CFD Analysis of Propeller Tip Vortex Cavitation in Ship Wake Fields

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Introduction (1)

Tip vortex cavitation (TVC) on ship propellers

• Rudder erosion, broadband pressure pulse ← Bursting of TVC
• Environmental concern for underwater radiated noise (URN)
• Increasing need for prediction of TVC

Bursting of tip vortex cavitation on full-scale navy tanker
(Arndt et al 2015)
Cavitation simulation on ship propellers with different tip loadings

- Lowering tip loading → Preventing TVC
  → Unstable sheet cavitation and cloud cavitation → Blade surface erosion
- Inevitable TVC
  → Safe way to make sheet cavitation depart from blade surface
- Intensified TVC at max engine power

Cavitating flows on propellers with different tip loadings
(Shin and Andersen 2015)
Introduction (3)

Numerical analysis on propeller TVC

- Hybrid method (Berger et al 2016)
  → Efficient in terms of computational effort
  → Limitation in considering interactions of hull wake, propeller-induced flow, rudder

- Extensive TVC simulation in open water by viscous flow sover (Viitanen et al 2017)
  → Steady TVC trajectory

- DES of extensive TVC with hull wake and rudder
  → Alterations in TVC trajectory
  → Challenging to resolve vortex core in CFD
Test case

Propeller on military inspection vessel

- 61 m Danish navy inspection vessel
- 4-blade controllable-pitch propeller
- Large-area propeller with $\frac{A_e}{A_o}=0.76$
- Model-scale propeller with $D=0.23$ m ($D=3.3$ m at full scale)
- Towing tank test in Force Technology
- Cavitation tunnel test in SSPA including hull model
  → Weak TVC in design condition (60% MCR)
  → Extensive TVC in 100% MCR condition
CFD Setup (1)

**CFD model**

- Cylindrical domain around propeller and rudder
- Inner cylindrical domain around propeller with rotating motion
- 3-D from inlet to propeller plane
- 3.5° shaft axis inclination
- Axial hull wake ← non-uniform inlet velocity
- Transverse hull wake ← momentum sources 0.6·D upstream from propeller plane

![Computational domain](image1)

![Exp](image2)

![CFD model with a cross section](image3)

![Experimental setup in cavitation tunnel test](image4)
CFD Setup

- DES with curvature-corrected k-ω SST turbulence model in StarCCM+
- VOF and vapor transport equation
- Inter-phase mass transfer model
  ← Asymptotic Rayleigh-Plesset equation
- Trimmed hexahedral mesh
- 6 prism layers with thickness of 0.2 mm
  → y+ ≤ 2
- Δx = 0.3-0.6 mm on blade surface
- Refinement along blade edge
- 6.0° rotation per Δt → 0.5° per Δt

Unsteady cavitation from experiment and DES (Shin et al. 2015)
Identifying TVC trajectory

- CFD on initial grid
- Iso-surface of Q-criterion = 100,000
- Good agreement before reaching rudder
- Pitch reduction from $P_H/D = 1.07$ to $1.04$
  $\leftarrow$ Rudder disturbance
  $\leftrightarrow$ 3% pitch increase in open-water exp (Kerwin 1976)
- Radius reduction from $D_H/D = 0.95$ to $0.8$
  $\leftarrow$ Propeller-induced flow
- Larger contraction than $D_H/D = 0.83$ (Kerwin 1976)
  $\leftarrow$ High propeller loading of $C_{Th} = 2.0$
- Upward tilting of TVC progress from -3.5 to 0.5
  $\leftarrow$ Upward hull wake
Adaptive Grid

**Grid refinement**

- Grid refinement to $\Delta x = 0.2 \text{ mm}$ along TVC trajectory
- Overset grid over rudder
- Cavitation simulation on refined grid
Cavitation simulation result

- Iso-surface of 10% vapor fraction as cavitation interface
- Good agreement in LE sheet cavitation
- Extended TVC after grid refinement
- Pronounced spiral structure of TVC
- Shorter extent of TVC than exp
- Fragment of TVC at rudder bottom
  → Repetitive grid refinements
  → Further improvement
Pressure Pulse

Pressure pulse above propeller
- Two points on hull surface near rudder headbox
- No hull surface in CFD
  → Increased by factor of 2 (Hasuike et al 2011)
- Increase of high-order pressure pulses
  ← Grid refinement
- Underestimation of high-order pressure pulses
  ← Bursting of TVC at rudder headbox

![Experimental model](image)

**TVC in experiment**

![Graphs showing pressure pulse](image)

**Graphs showing pressure pulse**

- Experiment
- DES on initial grid
- DES on refined grid

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Conclusion

• Adaptive grid
→ Improving TVC simulation
→ Improving estimation of high-order pressure pulse

• Visualization of TVC trajectory by iso-surface of Q-criterion
→ Useful for analyzing deformed TVC trajectory

• Continuous research for further improvement
← Repetitive grid refinement
← Anisotropic turbulence model
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