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Large eddy simulation of turbulent cavitating flows

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Abstract.

Large Eddy Simulation is employed to study two turbulent cavitating flows: over a cylinder and a wedge. A homogeneous mixture model is used to treat the mixture of water and water vapor as a compressible fluid. The governing equations are solved using a novel predictor–corrector method. The subgrid terms are modeled using the Dynamic Smagorinsky model. Cavitating flow over a cylinder at Reynolds number (Re) = 3900 and cavitation number (σ) = 1.0 is simulated and the wake characteristics are compared to the single phase results at the same Reynolds number. It is observed that cavitation suppresses turbulence in the near wake and delays three dimensional breakdown of the vortices. Next, cavitating flow over a wedge at $Re = 200,000$ and $\sigma = 2.0$ is presented. The mean void fraction profiles obtained are compared to experiment and good agreement is obtained. Cavity auto–oscillation is observed, where the sheet cavity breaks up into a cloud cavity periodically. The results suggest LES as an attractive approach for predicting turbulent cavitating flows.

1. Introduction

Turbulent cavitating problems pose unique challenges in that apart from resolving the wide range of length and time scales, steep gradients arising due to vapor cavity collapse have to be handled efficiently. A non–dissipative base scheme with dissipation added locally near the discontinuities is a very attractive candidate to address these challenges. Traditionally, RANS has been the preferred approach to simulate cavitating flows. However, RANS does not predict the unsteady nature of cavitation with great accuracy. LES can therefore be a good approach for highly unsteady cavitating flows. In this paper, we present LES of two turbulent cavitating problems using a numerical method developed by Gnanaskandan and Mahesh [1]: cyclic cavitation behind a circular cylinder and sheet to cloud cavitation over a wedge. We study cavitation over a cylinder at $Re = 3900$ and $\sigma = 1.0$ to understand the effect of cavitation on Karman vortex shedding and wake characteristics. While bluff body wakes have been studied extensively for single phase flows, only a few studies exist that shed light on the effect of cavitation on vortex shedding [2, 3, 4]. The second problem is sheet to cloud cavitation over a wedge at $Re = 200,000$ and $\sigma = 2.0$. Sheet to cloud cavitation causes severe damage to the underlying structure when the cloud collapses. Several experiments have been conducted to understand the sheet to cloud transition mechanism [5, 6, 7] and in this study, we numerically simulate sheet to cloud cavitation transition and compare to the experiments of Ganesh [8].

2. Physical model and numerical method

The physical model used is the homogeneous mixture model, which treats the mixture of water and water vapor as a single compressible fluid and assumes the constituent phases to be in thermal and mechanical equilibrium. The governing equations are the compressible Navier Stokes equation for the mixture of water and vapor along with a transport equation for mass fraction of vapor. The system is closed by a non–barotropic mixture equation of state obtained


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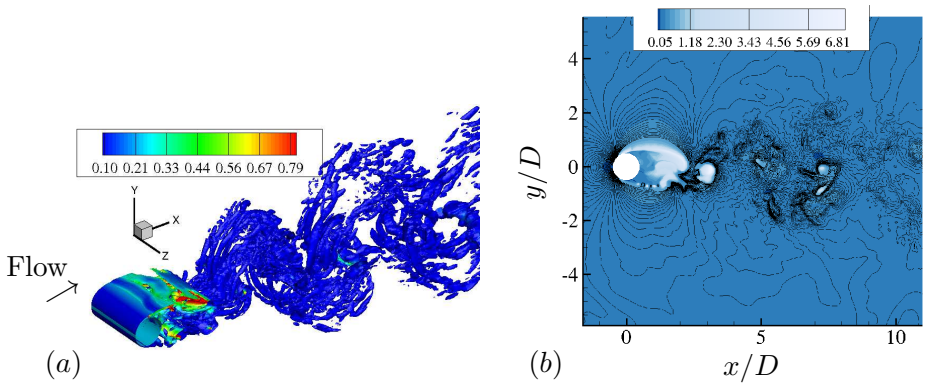


Figure 1. (a) Isocontours of Q-criterion colored by void fraction, (b) Instantaneous Mach number contours superimposed with lines of pressure.

from the stiffened equation of state for water and ideal gas equation of state for vapor. The density ratio of water to vapor in the simulations is 1000. The governing equations are Favre averaged and then spatially filtered to perform LES. The subgrid terms in the momentum and energy equation are modeled using the Dynamic Smagorinsky model (DSM), while the subgrid term in the mass fraction equation is neglected in the current study [1]. The numerical method uses a novel predictor–corrector algorithm. The predictor step uses a symmetric and non-dissipative scheme to obtain a predicted value for the conservative variables. The corrector step uses a characteristic-based filtering approach to add dissipation locally only in the vicinity of discontinuities. Further details on the predictor–corrector algorithm can be found in [1].

3. Turbulent cavitating flow over a circular cylinder

LES of turbulent cavitating flow at $Re = 3900$ and $\sigma = 1.0$ is performed. Figure 1(a) shows the instantaneous vortical structures in the form of Q-criterion colored by void fraction. Three dimensional flow structures of varying scales can be observed. The shear layer breaks up into smaller spanwise structures. The flow structures in the near wake, especially in the vapor cavity are larger when compared to the flow structures observed by Verma and Mahesh [9] in a single phase flow at the same Reynolds number. This is because of the effective lowering of Reynolds number by the presence of vapor. Further, small vapor pockets can be seen trapped in the smaller scale vortices downstream of the wake. Although the flow is three–dimensional inside the vapor cavity immediately downstream, breakdown to finer scales occurs downstream of the cavity closure. Figure 1(b) shows instantaneous contours of Mach number showing supersonic Mach numbers in the shear layer. Cavitation in wake vortices also causes locally supersonic Mach numbers there. The contour lines of pressure shows distorted fronts of pressure waves that are formed due to cavity collapse. Turbulence causes different points in the wave fronts to have different speeds resulting in their distortion. The Strouhal number corresponding to vortex shedding is 0.17 as compared to the single phase value of 0.2. Thus cavitation lowers the vortex shedding frequency.

The near–wake velocity profiles are compared to the single phase LES results of Verma and Mahesh [9] in Figure 2. The streamwise velocity profiles at all stations show a wider wake profile for the cavitating flow. The station $x/D = 3.0$ shows the maximum difference in the vertical velocity profile since it corresponds to the cavity closure region. Inside the cavity (except at $x/D = 1.06$), larger values of vertical velocity are obtained. Overall, cavitation yields a wider near–wake profile, representative of a low Reynolds number flow.

4. Turbulent cavitating flow over a wedge

LES of sheet to cloud cavitation over a wedge at $Re = 200,000$ and $\sigma = 2.0$ is performed. The averaged statistics presented in this section are obtained by performing a time average

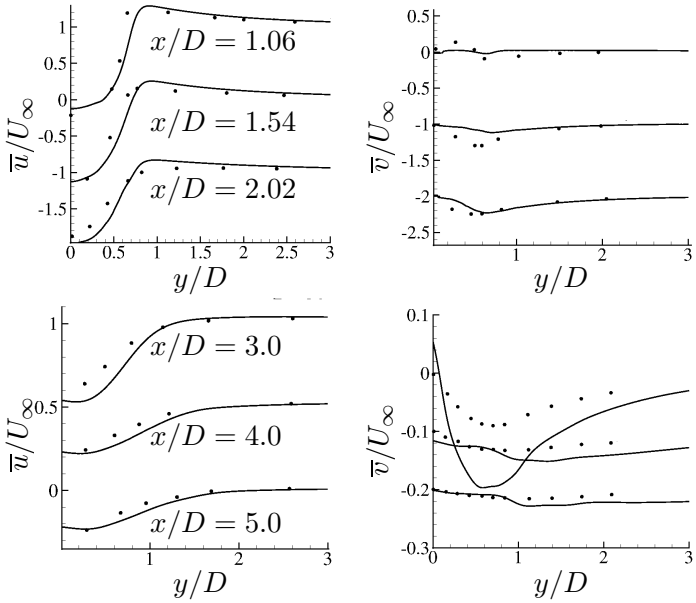
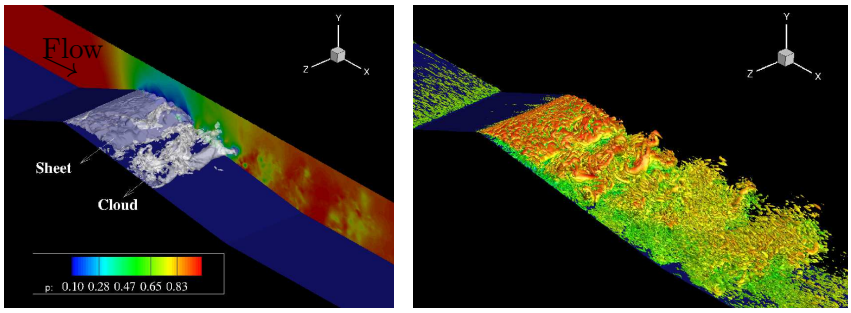


Figure 2. Comparison of velocity profiles at streamwise stations obtained from the present simulations to the single phase simulations at $Re = 3900$, • : Single phase results of Verma and Mahesh [9], —— : Cavitating flow (Present).



(*a*) (*b*)

Figure 3. (a) Instantaneous snapshots of isocontours of void fraction showing sheet and cloud cavities, (b) Isocontours of Q-criterion colored by streamwise velocity.

over 40 th/u_∞ and has approximately 30,000 samples, where h is the height of the wedge and u_∞ is the freestream velocity. The separation between the samples is 0.001 th/u_∞ which captures all relevant high frequencies. The non–dimensional time step used in the simulation is $tu_\infty/h = 1 \times 10^{-5}$. The nature of the instantaneous solution is illustrated using isocontours of void fraction in Figure 3(a) which shows the presence of both sheet and cloud cavities. The sheet cavity grows to an average length of $x/h = 2.1$. The leading edge of the sheet cavity in Figure 3(a) varies in the spanwise direction and these spanwise variations grow larger as we move towards the trailing edge of the cavity. After attaining its maximum length, the sheet cavity pinches off and the trailing edge of the sheet cavity rolls up into a cloud. This cloud is highly three dimensional and it is the collapse of this cloud that causes noise, vibration and surface erosion. The vertical plane in Figure 3(a) shows pressure contours. It can be observed that pressure exhibits both wave–like behavior (close to leading edge if the cavity) and a highly intermittent behavior (downstream of the cloud). The pressure waves produced on cavity collapse impinges on the growing sheet cavity and causes it to break into smaller cavities. Figure 3(b) shows isocontours of Q-criterion colored with streamwise velocity. The intensely vortical nature of the flow and wide range of length scales are apparent in both sheet and cloud regions. Small secondary cloud shedding occurs just before and after the main cloud

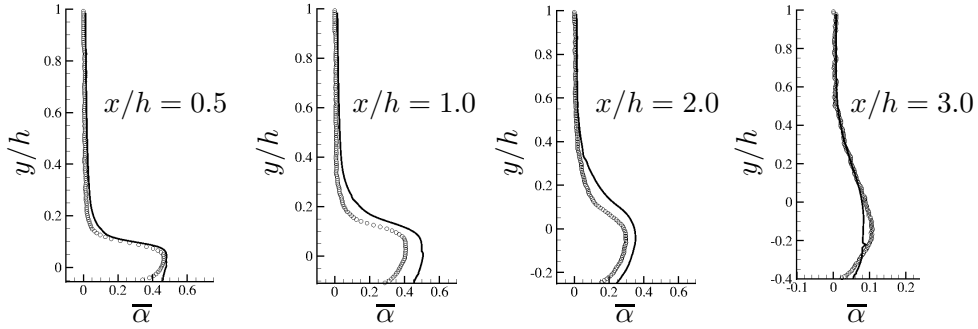


Figure 4. Comparison of mean volume fraction at different streamwise stations, —— : Present and ∘ : Experiment [8].

sheds, which is normally not captured in time averaged simulations. Leroux *et al.* [6] have observed these secondary cloud shedding in their experiments on a hydrofoil and the LES is also able to capture this secondary shedding. The Strouhal number corresponding to the auto–oscillation (extracted from spectra as well as animations) is 0.28, which lies within the range of 0.25-0.30 obtained by the experiments of Ganesh [8].

The time–averaged and span–averaged values of void fraction at different streamwise locations on the wedge is compared to the experimental results of Ganesh [8] in Figure 4. The agreement in the mean void fraction is very good at $x/h = 0.5$ and $x/h = 3.0$ stations, while LES slightly over–predicts void fraction at the other two stations. While the length of the cavity predicted by the simulation agrees well with the experiment, the simulation slightly over–predicts the thickness.

5. Summary

LES is used to study two different turbulent cavitating problems. In the cavitating flow over a cylinder, it is observed that cavitation suppresses turbulence in the near wake and delays three dimensional breakdown of the Karman vortices. Cavitation is also seen to reduce the vortex shedding frequency. In sheet to cloud cavitation over wedge, a cavity auto–oscillation is observed, where the sheet cavity breaks up and forms a cloud cavity. The sheet cavity is mildly unsteady with larger spanwise fluctuations near its trailing edge, whereas the cloud cavity is highly unsteady and three dimensional. The simulation is also able to predict secondary cloud shedding that is normally not captured using RANS. Good agreement with experiment is observed for both mean void fraction inside the cavity and auto–oscillation frequency.

6. Acknowledgments

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