Structured Summary of the Dissertation

Title:
Mechanisms and Mitigation of Unsteady Multiphase Cavitating Hydrodynamics in Bow Thrusters Using Scale-Resolving CFD

1. Background and Motivation

Bow thrusters are essential devices for low-speed maneuvering, berthing, and dynamic positioning. However, their operation is often associated with strong unsteady hydrodynamic loads, pressure pulsations, cavitation, vibration, and noise. These effects are intensified by the confined tunnel geometry, entrance-flow separation, vortex-wall interaction, blade-duct coupling, and cavitation. Although these phenomena are of major practical importance, a unified high-fidelity investigation of their underlying mechanisms, their dependence on operating direction, and their mitigation by passive and active control strategies has remained limited. This thesis addresses this gap through a scale-resolving computational investigation of full-scale bow-thruster hydrodynamics.

2. Objective of the Work

The thesis aims to advance the physical understanding and numerical modeling of unsteady cavitating bow-thruster flows under both design (pull) and off-design (push) operating conditions, with and without air injection. The specific objectives are:

- to identify and analyze the dominant flow mechanisms responsible for unsteady pressure pulsations and fluctuating hydrodynamic loads in bow thrusters,
- to assess the effectiveness and limitations of passive geometric modifications for mitigating flow separation and unsteady hydrodynamic effects,
- to investigate the influence of controlled air injection on cavitation dynamics, pressure fluctuations, and load spectra in confined bow-thruster geometries, and
- to evaluate the predictive capabilities and limitations of scale-resolving, three-phase CFD approaches for vibration- and noise-relevant flow phenomena.

3. Methodology

The work develops and applies a numerical framework based on OpenFOAM for incompressible multiphase flow. In addition to conventional two-phase cavitation modeling, a three-phase volume-of-fluid solver with merging-theory-based pressure closure is implemented in order to represent liquid, vapor, and non-condensable gas in a consistent manner. The methodology combines hybrid URANS-LES turbulence modeling, rotating-mesh treatment of the propeller, systematic verification and validation against experimental data, and detailed post-processing of vortex structures, cavitation topology, wall-pressure fluctuations, forces, and spectra. Within this framework, the thesis investigates baseline bow-thruster physics, reverse off-design operation, passive geometric mitigation, and active control by air injection.

4. Main Results

For the validated baseline configuration, the simulations show that the dominant sources of unsteady loading are tunnel-entry separation, strong confinement-induced vortex interaction, and azimuthally varying cavitation. These mechanisms jointly produce thrust fluctuations of approximately 17% to 18% of the mean thrust, showing that the main challenge in bow-thruster hydrodynamics is not only the prediction of mean forces, but also the understanding and reduction of vibration- and noise-relevant excitation.

The analysis of normal and reverse operating directions demonstrates that reverse operation modifies separation topology and cavitation distribution and increases pressure-pulsation intensity and spectral energy at blade-passing harmonics, even when the mean thrust remains comparable to or slightly higher than in the normal direction. This identifies off-design operation as particularly critical from the viewpoint of structural fatigue and underwater-noise emission.

Passive mitigation by optimization of the tunnel entrance and the protective grille reduces the primary source of inflow non-uniformity, weakens large-scale separation and coherent vortices, attenuates wall-pressure fluctuations, and reduces cavitation in the lower tunnel region. The results show that passive control acts mainly by improving the mean inflow topology and suppressing the hydrodynamic origin of unsteadiness. In particular, the optimized protective grille alone already provides a substantial reduction in unsteady thrust and pressure levels.

Active mitigation is investigated through controlled air injection using the newly developed three-phase cavitating-flow solver. The results show that air injection can effectively suppress cavitation and reduce unsteady force fluctuations, but that its success depends strongly on injector placement and injection rate. All ventilated cases reduce the overall fluctuation level relative to the non-ventilated reference case. The largest reduction is obtained for the 7-injector configuration at Cq =1.0%, where the summed force fluctuation decreases by 23.54%. At the same time, the dominant excitation frequencies remain nearly unchanged, indicating that air injection affects mainly the amplitudes of the unsteady response rather than its fundamental forcing frequencies.

5. Conclusions

This thesis provides a unified physical interpretation of why bow thrusters generate strong unsteady loads and demonstrates how these loads can be mitigated by mechanism-based design. The results show that passive and active mitigation strategies act through different physical mechanisms. Passive methods primarily improve the mean inflow topology by reducing entrance-induced non-uniformity and suppressing separation. Active air injection, by contrast, acts directly on the multiphase flow physics by modifying local phase composition, cavity dynamics, and collapse behavior. The study therefore establishes both improved physical understanding and a robust numerical framework for the analysis and design of vibration- and noise-relevant multiphase marine propulsion flows.

6. Related Publications

- Kazemi, M., and Kornev, N. (2025). *Bow Thruster at Normal and Off-Design Conditions. Journal of Marine Science and Engineering*, 13, 1463.
- Kazemi, M., Dause, M., Hinnenthal, J., and Kornev, N. (2025). *Numerical Study of Reduction of Unsteady Effects in Bow Thruster. Ocean Engineering*, 324, 120660.
- Kazemi, M., Kornev, N., and Hinnenthal, J. (2024). *Scale-Resolving Simulation of Unsteady Bow Thruster Hydrodynamics. Ocean Engineering*, 298, 117212.
- Kazemi, M., and Kornev, N. *Implementation and Validation of a Three-Phase Phase-Change Solver with Merging Theory for Gas--Liquid Cavitating Flows*. Under review.
- Kazemi, M., and Kornev, N. *Air Injection as an Active Control Strategy for Unsteady Loads in Bow Thrusters Based on a Three-Phase Merging-Theory Approach*. Under review.