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Dynamic behaviors of the turbulent cavitating flows based on the Eulerian and Lagrangian viewpoints

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ABSTRACT

In order to investigate the structures of the cavitating flow, a volume fraction transport equation with a hybrid turbulence model has been used to simulate the dynamics of the cavitation phenomenon over a two-dimensional ClarkY hydrofoil (AoA = 8°, $\sigma = 0.8$, and $Re = 7 \cdot 10^5$). From the Eulerian viewpoint, the interactions of pressure, vortex structure, and volume fraction have been evaluated, and the results have been validated carefully with the experimental observations. Four different flow stages can be categorized accordingly based on the development of the attached cavity, trailing edge cavities, and re-entrant jet.

Furthermore, the Finite-Time Lyapunov Exponent (FTLE) and the corresponding Lagrangian Coherent Structures (LCSs) have been used to separate dynamically distinct regions. Above the upper surface, the liquid flow captured by LCS A could travel along the cavity interface to the trailing edge. Similarly, the LCS C captures the liquid flow below the lower surface that can be attracted into the upper surface. From the corresponding particle tracking, these two flows meet near the trailing edge and mix together to form the re-entrant jet, which can be represented by the LCS B.

The current study shows that the LCS approach together with the Eulerian method can help us to have better understandings of the cavitating flow. The Lagrangian analysis especially indicates the underlying flow physics about the mixing process and bubble growth and decline behaviors. Most of the previous related studies only focus on the flow above the upper surface. The LCSs shown in this study also emphasize the importance of the flow structure of the lower surface, which provides more insightful information for the flow control and is worth further investigation.

1. Introduction

This study utilizes the Lagrangian Coherent Structures (LCSs) to get better understandings of the underlying physics of the turbulent cavitating flows. The introduction includes (i) the fundamentals of the cavitation and numerical modeling, and (ii) the basics of LCSs and the applications.

1.1. Cavitation

Cavitation occurs when the local liquid pressure is lower than the vapor pressure, leading to undesirable effects such as the noise, vibration, erosion, and power loss in components of the fluid machinery and underwater vehicle. The cavitation number σ is defined as $\sigma = (P - P_v)/0.5\rho_l U_\infty{}^2$ where P is the local fluid pressure, P_v is the vapor pressure, ρ_l is the liquid phase density, and U_∞ is the free stream velocity. The cavitation number is the most important dimensionless parameter to describe the cavitation intensity and tendency. As the cavitation occurs, the phase change process involves continuous evaporation and condensation [1,2]. In order to maintain the vapor phase inside the cavity, the heat transfer will be extracted from the liquid phase to overcome the latent heat. This is the so-called evaporative cooling. However, for most cases, such as the water under the room temperature, the thermal effect is insignificant due to the extremely large liquid-to-vapor density ratio (~O(5) at 298 K), and hence the isothermal assumption is usually applied to the cool water cavitation [3–5].

From computational aspects, the mixture model treats the vapor and liquid phase as a single continuous phase [4–6]. Under this framework, the Rayleigh–Plesset equation has been used widely to connect the phase change rate from a single individual bubble to the macroscopic bubble cluster [6–9]. The microscopic bubble interaction force and slip velocity between liquid and vapor phase are usually neglected to avoid further empirical modeling, and both phases share the same set of Navier–Stokes equations

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[6]. The mixture cavitation model is usually based on a transport equation of either volume fraction or mass fraction, and it assumes that the phase change takes place due to the difference between the local and vapor pressure. Accordingly, the evaporation term of the cavitation model is activated when the local pressure is lower than the vapor pressure, and vice versa for the condensation term. The details have already been well documented in Ref. [5,10]. Since the detail dynamics of cavitation is not well understood, additional empirical coefficients are usually necessary to regulate the strength of the evaporation and condensation rates. More details can be referred to Section 2.2.

Since the Reynolds number of the cavitating flow is usually very high (greater than O(5)), the turbulent modeling is unavoidable. Although the Large Eddy Simulation has (LES) already been implemented for the turbulent cavitating flows [10–13], the Favre-Averaged Navier–Stokes equations are still mainstream in the related fields due to its balance between the computational effort and accuracy. Within this category, the standard k–ε turbulence model usually tends to give excessive eddy viscosity and dissipates the possible large vortex motion. The implement of an eddy viscosity limiter can compensate this phenomenon [6]. Based on the resolution, the computed turbulence length scale can be compared with a given filter size. Once the turbulence length scale is larger than the filter size, the eddy viscosity can be reduced by a linear filter function [4–6,14,15]. Alternatively, since the sound of speed could drop several orders of magnitude as the phase change takes place [16,17], the induced compressibility could bring out the vortex motion that is difficult to be captured by the standard type turbulence model. As a result, the eddy viscosity limiter can be assigned as a function of the vapor volume fraction [6,7,17,18]. Alternatively, instead of using a limiter function for the eddy viscosity, the Partially Averaged Navier–Stokes (PANS) model directly imposes a constant ratio of the unresolved-to-total turbulent kinetic energy to reduce the eddy viscosity [19–20]. Further details of the turbulence modeling for cavitating flows can be referred to Section 2.3.

1.2. Lagrangian Coherent Structures

Contrast to the Eulerian viewpoint, such as the vorticity, Q, Q-R, Δ, and λ_2 criterion [19–24], the Lagrangian Coherent Structures (LCSs) can be regarded as a trajectory-based approach by considering the fluid flow as a dynamic system of fluid particles. The LCSs are extracted from the Finite-Time Lyapunov Exponent (FTLE), which characterizes the separation rate of neighborhood trajectories during a finite time. Therefore, the LCSs can separate the dynamically distinct regions of the flow fields [25–34]. This approach is frame-independent even under a rotational reference frame. For further detail dentitions of LCSs and FTLE, please refer to Section 3 and Ref. [25,29].

As for the applications of the LCSs, O'Farrell and Dabiri [26] have related the newly-growth LCSs to the initiation of the vortex pinch-off in the jet flow. Wilson et al. [27] have utilized the LCSs to study the swimming model of a self-propelling jellyfish. In their study, the Reynolds number of the biological locomotion is typically very low (O(1)–O(100)). Therefore, the flow visualization by vorticity is too dissipative and fails to distinguish different flow patterns. However, different mechanisms can still be identified by using LCSs. For a large environmental scale, Lekien and Leonard [28] have analyzed the high-frequency radar data of Monterey Bay by using the LCSs, and a clearer boundary of the current can be identified for pollution preventions. Similar study can also be found in Ref. [29]. Tang et al. [30] have further used the LCSs to analyze subtropical jet stream near Hawaii from the Weather Research and Forecasting (WRF) model. The LCSs corresponding to the turbulence can be identified and confirmed by the balloon measured data. Shadden et al. [31] have even utilized the LCSs to study the flow conditions in the healthy and ill cardiovascular system respectively.

For studies related to the propulsion and aerodynamics, Tang et al. [32] have used the LCSs to assess underlying physics of the gaseous jet injected into water, the particle tracking technique helps to understand the mechanisms of the gain of the propulsion during the back attack stage. The LCSs can also be applied to the foil with complex vortex structures [29,32–36]. Under the steady state condition, Shadden et al. [29] have shown a LCS starting from the separation point. Cardwell and Mohseni [33] have further analyzed the unsteady flow field around the foil. They have focused on where the particles come from by tracing the particle groups inside different LCS regions. Under similar framework, Tseng and Hu have further used LCSs to analyze the dynamic stall of a pitching foil [36], and their results shows that the reverse flow from the pressure side can interact strongly with the flow above the suction side. The topologies of the vortex shedding process have been evaluated in these studies through the particle tracking [32–36]. Consequently, the LCSs can potentially provide more insightful information for the flow control and is worth further investigation [33].

In this study, a volume fraction transport equation with a hybrid turbulence model has been used to simulate the dynamics of cavitation phenomenon over a two-dimensional ClarkY hydrofoil (AoA = 8°, σ = 0.8, and $Re = 7{\cdot}10^5$) [14,37]. Then the velocity data from the computational results is used to obtain the FTLE and LCSs. The goal in this study is to utilize the particle tracking around the LCSs to analyze the underlying cavitating dynamics

2. Numerical approaches for turbulent cavitating flows

The computational modeling in this study utilizes the Navier–Stokes equations with Favre-averaged turbulence closure. This section will introduce the governing equations.

2.1. Navier–Stokes equations

For the incompressible flow, the Reynolds-Averaged Navier–Stokes (RANS) model is used widely for the industry and academic purpose due to its balance between computational effort and accuracy [38–40]. However, for the compressible flow or flow field with substantial density variation, the Favre-Averaged Navier–Stokes model should be adopted. The mixture density ρ_m and pressure P come from the Reynolds-ensemble average, and while the velocity u is density-weighted average [4,39,40]. The continuity and momentum equations are listed below in Eqs. (1)–(4):

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial(\rho_m u_j)}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial \rho_m u_i}{\partial t} + \frac{\partial(\rho_m u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}^R) \quad (2)$$

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right) \quad (3)$$

$$\tau_{ij}^R = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\left(\mu_t\frac{\partial u_k}{\partial x_k} - \rho_m k\right) \quad (4)$$

In Eqs. (1)–(4), x is the coordinate, t is time, μ is the fluid viscosity, μ_t is the turbulent eddy viscosity, k is the turbulent kinetic energy, τ_{ij} is the stress, τ_{ij}^R is the Reynolds stress, and the subscript i and j stand for the Einstein notation. The nonlinear Reynolds stress τ_{ij}^R is approximated by the Boussinesq's gradient transport hypothesis in Eq. (4). The energy equation is not solved in this study due to the isothermal condition for the cool water cavitation [3–5].