Numerical 3D analysis of cloud cavitation shedding frequency on a circular leading edge hydrofoil with a barotropic cavitation model

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Abstract. A compressible density-based time-explicit low Mach number consistent viscous flow solver is utilised in combination with a barotropic cavitation model for the analysis of cloud cavitation on a circular leading edge (CLE) hydrofoil. For 5° angle of attack, cloud structure and shedding frequency for different cavitation numbers are compared to experimental data. A strong grid sensitivity is found in particular for high cavitation numbers. On a fine grid, a very good agreement with validation data is achieved even without explicit turbulence model. The neglect of viscous effects as well as a two-dimensional set-up lead to a less realistic prediction of cloud structures and frequencies. Comparative simulations with the Sauer-Schnerr cavitation model and modified pre-factors of the mass transfer terms underestimate the measured shedding frequency.

1. Introduction

Depending on geometry, fluid and flow conditions, different types of large-scale cavitation structures occur. One of the more aggressive types is cloud cavitation, which is characterised by a periodic separation of vapour sheets from a surface caused by a re-entrant jet and shedding of these vapour structures as clouds. This separation may also be influenced by shock waves from imploding vapour clouds [1]. Since cloud cavitation occurs in hydraulic machinery such as pumps, simple hydrofoil test cases are utilised to investigate cavitation models.

In the cavitation model of Schnerr and Sauer [2], referred to as Sauer-Schnerr model in the following, a mass transfer rate based on the Rayleigh equation is introduced as source/sink term in the void fraction transport equation and combined with an inviscid implicit flow solver. They determine a shedding frequency of 11 Hz for the NACA0015 hydrofoil at $\alpha = 6°$ and cavitation number $\sigma = 1.0$. For the same operating point and cavitation model, Li [3] and Oprea et al. [4] have found 11 Hz and 17 Hz as dominant frequency, respectively. Koop [5] and Sezal [6] apply a barotropic model and obtain 24 Hz and 9 Hz, respectively. Gosset et al. [7] compare different turbulence models in combination with the Sauer-Schnerr model for a wide range of operating points in 2D-simulations with one pre-factor $C_{cond} = 2$ in the mass transfer sink term. Frobenius [8] and Deimel et al. [9] have applied the Sauer-Schnerr model to a 2D circular leading edge (CLE) hydrofoil at $\alpha = 5°$ with a 2D computational set-up. Frobenius has restricted his investigations to cavitation numbers in a narrow range of $\sigma = 2.0$ to 2.2 and achieved a good agreement with measured shedding frequencies. Deimel et al. [9] have found that for higher cavitation numbers in contrast to the data no periodic shedding but steady sheet cavitation was predicted and introduced pre-factors in the source/sink term according to table 1 to obtain cloud cavitation in the entire range $\sigma = 2.0$ to 2.7. These exemplary cited and other CFD studies with mass transfer models based on a Rayleigh source/sink term show large scatter in shedding

frequency. Dular et al. [10] apply a 2D implicit pressure-based solver on the CLE-hydrofoil and use a barotropic model with a smoothed density gradient to avoid too steep density variations and overcome numerical stability problems. A shedding frequency of about 60 Hz at $\sigma = 2.3$ is obtained. The present work aims at the assessment of a barotropic model in combination with a pressure wave resolving hyperbolic solver for prediction of shedding frequencies on the CLE-hydrofoil.

2. Method
For all simulations OpenFOAM® is utilised. A homogeneous mixture of liquid and vapour within each computational cell is assumed. For the Sauer-Schnerr model two empirical pre-factors C_{cond} and C_{vap} for the source/sink term in the vapour volume fraction equation enable calibration to specific flow problems, whose values have been adapted for CLE-hydrofoil simulations in a 2D numerical set-up in [9], as specified in table 1. The Sauer-Schnerr model is combined with an incompressible, time-implicit solver. The SST turbulence model [11] with a modification by Reboud [12] is used, which limits the eddy-viscosity in the two-phase region.

Table 1. Cavitation models.

Model	Sauer-Schnerr [2]	barotropic [13]
Model type	mass transfer, Rayleigh equation	equilibrium, equation of state
Parameters	$C_{cond} = 4$, $C_{vap} = 16$ [9]	free of parameters
Num. solver	implicit, pressure-based	explicit, density-based [14]
Friction/turbulence	SST model [11] with limited eddy-viscosity [12]	without explicit turbulence model

On the other hand a barotropic cavitation model [13] representing an isentropic path at thermodynamic equilibrium is applied as an equation of state $p(\rho)$ in combination with a compressible, density-based solver with low Mach number consistent flux functions and modified four-stage Runge-Kutta scheme with enlarged stability region, proposed by Schnerr et al. [14]. Density and velocity are reconstructed with the schemes MINMOD [15] and GammaV [16], respectively. This method accurately resolves the propagation of cavitation-induced pressure waves as shown by [5] for hydrodynamic cavitation and [17] for the prediction of erosion sensitive areas in acoustic applications. The OpenFOAM® implementation was done by [18].

3. CLE-hydrofoil
Böhm [19], Hofmann [20] and Bachert [21] have determined the shedding frequency of vapour clouds by means of high speed video analysis and FFT with a Hann-window of four pressure sensors on the suction side of the hydrofoil. The shedding frequency increases with cavitation number, with a low dependence on the Reynolds number, see figure 5. For our simulations we reproduce the test section geometry of [19] and choose a 5° angle of attack, see figure 1. Two grid resolutions, corresponding to O-Grid cell numbers of 196x35x50 and 392x70x100 in circumferential, wall-normal and spanwise direction, are investigated. The y^+ wall values are about 100 and 60, respectively. At the inlet a fixed velocity $u = 13\,\mathrm{m/s}$ corresponding to $Re = 1.3 \cdot 10^6$ is specified. The fluid is water.

A time step of $2 \cdot 10^{-6}$ s is chosen for the implicit time integration with the Sauer-Schnerr model and corresponds to a convective CFL number of 0.2 and a resolution of one shedding cycle with more than 3000 time steps. For the explicit time integration with the barotropic model the time step is limited to a maximum of $4 \cdot 10^{-8}$ s (acoustic CFL number < 0.95).
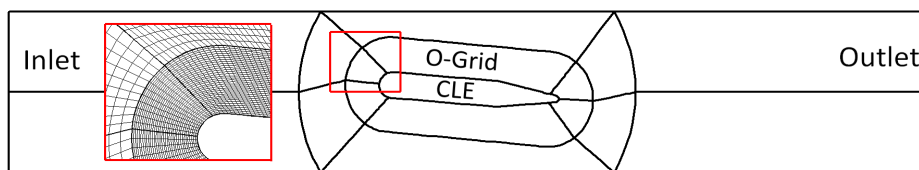

Figure 1. Block structure and zoom of coarse mesh (0.35 million cells).
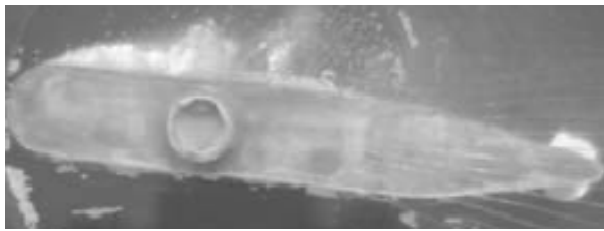
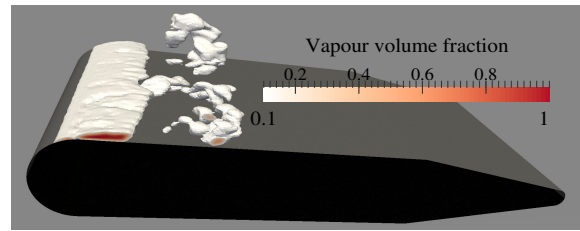**Figure 2.** CCD image [21] of cloud structures at $\sigma = 2.5$.

Figure 3. Exemplary time instant for a 3D Navier-Stokes simulation at $\sigma = 2.5$ with barotropic model on the fine mesh.

4. Results

For the assessment of the cloud structures in the simulation, iso-surfaces of void fraction are compared to integral data in spanwise direction from transmitted light images (see figure 2) as well as local data from light-section images [19]. The frequency is obtained in the same way as in the experiments applying a FFT to virtual pressure sensors [9], see figure 4. Since some ambiguity was found in particular for 2D results as already reported by [9], the FFT analysis is supported by a manual count of shedding structures.
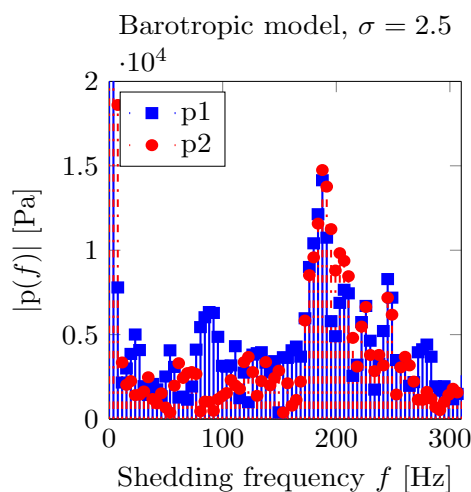

Figure 4. Exemplary FFT result of two virtual pressure sensors on the 3D coarse mesh.
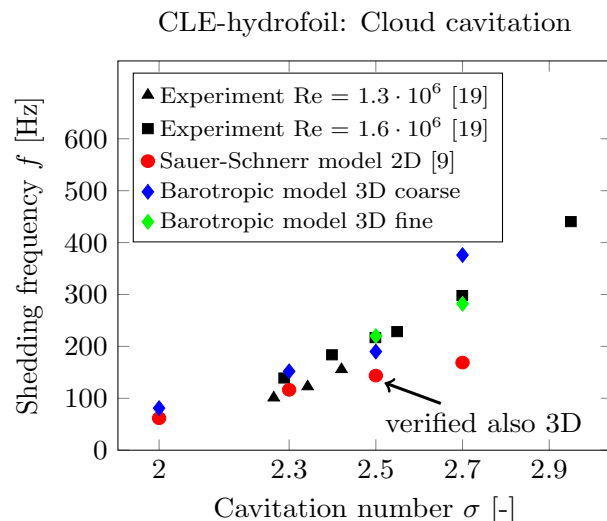

Figure 5. Frequency obtained with experiments and both cavitation models for different operating points.

For the barotropic model, after a relatively short initial-solution influenced time period, a quasi-periodic shedding occurs. By a time convergence study for $\sigma = 2.5$ on the coarse grid where up to 100 cycles have been calculated, a dependence of the shedding frequency on the number of evaluated cycles is found. Compared to the dominant frequency obtained after about 100 cycles, the deviation drops below 5 % for an analysis interval of 10 and more cycles. Due to the high calculation time on the fine grid, between 9 and 20 cycles are calculated for the barotropic model. We estimate that the frequency error is negligible on the coarse grid and lower than 7 % on the fine grid.

2D results by [9] are available for the Sauer-Schnerr model. Deimel et al. [9] have demonstrated that the fine grid of the present study yields grid-independent 2D results. In the present study 3D fine grid simulations for $\sigma = 2.5$ are performed to assess the influence of 3D effects. 3D structures develop in spite of the 2D geometry. However, the 3D-simulation yields only minor differences to the 2D set-up shedding frequency. On the other hand for 2D simulations with barotropic model and $\sigma = 2.5$, too low frequencies are found in combination

with shedding clouds that are too small near the leading edge and too big near the trailing edge compared to measurements. For 3D-simulations, frequencies can be uniquely deduced from the FFT (exemplary 190 Hz for $\sigma = 2.5$ on the coarse grid, see figure 4), which are closer to the experiment. A similar cloud structure as observed in the experiment is found and shown for an exemplary time instant in figure 3.

By a comparison of the 3D Navier-Stokes with 3D Euler results for $\sigma = 2.5$, the effect of viscosity is assessed. In Euler simulations for the barotropic model, the re-entrant jet occurrence rate as well as shedding frequency are overestimated compared to data. The cloud structures are smaller due to the shorter periods between shedding events and in particular smaller than observed in the experiments. For Euler simulations with the Sauer-Schnerr model also a higher occurrence rate of the re-entrant is observed. However, bigger cloud structures develop, since clouds rotate without being advected and coalesce to bigger clouds which finally extend over more than one half (instead of one third as in the experiment) of the CLE-hydrofoil. Shedding of the bigger clouds leads to lower frequencies (e.g. 100 Hz at $\sigma = 2.5$).

Frequency vs cavitation number is shown in figure 5 for experiment and viscous simulations. Since 3D effects seem to have a minor effect for shedding frequencies obtained by the Sauer-Schnerr model, 2D results by [9] are included while as discussed above an exemplary 3D simulation reproduced the 2D shedding frequency for $\sigma = 2.5$. For the 3D barotropic model results, a serious grid dependence is observed, and no unique trend of the grid resolution is discernible for $\sigma = 2.5$ and $\sigma = 2.7$. The fine grid results are significant closer to experimental data, so that the coarse grid results are considered unreliable. Both cavitation models capture the increase of frequency with increasing cavitation number, while the Sauer-Schnerr model underestimates the data significantly for higher cavitation numbers. For these higher cavitation numbers, the barotropic model fine grid results are in very good agreement with the data.

5. Conclusions

Although empirical pre-factors in the URANS Sauer-Schnerr model have been modified to obtain the best agreement with data, the barotropic model shows particularly for high cavitation numbers a better shedding frequency prediction in spite of its simplifying assumption i.e. equilibrium thermodynamics and no use of an explicit turbulence model. However, the grid study needs to be extended to even finer grids. Due to the promising results of the barotropic model and since it does not contain empirical parameters, it is planned to further assess its potential to predict cloud cavitation also for more complex test cases, in spite of a strong grid dependence and high CPU times.

References

[1] Arndt R E A 2011 *WIMRC Proc. 3rd Int. Cavitation Forum* (University of Warwick)
[2] Schnerr G H and Sauer J 2001 *ICMF Proc. 4th Int. Conf. on Multiphase Flow* (New Orleans)
[3] Li Z R 2012 *PhD Thesis* (TU Delft)
[4] Oprea O I and Bulten N 2011 *WIMRC Proc. 3rd Int. Cavitation Forum* (University of Warwick)
[5] Koop A H 2008 *PhD Thesis* (University of Twente)
[6] Sezal I H 2009 *PhD Thesis* (TU Munich)
[7] Gosset A, Lema M and López Peña F 2012 *Proc. 8th Int. Symp. on Cavitation* (Singapore)
[8] Frobenius M 2004 *PhD Thesis* (TU Munich)
[9] Deimel C, Günther M and Skoda R 2014 *EPJ Web of Conf.* **67** 02018
[10] Dular M and Coutier-Delgosha O 2009 *Int. J. for Numer. Meth. Fluids* **61** pp 1388-410
[11] Menter F R 1994 *AIAA Journal* **32** pp 1598-605
[12] Reboud J L, Stutz B and Coutier-Delgosha O 1998 *Proc. 3rd Int. Symp. on Cavitation* (Grenoble)
[13] Iben U 2002 *Systems Analysis Modelling Simulation* **42** pp 1283-307
[14] Schnerr G H, Sezal I H and Schmidt S J 2008 *Physics of Fluids* **20** 040703
[15] Harten A 1983 *J. Computational Physics* **49** pp 357-93
[16] Jasak H, Weller H G and Gosman A D 1999 *Int. J. for Numer. Meth. Fluids* **31** pp 431-49
[17] Mottyll S, Müller S, Niederhofer P, Hussong J, Huth S and Skoda R 2014 *EPJ Web of Conf.* **67** 02078
[18] Deimel C and Skoda R 2014 *9th OpenFOAM workshop* (Zagreb)
[19] Böhm R 1998 *PhD Thesis* (TU Darmstadt)
[20] Hofmann M 2000 *PhD Thesis* (TU Darmstadt)
[21] Bachert B 2004 *PhD Thesis* (TU Darmstadt)