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# A numerical study of unsteady cavitation on a hydrofoil by LES and URANS method

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**Abstract.** In this paper, the unsteady cavitation phenomena on a NACA0015 hydrofoil is numerically simulated by unsteady Reynolds-Averaged Navier-Stokes (URANS) method and Large Eddy Simulation (LES) in single-fluid approaches to multiphase modelling, respectively. It is observed that the large-scale structures and characteristic periodic shedding predicted by the URANS with the modified SST  $k-\omega$  turbulence model show a good qualitative match with the experimental observations but with quantitative discrepancies, such as a different cavity length and volume, and a different location of shedding. Compared to the URANS results, the LES results reproduce more details of unsteady dynamics with an improved quantitative agreement.

## 1. Introduction

Cavitation is a complex physical phenomenon of phase change from liquid to vapor at almost constant temperature in regions where the pressure is lower than a certain critical pressure. It commonly occurs in marine propulsion systems and other hydraulic machinery. Due to the possible limitations imposed on the attainable propulsor thrust and propulsion efficiency by cavitation, it is essential to predict cavitation phenomena and make an assessment of cavitation nuisance in an early design stage.

As one of the remarkable catastrophic consequences, cavitation erosion is a great challenge to be assessed since it involves multi-scale hydrodynamic processes in combination with the response of solid material exposed to various cavitation regimes. Although much is known about the behavior of individual bubble cavitation and the material reaction, the establishment of a reliable general-purpose model for cavitation erosion assessment is still a big challenge and remains a major concern for the industry [1-4]. From a number of experimental studies, it is confirmed that a crucial phase in the process leading to cavitation erosion is the break-up of the macroscopic sheet cavity into cloudy cavities [5-7]. As a result, the capture of characteristic unsteady dynamics of sheet/cloud cavitation becomes an essential phenomenon in the assessment of the cavitation erosion risk based on computational fluid dynamic (CFD) tools and experimental observations.

Additional difficulties arise in the numerical modelling of unsteady cavitation phenomena due to the complex mechanism involving turbulent fluctuations over a wide range of length and time scales. It is noted that suitable turbulence modelling is of significant importance due to the presence of high Reynolds number and strong unsteady dynamics, such as the formation of the re-entrant jet, and the periodic shedding and collapse of cloudy cavitation [8]. This paper firstly carries out numerical



simulation of the cavitating flow around the NACA0015 hydrofoil through the URANS method using a modified SST  $k-\omega$  turbulence model. Subsequently, the capability of an alternative methodology for turbulent flow predictions, the LES approach, to reproduce unsteady cavitation phenomena is explored. A quasi-2D run with the 3D LES code is adopted here. It is supposed to overcome the shortcoming of the RANS method in a poor resolution of dynamic flow structures of multiple length and time scales and an over-prediction of eddy viscosity production in regions of higher vapor volume fraction. The LES results are then compared with URANS results for verification of refined resolution of transient unsteady dynamics and also improved quantitative agreement with experimental observations.

## 2. Numerical Modelling

The governing equations for the liquid/vapor two-phase flow are based on a single-fluid approach. The flow field is solved by the mixture continuity and momentum equations, which are obtained by averaging or filtering of the original Navier-Stokes equations, corresponding to URANS method and LES approach, respectively. The cavitation model developed by Schnerr and Sauer[9] has been used for the mass transfer between the vapor and liquid phases in cavitation.

For the numerical simulation conducted by URANS method, the SST  $k-\omega$  turbulence model developed by Menter [10] with a modification of the turbulent viscosity is applied following the idea of Reboud et al. [11] for better simulation of the unsteady dynamics. For the LES approach, subgrid-scale (SGS) terms resulting from the filtering of the Navier-Stokes equations are modeled by the Smagorinsky-Lilly model[12].

## 3. Case description

The test geometry is a NACA0015 hydrofoil at 8 degree angle of attack with a chord length  $C=60\text{mm}$ . The computational domain is obtained by extending 3.0 chord lengths ahead of the leading edge and 5.5 chord lengths behind the trailing edge of the hydrofoil. A coarse grid with 264 edges are set on the hydrofoil for the URANS method, and a finer grid with 528 edges on the hydrofoil has been used for the LES computation, ensuring the near-wall mesh resolution along the hydrofoil surface is  $y^+ < 1$ .

A velocity inlet condition is applied at the upstream flow. A pressure outlet condition is used at the outlet boundary, where the specified pressure at the outlet can be derived from the cavitation number under consideration,  $\sigma=2.2$ , which is characterized by typical unsteady cavitation. The top and bottom boundaries are taken as no-slip walls. The experiments to be compared with the numerical simulations are performed by MARIN in cooperation with Lloyd's Register [7,13].

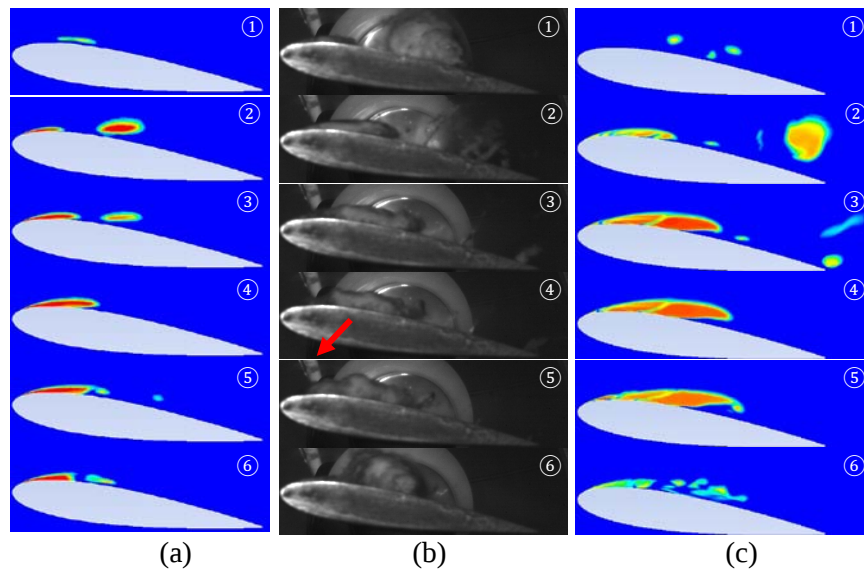
## 4. Numerical results

### 4.1. Unsteady shedding and collapse

As shown in figure 1-(b), the observed essential features can be characterized as follows: A sheet cavity is initiated and growing from the leading edge after the detachment of last cloudy cavities; The sheet cavity grows to a certain extent and becomes unstable, simultaneously the cloudy cavities travels with the main flow towards downstream and finally collapses near the trailing edge of the hydrofoil; Re-entrant flow forms and moves upstream towards to the leading edge until it breaks the main sheet cavity into a bubbly cloud, which is shed periodically at a frequency around 210 Hz.

The URANS results basically capture the features of the unsteady cavitation, such as the break-up of the sheet cavity and the detachment of the cloudy cavities from the sheet cavity and its collapse. It shows a good qualitative match with the experimental observations but with a much smaller cavity length and volume, and different locations of the prominent shedding and collapses of the bubbly cloud, as shown in figure 1-(a). A shedding frequency of 280 Hz has been predicted.

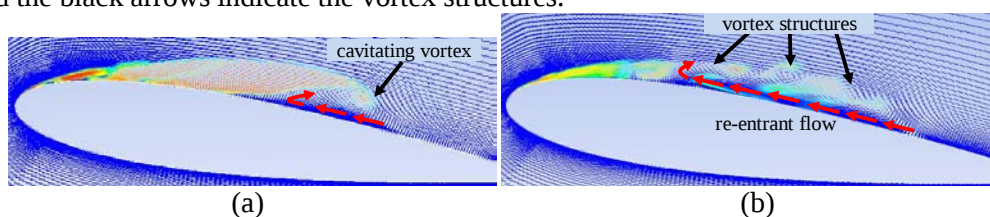
In figure 1-(c), the LES results show a better agreement in the prediction of the cavitation behavior than the URANS results. It reproduces the unsteady shedding and collapses with larger cavity extent and closer locations of shed bubbly clouds at a lower frequency of roughly 170 Hz. This would emphasize the possible improvement by a LES approach in the assessment of cavitation erosion.



**Figure 1.** Time sequences of contours of vapor volume fraction obtained by (a) URANS method; (b) Experimental observations and (c) LES approach.

However, both approaches failed to capture the exact location where the re-entrant jet clearly cuts off the main sheet cavity just alike the experimental observations, which is almost at the leading edge, as indicated by red arrow in figure 1-(a)- ⑤. It is suggested that the numerical simulations conducted here in the 2D domain would miss the three-dimensionality effect of the flow, thus decreasing the thickness of the re-entrant jet in a weaker jet. This hypothesis has been confirmed by comparing 2D URANS results with the results from a 3D URANS computation, where the cut-off appears close to the leading edge and also clear horse-shoe shaped cloudy cavities can be reproduced[13,14].

By investigation of the characteristic shedding behavior predicted by LES approach, it is observed that the detachment of cloudy cavities is dominant by both reversed flow travels towards upstream, which will cut off cloudy cavities, and rotational motion of vortex structures, which will forms cavitating vortices at its center when the pressure falls below the vapor pressure. It confirms the statement from Hoekstra that the motion of the widely accepted re-entrant jet mechanism is a visual illusion because the motion of the cavity-liquid interface is not necessarily the same as the motion of the fluid particles[15]. In figure 2, the red arrows represent the main direction of the reversed liquid flow, and the black arrows indicate the vortex structures.

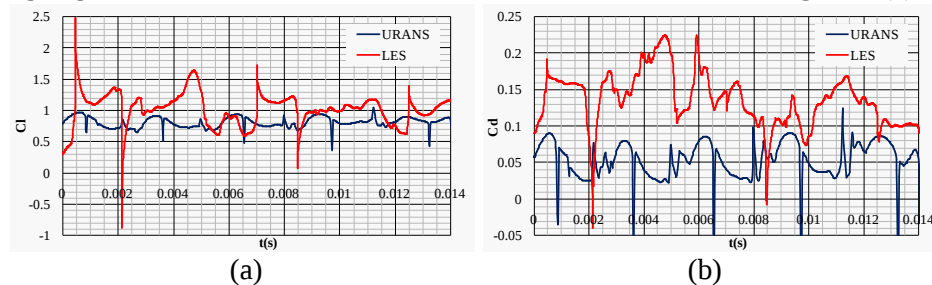


**Figure 2.** The velocity vectors colored by the vapor fraction corresponding to typical instants predicted by LES approach: (a) instant ⑤; (b) instant ⑥.

#### 4.2. Lift and drag

The lift and drag acting on the hydrofoil is greatly affected by the unsteady behavior of the cavitating flow, which will result in fluctuating forces with sudden peaks or drops that indicates high impact may occur. For time-histories of lift and drag coefficients obtained by URANS and LES computations, periodic lift and drag signals are predicted to reveal the regularly repeated unsteady dynamics, as shown in figure 3. It is noted that more unstable fluctuating force signals have been predicted by the LES computation in combination with remarkable peaks and troughs, interpreted for a higher averaged

lift and drag. The largest peak during one cycle can be correlated to the collapse of the cloudy cavities near the trailing edge, as indicated a moment between the instant ③ and ④ in figure 1-(c).



**Figure 3.** Time histories of (a) lift and (b) drag coefficients by URANS and LES computations.

## 5. Conclusions

The following conclusions can be drawn from this study:

- The LES results show better quantitative agreement with the experimental observations than the URANS computations, displaying a larger cavity extent and better prediction of the locations of the prominent shedding and collapses of the bubbly cloud.
- The inability to predict the exact location where the re-entrant jet clearly cuts off the main sheet for both approaches can be attributed to loss of three-dimensionality, which weakens the strength of the re-entrant jet.
- The break-off of the main sheet cavity and the shedding of cloudy cavities are associated with two typical mechanisms: the reversed flow travels upstream and cuts off cloudy cavities, and the inertia driven rotational motion of the flow at the closure of the sheet cavity causes shedding of vortex cavities.

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