Cavitation Simulation on Ship Propellers with Erosion Safety Index

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Introduction (1/3)

- Suction-side sheet cavitation
- Tip vortex cavitation
→ Acceptable to some extent

- Hub vortex caviation
- Blade root cavitation
→ Unavoidable in high-loading conditions

- Cloud cavitation
- Bubble cavitation
- Pressure-side cavitation
→ Erosion risk → Unacceptable

Introduction (2/3)

- Collective burst of cloud cavitation
  → High erosion risk

- Research on static hydrofoil
  → Cloud cavitation mechanism
  ← Re-entrant jet
  ← Extensive sheet cavitation

- Cloud cavitation on oscillating hydrofoil
  ← Periodic change of AoA
  → Cloud cavitation on ship propellers

Introduction (3/3)

• Cloud cavitation on ship propellers
  ← Extensive sheet cavitation
  ← Irregular hull wake

• CFD on propeller designs
  with different tip loadings
   — Abrupt tip unloading
   → Cloud cavitation

   — Gradual tip unloading
   → Conversion of sheet cavitation into tip vortex cavitation
   → Safe way for avoiding cloud cavitation

Pitch ratio with respect to radius

Shin, K. W. & Andersen, P. ‘CFD analysis of cloud cavitation on three tip-modified propellers with systematically varied tip geometry’ CAV2015, Lausanne, Switzerland
CFD Setup (1/5)

Computational model

- Propeller and rudder in cylindrical fluid domain
- Rigid body motion and sliding mesh in rotating domain
- Unsteady simulation with 6° rotation per Δt → 0.5°
- Trimmed hexahedral mesh
- Grid refinement along blade edges
- ~20 mil cells → ~50 hours with 192 cores
- Fine mesh in outer-radius region
  → Resolving cavitating flows
CFD Setup (2/5)

**CFD solver**

- Commercial CFD software StarCCM+
- DES (Detached-eddy simulation) → Better prediction of detached cavitation than RANS
- Cavitation model ← Inter-phase mass transfer model based on asymptotic Rayleigh-Plesset equation
- VOF method → Vapor volume fraction → Fluid property → Eulerian multi-phase model
- Vapor transport equation
- Incompressible flow solver

Shin, K. W. ‘Cavitation simulation on Kappel propeller with a hull wake field’. Proc. of 16th NuTTS, Marstrand, Sweden, 2014
Hull wake modeling

- Numerical modeling of hull wake instead of including hull geometry
  ← Hull geometry unavailable for propeller designers in commercial project
  → Reducing computational effort

- Axial hull wake
  ← Non-uniform inlet velocity

- Transverse hull wake
  ← Momentum source 0.6·D upstream from propeller plane

- Wake model test in the same computational domain excluding propeller model
Cavitation simulation condition

- Model-scale simulation
  → Propeller diameter of ~25 cm

- Following the condition of cavitation tunnel test
  ← Propeller speeds of 24 – 30 rps
  ← Not complying with Froude’s law
  → Increasing Reynolds number

- Cavitation number from full-scale condition
  → Model-scale reference pressure

- Worst cavitating condition of 100% MCR and ballast draft

Cavitation tunnel in SSPA in Gothenburg, Sweden (www.sspa.se)
CFD Setup (5/5)

Erosion safety index

- Potential energy of cavity collapse
  \[ E_{pot} = V_V \cdot (p - p_v) \]
- Potential power of cavity collapse
  \[ P_{Pot} = (p - p_v) \cdot \partial V_V / \partial t + V_V \cdot \partial p / \partial t \]
- Erosion safety index based on \( P_{Pot} \)
  → Deviations from experiment results
  \( \Delta t = 50 – 100 \) µs in DES
  > Duration of collective bubble collapse
  = order of 1 – 10 µs

- Adopting erosion index based on \( E_{Pot} \)
- Calculating erosion index on cells adjacent to propeller blade surface
- Accumulation of erosion index for a propeller revolution after achieving converged solution

Pfitsch, W., Gowing, S., Fry, D., Donnelly, M. & Jessup, S. ‘Development of measurement techniques for studying propeller erosion damage in severe wake fields’. Proc. of CAV2009, Ann Arbor, MI, USA

CFD Result – Case 1 (1/10)

Validation of cavitation simulation

- 4-blade Kappel propeller for bulk-carrier
- Cavitation tunnel test in SSPA

- 10% vapor fraction for cavitation interface
- Good agreement in unsteady sheet cavitation
- Large-scale structure of cloud cavitation in CFD

CFD Result – Case 2 (2/10)

Tip vortex cavitation (TVC)

- CFD with adaptive grid
  ↩ Tip vortex trajectory predicted by iso-surface of Q-criterion
- Good agreement in LE sheet cavitation
- Extended TVC after grid refinement
- Pronounced spiral structure of TVC
- Shorter extent of TVC than exp
  → Repetitive grid refinement

Shin, K. W. & Andersen, P. ‘CFD analysis of propeller tip vortex cavitation in ship wake fields’. Proc. of Cav2018
CFD Result – Case 2 (3/10)

Pressure pulse above propeller

- Two points on hull surface near rudder headbox
- No hull surface in CFD → Increased by factor of 2
- Increase of high-order pressure pulses ← Grid refinement
- Underestimation of high-order pressure pulses ← Bursting of TVC at rudder headbox

Shin, K. W. & Andersen, P. ‘CFD analysis of propeller tip vortex cavitation in ship wake fields’. Proc. of Cav2018
CFD Result – Case 4 (7/10)

Cavitation simulation

- No cavitation tunnel test result
- Leading-edge sheet cavitation
- Cavitation detachment before reaching tip
- Cavitation streak at $r/R = 0.99$
- Pressure fluctuations
CFD Result – Case 5 (9/10)

Thrust breakdown

- INSEAN E779A propeller
- Model tests with varying cavitation number
- Good agreement for moderate cavitation
- Overestimation for extensive cavitation

← Blockage effect in cavitation tunnel
← Open-water test in a small tunnel

Shin, K. W. & Andersen, P. ‘CFD analysis of ship propeller thrust breakdown’. Proc. of SMP19, 2019
CFD Result – Case 5 (10/10)

Seed density in CFD

• Seed density → Cavity growth and collapse
• Overestimation of LE cavitation at $\sigma_n = 1.763$
• Overall overestimation at $\sigma_n = 0.630$
• Common overestimations in cavitation simulations on the same case made by multiple institutes

Shin, K. W. & Andersen, P. ‘CFD analysis of ship propeller thrust breakdown’. Proc. of SMP19, 2019
Closing Remarks (1/2)

Cavitation simulation with hull wake modeling

• Practical cavitation predictions for ship propeller designs
  → Simplified approach for saving computational effort

• Reproducing destabilization and detachment of cavitation
  → Resolving micro-scale structure & dynamic collapse of cavitation bubble
  → Improving simulations on tip vortex cavitation
  → Tests on pressure-side cavitation and full-scale cavitation
Closing Remarks (2/2)

Erosion safety index

- Quantitative evaluation of erosion safety
- Reasonable agreement with model test results and observations
- Erosion spot predicted upstream from those in model tests & observations → Numerical study with refining temporal and spatial discretization

Shin, K. W. & Andersen, P. ‘Numerical study on characteristics of cloud cavitation on a ship propeller’. Proc. of 3rd Int. Meeting on Propeller Cavitation, 2018
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Thank you very much!