Extension and Validation of the CFX Cavitation Model for Sheet and Tip Vortex Cavitation on Hydrofoils

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Overview

• Introduction
• Cavitation project
  – Goals
  – Cavitation model
  – Testcases
• Results
  – Testcase set-up
  – Validation studies
• Summary
Cavitation on Pumps, Propellers & Hydrofoils

- Cavitation phenomena
- Propeller
  - Tip vortex cavitation
- Hydrofoil
  - Sheet & cloud cavitation
Cavitation Project

• **Title**
  – Investigation of higher order pressure fluctuations and its influence on ship stern, taking into account cavitation at propeller blades

• **Project partners**
  – SVA Potsdam, ANSYS Germany

• **Duration**
  – July 2005 to June 2008

• **Funded by German Ministry of Education and Research (BMBF)**

• **Main issues**
  – CFD & experiments for ship propeller cavitation
  – Cavitation including transient effects
  – Cavitation induced pressure fluctuations and interaction with ship stern
Cavitation Model-Rayleigh-Plesset Equation

- Interfacial mass transfer

\[ \Gamma_{lv} = \dot{m}_{lv} A_{lv} \]

\[ \dot{m}_{lv} = \frac{d m_v}{d t} = \rho_v \frac{d R}{d t} \]

\[ \frac{d R}{d t} = \sqrt{\frac{2}{3}} \frac{P_v - P}{\rho_1} \]
Cavitation Model-Rayleigh-Plesset Equation

\[ \Gamma_{lv} = F_{vap} \frac{3 \alpha_{nuc} (1 - \alpha_v)}{R} \rho_v \sqrt{\frac{2}{3} \frac{P_v - P}{\rho_1}} \text{ if } P < P_v \]

\[ \Gamma_{vl} = -F_{con} \frac{3 \alpha_v}{R} \rho_v \sqrt{\frac{2}{3} \frac{P - P_v}{\rho_1}} \text{ if } P > P_v \]

- Modified interfacial area density for vapourisation
- \( F_{vap} = 50, \ F_{con} = 0.01 \)
- \( \alpha_{nuc} = 5 \times 10^{-4} \)
Turbulent Pressure Fluctuations

Pressure fluctuations in the (U)RANS equations:

\[ P = \overline{P} + p' \]

Where

\[ \tilde{p} = \sqrt{p'^2} \sim CAV_{\text{coef}} \rho (1 - \alpha_v)k = \frac{1}{2} CAV_{\text{coef}} \rho (1 - \alpha_v) (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \]

Therefore:

\[ \frac{dR}{dt} = \sqrt{\frac{2(P_v - \overline{P} - \tilde{p})}{3\rho_i}} \]

CAV_{\text{coef}} = 0.39
Project Testcases

Arndt: 3D profile

Le: 2D profile
• Measurements of Le et al. (1993) & Franc (2001)
  – Two-dimensional profile
  – Different cavitation phenomena

\[ \sigma = \frac{P_\infty - P_1}{0.5 \rho v_\infty^2} \]
Set-up: Boundary Conditions

- **Inlet**: Specified velocity (from Reynolds number)
- **Walls**: Free slip
- **Outlet**: Static pressure for entrainment
Meshing: Grid Hierarchy

- ICEM CFD HEXA
  - Geometry rotation for different angle of attack
- 2d refinement between grids by scale factor 2×2

<table>
<thead>
<tr>
<th>Grid</th>
<th>Coarse(2)</th>
<th>Medium(3)</th>
<th>Fine(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes</td>
<td>56,452</td>
<td>224,264</td>
<td>893,986</td>
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<tr>
<td>Number of elements</td>
<td>27,840</td>
<td>111,360</td>
<td>445,440</td>
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<td>Minimum grid angle</td>
<td>41°</td>
<td>38°</td>
<td>43°</td>
</tr>
<tr>
<td>First layer distance y [µm]</td>
<td>10</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>Average y⁺</td>
<td>4</td>
<td>2</td>
<td>1</td>
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Validation: Cavitation Length

$C_0 = 0.198\text{m}$

- Transient simulations, time averaged data

$\alpha = 4^\circ$
$\sigma = 0.5$

$\alpha = 0^\circ$
$\sigma = 0.4$

$\alpha = -4^\circ$
$\sigma = 0.3$
Validation: Cavitation Length

- Transient simulation, $\alpha=4^\circ$, $\sigma=0.5$
Validation: Pressure Distribution

- Pressure coefficient distribution on foil upper side
- Angle of attack: $\alpha = 2.5^\circ$ and $\alpha = 3.5^\circ$

$\sigma = 0.55$

Transient simulations, time averaged data

\[ c_p = \frac{P - P_\infty}{0.5 \rho v_\infty^2} \]
• Pressure coefficient distribution on foil upper side
• Angle of attack: $\alpha=3.5^\circ$, $\sigma=0.55$

• Transient simulations, time averaged data
Arndt Profile

• Measurements by Arndt, R.E.A. and Dugue (1992)
Set-up: Boundary Conditions

- **Inlet**
  - Computed from Re number
- **Outlet**
  - Static pressure for entrainment
- **Walls**
  - No slip
Meshing: Topology

- ICEM CFD structured meshes
  - C-Grid type grid around foil surface
  - Quarter O-Grid between C and O-Block connection at blade tip
Meshing: Grid Hierarchy

- Boundary layer resolution
  - Relation of first cell spacing to \( y^+ \) value
    \[
    \Delta y = L \sqrt{80} \Re_L^{-13/14} \Delta y^+
    \]
- Scaling factor between grids \( \sim 3\sqrt[4]{4} \times 3\sqrt[4]{4} \times 3\sqrt[4]{4} \)

<table>
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<th>Coarse (1)</th>
<th>Medium (2)</th>
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<td>Number of nodes</td>
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<td>Number of elements</td>
<td>341,596</td>
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<td>5,337,217</td>
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<td>Minimum grid angle</td>
<td>21°</td>
<td>21°</td>
<td>21°</td>
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<td>First layer distance ( y [\mu m] )</td>
<td>30</td>
<td>15</td>
<td>7.5</td>
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<tr>
<td>Average ( y^+ )</td>
<td>14.3</td>
<td>7.1</td>
<td>3.6</td>
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</table>
Set-up: Physical Models

- **Spatial discretization**
  - High Resolution for hydrodynamic system
  - Upwind / High Resolution for $k-\omega$ equations

- **Time integration**
  - 2nd order Backward Euler

- **Two-phase flow**
  - Water, water vapour

- **Mass transfer**
  - Rayleigh-Plesset cavitation model

- **Turbulence**
  - SST, **SST with Curvature Correction**, BSL-RSM
Validation: Tip Vortex Trajectory

- Multiple measurements:
  - Various Re numbers
  - Various angle of attack
Validation: Lift Curve

- Lift coefficients vs. Effective angle of attack ($\alpha - \alpha_0$)
- Experiments: $Re_c = 9.2 \times 10^5$, Simulation: various $Re_c$
• **Measurement planes**
  - Evaluation of vortex velocity at plane perpendicular to flow at $x/c=0.5$, 1.0, 2.0 behind hydrofoil
Validation: Tip Vortex Velocity

\[ \alpha_{\text{eff}} = 12^\circ, \text{ Re} = 5.2 \times 10^5 \]

Vortex velocity distributions
Cavitation inception in core of tip vortex
Validation: Tip Vortex Velocity

Turbulence model variation:
• Standard SST model
• Spatial discretization
  – High Resolution for all equations except turbulence
  – High Resolution for all equations
• Curvature correction
  – Turbulence strongly affected by swirl and streamline curvature
  – Effects are not accounted for in standard 2-equation model
  – Additional terms in SST turbulence equations
• BSL-RSM model
  – One equation for each stress tensor component
Validation: Tip Vortex Velocity

$\alpha_{\text{eff}} = 12^\circ$, $Re = 5.2 \times 10^5$

SST (Fine)
SST High Res (Fine)
SST High Res CC (Fine)
RSM (Medium)
RSM (Coarse)
Experiment

BSL-RSM

+ High Resolution for turbulence equations
+ Curvature correction terms
Tip Vortex Vapour volume fraction

- Medium grid
- $Re=5.2\times10^5$
- $\alpha_{eff}=12^\circ$, $\sigma=0.58$

$\alpha_{eff}=9.5^\circ$, $\sigma=0.58$, $Re=5.2\times10^5$
Valdation: Cavitation Inception

- Arndt & Dugue (1992), Arndt et al. (1991) ⇒
  - Cavitation inception vs. lift, correlation for model scaling: $\sigma_i \propto 0.063 c_l^2 \text{Re}^{0.4}$

![Graph showing cavitation number vs. $c_l^2 \times \text{Re}^{0.4}$]
Summary

• SVA Potsdam & ANSYS Germany cavitation project (BMBF)
• ANSYS CFX cavitation model
• Validation test cases for hydrofoil cavitation:
  – Le et al. → 2d hydrofoil cavitation
  – Arndt et al. → tip vortex cavitation
• Work in progress
  – Isolated propeller P1356
  – Non condensible gas cavitation
  – Ship propeller with ship stern.
    • Rotor-Stator interface
    • Influence of the turbulence model
Thank You!