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Effects of the advance ratio on the evolution of a propeller wake

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ABSTRACT

We numerically investigate the effect of the advance ratio on the wake characteristics of a marine propeller in a propeller open water test. Numerical simulations are performed for a wide range of advance ratios ($0.2 \leqslant J \leqslant 0.8$). At lower advance ratios, the propeller wake is apparently classified into three regions occupied by the high speed flow, the free-stream vortices, and the tip vortices. However, at higher advance ratios, the free-stream velocity is comparable to the slipstream induced by the propeller, resulting in an indistinct boundary between the slipstream and the free-stream. Three-dimensional (3-D) vortical structures show that the tip vortices merge with each other and with the neighboring trailing vortices, forming a larger vortex downstream at lower advance ratios. However, as the advance ratio increases, the merging of vortices is delayed further downstream, resulting in a periodic array of consecutive tip vortices farther downstream. In particular, root-side vortices are clearly observed at higher advance ratios. The slope of the contraction ratio in the lower advance ratios is roughly five times greater than that in the higher advance ratios. Empirical models of 3-D helices of tip vortices are suggested based on the present numerical results, which could provide guidance in establishing a reliable approach to wake modeling.

1. Introduction

The prediction of marine propeller performances is crucial for the success of a new ship design [5,10,19,2,21]. A propeller operates in various environments according to the sea condition. Moreover, the characteristics can significantly change during operation because of environmentally-induced motions (waves, wind, and currents). In these circumstances, the propeller must work in various conditions. Non-ideal conditions can trigger energy loss induced by cavitation, vibration, and noise, which in turn can amplify the magnitude as well as the harmonic content of hub loads [9].

From a physical point of view, the characteristic of the propeller wake is the crucial factor that causes energy loss. Consequently, propulsive loads need to be analyzed in detail. Various researchers have investigated the physical phenomenon with experiments. However, these experiments covered one or the narrow range of the advance ratio.

Di Felice et al. [7] used particle image velocimetry (PIV) to investigate the main characteristics of a propeller wake at three different loading conditions by using phase sampling techniques. Reduced velocity gradients near the hub and the tip vortices, which indicate weaker vortex circulation, were clearly verified at lower loading conditions. When decreasing the blade loading, they observed a significant reduction in the turbulence levels of the turbulent diffusion from the tip vortices, as well as a less-strong dissipation of the blade wake turbulence.

Lee et al. [20] used a stereoscopic PIV (SPIV) technique to measure the three-dimensional (3-D) flow structure of the turbulent wake behind a rotating propeller at three different advance ratios. The out-of-plane velocity component was determined in order to analyze wake characteristics in more detail. The effect of propeller loading conditions on the wake structure was also investigated. As the wake moved downstream and the propeller loading decreased, the strength and skew of the tip vortices decreased.

Felli et al. [11] performed an experimental analysis of the velocity and pressure fields behind a marine propeller by PIV and the slotting technique, respectively, to investigate the evolution of the velocity components for two different advance ratios. The results show that within the slipstream contraction, the highest values of the pressure fluctuations correspond to a radial position around the propeller tip, coinciding with the tip vortex passage. Far downstream of the slipstream contraction, vortex breakdown occurs, and the strong deformation of the hub vortex contributes

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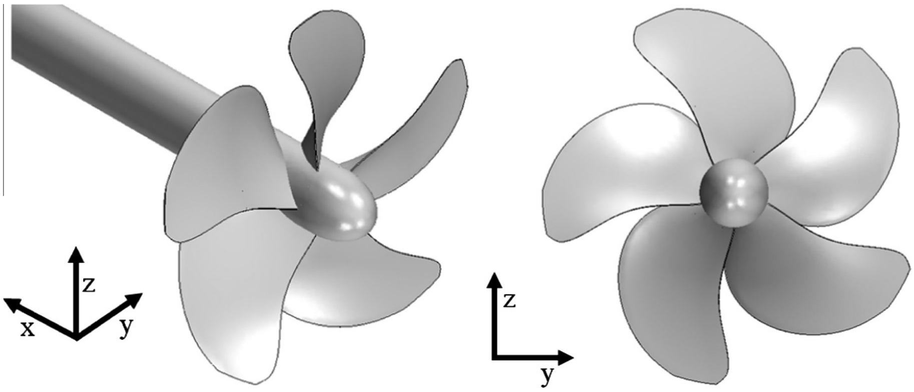

Fig. 1. Coordinate system of KP505.

Table 1
Propeller parameters of KP505.

KP505	Principal
Scale ratio	31.6
Diameter, D (m)	0.250
Pitch/diameter mean	0.950
A_e/A_o	0.800
Hub ratio	0.180
Number of blades	5
Section	NACA66

to pressure signal generation at the frequency of the shaft rate. Later, Felli et al. [13] studied the mechanisms of the evolution of propeller tip and hub vortices in the transitional region and the far field according to the blade configurations. They also examined the effect of the spiral-to-spiral distance on the mechanisms of wake evolution using laser Doppler velocimetry (LDV).

Paik et al. [25] used PIV to investigate the wake characteristics behind a marine propeller. They focused on studying the spatial evolution of a propeller wake in the region ranging from the trailing edge to a location one propeller diameter (D) downstream. The Galilean decomposition method and vortex identification method using swirling strength calculations were used to clarify the vortex behaviors in the propeller wake region. The slipstream contraction occurred in the near-wake region. Thereafter, unstable oscillation occurred because of the reduction of interaction between the tip vortex and the wake sheet behind the maximum contraction point.

As computer technology improves, propulsion research has developed rapidly. But most propeller studies using computational fluid dynamics (CFD) are mainly focused on the validation of the numerical method, grid dependency, the turbulence model dependency, and the effects of cavitation.

Morgut and Nobile [23] analyzed the effect of the grid type and turbulence model on the numerical prediction of flow around marine propellers, by comparing with the available experimental data. Ji et al. [17] numerically analyzed unsteady cavitating turbulent flows around a conventional marine propeller in a non-uniform wake to predict excited pressure fluctuations. The evolution of unsteady cavitation and pressure fluctuations are in fairly good agreement with the experimental results. Their results demonstrate that their proposed numerical methodology is suitable for simulating unsteady cavitating flows around a propeller. Also, Seol [29] addressed the pressure fluctuation induced by propeller sheet cavitation. The mechanism of pressure fluctuation induced by propeller sheet cavitation is clarified and analyzed. Also, the developed numerical prediction method was evaluated. Muscari et al. [24] analyzed the flow past a rotating marine propeller with the aim of establishing limits and capabilities, and the field of applicability of different turbulence modeling approaches for this class of problems. The eddy viscosity model and the detached eddy simulation (DES) approach were used.

Dubbioso et al. [8] numerically simulated a marine propeller working in oblique flow conditions with the unsteady Reynolds-averaged Navier–Stokes equations (URANSE) and a dynamically overlapping grid approach. Two different loading conditions were analyzed at different incidence angles (10°–30°) in order to characterize the propeller performance during idealized off-design conditions, similar to those experienced during a tight maneuver. As a result of the non-symmetric inflow condition,

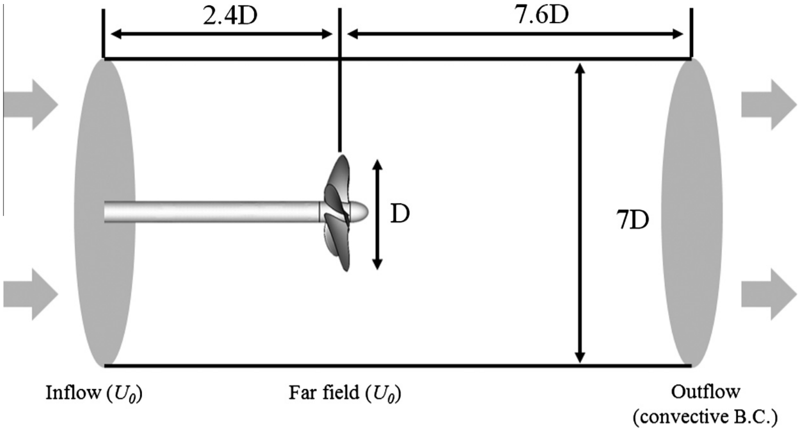

Fig. 2. Schematic of the computational domain and boundary conditions.