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Image-based measurements for examining model predictability of cavitation on a marine propeller surface

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A B S T R A C T

Because of its complex nature, cavitation associated with marine propellers poses a challenge to numerical simulations for predicting it. This paper experimentally examines the predictions of vapor volume fraction (VVF) done by RANS simulations with three cavitation models for a propeller whose design is to suppress sheet cavitation. The equality of VVF and cavitation occurrence probability (COP), whose distribution can be measured with cavitation images acquired using the phase-locked imaging technique in an open-water test, is found and becomes the base of a methodology developed for examining model predictability of cavitation. By comparing and correlating the distributions of VVF computed using different cavitation models with that of measured COP, predictabilities of cavitation models can be quantified to elucidate modeling issues and possible remedies for them.

1. Introduction

Cavitation can be generated by marine propellers because of their operational conditions combined with the factors of their blade designs. For example, sheet cavitation on a propeller blade surface is formed mainly owing to the large angle of attack of the inflow to the blade, and may have significant impact on the propeller's performance (Franc and Michel, 2004; Kuiper, 1998). In order to design a propeller having high efficiency and long life cycle, the characteristics of cavitation (especially the occurrences and the ranges of cavitation on a propeller blade surface) associated with propeller flows must be understood to certain degree.

In the past, propeller designers conducted model testing experiments to investigate cavitation effects. However, the number of cases studied using the experimental approach was quite limited because of the cost and the length of time consumed. This situation, along with the fact that computing power grows rapidly, has made numerical simulations increasingly popular for recent years. For computing propeller flows, three numerical schemes have been widely used: the vortex-lattice method (Greeley and Kerwin, 1982), the panel method (Hsin, 1990), and the RANS (Reynolds-averaged Navier-Stokes equation solver). The first two methods assume inviscid fluid and use empirical formula to account for the effect of viscosity. The RANS, alternatively, computes flows with fluid viscosity. As a result, the RANS is capable of capturing (at least qualitatively) viscous phenomena such as flow separation and tip vortex (Pope, 2000). To simulate cavitating propeller flows, the RANS coupled with cavitation models can be used to yield feasible results even with increased flow complexity due to cavitation (e.g., Rhee et al., 2005; Liu et al., 2008). However, it is well known that the results of RANS simulations are sensitive to the cavitation and turbulence models chosen. Therefore, the predictability of RANS needs to be validated with experimental data at least in some benchmark tests in order for the RANS to be accepted as an effective design tool.

In order to provide objective and informative comparisons for numerical results, experimental data should be acquired and analyzed in such a way that the occurrences and ranges of cavitation can be quantified. Perhaps owing to less demands in the past from the numerical simulation community, however, previous experimental works on marine propeller cavitation have rarely adopted quantitative methodologies. Examples include: Konno et al. (2000) used only hand-made sketches to illustrate the process of tip vortex cavitation bursting; Chen (2008) took random image snapshots of cavitation incurred on the root of a propeller at inclined-shaft conditions and described the cavitation characteristics without performing any image analysis; Bertetta et al. (2012) took images of cavitation occurring on two CPP propellers, and directly and qualitatively compared them with the numerical results of a panel code; Lee et al. (2015) and Aktas et al. (2016) respectively investigated exciting forces and noises induced by propeller cavitations using cavitation images to qualitatively identify the effects; Gaggero et al. (2012) qualitatively compared their RANS

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Nomenclature

α	vapor volume fraction (VVF)
α_{nuc}	nucleation site volume fraction
ρ	fluid mixture density
ρ_l	liquid density
ρ_v	vapor density
ν_l	liquid viscosity
σ	cavitation number
f_v	vaper mass fraction
f_g	mass fraction of non-condensable gas
F_{vap}	evaporation coefficient
F_{cond}	condensation coefficient
J	advance coefficient
k	turbulent kinetic energy
$\dot{m}_{ji}$	mass transfer per unit volume from phase j to phase i
$\dot{m}_{ij}$	mass transfer per unit volume from phase i to phase j
n_b	bubble number per unit volume of liquid
P	local far-field pressure
P_B	bubble pressure
P_v	saturation vapor pressure
$\Re_B$	bubble radius
R_e	mass source term associated with the growth of vapor bubbles
R_c	mass source term associated with the collapse of vapor bubbles
$\Im$	surface tension of bubble

simulation results and images of (steady) sheet cavitation for the CLT propeller; Yamasaki et al. (2009) conducted RANS simulations and cavitation imaging at different angles for three propellers with different loading distributions near the blade tips; Kinnas et al. (2015) in the second Workshop on Cavitation and Propeller Performance compiled comprehensively the numerical results of a specific propeller in oblique flow from different research groups and compared them to the hand-made sketches of cavitation pattern directly observed from the cavitation images. As a common practice, the contours of vapor volume fraction (VVF) computed in RANS simulations are used to identify the occurrences and ranges of cavitation by setting a VVF threshold (0–100%), i.e., any spatial point having VVF greater than the threshold is regarded to be within the cavity. For example, the VVF threshold values were respectively set to be 50%, 50%, 40% and 60%, and 30% in Gaggero et al. (2012), Yamasaki et al. (2009), Kinnas et al. (2015), and Zhu (2015). It is clearly evident that the choice of VVF threshold value may vary from case to case.

Salvatore et al. (2009) presented the results of the VIRTUE 2008 Rome Workshop, where six RANS codes (with different cavitation and turbulence models), one LES (Large Eddy Simulation) code and one BEM (Boundary Element Method) code computed the flow case of a propeller whose experimental data of cavitation were acquired by Pereira et al. (2004). They analyzed their phase-locked images of cavitation using the cross-correlation method to identify the extension of sheet cavity on the propeller surface. Because of the fact that their cavitation patterns are quite regular and steady, i.e., the shape and range of the cavitation area is almost fixed from image to image, one may easily quantify the differences between the experimental and numerical results of this case. It is clearly evident that once the cavitation phenomena encountered are unsteady and complex, one needs to develop a statistical methodology to quantify the occurrences and ranges of cavitation in order for the numerical results to be compared in a meaningful way. This statement also serves as the main purpose of the present paper.

The present paper deals with unsteady cavitation occurrences on a marine propeller surface and focuses on the predictability assessment for three cavitation models built in the commercial CFD code FLUENT from Singhal et al. (2002), Zwart et al. (2004) and Schnerr and Sauer (2001). Using the phase-locked imaging technique, and processing and analyzing the images acquired (details follow), the spatial distribution of the probability for the occurrence of cavitation (cavitation occurrence probability, COP) on the propeller blade is thus obtained. We will show that the meaning of COP is equivalent to that of VVF which is obtained from a RANS simulation. As a result, a meaningful, quantitative comparison between the experimental and numerical results can be established and the predictabilities associated with cavitation models can be evaluated.

2. Model propeller

A four-bladed propeller (designated as P4012) with diameter of 250 mm was used in this study. The blade shape was designed using the foil section developed by Scherer and Stairs (1994). The aspect ratio and the pitch ratio (at 0.7 radius) of the blade are 1 and 1.41, respectively. Other detailed geometrical parameters are listed in Table 1. The design goal of this propeller was to unload the root and to suppress sheet cavitations (Kehr, 1999). Its design point is at the advance coefficient (J) of 1.14.

3. RANS simulations

RANS simulations for predicting the viscous flow around and the cavitations on the model propeller in a uniform inflow (simulating the open-water test conducted in a cavitation tunnel) were performed using the commercial CFD software FLUENT. FLUENT adopts the finite-volume methodology with the SIMPLE scheme for computing fluid pressure. The SST k-ω model (Menter, 1994) was used for turbulence closure.

As shown in Fig. 1, computing grids were generated for one propeller blade using GRIDGEN. To accommodate the complicated geometry of the blade, unstructured grids were used for the zones around it, whereas structured grids were adopted for the regions away from it. This kind of hybrid arrangement of grids has been used frequently for flow problems with complex geometries like propellers (e.g., Rhee et al., 2005). A grid convergence test was performed with four grid numbers: $1.0{\cdot}10^6$, $1.4{\cdot}10^6$, $2.0{\cdot}10^6$ and $2.6{\cdot}10^6$. Thrust was computed without any cavitation model for each grid number, as

Table 1
Geometrical parameters of the model propeller P4012.

Propeller No.	**P4012**			
Number of Blade	**4**			
Diameter (D)	**0.25 m**			
Expanded Area Ratio (EAR)	**1.00**			
Foil Section	Scherer and Stairs (1994)			
r/R	**P/D**	**C/D**	**F/C**	**T/D**
0.20	**1.3000**	**0.3511**	**0.0121**	**0.0411**
0.25	**1.3330**	**0.3771**	**0.0156**	**0.0386**
0.30	**1.3580**	**0.4036**	**0.0182**	**0.0361**
0.40	**1.3910**	**0.4586**	**0.0215**	**0.0307**
0.50	**1.4070**	**0.5111**	**0.0234**	**0.0259**
0.60	**1.4110**	**0.5561**	**0.0240**	**0.0207**
0.70	**1.4100**	**0.5923**	**0.0238**	**0.0162**
0.80	**1.4070**	**0.6011**	**0.0232**	**0.0121**
0.90	**1.4010**	**0.5111**	**0.0223**	**0.0077**
0.95	**1.3970**	**0.4049**	**0.0218**	**0.0056**
1.00	**1.3880**	**0.0000**	**0.0212**	**0.0037**

P: pitch, C: chordlength, F: camber, T: thickness