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Verification and validation of URANS simulations of the turbulent cavitating flow around the hydrofoil *

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Abstract: In this paper, we investigate the verification and validation (V&V) procedures for the URANS simulations of the turbulent cavitating flow around a Clark-Y hydrofoil. The main focus is on the feasibility of various Richardson extrapolation-based uncertainty estimators in the cavitating flow simulation. The unsteady cavitating flow is simulated by a density corrected model (DCM) coupled with the Zwart cavitation model. The estimated uncertainty is used to evaluate the applicability of various uncertainty estimation methods for the cavitating flow simulation. It is shown that the preferred uncertainty estimators include the modified Factor of Safety (FS1), the Factor of Safety (FS) and the Grid Convergence Index (GCI). The distribution of the area without achieving the validation at the U_v level shows a strong relationship with the cavitation. Further analysis indicates that the predicted velocity distributions, the transient cavitation patterns and the effects of the vortex stretching are highly influenced by the mesh resolution.

Key words: Cavitating flow, cavitation, verification and validation (V&V), uncertainty

Introduction

In the past, much attention was paid on the cavitating flow for its complicated two-phase flow features[1-3]. Numerous experimental and numerical researches were conducted and many significant phenomena and mechanisms were revealed[4-6]. The cavitation can be divided into four stages, the incipient stage, the sheet stage, the cloud stage and the super cavitation stage[7]. The nuclei size and the nuclei density were considered by Arndt as the main factors for the cavitation inception[8], and related researches[4] were conducted for understanding the mechanism of the cavitation inception. Violently unsteady and quasi-periodic process is observed due to the sheet/cloud cavitation shedding. The re-entrant jets were claimed to be responsible for the cloud cavitation shedding based on the experimental and numerical investigations[9-11]. More recently, Peng et al.[12] observed the U-type flow structures around the hydrofoils in the cavitation tunnel. It is a common phenomenon in the U-type flow structures with the cloud cavity. All these show the great complexity and difficulties in the cavitation research. So far, there have been no unified explanations and conclusions for the cavitation.

It is worth mentioning that the numerical simulations have achieved a remarkable progress for the cavitating flow in the last two decades[1]. The Reynolds-averaged Navier-Stokes (RANS) simulations were widely applied in the cavitation flow and

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practical applications[13-16]. Numerical methods such as the large eddy simulation (LES)[17-20] are more accurate than the RANS and are widely used nowadays in the cavitating flow simulations. However, little attention has been paid on the verification and validation (V&V) in the cavitating flow simulations with the RANS or LES methods, although it was well understood that the mesh influence was a great concern[3,11,16]. The V&V is a basic procedure to evaluate the reliability before accepting the simulated results. In our previous study[18], it was suggested that the V&V is an important and essential part of the CFD. In view of the violently unsteady flow feature and the high noise level, the numerical results may contain a great number of uncertainties and variations in the cavitation simulations. Thus, the V&V of the cavitating flow simulations should be an urgent issue to be investigated and applied in the practice.

The current quantitative uncertainty estimates for the RANS are mainly built based on the Richardson extrapolation methods. The Grid Convergence Index (GCI) proposed by Roache[21] is used extensively and recommended by American Society of Mechanical Engineers and American Institute of Aeronautics and Astronautics. The GCI and the variations of the grid convergence index, i.e., the Grid Convergence Index modified by Oberkampf and Roy (GCI-OR)[22], the grid convergence index modified by Logan and Nitta (GCI-LN)[23], and the Grid Convergence Index modified by Roache (GCI-R)[24], see a wide applications in many fields[21-25]. In the Correction Factor Method (CF) developed by Stern et al.[26], a correction factor is used to indicate how far away from the asymptotic range. Wilson et al.[27] expressed the assessments and put forward some modified ideas, and then the modified CF is recommended by the ITTC for the uncertainty analysis in the CFD V&V.

As pointed out by Xing and Stern[28] and Stern et al.[29], the GCI and the CF have two main drawbacks. The first drawback is that the estimated uncertainty is unreasonably small when the observed order of accuracy is less than the formal order of accuracy. The second drawback is that the confidence levels with few statistical evidence for the GCI and the CF are not well explored. In this context, the Factor of Safety Method (FS) and its modified version (FS1) were proposed by Xing and Stern[28, 30] to overcome the two main drawbacks in the CF and the GCI. The FS and FS1 methods show the best conservativeness compared to other methods with large calculations in Xing and Stern' s studies[28,30].

All these seven methods were evaluated with large amount of practice[21-28]. Most of these studies focus on the uncertainty estimation with much mitigating flow compared to the unsteady cavitating flow, but the calculation of solution quantities is at a high noise level in unsteady cavitating. Therefore, the appropriateness of all uncertainty estimators applied in the URANS simulations of the cavitating flow remains an issue for more studies and practices.

The current CFD V&V for the LES was proposed and applied[31-33], but with many unsolved problems even in the simulation of simple flow phenomena such as the channel flow. So far, there is no clear and practical guideline for the V&V of the LES applied in the engineering field. It is a challenging work for the V&V of LES in the future.

Inspired by the above studies, this paper pays attention to the V&V procedures for the URANS simulations of the turbulent cavitating flow around a Clark-Y hydrofoil. The main focus of this study is to investigate the feasibility of various Richardson extrapolation-based uncertainty estimators in the cavitating flow simulation. It is an attempt to carry on the V&V of URANS simulations of the turbulent cavitating flow, and also a preparation for future in-depth investigations of the LES V&V in the cavitation simulation. The experimental data in published papers[7,16] are chosen to carry on the validation procedure. Simulated cavitation results are discussed with respect to different mesh resolutions.

1. Numerical methods and uncertainty estimators

To simulate the unsteady cavitating flow, the standard RNG k-ε turbulence model modified by the density corrected model (DCM)[34,35], whose advantages and accuracy in the cavitation simulation were widely validated[34-37], is employed coupled with a mass transfer cavitation model. The main features of the models are as follows.

1.1 *Physical cavitation model*

The Zwart model[38] is used to describe the mass transfer in the ANSYS CFX solver, and it was used and validated widely to accurately capture the feature of the cavitation. The mass transfer equation is as follows

$$\frac{\partial(\rho_v \alpha_v)}{\partial t} + \frac{\partial(\rho_v \alpha_v u_i)}{\partial x_i} = \dot{m}^+ - \dot{m}^- \tag{1}$$

where α_v is the vapor volume fraction. The source terms $\dot{m}^+$ and $\dot{m}^-$ in Eq.(1) are the mass transfer rates for the vaporization and condensation processes, respectively. The Rayleigh-Plesset equation describing the single bubble dynamics is simplified as:

$$\frac{3}{2}\left(\frac{\mathrm{d}R_B}{\mathrm{d}t}\right)^2 = \frac{p_v - p}{\rho_l} \tag{2}$$

$$\frac{\mathrm{d}R_B}{\mathrm{d}t} = \sqrt{\frac{2}{3}\frac{|p_v - p|}{\rho_l}} \tag{3}$$