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A comparative DES study of wake vortex evolution for ducted and non-ducted propellers

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ABSTRACT

A comparative numerical analysis was conducted on the evolution of wake vortices generated by ducted and non-ducted propellers in open-water tests. The simulations employed detached eddy simulation (DES) method with a focus on the detailed analysis of the composition of vortices and spatial evolution mechanism under various loading conditions. Compared with non-ducted propellers, the interference between the duct and the propeller directly changed the morphology of vortices and wake contraction, altered the energy distribution in the internal flow fields and thereby strengthened the self- and mutual induction and accelerated the primary merging and grouping processes. The results indicated that the shear layer vortices shedding from the duct displayed a strong interaction with the distorted tip vortices in an irregular manner and ejected the secondary coherent structures. Numerous secondary vortices were observed during the transition regime of the dynamic evolution. Followed by the energy dissipation and instabilities in the wake vortices, the wake vortex structures gradually broke down. The spectra of kinetic energy (KE) analyses of the wake field quantitatively confirmed the evolution of wake vortical structures in the temporal domain. The ducted propellers possessed a characteristic frequency that corresponded to its shaft frequency, blade passing frequency (BPF) and their harmonics.

1. Introduction

Ducted propellers are capable of generating high levels of thrust and efficiently operating under heavy loads, and they are widely utilized in specialised vessels and marine dynamic positioning systems. Special propulsions for ships constitute an important category of rotating machinery. A thorough understanding of flow mechanisms of rotating machines is of vital importance as it offers fundamental details for the hydrodynamic performance prediction. Currently, researches in the field focus on the structural composition, disturbance, and instability mechanism of vortices in the wake fields of rotating machinery. It is verified that the dynamic structure of wake vortices significantly affects the oscillations of rotating systems and their radiated noise performance (Korkut and Atlar, 2012).

Several studies have investigated the wake vortices characteristics of different rotating machinery (Felli et al., 2006; Lignarolo et al., 2015; Okulov and Sorensen, 2007; Paik et al., 2007). Nowadays, researchers have reached a consensus on the composition of rotating-machine wake vortices. Conceptually, the wake vortex system of a conventional propeller with N blades comprises of N blade vortices and a hub vortex, in which the former includes a tip vortex, thin vortex sheet shed off the edge of the blade and root vortex. The thin vortex sheet connects the tip vortex with the hub vortex. Felli et al. (2011) provided a detailed description of self- and mutual induction between tip vortices in the wake of axisymmetric flows and determined that the evolution process of wake vortices is divided into three different regimes. Kumar and Mahesh (2017) discovered that in addition to interactions between tip vortices, interactions also occur between tip vortices and smaller vortices generated by the roll-up of the blade trailing edge wake in the near wake and that vortical structures gradually break up and diffuse into the far wake in the unstable regime.

Numerous experimental studies were performed on non-ducted propellers. For example, Di Felice et al. (2004) and Felli et al. (2006) studied the velocity, pressure, and distribution of turbulent kinetic energy in the blade and tip vortex sheets of a propeller (E779A) by using particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) measurements. Their studies revealed that viscosity and diffusion lead to the gradual dissipation of vortex sheets that are shed off the blades, and the point at which the shed vortex sheets disappear corresponds to the starting point of the roll-up process from which the wake vortices subsequently evolve into the transitional regime. Felli et al. (2011) investigated propeller wake evolution of propeller E779A configured with different numbers of

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Nomenclature

D	propeller diameter[m]
q	isovalue of Q-criterion[s^{-2}]
R	propeller radius[m]
k	wavenumbers
n	propeller rotational speed [rps]
O-xyz	Cartesian coordinate system
ε	pitch(°)
ω_x	normalised axial vorticity (*Vorticity[i]/(Ux/D)*)
U_∞	advance speed in open water [m/s]
u, v, w	local velocity components[m/s]
U	local velocity magnitude [m/s]
Ux	local axial velocity [m/s]
Re	Reynolds number
J	advance coefficient (U_∞/nD)
ρ	fluid density [kg m^{-3}]

Abbreviations

T	non-dimensional period of revolution
URANS	Unsteady Reynolds-averaged Navier-Stokes equations
Δt	time step
DES	Detached Eddy Simulation
Ktp	propeller thrust coefficient
DPM	Ducted Propeller Model
Ktd	duct thrust coefficient
NPM	Non-ducted Propeller Model
Kq	torque coefficient
PSD	Power Spectral Density
Vorticity[i]	axial vorticity [s^{-1}]
BPF	Blade Passing Frequency

blades in a cavitation tunnel, in which different grouping mechanisms in the vortex structures were observed with changes in the number of blades.

Numerical simulations were also widely applied in studies on the wake vortices of non-ducted propellers. Morgut and Nobile (2012) discussed the effects of the type of grid and turbulence model on predicting propeller wake flow fields. Baek et al. (2015) numerically examined wake flow fields and 3-D vortical structures of a propeller (KP505) with different advance ratios by solving unsteady Reynolds-averaged Navier-Stokes (URANS) equations, and an empirical model to describe the radial trajectories of propeller tip vortices was constructed. Muscari et al. (2013) numerically simulated the wake of a propeller (E779A) via URANS and detached eddy simulations (DES), wherein they discovered that the latter was reliable in reproducing the complex vortex structures in the far wake. Additionally, Dubbioso et al. (2013) and Di Mascio et al. (2014) conducted simulations on the wake field characteristics and wake vortex evolution of E779A model propeller in oblique flows by using URANS and DES methods. They discovered that secondary vortices play an important role in the dynamic evolution of wake vortices. Furthermore, Mahesh et al. (2015) and Balaras et al. (2015) utilized large eddy simulations (LES) to perform high-fidelity numerical simulations on the characteristics of instabilities of the propeller wake.

Bhattacharyya et al. performed extensive studies on predicting ducted propeller performance from the model scale to full scale. They utilized computational fluid dynamics (CFD) in the design of the ducted propeller (Bhattacharyya et al., 2015) and systematically investigated the scaling approach and scale effects of the ducted propellers (Bhattacharyya et al., 2016a, 2016b). Gaggero et al. (2014) used the RANS method to perform numerical predictions on cavitating tip vortices in ducted propellers, and the meshing and refinement topology used in the study are highly valuable as a reference for numerical studies since they attempted to capture the details of the flow field. Recently, Go et al. (2017) investigated the effect of a duct on propeller performance, in which the duct was located in front of the propeller. The results revealed 3-D vortical structures originating from the propeller tip and complex wake fields, and found that the duct could affect the flow field in a different manner.

Propeller blade loads and geometrical models affect the evolution of wake vortices generated by non-ducted propellers. In the case of ducted propellers, the flow separation derived from the duct and interfering interactions of the vortices in the wake field constitute primary factors that determine the hydrodynamic performance of ducted propellers. Hence, the composition and evolutionary mechanism of wake vortices are significantly more complex in ducted propellers when compared to those in non-ducted propellers. Most previous studies focused on the overall hydrodynamic performance of ducted propellers. Hence, it is meaningful to perform a detailed study on the vortical structures of ducted propeller and its evolution in wake fields. Therefore, the present study performs a comparative analysis on the wake vortex characteristics of ducted and non-ducted propellers by using the DES approach. It overcomes the inherent weaknesses of the RANS method in the simulation of vortex structures. The study investigates the effects of the numerical method, grid resolution, and loading on the simulation of wake vortex structures. Furthermore, the evolutionary process (deformation, grouping, and diffusion) of wake vortices of both propulsion configurations are analysed. It is expected that the findings of the study will aid in expanding and enriching the collective understanding of the mechanistic aspects of the hydrodynamic performance of specialised rotating machines.

The objectives of the numerical study include the following aspects: 1) assessing the applicability of DES in capturing the dynamic evolution of complex wake vortices; 2) comparing the structural composition and evolutionary processes of the wake vortex structures of ducted and non-ducted propellers under the same working conditions; and 3) quantitatively determining evolutionary processes of wake vortices based on power spectral density (PSD) analyses on the kinetic energy (KE) of the wake fields. The study is organized as follows. Section 1 describes the theoretical background. Section 2 discusses the setting of numerical models and assesses the uncertainty of the numerical simulations. In Section 3, the structural composition and evolution of wake vortices of the two models are qualitatively and quantitatively analysed. This is followed by discussing the wake vortices differences between the DES and URANS methods in Section 4. Finally, the conclusions are detailed in Section 5.

2. Theoretical background

2.1. Mathematical models

The numerical simulations of the viscous flow field are performed by the integration of the RANS equation. The motion of incompressible Newtonian fluids is integrated with the continuity equation and momentum conservation equation (Wang et al., 2015) as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) + S_j \tag{2}$$

where u_i and u_j denote the time-averaged values of velocity components ($i, j = 1, 2, 3$), p denotes time-averaged pressure, μ denotes the dynamic viscosity coefficient, $\rho \overline{u_i' u_j'}$ denotes the Reynolds stress term, and S_j