Ocean Engineering 95 (2015) 94–105

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Analytical and experimental study of hydrodynamic and hydroacoustic effects of air injection flow rate in ventilated supercavitation

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ARTICLE INFO

Article history:
Received 1 December 2013
Accepted 30 November 2014

Keywords:
Hybrid hydroacoustic model
Supercavitation
Large eddy simulation
Physical source and sink model

ABSTRACT

Formation of supercavity around an underwater vehicle improves the hydrodynamic performance of fluid flow and causes vehicle to reach higher speeds. However, sound generated by the supercavitation is very effective in recognition of the vehicle and reduction in its controlled precision. In this study, compressible Navier–Stokes equations were solved by using the method of Large Eddy Simulation and combining them with the physical source and sink model to simulate supercavitation flow numerically. The qualitative and quantitative parameters from numerical results compared and confirmed with experimental results. Subsequently, by considering a suitable control surface around the simulated supercavity, the needed parameters for acoustic analysis were provided. Eventually, by solving the hybrid hydroacoustic model presented by Riahi et al. the far field noise of supercavity was estimated. In light of important role of air injection flow rate in the formation of ventilated supercavity, hydrodynamic and hydroacoustic results for three different lengths of supercavity stemmed by different air injections, were compared with each other. According to the obtained results, acoustic behavior of the supercavity was changed by increasing of air injection.

1. Introduction

Underwater vehicles like submarines and torpedoes cannot reach high speeds due to the existence of friction drag over their body (Choi and Ruzzene, 2006). Supercavitation is a phenomenon which reduces the friction drag of underwater vehicle more than 90% and causes the vehicle to reach speeds up to 120 (m/s) (Moghimi, 2009; Honghui and Makoto, 2004). By formation of supercavity in the flow, the distribution of noise sources with different frequencies in the flow field are formed (Moghimi, 2009; Morán, 1984). Low frequency sound generated by these sources leads to the detection of underwater vehicles and high frequency acoustic waves interface with navigation system of underwater vehicle (Ho et al., 2011). As a result, next to the hydrodynamic advantages, acoustic noise stemmed from the supercavity is considered as an undesired occurrence. In light of positive and negative aspects of supercavity formation, hydrodynamic and hydroacoustic investigations of supercavitation flow has expanded and developed drastically.

Since 1994, two models of slender-body and boundary elements have been presented for axisymmetric supercavities (Kirschner et al., 1995; Varghese et al., 1997). Both models simulate the supercavity's area with high precision. In recent years, Shafaghat et al. (2009), by using a direct boundary element method along with Riabouchinsky model, studied potential flow around conic and disc types of cavitators for simulating supercavitation. Nouri et al. (2010), by introducing physical source and sink model and using artificial viscosity, modeled the supercavitation flow around 2-D cavitator and obtained supercavity wall vividly. Amromin (2007) studied effects of shallow water on the cavity shape. Saranjam (2013) numerically investigated formation, evolution and dissolving of natural supercavity around an underwater vehicle. This simulation was done by combining unsteady RANS equations with a six-degree-of-freedom rigid body motion model. He compared and verified the numerical results with obtained experimental results from high speed cameras, qualitatively. Nouri and Eslamdoost (2009) analyzed supercavitating potential flow by using boundary element method (BEM), numerically. Zou et al. (2013) modeled effects of gravity and angle of attack on ventilated supercavity. Xiang et al. (2011) studied drag reduction by production of ventilated partial cavity as well as dispersed micro bubbles stemmed from partial cavity.

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http://dx.doi.org/10.1016/j.oceaneng.2014.11.013
0029-8018/

The acoustical study of cavitation could be known to start from investigations on single bubble flow dynamics and collapse. Studies conducted by Rayleigh and Plesset are considered fundamental in this regard (Knapp et al., 1970). Wang and Brennen (1999), by using Rayleigh–Plesset equation, could numerically model linear, weak nonlinear and completely nonlinear growth and collapse of cavitation bubbles. Also, Reisman (1997) experimentally investigated noise stemmed from shock wave generated in cloud cavitation over a hydrofoil in water tunnel. His study indicated that generated noise by collapsing of cloud cavitation is by far more than noise produced by adding noise due to collapse of each single bubble (existing in a cloud). Another group of researchers studied underwater propeller noise with and without cavitation by using Ffowcs–Williams and Hawkings (FWH) equation (Salvatore and Ianniello, 2003; Salvatore et al., 2009; Seol et al., 2002). Seo et al. (2008) chose Direct Numerical Simulation (DNS) method for estimating cloud cavitation noise. He estimated cavitation flow noise by using compressible Navier–Stocks equations and applying density-based homogeneous equilibrium model.

In another group of studies conducted in recent years, noise of supercavitation flow was investigated experimentally and analytically by Foley et al. (2010), Foley and University (2009). Foley et al. (2008) equated artificial supercavity with a spheroidal model and studied the noise caused by the exiting gas in different frequencies analytically. Howe et al. (2009) studied acoustic self-noise generated at the nose of underwater vehicle due to supercavity wall oscillations. Ramesh et al. (2012) analyzed high frequency noises generated by supercavity in the frequency domain by using boundary element method (BEM). Riahi et al. (2013), in order to obtain a suitable mathematical model for analysis of noise associated with cavitation, by employing perturbation method to conservation equations, decompose these equations into two groups of leading and first order. Based on their finding, equations of first order are suitable mathematical model for simulation of noise associated with cavitation and supercavitation flow.

As supercavitation noise with low and high frequency has significant effects on recognition and navigation of underwater vehicle, it is try in this study to introduce a hybrid method for estimating supercavitation noise. This method has no restriction in range of frequency and considers both low and high frequency sound. This hybrid approach is developed based on mathematical model presented by Riahi et al. (2013) and estimated supercavitation noise in two steps of hydrodynamic and hydroacoustic. Also, the other methods or models for estimating of supercavity noise assume that oscillations of supercavity wall are the main source of sound. On the other hand, the impingement of gas to cavity wall is the main factor for oscillation of supercavity wall. So, those methods are based on this assumption that the only source of generating sound in ventilated supercavitation flow is impingement of gas to supercavity wall. However, the presented method beside of considering gas impingement as the main factor for oscillation of cavity, considers oscillation due to other phenomena like the reentrant jet. For achieving these, in the present study initially, hydrodynamics of flow is investigated experimentally and numerically. Then, according to the reality behavior of simulated supercavity that validated with experiment, the generated noise could be estimated.

For numerical modeling of hydrodynamic behavior of supercavitation flow, the obtained leading order mathematical model presented by Riahi et al. (2013) was simulated by using LES (Large Eddy Simulation) coupled with the physical source and sink model presented by Nouri et al. (2010). Also, as hydroacoustic equations being coupled with hydrodynamic (according to Ref. Riahi et al., 2013), for acoustic analysis of supercavitation, it is necessary to develop a hybrid method between these two fields. This hybrid method is developed in two steps. It is based on using hydrodynamic results over a control surface as a boundary condition for acoustic step and solving of first order equations obtained by Riahi et al. (2013). Also, by defining a benchmark problem in the acoustic field, acoustic equations and the solution algorithm have been validated. Finally, hydrodynamic result (Experimental and Numerical) as well as hydroacoustic result (Numerical) for different air injection flow rate have been compared.

2. Governing equations

Since acoustic is part of flow dynamic, conservation equation of mass, momentum and energy beside of state equation are recognized as the fundamental equations in the analysis of supercavitation noise. Riahi et al. (2013) decompose the conservation equations by using perturbation method. Based on their study, leading order equations indicating mathematical model of flow hydrodynamic is presented as following;

$$(St)\frac{\partial \rho_0}{\partial t}+\nabla\cdot\left(\rho_0\vec{u}_0\right)=0 \tag{1}$$

$$(St)\left[\frac{\partial\left(\rho_0\vec{u}_0\right)}{\partial t}\right]+\left[\vec{u}_0\nabla\cdot\left(\rho_0\vec{u}_0\right)\right]=(Eu)\left[-\nabla p_0\right]+\frac{1}{\text{Re}}\left[\nabla^2\vec{u}_0+\left(\frac{1}{3}+\frac{\mu_v}{\mu}\right)\left(\nabla div\left(\vec{u}_0\right)\right)\right] \tag{2}$$

$$(St)(Eu)\frac{\partial p_0}{\partial t}+(Eu)\left(\vec{u}_0\cdot\nabla\right)p_0=\left(\frac{c}{\tilde{U}}\right)^2\rho_0\left(\nabla\cdot\vec{u}_0\right)+\left(\frac{c^2\beta}{c_p}\right)\left[\frac{1}{\text{Re}_\upsilon}\left(\nabla\cdot\vec{u}_0\right)^2+\frac{1}{\text{Re}}2\left\{e^0_{ij}e^0_{ji}-\frac{1}{3}\left(\nabla\cdot\vec{u}_0\right)^2\right\}\right] \tag{3}$$

It is evident that these equations are compressible form of Navier–Stocks equations (Nouri et al., 2010). Also, first order equations presented in Eqs. (4)–(6) representative of the presented hydroacoustic model (Riahi et al., 2013);

$$(St)\frac{\partial \rho_1}{\partial t}+\nabla\cdot\left(\rho_0\vec{u}_1\right)+\nabla\cdot\left(\rho_1\vec{u}_0\right)=\rho_0 Q_0 \tag{4}$$

$$\begin{aligned}&(St)\left[\frac{\partial\left(\rho_1\vec{u}_0\right)}{\partial t}\right]+(St)\left[\frac{\partial\left(\rho_0\vec{u}_1\right)}{\partial t}\right]+\left[\left(\vec{u}_0\cdot\nabla\right)\left(\rho_1\vec{u}_0\right)\right]\\&+\left[\left(\vec{u}_0\cdot\nabla\right)\left(\rho_0\vec{u}_1\right)\right]+\left[\left(\vec{u}_1\cdot\nabla\right)\left(\rho_0\vec{u}_0\right)\right]\\&=(Eu)\left[-\nabla p_1\right]+\frac{1}{\text{Re}}\left[\nabla^2\vec{u}_1+\left(\frac{1}{3}+\frac{\mu_v}{\mu}\right)\left(\nabla\left(div\left(\vec{u}_1\right)\right)\right)\right]+\rho_0 u_0 Q_0\end{aligned} \tag{5}$$

$$\begin{aligned}&(St)(Eu)\frac{\partial p_1}{\partial t}+(Eu)\left(\vec{u}_0\cdot\nabla\right)p_1+(Eu)\left(\vec{u}_1\cdot\nabla\right)p_0\\&=-\left(\frac{c}{\tilde{U}}\right)^2\rho_0\left(\nabla\cdot\vec{u}_1\right)-\left(\frac{c}{\tilde{U}}\right)^2\rho_1\left(\nabla\cdot\vec{u}_0\right)\\&+\left(\frac{c^2\beta}{c_p}\right)\left[\frac{2}{\text{Re}_\upsilon}\left(\nabla\cdot\vec{u}_0\right)\left(\nabla\cdot\vec{u}_1\right)\right.\\&+\frac{2}{\text{Re}}\left\{\frac{1}{4}\frac{\partial \mathrm{u}_{0\mathrm{i}}}{\partial \mathrm{x}_\mathrm{j}}\frac{\partial \mathrm{u}_{1\mathrm{j}}}{\partial \mathrm{x}_\mathrm{i}}+\frac{1}{4}\frac{\partial \mathrm{u}_{0\mathrm{i}}}{\partial \mathrm{x}_\mathrm{j}}\frac{\partial \mathrm{u}_{1\mathrm{i}}}{\partial \mathrm{x}_\mathrm{j}}+\frac{1}{4}\frac{\partial \mathrm{u}_{1\mathrm{i}}}{\partial \mathrm{x}_\mathrm{j}}\frac{\partial \mathrm{u}_{0\mathrm{j}}}{\partial \mathrm{x}_\mathrm{i}}+\frac{1}{4}\frac{\partial \mathrm{u}_{0\mathrm{j}}}{\partial \mathrm{x}_\mathrm{i}}\frac{\partial \mathrm{u}_{1\mathrm{j}}}{\partial \mathrm{x}_\mathrm{i}}\right.\\&\left.\left.-\frac{2}{3}\left(\nabla\cdot\vec{u}_0\right)\left(\nabla\cdot\vec{u}_1\right)\right\}\right]\end{aligned} \tag{6}$$

In these relations, p_0, $\vec{u}_0$, ρ_0 and Q_0 are non-dimensional pressure, velocity, density and fluid mass source or sink in the hydrodynamic order. p_1, $\vec{u}_1$, ρ_1 and Q_1 are non-dimensional pressure, velocity, density and fluid mass source or sink in the hydroacoustic order. $\tilde{U}$ is the scale term of velocity that used for scale analysis, c is speed of sound, C_p is the heat capacity at constant pressure and$\beta=1/\rho(\partial\rho/\partial T)_{p_0}$ is constant. Also, *Re*, *Eu* and *St* are Reynolds, Euler and Strouhal number. Presence of leading order terms (means p_0, $\vec{u}_0$, ρ_0 and Q_0) in the