In the field of aero-elasticity, much analytical work focused on development of one-dimensional beam or box beam models [2,6,9,10]. However, the authors are not aware of analytical models for composite marine propellers in the open literature.

To facilitate the understanding and utilization of deformation coupling behavior of composite marine propellers, an analytical model is formulated in the current work based on plate theories. The analytical model can be used to study the influence of material properties and fiber orientations on the parasitic twisting deformation. A series of numerical simulations is carried out for typical composite propellers to reveal the relationship between the parasitic twisting deformation, the pitch alteration, and the performance enhancement. A design strategy is proposed for the proper design of self-twisting propellers, which guarantees that the performance of the flexible composite propeller to be the same as its rigid counterpart under the design condition, and to be better than its rigid counterpart in off-design conditions. A sample design is given to demonstrate the feasibility of performance enhancement from self-twisting composite propellers.

2 Theoretical Models

2.1 Analytical Model

In general, marine propeller blades can be treated as cantilevered beams or plates. Analytical solutions for elastic behaviors of generic clamped-free structures under general loading conditions are not tractable. However, a closed-form solution can be obtained for a uniform, generally orthotropic, homogeneous, plate-like structure subject to simple loading, e.g., pure bending or twisting. Physical prototype of a cantilevered structure subject to pure bending is shown in Fig. 1. The cantilevered plate has a length a, width b, and thickness t. At the free end, the plate is subject to a bending moment M^b. The middle surface of the plate lies in the x-y plane, and the normal is in the z direction. The reason to examine this particular configuration is based on two considerations. The first consideration is that the behavior of clamped-free structures subject to pure bending is close to those subject to lateral bending under hydrodynamic pressure. The second is that for composite marine propellers, the bending-twisting coupling effects are of utmost importance, since the twisting (pitch) angle is directly related to the hydrodynamic performance of the propeller.

Based on the classical lamination theory (CLT) [5,8], a closed-form solution can be obtained for the twisting rate as: $\kappa_{xy}^b = -M^b d_{16}/2$, where M^b is the applied external moment, d_{16} is the bending-twisting coupling compliance, which is a function of composite material properties and lamina orientations. Detailed formulations are not shown here due to space limitations.

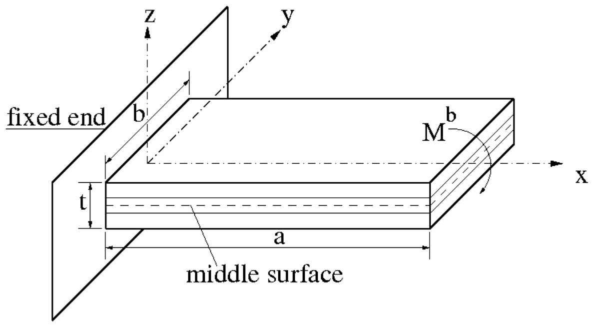

Fig. 1. Physical prototype of a cantilevered structure subject to pure bending

2.2 Numerical Model

A coupled boundary element method (*BEM*-*finite element method (FEM)* numerical solver is adopted to model the fluid-structure interaction (*FSI)* behavior of flexible composite marine propellers. The *BEM* is applied to determine the unsteady fluid cavitation patterns and pressure distributions, and the *FEM* is applied to determine the time-dependent stress distributions and deformation characteristics. User-defined subroutines for *ABAQUS/Standard* [1] are developed to couple the *BEM* and *FEM* to account for *FSI* effects. The details of the numerical model are presented as a separate paper in [14].

In short, for steady flow, the solution procedure involves first computing the hydrodynamic pressure due to rigid blade rotation via the *BEM*. The calculated hydrodynamic pressure is then applied as surface traction for the *FEM* solid model to obtain the deformed geometry. Since the hydrodynamic pressure is geometry dependent, iterations are implemented between *BEM* and *FEM* solvers to obtain the converged solution. For unsteady flows, the hydrodynamic added mass and damping matrices associated with elastic blade acceleration and velocity, respectively, are computed using the *BEM* in addition to the hydrodynamic pressure due to rigid blade rotation. The added mass and hydrodynamic damping matrices are superimposed onto the structural mass and damping matrices via user-defined hydroelastic elements in *ABAQUS/Standard*. The centrifugal and Coriolis body forces are applied as element-based loads. Iterations are also implemented between the *BEM* and *FEM* solvers to account for the time-dependent blade deformations.

2.3 Design Strategy

For rigid propellers, geometrical characteristics are the core of a specific design. However, for flexible composite propellers, material properties and orientations become important in addition to geometries. Simultaneous determination of the material and geometry is not feasible at this time. This is because composite propeller blades will bend and twist when subject to hydrodynamic loading. That is to say, the geometrical and material designs of composite propellers are fully coupled. An iterative process is required to satisfy all the design criteria.

In this work, a design strategy is proposed. The design objectives include: (I) the flexible propeller performs the same as its rigid counterpart under the design condition; (II) the flexible propeller performs better than its rigid counterpart in off-design conditions and in asymmetric flows. The flow chart of the design strategy is shown in Fig. 2. In the flow chart, the mean-load geometry *G0* refers to the optimal geometry of the rigid propeller under the design condition, and the no-load geometry *GN* refers to the un-deformed (unloaded) geometry of the flexible composite propeller. It is required that the deformed geometry of the flexible composite propeller matches with the mean load (optimal rigid blade) geometry *G0* under the design flow condition, as proposed in [4]. An iterative scheme is implemented to calculate the no-load geometry *GN* of the flexible composite propeller as shown in Fig. 2. In other words, the design is formulated as an inverse problem where the deformed geometry of the flexible composite propeller is known, but the initial un-deformed geometry is unknown. This inverse problem is solved in an iterative manner. A relaxation factor λ=1.4 is used to accelerate the iteration convergence. Notice that the material and geometrical design of the flexible composite propeller is fully coupled. For a particular selection of materials (including material properties and ply orientations), a corresponding un-deformed geometry (*GN*) needs to be obtained.

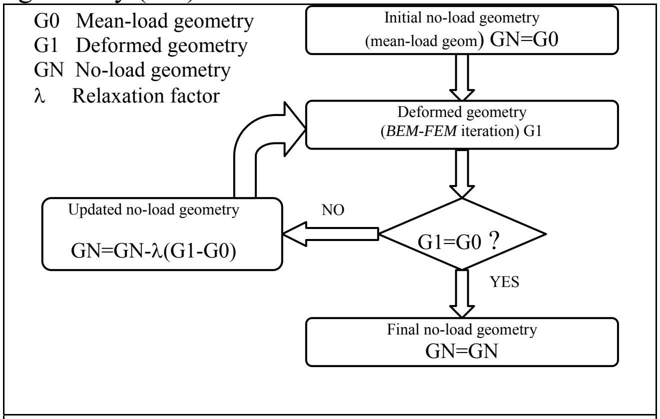

Fig. 2. Flow chart of the design strategy

3 Results

3.1 Deformation Coupling

Self-twisting composite propellers are designed to not only bend, but also to twist under hydrodynamic loading. The twisting deformation is mainly due to deformation coupling intrinsic to the anisotropic composite blade structure. The twisting mode of propeller deformation is identified as the main source of performance enhancement. Results from the analytical and numerical models are used to illustrate this point.

3.1.1 Analytical Results

The two primary factors that influence the deformation coupling effects are the material properties and lamination schemes. To study the influence of the material properties, a set of typical composite materials tabulated in [3] are used. To investigate the influence of lamination schemes, special symmetric angle-ply laminates are considered [5]. In the thickness direction, the blades are assumed to have odd number of layers of the same material with the same thickness, and the principle material direction is alternatively oriented at θ and $-\theta$ to the laminate x axis. Single-layer (θ) and triple-layer ($\theta/-\theta/\theta$) configurations are typical examples of this type of laminates. Orientations of special symmetric angle-ply laminates are controlled by a single parameter θ. Hence it is easy to study the influence of layer orientations and the number of layers.

To study the influence of material properties, the twisting rate κ_{xy}^{b} due to pure bending corresponding to typical composite materials are plotted in Fig. 3. Among them, Kevlar 49/Epoxy yields the highest peak value of the twisting rate due to its low in-plane shear modulus. In the preliminary design of flexible composite marine propellers, materials with low in-plane shear modulus should be given favorable considerations as long as they satisfy the required strength and vibration characteristic requirements, as well as provide the proper thermal properties, corrosion resistance, and impact strength.

To study the influence of number of layers, Carbon/PEEK AS4/APC2 is used here for illustration purpose. It has the following material properties: E_1=138.9 GPa, E_2=10.2 GPa, G_{12}=5.7 GPa, ν_{12}=0.3. The influences of ply orientations θ on the twisting rate κ_{xy}^{b} for special symmetric angle-ply laminates are plotted in Fig. 4. It can be found that the twisting rate peaks at approximately $\pm 45^{\circ}$ and $\pm 30^{\circ}$, respectively, for the single-layer (θ) and triple-layer ($\theta/-\theta/\theta$) configurations. Notice that positive orientation corresponds to negative twist in the analytical model and to de-pitch in realistic propellers. Hence positive orientations (counter-clockwise with respect to the local span-wise direction) should be used to achieve de-pitch behavior. The peak value for the single-layer (θ) configuration is higher than that of the triple-layer ($\theta/-\theta/\theta$) configuration. Hence, the number of layers not only influences the particular orientations corresponding to the peak twisting rate, but also the magnitude of peak values. In Fig. 4, odd layer configurations are shown up to nine layers. The magnitude of twisting rate decreased with increasing number of layers is clearly evidenced. The reason behind this is that with the increasing of number of layers, the degree of anisotropy decreases, and hence the coupling effect also decreases. One can expect that the bending-twisting coupling effects essentially die off for infinite number of layers for the alternating θ and $-\theta$ layering configuration.

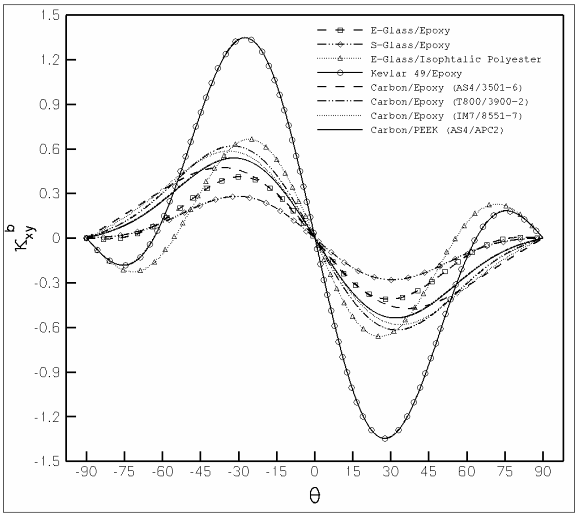

Fig. 3. Influence of material properties on the twisting rate

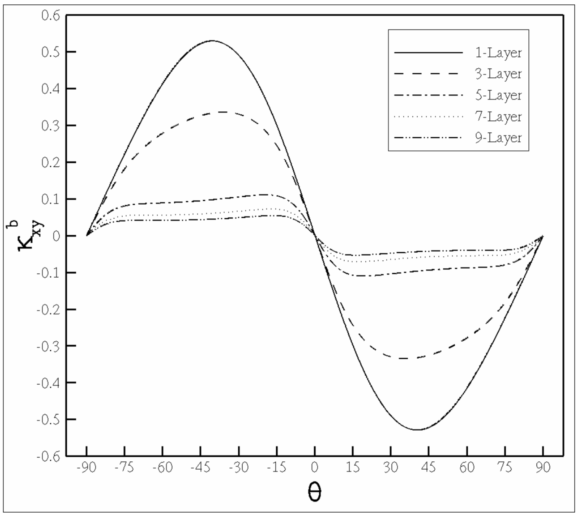

Fig. 4. Influence of number of layers on the twisting rate

3.1.2 Numerical Results

In order to investigate the bending-twisting coupling effects, a special class of laminates is selected using the configuration investigated in Section 3.1.1. They are respectively the single-layer (θ) and triple-layer (θ/-θ/θ) composite laminates, which are typical symmetric configurations.

The same material properties (Carbon/PEEK AS4/APC2) as used in section 3.1.1 are used for the numerical simulation (E_1=138.9 GPa, E_2=10.2 GPa, G_{12}=5.7 GPa, ν_{12}=0.3). The propeller geometry used is that of propeller 5479, which is shown in Fig. 5. It should be noted that propeller 5479 has the same geometry as one of the flexible composite propellers tested at the water tunnel at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The simulated operating conditions are $J=V/nD=0.66$ and $\sigma=(P_0-P_c)/(0.5\rho(nD)^2)=999$, where 'V', 'n', and 'D' denote the propeller advance speed, rotational frequency, and diameter, respectively. 'ρ' is the fluid density. P_0 and P_c denote the static pressure far upstream on the shaft axis and the saturated vapor pressure of water, respectively. The efficiency is defined as $\eta=(K_T/K_Q)(J/2\pi)$, where K_T and K_Q are the thrust and torque coefficients, respectively.

For the single-layer (θ) configuration, the variation of blade tip deflection, propeller efficiency (η), and fundamental frequency in air with the ply angles are shown in the top plot in Fig. 6. The bottom plot in Fig. 6 depicts the change in blade tip pitch angle, skew angle, and rake (non-dimensionalized by the propeller diameter) with ply angle θ. As shown in Fig. 6, the efficiency and pitch profiles have close correspondence. Basically, the increasing in pitch leads to decreasing in efficiency, and the decreasing in pitch leads to increasing in efficiency. A direct correlation between the pitch alteration and twisting rate can be identified by comparing the pitch alteration profile in Fig. 6 with the twisting rate profile in Fig. 4 (1-Layer). They both peak at around ±45°.

The tip deflection and change in tip skew and rake take maximum values at around ±90° and minimum values at 0°. This is because the blade has the highest bending compliance at ±90° fiber orientation, while lowest at 0° fiber orientation. The fundamental frequency takes the maximum and minimum values at ±90° and 0°, respectively, since the first mode is bending. Hence, the fundamental frequency is inversely proportional to the square root of the bending compliance. It should be noted that the results are not symmetric with respect to θ=0° due to the non-zero skew, rake, and pitch distribution of the propeller.

For the triple-layer (θ/-θ/θ) configuration (Fig. 7), the deformation and performance profiles are similar to those for single-layer case, except that the range of variation with respect to 'θ' is much lower. With the increasing of number of layers, the composite material has decreasing anisotropy. One can expect that for infinite number of layers, the composite configuration is essentially isotropic. The three-layer (θ/-θ/θ) configuration is still symmetric and hence there still exists bending-twisting coupling effects.

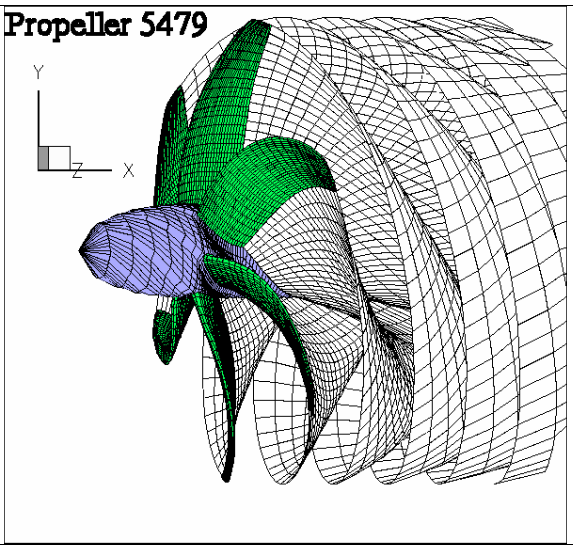

Fig. 5. Geometry of propeller 5479

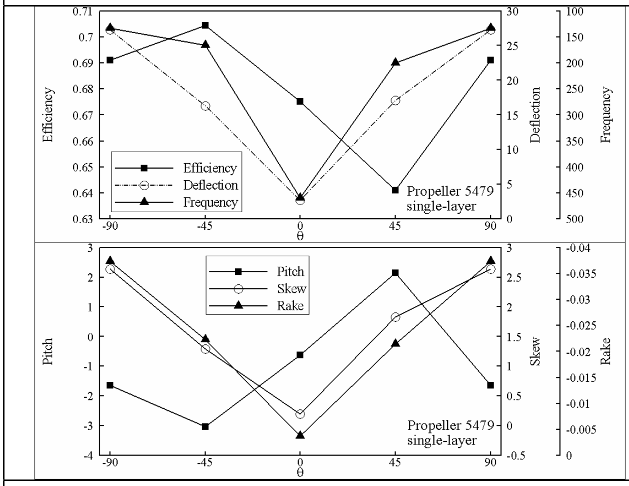

Fig. 6. Influence of fiber orientation on single-layer (θ) propeller behavior.

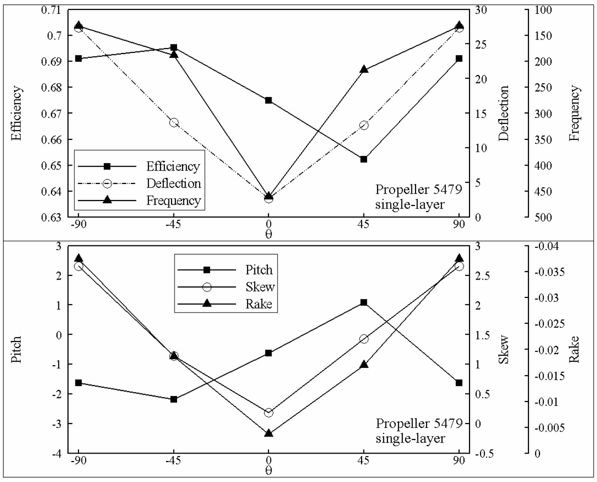

Fig. 7. Influence of fiber orientation on triple-layer (θ/−θ/θ) propeller behavior.

3.2 Sample Design

In the previous section, a direct correlation has been found between the parasitic twisting deformation, pitch alteration, and efficiency improvement. The objective of this section is to apply the design strategy proposed in the current work to demonstrate the feasibility of performance enhancement via deformation coupling in self-twisting composite propellers.

In the sample design, the base geometry is that of propeller 5474, a rigid composite propeller examined experimentally at NSWCCD and analyzed numerically in [14]. Numerical simulations showed that the original geometry of propeller 5474 is not yet optimal under the design condition. A linear pitch alteration scheme was applied on the original geometry of propeller 5474 to obtain the optimal mean-load geometry *G0* for the base rigid propeller. The reason to apply linear pitch alteration is based on the fact the pitch distribution along the radius is almost linear (except at the root region). For simplicity, the flexible composite propeller is assumed to be 24 inches in diameter, and to be made of a single layer of graphite/epoxy. The fibers are oriented 20° counter-clockwise from the local span-wise direction as shown in Fig. 8. The design condition in open water flow is chosen to be: $J=0.66$ and $n=780$ *rpm*. Applying the design strategy described in Section 2.3, the no-load geometry *GN* can be obtained. Comparisons of the un-deformed (no-load *GN*) and deformed (mean-load *G0*) geometries of the designed flexible propeller are shown in Fig. 9. It should be reminded that, at the design condition, the deformed geometry of the flexible composite propeller is required to be the same as the base rigid propeller.

The comparison of the efficiency between the rigid and flexible composite propellers is shown in Fig. 10. It can be seen that, the efficiency matches at the design condition J=0.66 as required by the design criteria. Moreover, the efficiencies of the flexible propeller are higher than its rigid counterpart in off-design conditions, which is as expected. The efficiency improvement increases as the flow condition further deviates from the design condition. Also shown in Fig. 10 is the optimal efficiency curve, which represents the maximum achievable efficiency for each operation condition. It was obtained via a series of numerical simulations by linearly altering the pitch distribution to obtain the optimal pitch and thus optimal efficiency. As shown in Fig. 10, there exists a difference between the flexible and optimal efficiencies, which means there is potential for further performance enhancement via deformation coupling. This problem is tentatively tackled in a related paper [7] in this conference using a genetic algorithm based constraint optimization scheme.

4 Conclusions

An analytical model has been proposed based on the classical lamination theory to investigate deformation coupling effects on the hydroelastic behavior of composite marine propellers. The analytical model was used to study the influence of material properties and fiber orientations on the parasitic twisting deformation. It was shown that twisting deformation not only depends on material properties, but also on the fiber orientations and the number of layers. A series of coupled numerical simulation was performed to investigate the influence of material configurations on propeller deformation and performance indices. A strong correlation was identified among the parasitic twisting deformation, the pitch alteration, and performance enhancement. A design strategy was proposed for the proper design of composite propellers. A sample design was given to demonstrate the feasibility of performance enhancement from self-twisting composite propellers. It was shown that properly design self-twisting composite propellers can significantly improve efficiencies over a wide range of operation speed.

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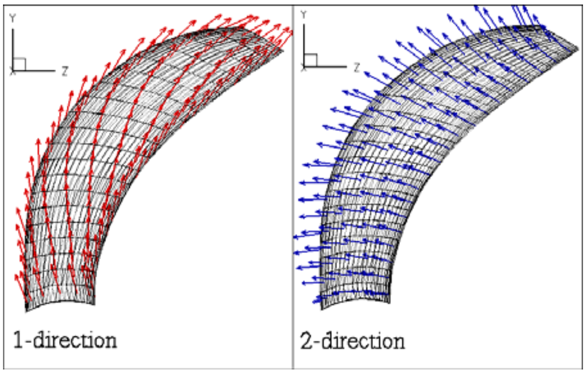

Fig. 8. Fiber orientation vectors for the sample design

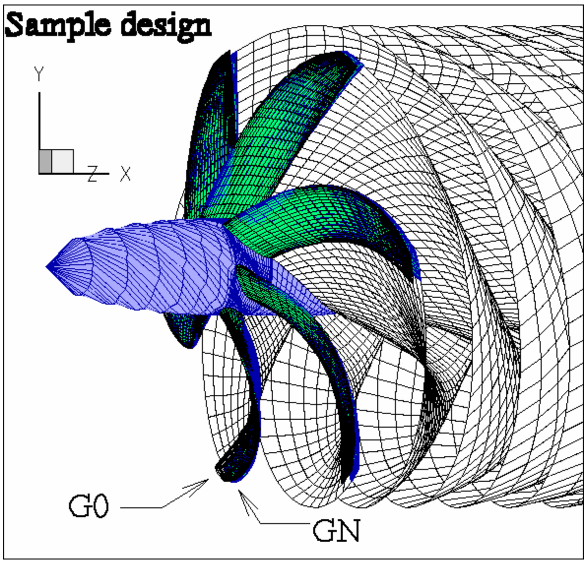

Fig. 9. Mean-load geometry *G0* and no-load geometry *GN* of the sample design

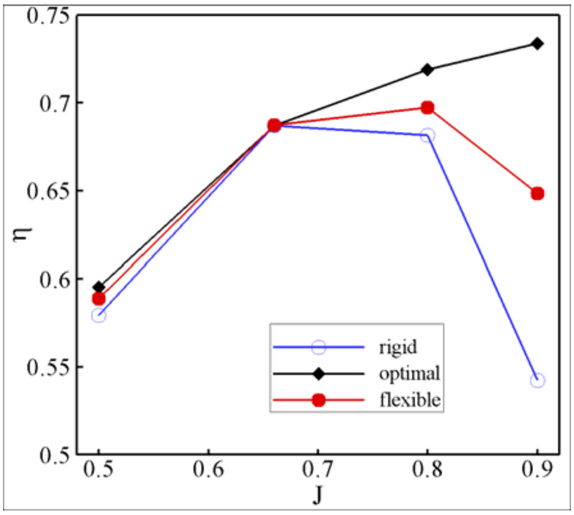

Fig. 10. Efficiency comparison between rigid and flexible propellers

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