LES Study of Unsteady Cavitation Characteristics of 3-D Hydrofoils with Wavy Leading Edges

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18th October 2019
Motivation

- Bioinspired geometries
- Cavitation Reduction
- Cavitation Stabilization

Vapor shedding

Wind turbine
Rudders
Humpback Whales

Tubercles on the flippers of humpback whales
Cavitation

- Cavitation seriously influences the hydrodynamic performance due to its complex unsteady nature; it may cause:
  - Lift reduction/oscillation
  - Erosion
  - Vibration
  - Noise

- Considering the performance and reliability of modifying hydrofoils Wavy Leading Edge (WLE) vs. straight leading edge (SLE)
### Geometries

**NACA 634-021 profile**

\[
x_{LE} = h_{LE} \sin \left( \frac{2\pi z}{\lambda_{LE}} \right) \quad \text{for} \quad 0 \leq z \leq L_z
\]

\[
x_{TE} = c, \quad y_{LE} = y_{TE} = 0
\]

**Sinusoidal leading edge**

$\lambda_{LE}$

<table>
<thead>
<tr>
<th>Case (1)</th>
<th>$h_{LE}$</th>
<th>$\lambda_{LE}$</th>
<th>$I_z$</th>
<th>$N_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SLE</td>
<td>SLE</td>
<td>0.4c</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case (2)</th>
<th>$h_{LE}$</th>
<th>$\lambda_{LE}$</th>
<th>$I_z$</th>
<th>$N_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>0.5</td>
<td>0.4c</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case (3)</th>
<th>$h_{LE}$</th>
<th>$\lambda_{LE}$</th>
<th>$I_z$</th>
<th>$N_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>0.25</td>
<td>0.2c</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case (4)</th>
<th>$h_{LE}$</th>
<th>$\lambda_{LE}$</th>
<th>$I_z$</th>
<th>$N_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
<td>0.5</td>
<td>0.5c</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case (5)</th>
<th>$h_{LE}$</th>
<th>$\lambda_{LE}$</th>
<th>$I_z$</th>
<th>$N_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>0.25</td>
<td>0.4c</td>
<td>2</td>
</tr>
</tbody>
</table>
Computational domain

• Computational domain comprises $\frac{x}{c} \in (-5, 7), \frac{y}{c} \in (-1.5, 1.5)$
and $\frac{z}{c} \in (-0.2, 0.2)$ (Johari et al., 2007)

• $U$ is specified at the inflow boundary at 10 m/s
Numerical Setup

- Large eddy simulation (LES) and Kunz mass transfer model were used to simulate the dynamic cavitation
- SGS: OEEVM
- Volume of fluid (VOF)
- InterphaseChangeFoam solver
- The velocity-pressure coupling is performed using the PIMPLE
Numerical Discretization in OpenFOAM

- Details of the employed discretization scheme
- Second order accuracy is considered

<table>
<thead>
<tr>
<th>Discretization</th>
<th>Schemes</th>
<th>Description/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time schemes</td>
<td>Backward difference</td>
<td>2\textsuperscript{nd} order, implicit</td>
</tr>
<tr>
<td>Spatial discretization</td>
<td>Gradient</td>
<td>2\textsuperscript{nd} order (Gaussian integration), Linear interpolation (central differencing)</td>
</tr>
<tr>
<td></td>
<td>Gauss linear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Divergence</td>
<td>2\textsuperscript{nd} order unbounded (Gaussian integration), Upwind differencing</td>
</tr>
<tr>
<td></td>
<td>Gauss upwind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laplacian</td>
<td></td>
</tr>
<tr>
<td></td>
<td>surface normal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>gradient</td>
<td>Unbounded, 2\textsuperscript{nd} order, Conservative</td>
</tr>
<tr>
<td></td>
<td>Gauss linear corrected</td>
<td></td>
</tr>
</tbody>
</table>
Grid Check

Three-dimensional structured mesh generated around the NACA 634-021 hydrofoil surface

Streamwise ($n_\xi$), vertical ($n_\eta$), and spanwise ($n_\zeta$) directions

<table>
<thead>
<tr>
<th>Case</th>
<th>$h_{LE}/c_{ref} = 0.05$, $\lambda_{LE}/c_{ref} = 0.5$</th>
<th>$n_\xi$</th>
<th>$n_\eta$</th>
<th>$n_\zeta$</th>
<th>Nodes (million)</th>
<th>$C_L$</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (Coarse)</td>
<td></td>
<td>330</td>
<td>290</td>
<td>26</td>
<td>2.5</td>
<td>0.55</td>
<td>0.069</td>
</tr>
<tr>
<td>Case 2 (Medium1)</td>
<td></td>
<td>430</td>
<td>350</td>
<td>28</td>
<td>4.2</td>
<td>0.53</td>
<td>0.062</td>
</tr>
<tr>
<td>Case 3 (Medium2)</td>
<td></td>
<td>570</td>
<td>470</td>
<td>28</td>
<td>7.6</td>
<td>0.604</td>
<td>0.066</td>
</tr>
<tr>
<td>Case 4 (Fine)</td>
<td></td>
<td>685</td>
<td>530</td>
<td>30</td>
<td>10.6</td>
<td>0.612</td>
<td>0.069</td>
</tr>
</tbody>
</table>
Validation with Johari et al. (2007)

- For the non-cavitating flows
- $Re=1.83 \times 10^5$
- $\sigma=0.8$
Formation of a low-pressure zone behind the troughs of the WLE hydrofoil

- Two kinds of low-pressure zones: 1- right behind the troughs (high curvature, flow acceleration), no flow separation occurs 2- at the separation zone and is identified as the laminar separation bubble (LSB)
- These two areas combined in the non-cavitating flow and create one stronger low-pressure region
Wall shear stress

- Uniformity vs. non-uniformity
- Behind the peak, the flow remains attached to the foil until approximately half of the chord
- Behind the trough, the flow locally separates and immediately attaches to the foil and the shear stress is approximately zero due to the flow separation
Zero streamwise velocity

Laminar Separation Bubble (LSBs)

- Separated flow region in the SLE case is larger than in the WLE case
- The early development of LSBs near the leading edge of the WLE hydrofoil prevents large flow separation
- In the SLE case, however, the flow is completely separated without reattachment
Volume fraction besides the zero streamwise velocity isosurface

- At the trough, the flow is separated and reattached twice before it separates near the trailing edge.

- In the slice with the maximum chord length, there is no early separation and reattachment; however, the flow separates significantly at approximately 0.6 of the chord.
Time histories through three consecutive cavitation cycles

Lift coefficient

- Oscillations are observed in the force coefficients in the shedding stage and during the turbulent development of vapor cavity.

A: Maximum cavity length
B: Maximum cavity volume
C: Oscillation of detached cavities
D: Minimum lift

- Cavity shedding becomes dominant and the force coefficient experiences drastic oscillations

- The lift coefficient decreases as a result of the detached cavity near the trailing edge.
Iso-surfaces in three consecutive cavitation cycles

Cavitation initiated in the troughs of the protuberances. This was due to the larger leading edge radius in the troughs leading to the lowest local pressures.

Non-uniformity and is observed at the tip

Lack of integrity
SLE and WLE at $\sigma=0.8$

Higher length of the attached cavity as there is stronger detachment in the SLE

In the SLE case, cavity sheds in tube-like vapor clouds; for the WLE case, however, it follows a horseshoe shape.
Vapor volume fraction besides the zero streamwise velocity isosurface, 2D vapor volume fraction contour besides the streamlines (middle)
\[ [(\omega \cdot \nabla)\vec{V}]_z = \omega_x \frac{\partial V_z}{\partial x} + \omega_y \frac{\partial V_z}{\partial y} + \omega_z \frac{\partial V_z}{\partial z} \]

**Vorticity stretching**

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>WLE, Max</th>
<th>WLE, Mean</th>
<th>WLE, Min</th>
<th>SLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<td>5</td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td>10</td>
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<tr>
<td>12.5</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
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<tr>
<td>15</td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
</tr>
<tr>
<td>17.5</td>
<td><img src="image21.png" alt="Image" /></td>
<td><img src="image22.png" alt="Image" /></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
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<tr>
<td>20</td>
<td><img src="image25.png" alt="Image" /></td>
<td><img src="image26.png" alt="Image" /></td>
<td><img src="image27.png" alt="Image" /></td>
<td><img src="image28.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Since vortex stretching is calculated in the z-direction, spanwise velocity is highly important.

- For the SLE case, the vortex stretching magnitude is in the order of $O(10^3)$; for the WLE case, contrarily, it is in the order of $O(10^6)$.
- The spanwise velocity is negligible in the SLE case, while the presence of tubercles in the WLE case; vortex stretching becomes important.
- In contrast to its magnitude, its distribution is similar for the SLE and WLE cases and dependent on the cloud cavity evolution.
Vorticity dilatation

\[ ([\omega(\nabla \cdot \vec{V})]_z = \omega_z \left( \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right) \]

- Vorticity dilatation is dominant inside the cavity, while the vorticity stretching is stronger outside the cloud cavity.
- Vorticity dilatation is in the same order for both cases, SLE and WLE.
- This term is important during the entire process.
Conclusions

• NACA 634-021 hydrofoil with WLE and SLE was considered.

• When the flow passes over the tubercles, it is deflected toward the troughs and a low-pressure zone forms behind the trough.

• Presence of tubercles on the LE results in a spanwise flow on the suction side of WLE hydrofoil.

• Flow separation in SLE case is greater than WLE case, because the early development of LSBs near the leading edge of WLE hydrofoil prevents large flow separation. While in the SLE case, no early separation happens and flow is completely separated without reattachment.
Conclusions

- Results show that there is a contrast between vorticity stretching and vorticity dilatation.

- The latter is dominant inside the cavity, while the former is stronger outside the cloud cavity and particularly in the wake, where cavity shedding is dominant.

- Vortex stretching is almost negligible for SLE case in comparison to the WLE case.

- Vortex stretching is calculated in z-direction which causes that the spanwise velocity becomes very important. In the SLE case, the spanwise velocity is negligible.

- The vorticity dilatation is important during the whole process of cavitation cycle, because it is proportional to the velocity divergence.

- Its value is negative inside the cavity, while it is positive at the closure point of cavity.
Further Reading

Movahedian, A., Passandideh-Fard, M., Roohi, E., LES Study of Sheet-Cloud Cavitation around the 3-D Twisted wing with NACA16012 hydrofoil, Accepted at Ocean Engineering.


Thank you

Questions?
Cavitation in nature

• Joint Cavitation

Cracking sounds occur when bubbles form in joints as they are pulled apart. [1] Cavitation within the joint—small cavities of partial vacuum form in the synovial fluid and then rapidly collapse, producing a sharp sound.

Peacock mantis shrimp use a pair of large raptorial appendages (A, white arrow) to strike hard objects with such high speeds that cavitation bubbles form between the appendage and striking surface (Patek et al., 2004).
Mantis Shrimp

Mantis shrimp dactyl heel striking force sensor. Filmed at 100,000 fps, played here at 10 fps.