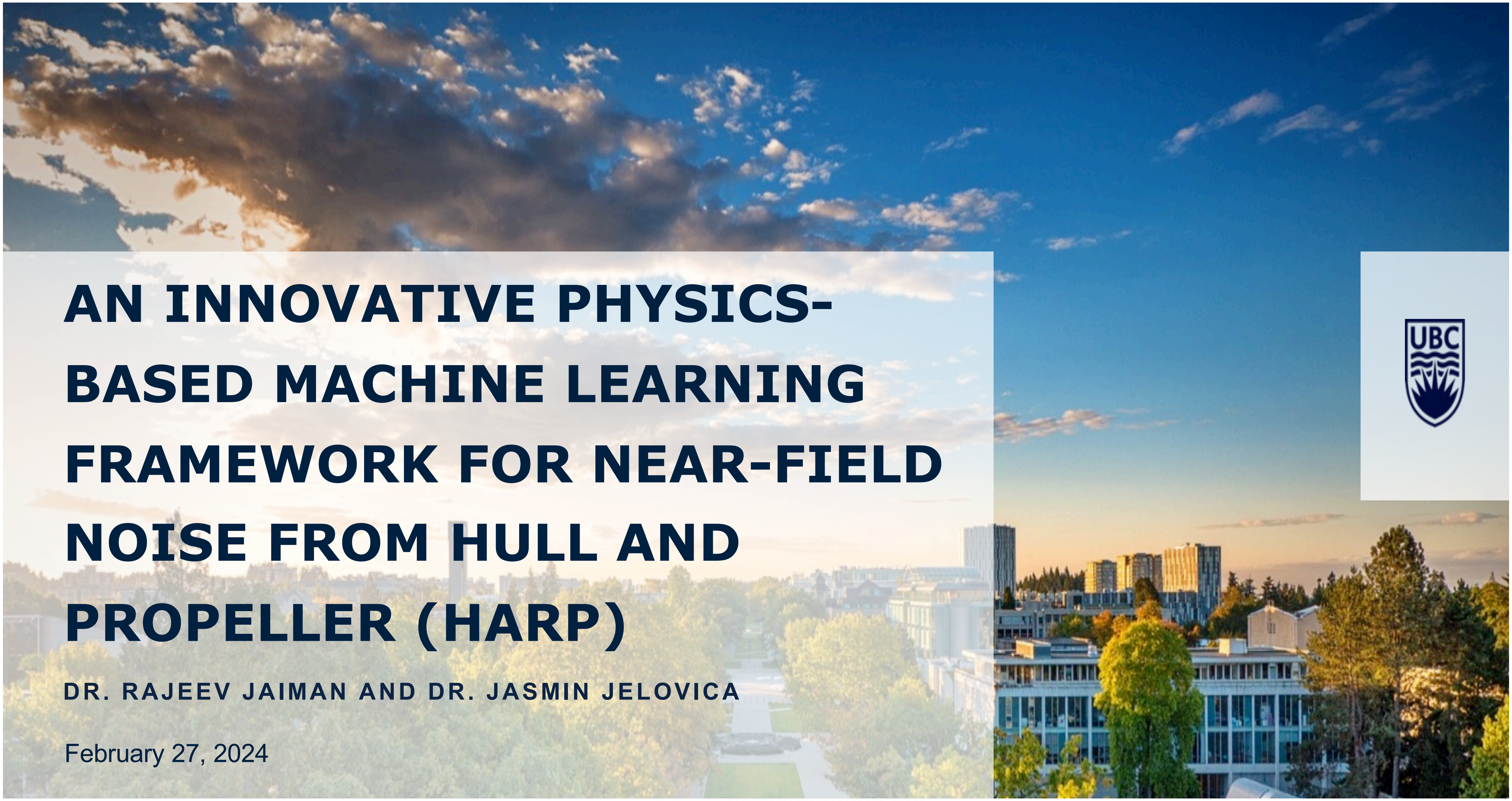

AN INNOVATIVE PHYSICS-BASED MACHINE LEARNING FRAMEWORK FOR NEAR-FIELD NOISE FROM HULL AND PROPELLER (HARP)

DR. RAJEEV JAIMAN AND DR. JASMIN JELOVICA

February 27, 2024

NSERC CRSNG
Transport Canada
Canada
VARD a Fincantieri company

Outline

- ❑ Background/context
  - ▶ Ship noise problem

- ❑ HARP overview
  - ▶ Objectives
  - ▶ Research Activities

- ❑ HARP research highlights
  - ▶ Propeller cavitation modeling
  - ▶ Near-field noise predictions
  - ▶ Link with MELO project

- ❑ Summary and way forward

MELO/HARP Research Team


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Far-field noise and AI/ML
(MELO Project)


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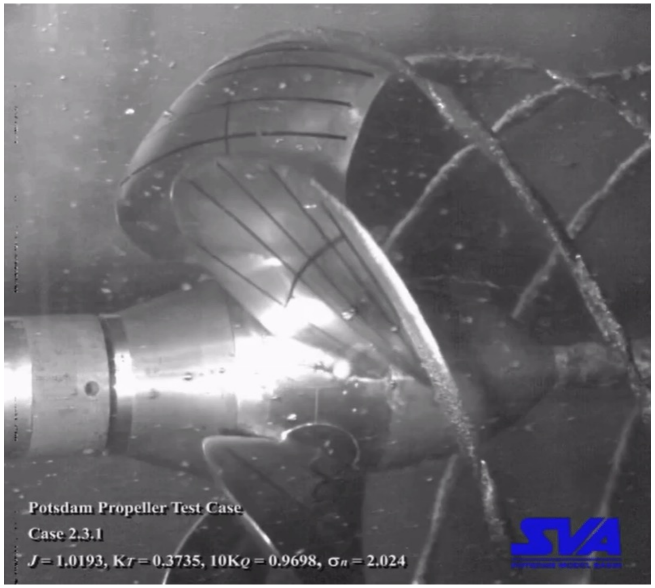
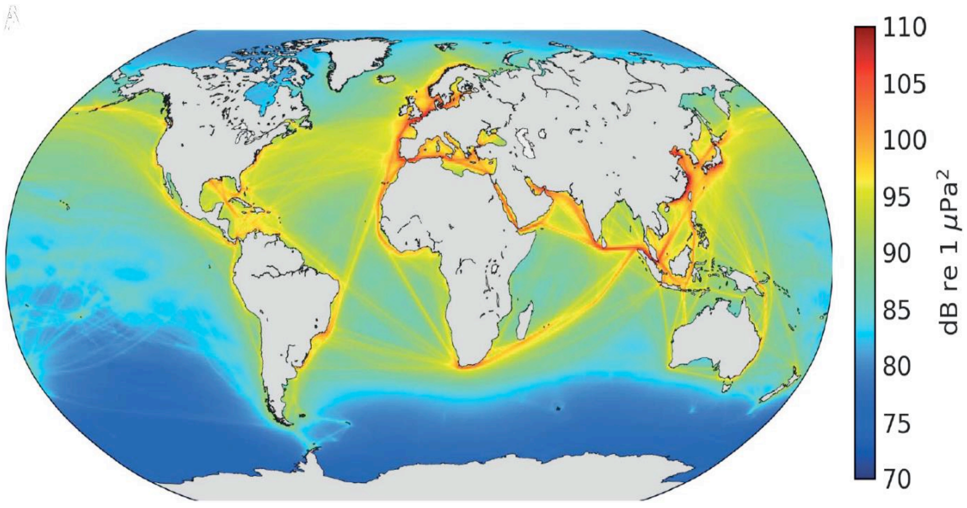
Near-field propeller and vessel noise
(HARP Project)



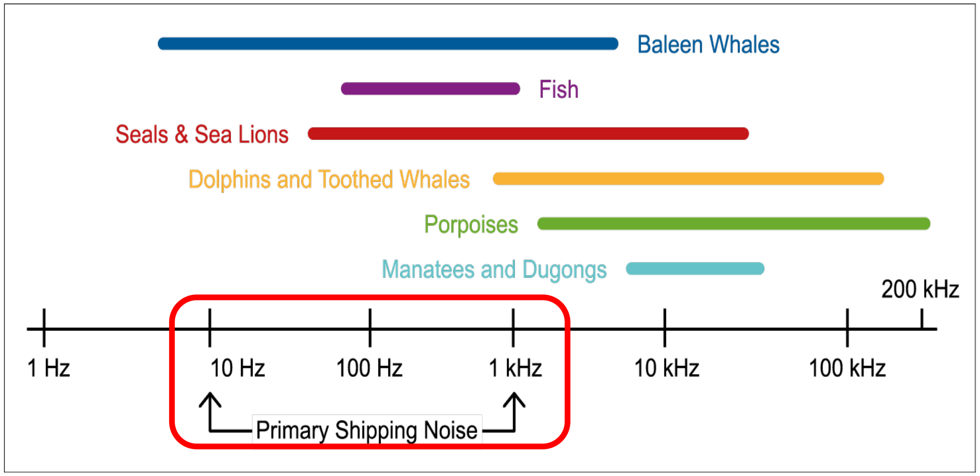
SHIP NOISE AND KILLER WHALE

Ship Noise Problem

- Marine vessels generate noise at frequencies which overlap with those used by marine mammals
  - Impact on finding prey, social interactions, navigation, and other activities
- Propeller, hull vibration and ship machinery are main sources
  - Large vessels produce noise up to 180-195 dB with maximum level about 200 Hz
  - Cavitation produces highest level of underwater radiated noise



Sound level estimates from marine traffic
(Duarte et al, 2021)

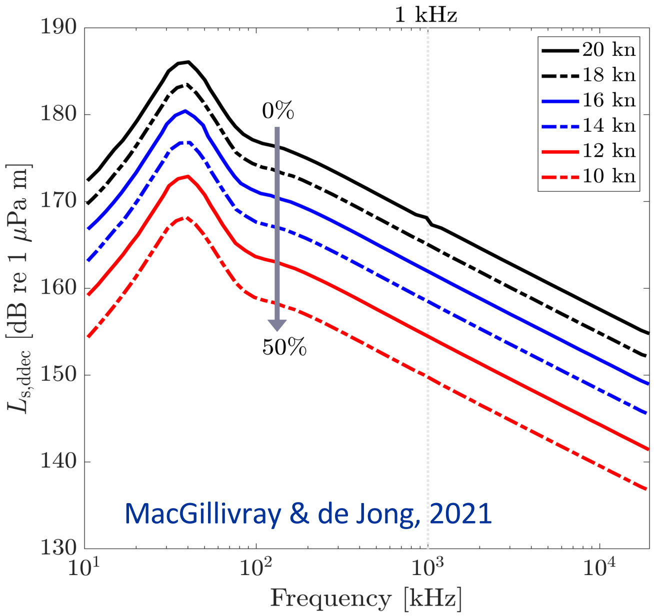


B. Southall, NOAA

Current Status of Ship Noise Problem

- ☐ There is a trade-off between noise reduction and operational efficiency (i.e. fuel consumption)
- ☐ There are currently no regulations, only voluntary guidelines (unlike IMO’s onboard/airborne ship noise)
- ☐ Noise adversely effects marine life, but severity and its impact on population not understood
- ☐ Vessel noise limit and measurement procedure have not been established for URN

Need intelligent ship design and operation for reducing noise impacts over ecologically-relevant scales



MacGillivray & de Jong, 2021

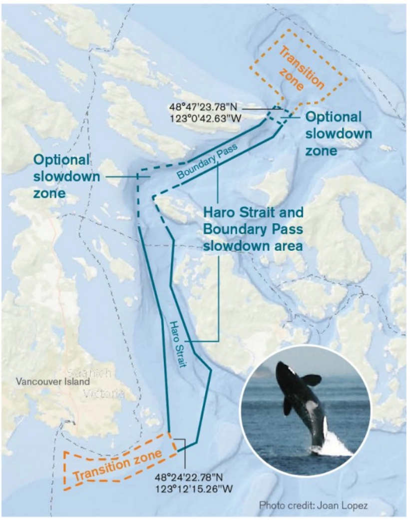
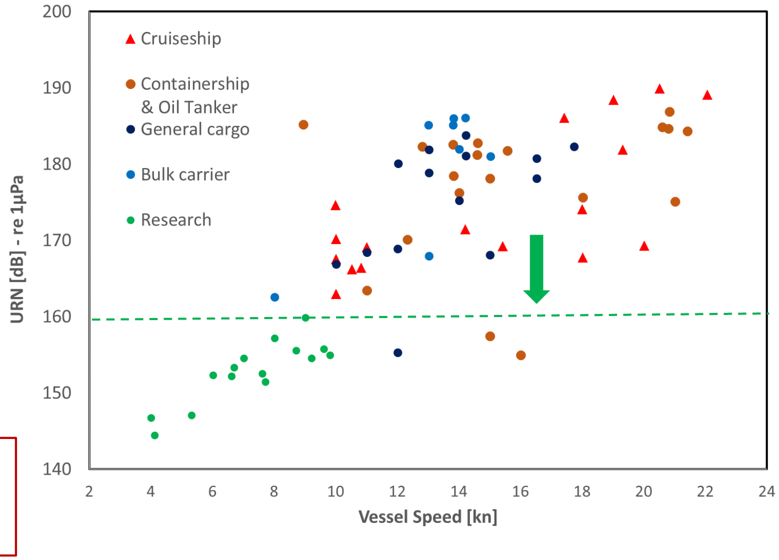
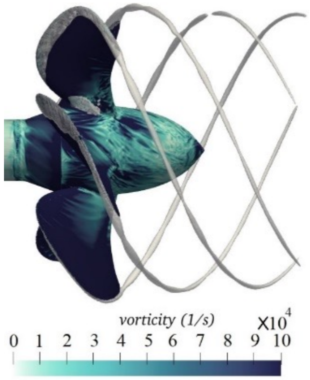


Photo credit: Joan Lopez

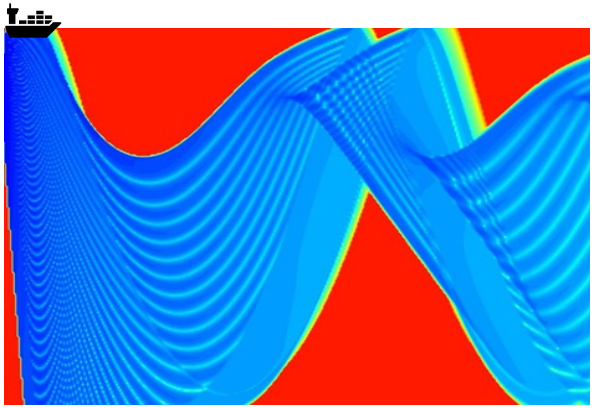


20 dB reduction goal for commercial ships

Can we build AI-based design and multiphysics solution to mitigate the impact of ship noise on killer whales?



Near-field noise



Far-field propagation

Mammal location and acoustics

Objectives of HARP Project

- The project will develop new tools to help vessel designers predict the underwater vessel noise performance during the design stage
- Identify the potential sources of vessel noise, including on-board machinery and propeller noise
- Better design models are expected to help industry ensure that the next generation of ships embrace quiet technologies, while maintaining safety, productivity and environmental performance

Major Activities of the Project

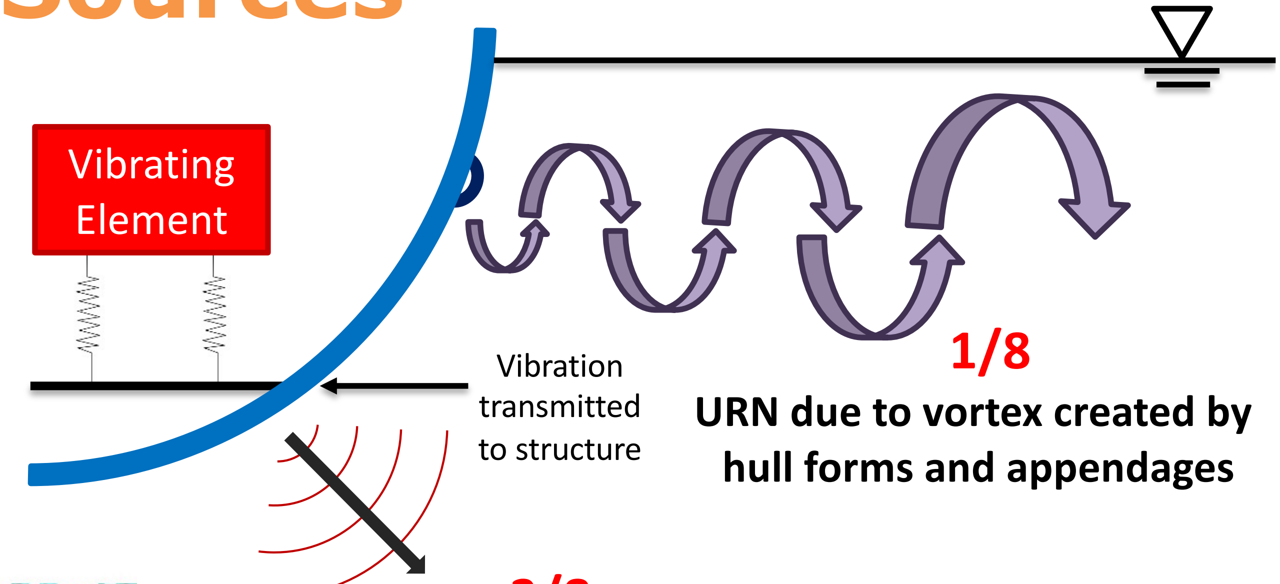
- ❑ WP1: New high-fidelity mathematical model to analyze vibration of hull panels and propeller blades coupled with moving fluid
  - ► Coupled CFD/FEA analysis

- ❑ WP2: Broadband vibro-acoustic analysis of URN on the full frequency range and development of physics-based machine learning (PBML) framework
  - ► Data-driven acoustic analysis

- ❑ WP3: Development of advanced solutions and optimization/control techniques for minimization of URN
  - ► Data-driven vibration analysis and control

Underwater Radiated Noise (URN) Sources

CCGS Sir John Franklin



Vibrating Element

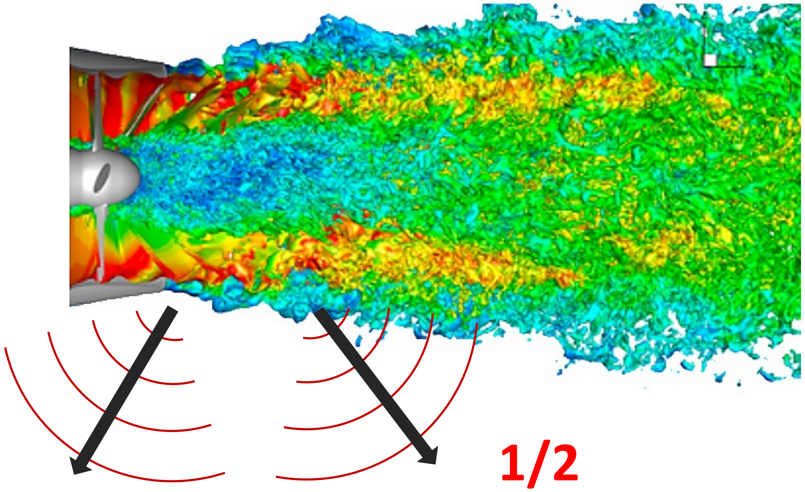
Vibration transmitted to structure

1/8

URN due to vortex created by hull forms and appendages

3/8

URN due to structure vibration creating pressure waves



1/2

URN peaks due to gear mesh

URN due to propeller crating pressure waves

HARP research:

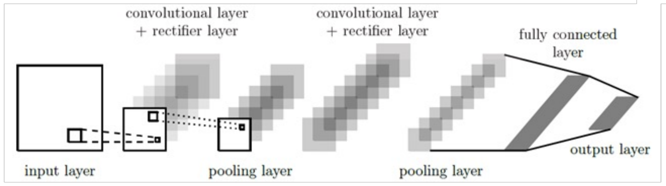
- ✓ Examine cavitation and hydro-structure interactions with unique hull and propeller/rudder design
- ✓ Efficient predictive tools for tonal and broadband noise generation and propagation analysis

HARP Framework: Physics + AI Integration

LOW computational expense (+)

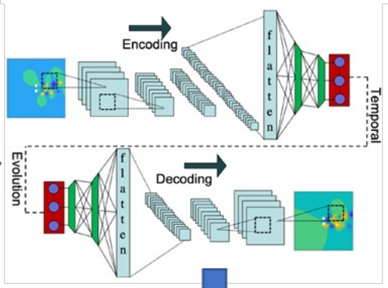
Data-driven, little or no physics (-)

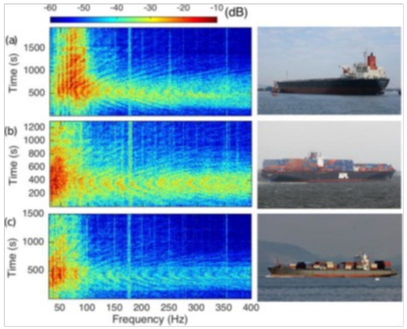
DL model



Complex machine learning/deep learning (ML/DL) models

Physics-based ML for URN forecasting: computational efficiency + physical consistency





URN forecasting

More data

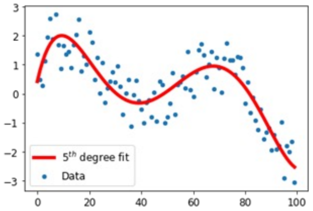
Basic analytical/empirical models

HIGH physical accuracy (+)

LARGE computational expense (-)

Physical information

Regression-based models with low data

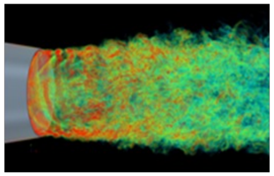


Simplified physical models

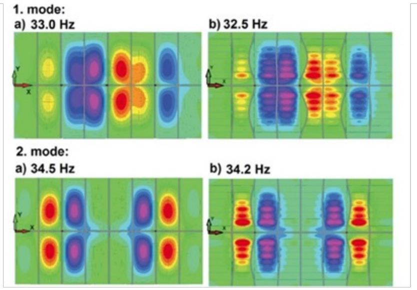
$$\frac{\partial^2 p}{\partial t^2} - v^2 \frac{\partial^2 p}{\partial x^2} = q(x,t)$$

More physics

URN from propeller fluid-structure interaction



URN from hull structural vibrations



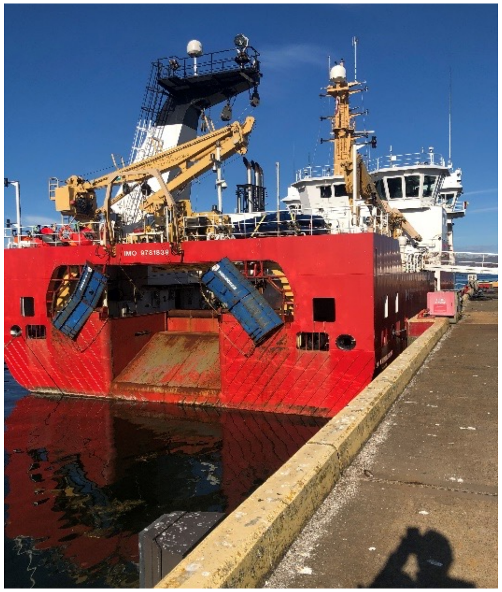
Data

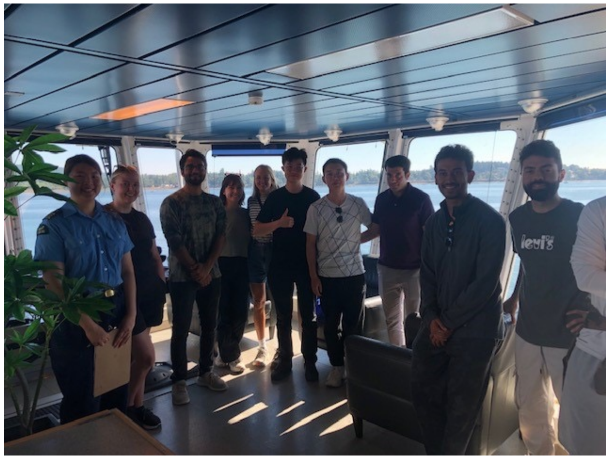
Physical accuracy

CCG Franklin Noise Measurements

- ❑ Transport Canada Quiet Vessel Initiative
  - ► MELO: Clear Seas and UBC Marine Biology

CDT Measurement





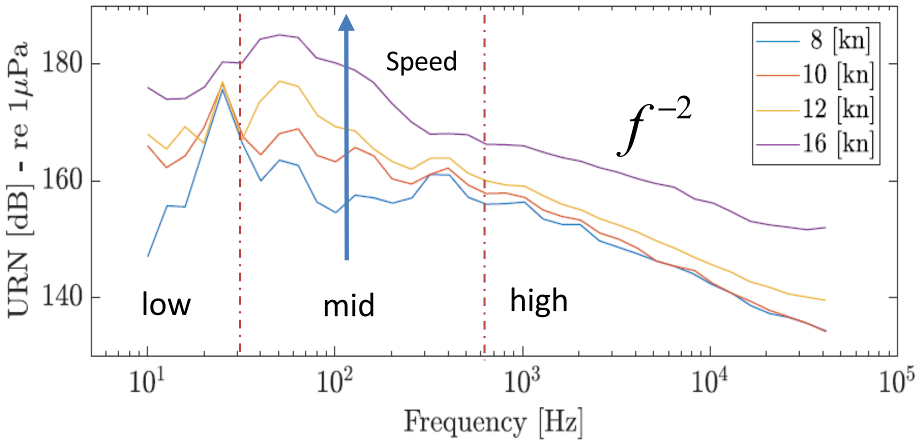
Cavitation Noise Generation: Field Data

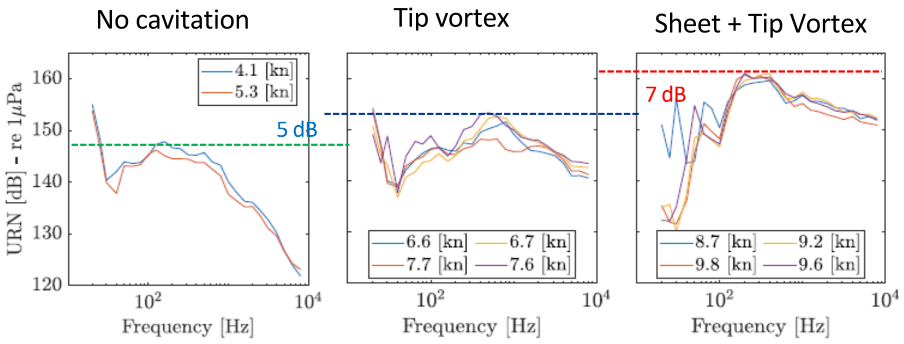
RV Princess Royal, Newcastle

- ❑ Three frequency regimes:
  - ▶ Low-frequency
  - ▶ Mid-frequency
  - ▶ High-frequency

- ❑ Vessel speed increases noise level

- ❑ Tip vortex and sheet cavitation dominate noise generation





Kalikatzarakis et al, 2023

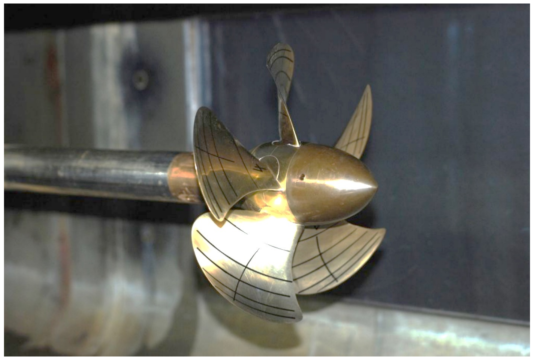
Marine Propeller Analysis and Best CFD Practices

❑ CFD-based tools

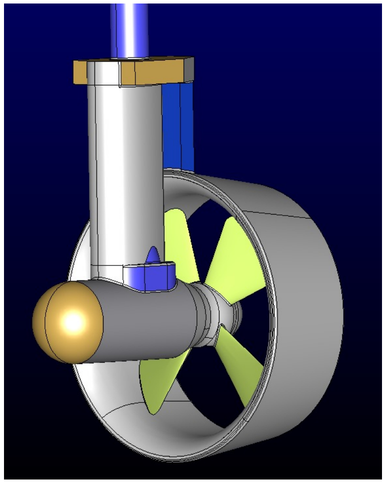
- ▶ RANS and Hybrid LES turbulence models
- ▶ Cavitation modeling (mixture theory)
- ▶ Acoustic analysis (FWH and Acoustic Perturbation)

HARP
Approach

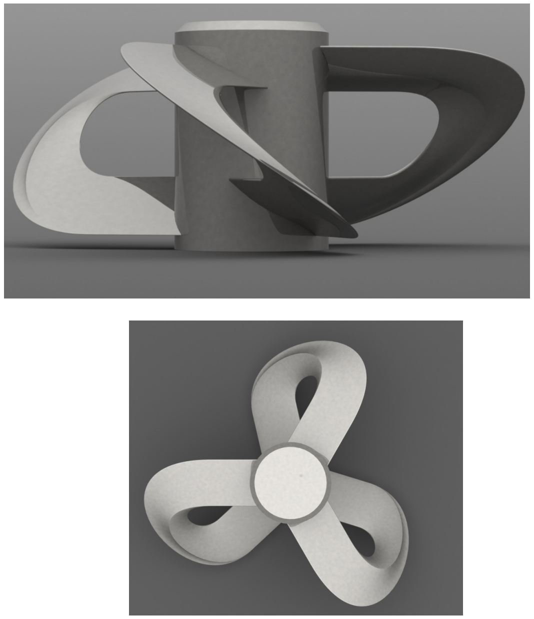
❑ Propeller Validation Cases



PPTC open propeller



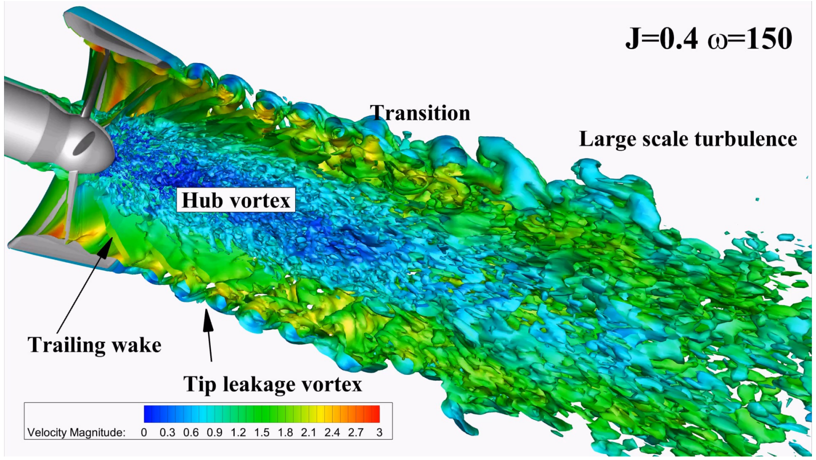
MARIN TRUST JIP
Single Ducted Propeller

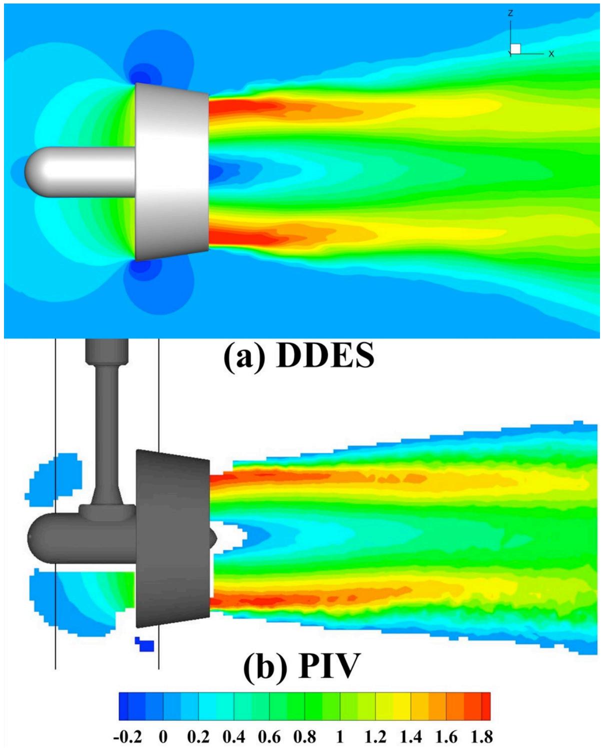


Toroidal Propellers

Validation and Physics of Ducted Propeller

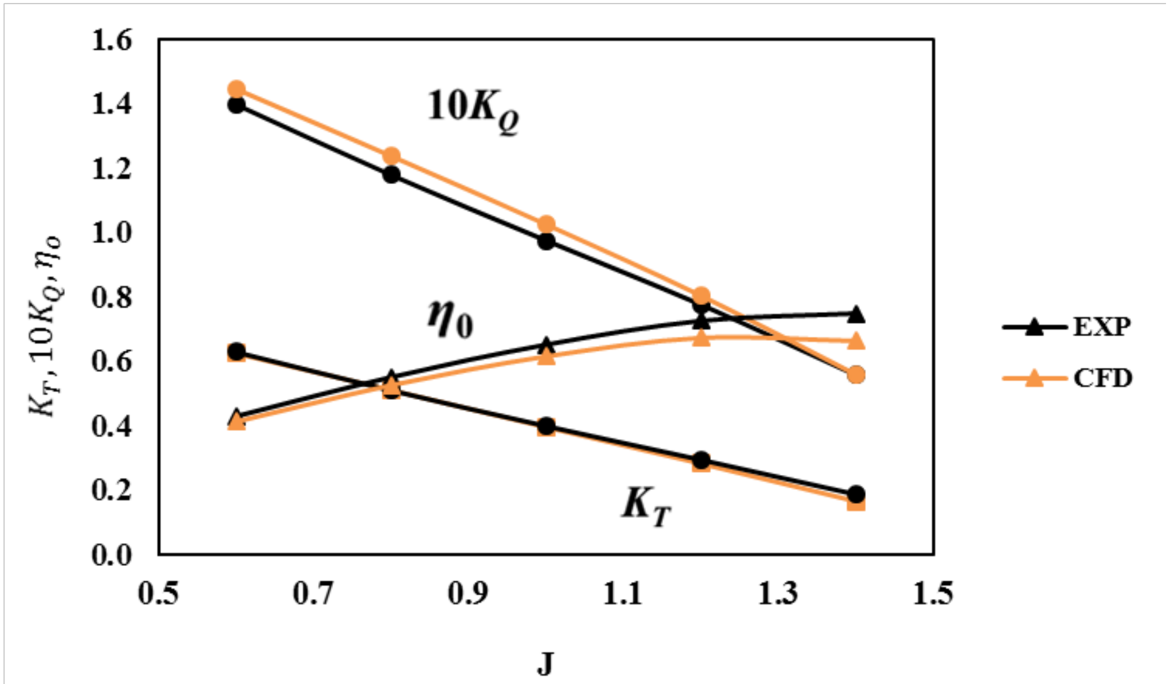
- ❑ Non-cavitating propeller dynamics
  - ▶ Complex turbulent wake
  - ▶ Vortex-blade interactions



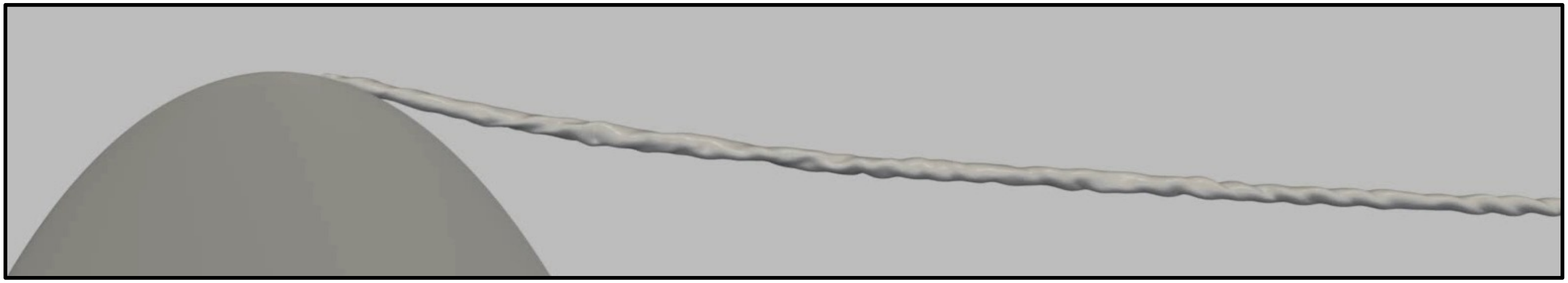


(a) DDES

(b) PIV

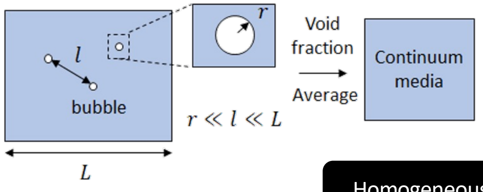


Zhang & Jaiman, JOE 2019



FUNDAMENTAL STUDIES ON PHYSICAL MECHANISMS

In-House Cavitation Solver with Flexible Boundaries

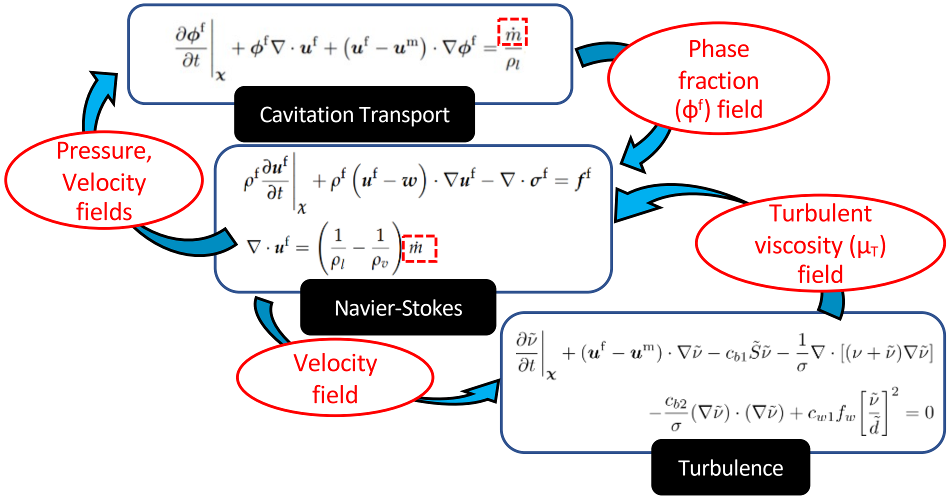


$r \ll l \ll L$

$$\phi^{\mathrm{f}}(\boldsymbol{x}^{\mathrm{f}}, t) \longrightarrow \begin{aligned} \rho^{\mathrm{f}} &= \rho_l \phi^{\mathrm{f}} + \rho_v \left(1 - \phi^{\mathrm{f}}\right) \\ \mu^{\mathrm{f}} &= \mu_l \phi^{\mathrm{f}} + \mu_v \left(1 - \phi^{\mathrm{f}}\right) \end{aligned}$$

(Phase fraction of liquid in mixture)

Homogeneous mixture



$$\left.\frac{\partial \phi^{\mathrm{f}}}{\partial t}\right|_{\boldsymbol{\chi}} + \phi^{\mathrm{f}} \nabla \cdot \boldsymbol{u}^{\mathrm{f}} + (\boldsymbol{u}^{\mathrm{f}} - \boldsymbol{u}^{\mathrm{m}}) \cdot \nabla \phi^{\mathrm{f}} = \frac{\boxed{\dot{m}}}{\rho_l}$$

Cavitation Transport

Phase fraction (ϕ^{f}) field

Pressure, Velocity fields

$$\rho^{\mathrm{f}} \left.\frac{\partial \boldsymbol{u}^{\mathrm{f}}}{\partial t}\right|_{\chi} + \rho^{\mathrm{f}} \left(\boldsymbol{u}^{\mathrm{f}} - \boldsymbol{w}\right) \cdot \nabla \boldsymbol{u}^{\mathrm{f}} - \nabla \cdot \boldsymbol{\sigma}^{\mathrm{f}} = \boldsymbol{f}^{\mathrm{f}}$$

$$\nabla \cdot \boldsymbol{u}^{\mathrm{f}} = \left(\frac{1}{\rho_l} - \frac{1}{\rho_v}\right) \boxed{\dot{m}}$$

Navier-Stokes

Turbulent viscosity (μ_T) field

Velocity field

$$\left.\frac{\partial \tilde{\nu}}{\partial t}\right|_{\chi} + (\boldsymbol{u}^{\mathrm{f}} - \boldsymbol{u}^{\mathrm{m}}) \cdot \nabla \tilde{\nu} - c_{b1} \tilde{S} \tilde{\nu} - \frac{1}{\sigma} \nabla \cdot [(\nu + \tilde{\nu}) \nabla \tilde{\nu}] - \frac{c_{b2}}{\sigma} (\nabla \tilde{\nu}) \cdot (\nabla \tilde{\nu}) + c_{w1} f_w \left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2 = 0$$

Turbulence

Cavitation model by Schnerr et al.

$$\boxed{\dot{m}_A} = \frac{3\rho_l \rho_v}{\rho^{\mathrm{f}} R_B} \sqrt{\frac{2}{3\rho_l |p^{\mathrm{f}} - p_v|}} \Big[C_c \phi^{\mathrm{f}} (1 - \phi^{\mathrm{f}}) \max(p^{\mathrm{f}} - p_v, 0) + C_v \phi^{\mathrm{f}} (1 + \phi_{nuc} - \phi^{\mathrm{f}}) \min(p^{\mathrm{f}} - p_v, 0) \Big]$$

Governing equations

$$\begin{bmatrix} \boldsymbol{K}_{\Omega^{\mathrm{f}}} & \boldsymbol{G}_{\Omega^{\mathrm{f}}} \\ -\boldsymbol{G}^T_{\Omega^{\mathrm{f}}} & \boxed{\boldsymbol{C}_{\Omega^{\mathrm{f}}}} \end{bmatrix} \begin{Bmatrix} \Delta \boldsymbol{u}^{\mathrm{f}} \\ \Delta p \end{Bmatrix} = \begin{Bmatrix} \tilde{\mathcal{R}}_{\mathrm{m}} \\ \boxed{\tilde{\mathcal{R}}_{\mathrm{c}}} \end{Bmatrix}$$

Momentum and mass conservation

$$\boxed{[\boldsymbol{K}_{\phi}]} \{\Delta \phi\} = \{\boxed{\tilde{\mathcal{R}}_{\phi}}\}$$

Cavitation equation

	$\dfrac{\partial \dot{m}^{\mathrm{f,n}+\alpha}}{\partial p^{\mathrm{f,n+1}}}$	$\dfrac{\partial \left(s\phi^{\mathrm{f,n}+\alpha}\right)}{\partial \phi^{\mathrm{f,n}+\alpha}}$
$p_h^{\mathrm{n+1}} > p_v$	$C_c \phi_h^{\mathrm{f,n}+\alpha} (1 - \phi_h^{\mathrm{f,n}+\alpha}) \dfrac{\rho_l \rho_v}{\rho^{\mathrm{f}} R_B} \sqrt{\dfrac{3}{2\rho_l (p_h^{\mathrm{n+1}} - p_v)}}$	$-C_c (1 - 2\phi_h^{\mathrm{f,n}+\alpha}) \dfrac{3}{R_B} \sqrt{\dfrac{2(p_h^{\mathrm{n+1}} - p_v)}{3\rho_l}}$
$p_h^{\mathrm{n+1}} < p_v$	$C_v \phi_h^{\mathrm{f,n}+\alpha} (1 + \phi_{nuc} - \phi_h^{\mathrm{f,n}+\alpha}) \dfrac{\rho_l \rho_v}{\rho^{\mathrm{f}} R_B} \sqrt{\dfrac{3}{2\rho_l (p_v - p_h^{\mathrm{n+1}})}}$	$C_v (1 + \phi_{nuc} - 2\phi_h^{\mathrm{f,n}+\alpha}) \dfrac{3}{R_B} \sqrt{\dfrac{2(p_v - p_h^{\mathrm{n+1}})}{3\rho_l}}$
$p_h^{\mathrm{n+1}} = p_v$	0, using $\lim_{p_h^{\mathrm{n+1}} \to p_v} \dfrac{p_h^{\mathrm{n+1}} - p_v}{\sqrt{\lvert p_h^{\mathrm{n+1}} - p_v \rvert}} = 0$	0, using $\lim_{p_h^{\mathrm{n+1}} \to p_v} \dfrac{p_h^{\mathrm{n+1}} - p_v}{\sqrt{\lvert p_h^{\mathrm{n+1}} - p_v \rvert}} = 0$

Novel stable linearizations

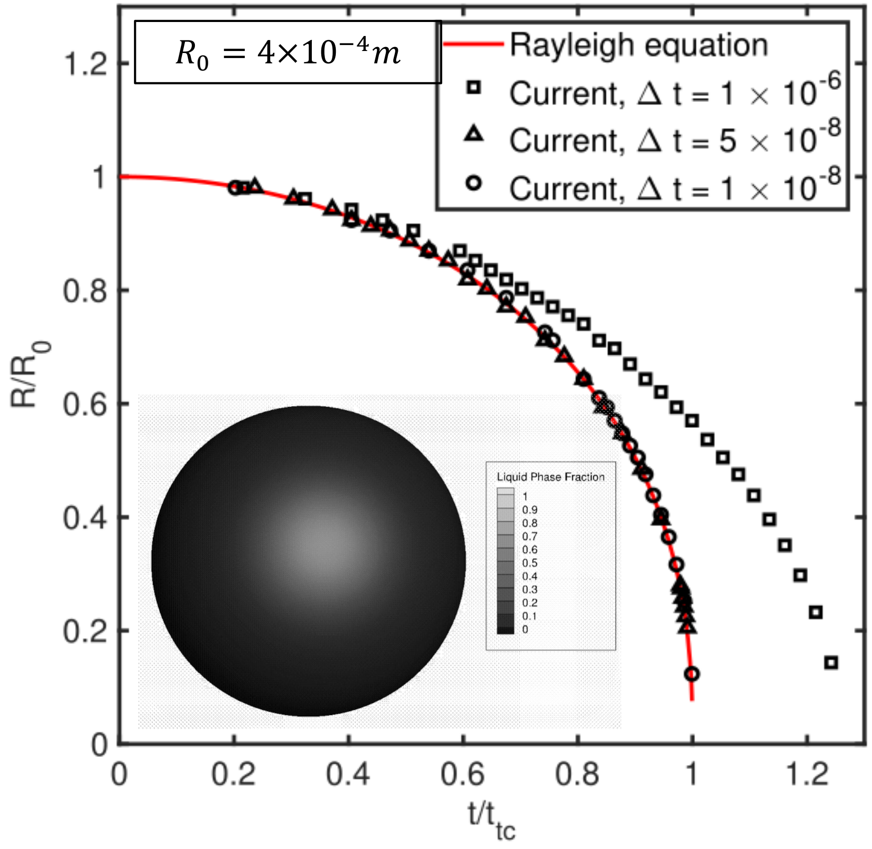
Robustness criteria for numerical study

- Accurate prediction of pressure field
- Handling large density ratios (ρ_l/ρ_v) $O(10^2 - 10^3)$
- Absence of numerical pressure spikes across cavity interface

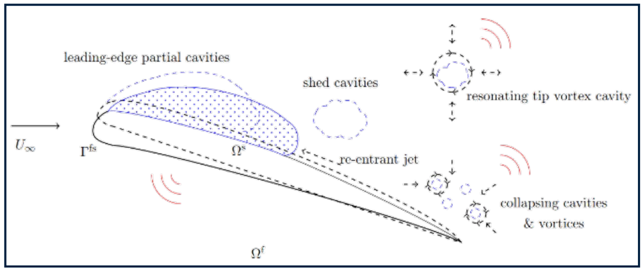
Kashyap and Jaiman, 2021 (CAMWA) https://doi.org/10.1016/j.camwa.2021.10.024

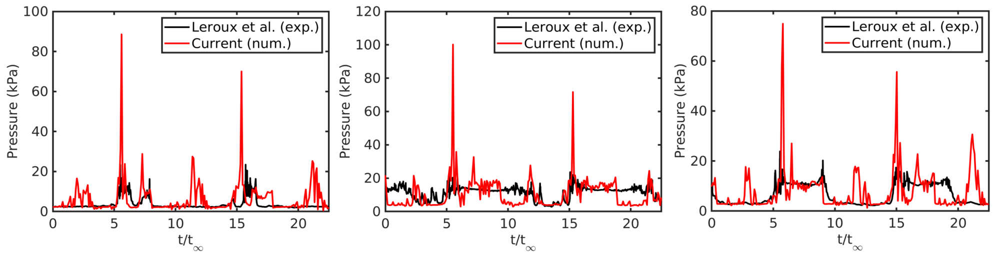
Nihar & Jaiman, 2024 (CAF)

Bubble and Sheet Cavitation



Micro-scale collapse of a spherical vaporous bubble



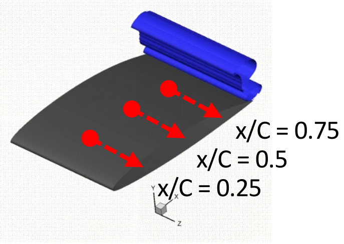


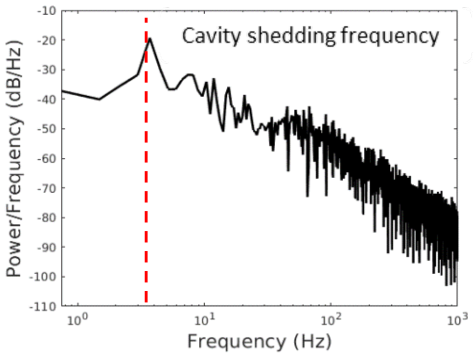
x/C = 0.25

x/C = 0.5

x/C = 0.75

Pressure probe data





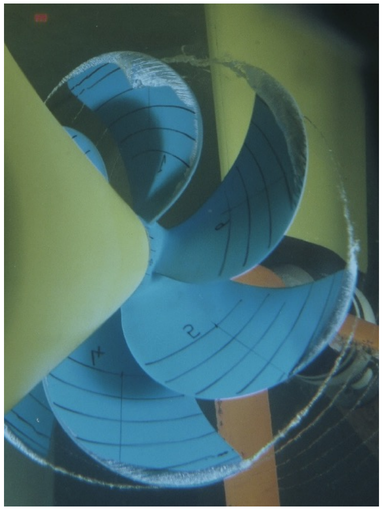
PSD of pressure coefficient x/C = 0.75

- Handling large density ratios (ρ_l/ρ_v) $O(10^2 - 10^3)$
- Absence of numerical pressure spikes across cavity interface

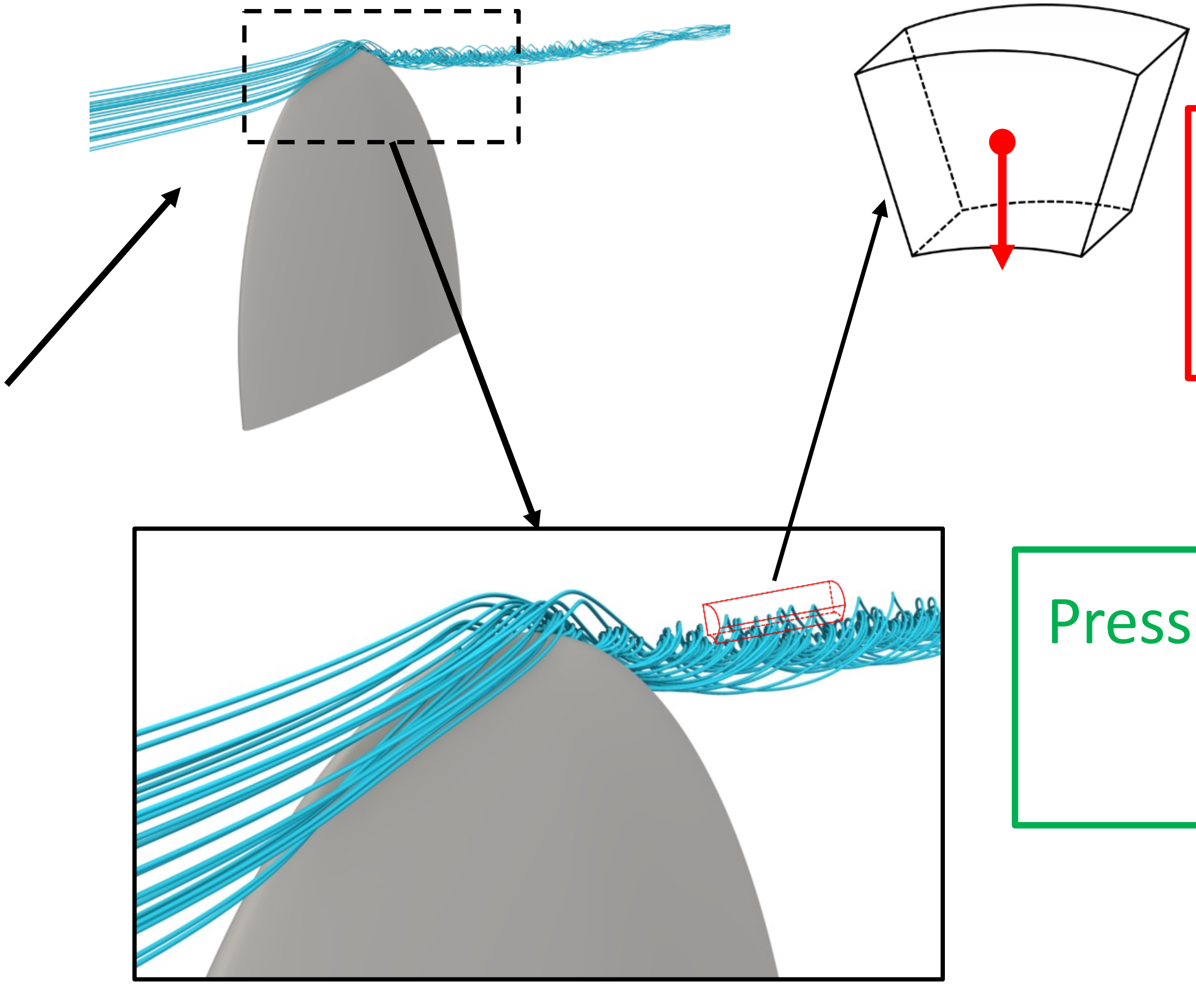
Macro-scale turbulent cavitating flow
Cavitation Number (σ) = 1.25; angle of attack= 6^0

Kashyap & Jaiman, IJMF 2022

Review: Tip Vortex Cavitation



Sheet and tip vortex cavitation on a propeller in MARIN’s cavitation tunnel

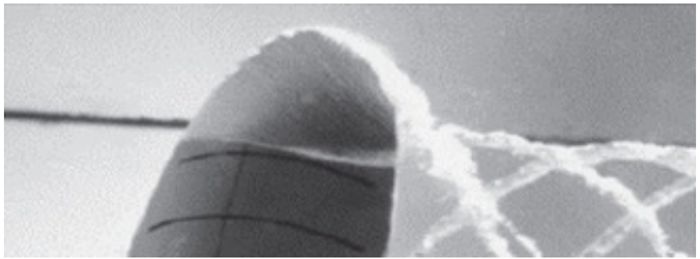


What is providing the centripetal force?

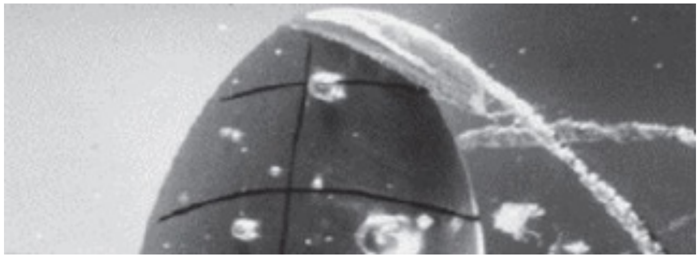
Pressure gradient!

$$\frac{\partial P}{\partial r}$$

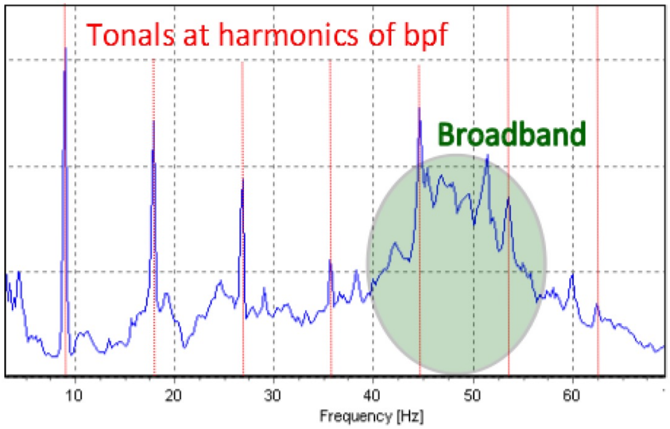
Tip Vortex Cavitation Noise



Sheet Cavitation



Tip Vortex Cavitation



Hull pressure fluctuations spectrum

(**Source**: van Wijngaarden et al. (2005). Aspects of the cavitating propeller tip vortex as a source of inboard noise and vibration.)

Broadband "hump" in HPF

Need for TVC mitigation strategies

First step: Understanding the phenomenon

Challenging to simulate!

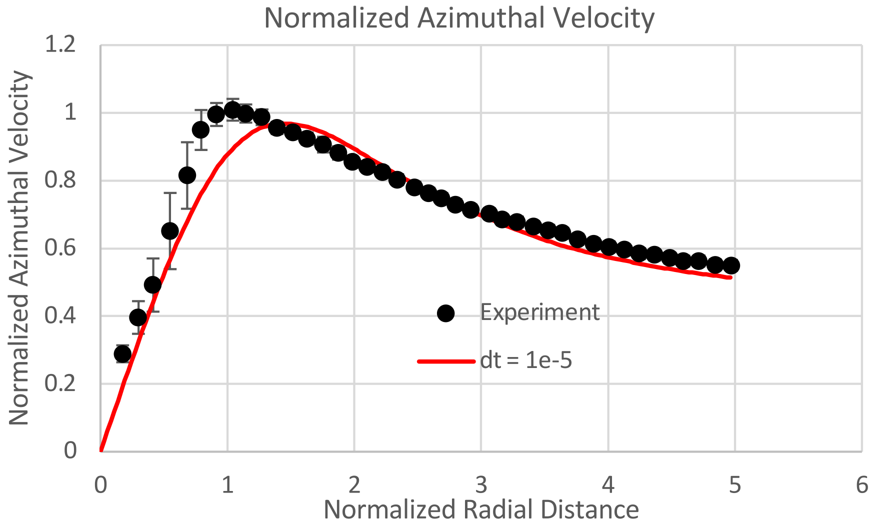
- High gradients
- Highly anisotropic
- Tip vortex-boundary layer interactions
- Tip vortex wandering

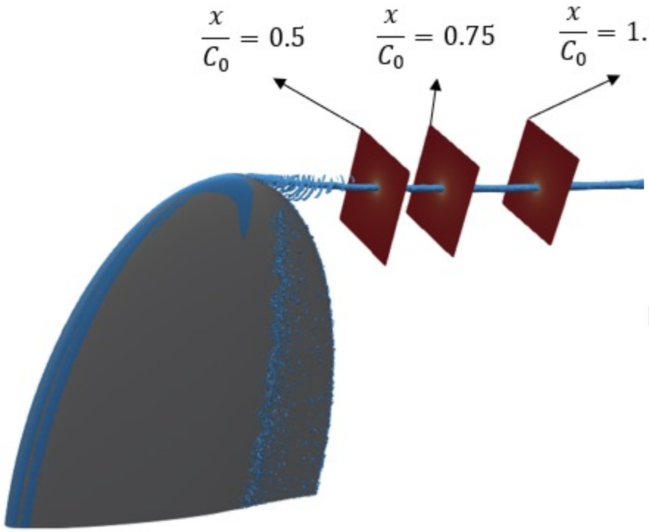
Problem-specific meshing strategy is required

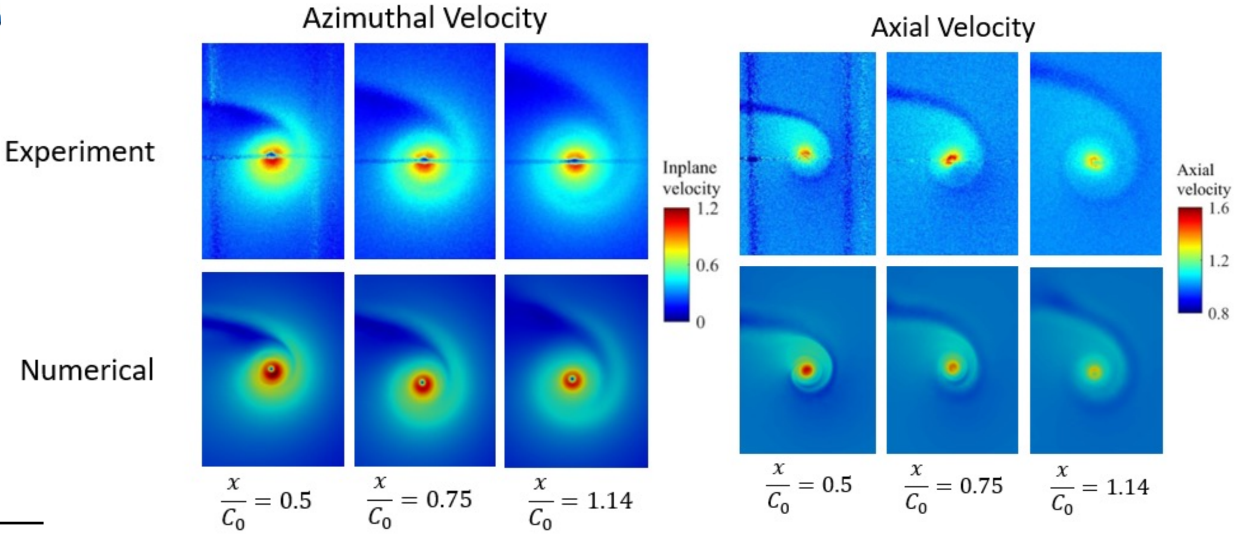
RANS cannot be used → **LES**

Tip Vortex Cavitation: Validation

- ☐ Low pressure region within the tip vortex core leads to cavitation
  - ▶ Highly 3D anisotropic turbulent flow
  - ▶ Non-spherical behavior of bubbles
- ☐ Asymmetric blade (NACA 66(2)-415)



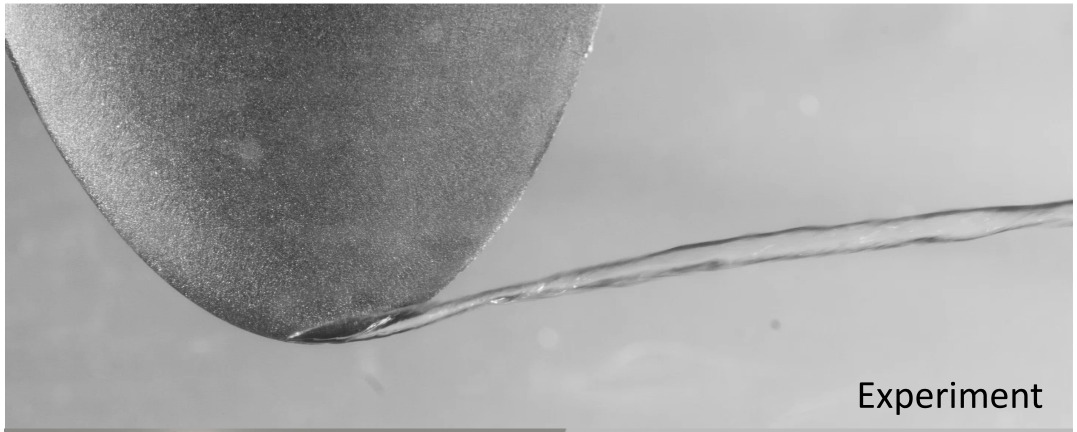


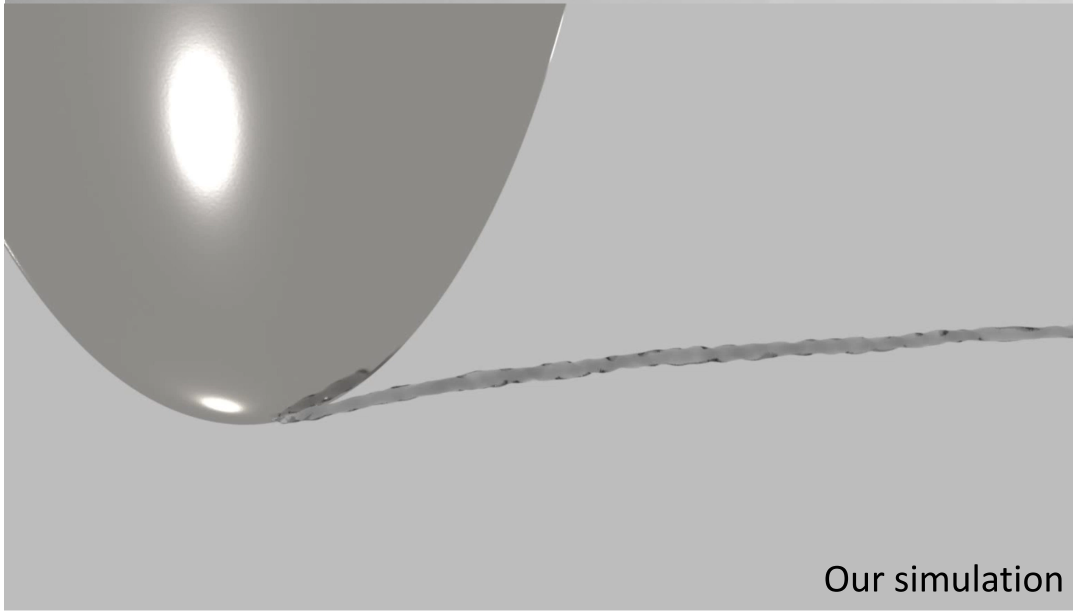


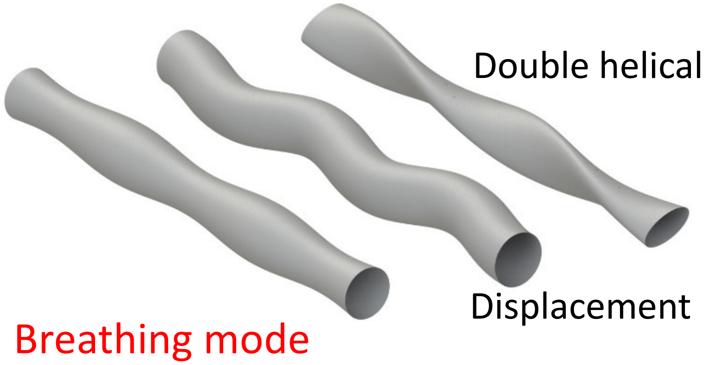
$$\text{New scale } \Delta r^* = \frac{\Delta r}{\mathcal{L}_\tau} = \frac{\Delta r}{\left(\frac{16\pi^2}{C_L^2 Re^{2.6}}\right)^{\frac{1}{3}} c_0}$$

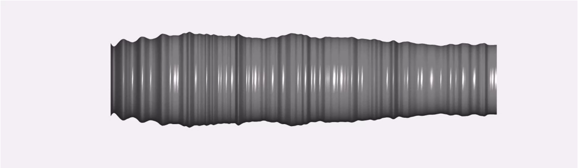
$\mathcal{L}_\tau$: Pressure-gradient-based length scale
Δr: Mesh resolution in tip vortex flow region
c_0: Root chord length

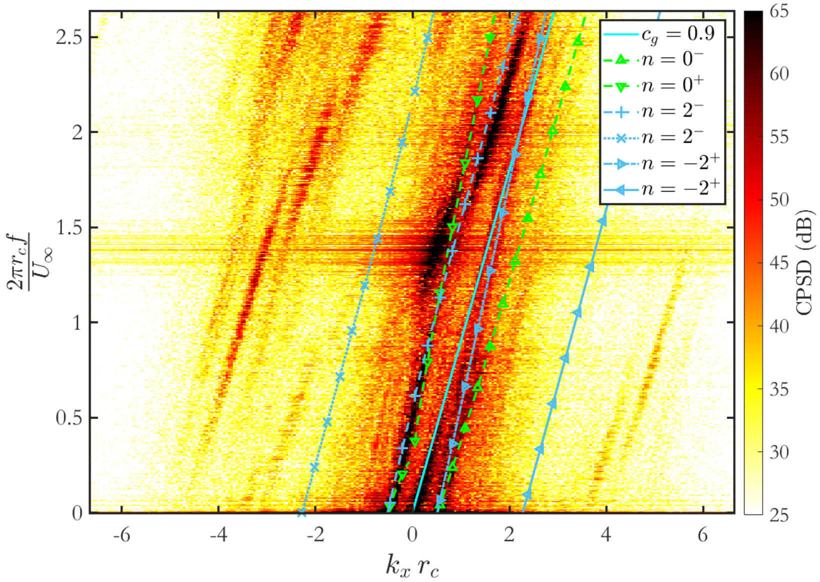
Breathing Mode Oscillation











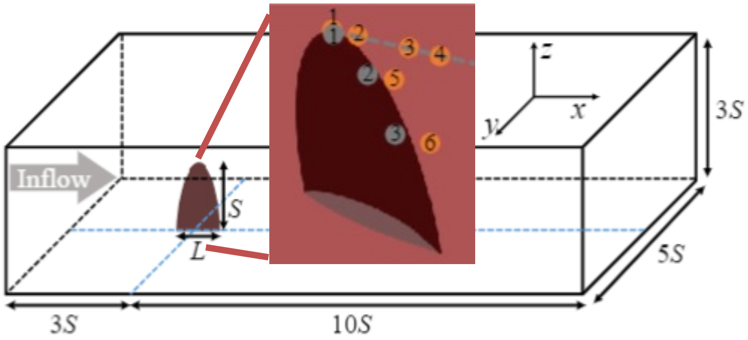
n: Azimuthal wavenumber (oscillation mode)
r_c: Cavity radius
$\widetilde{U}_x$: Non-dimensional axial velocity on cavity interface
$\widetilde{U}_\theta$: Non-dimensional azimuthal velocity on cavity interface
K_σ: Non-dimensional stiffness coefficient
k_x: Streamwise wavenumber
K_n: Modified Bessel function of second kind

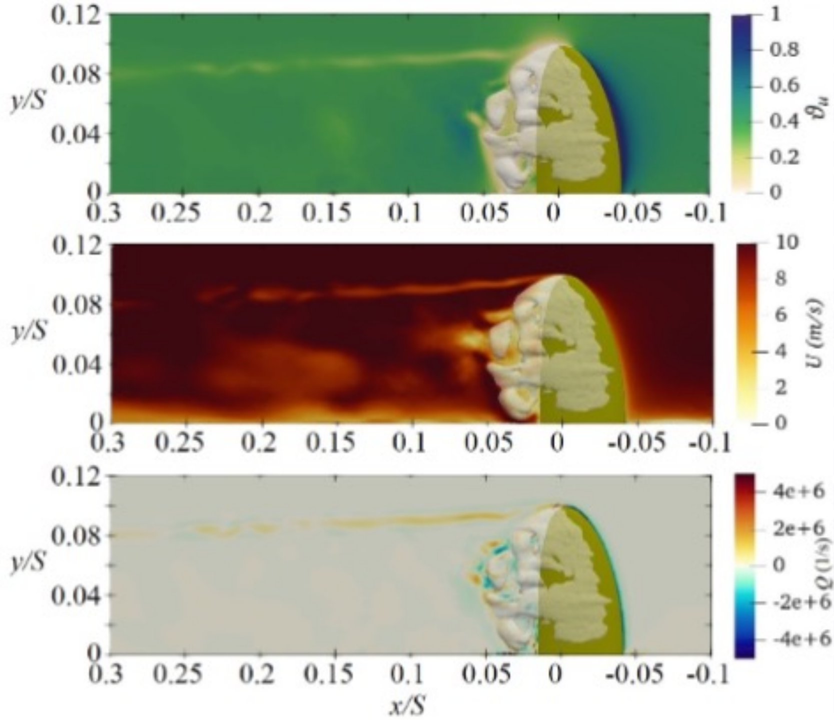
Semi-analytical dispersion relation

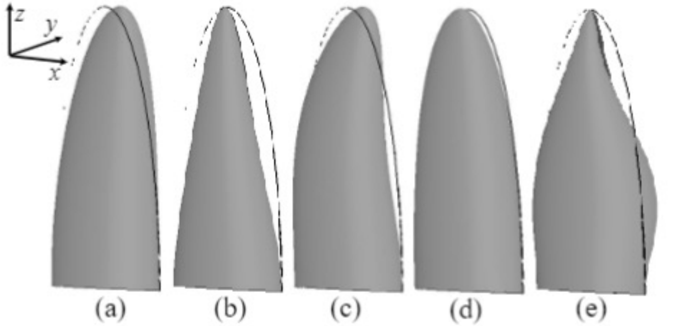
$$\frac{2\pi r_c f^{\pm}}{U_\infty} = \widetilde{U}_x k_x r_c + \widetilde{U}_\theta n \pm \sqrt{K_\sigma}\sqrt{\frac{-\,|k_x r_c|\,K_n'(|k_x r_c|)}{K_n(|k_x r_c|)}T_\omega}$$

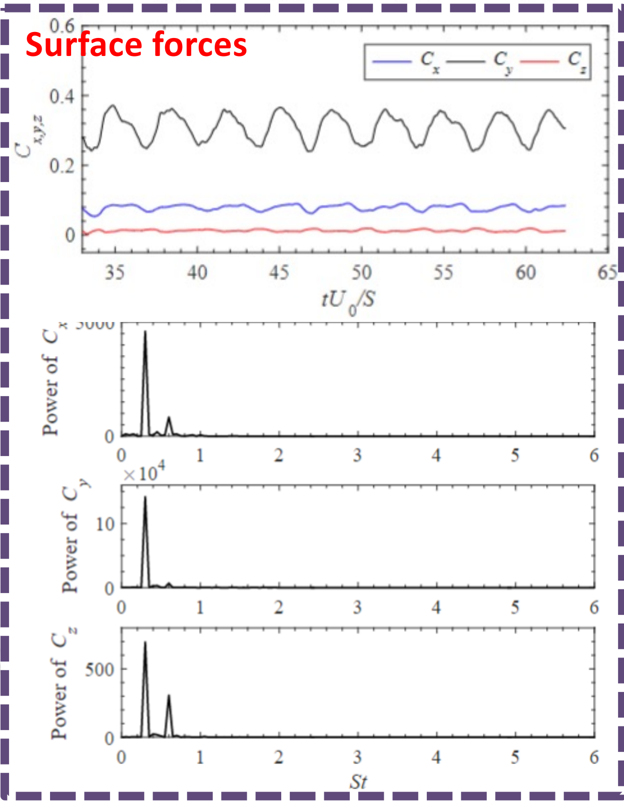
Lak & Jaiman, JFM 2024

Propeller Singing: Tonal Noise

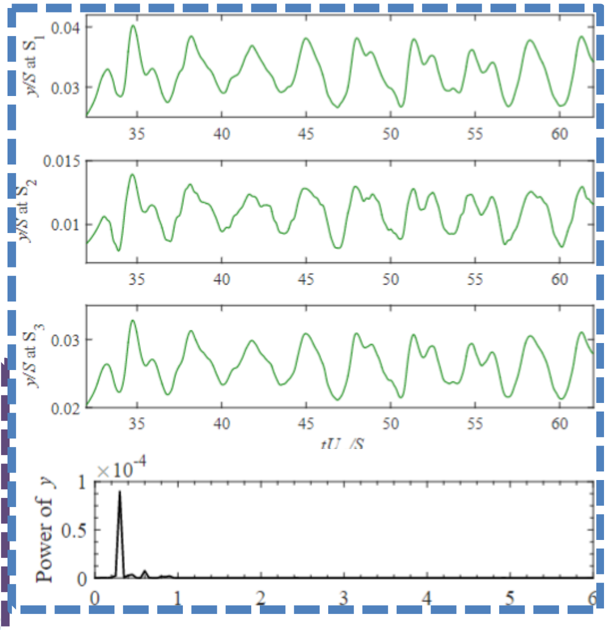




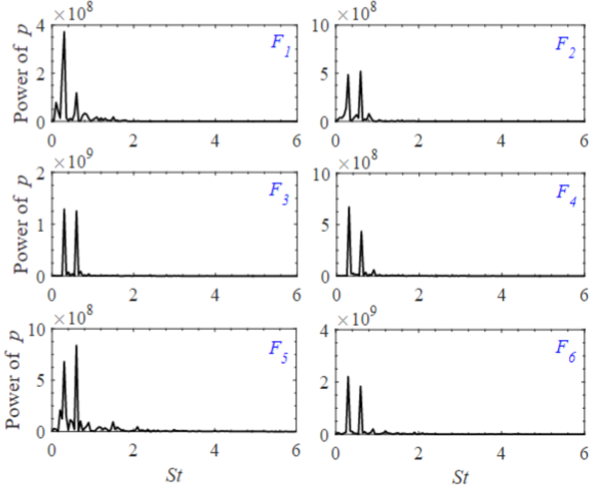



Surface forces

Vibration displacements



Field pressure



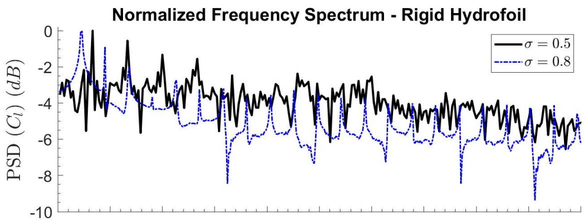
Discovered novel mechanism of synchronized hydroelastic lock-in of cavitating propeller with structural natural frequencies

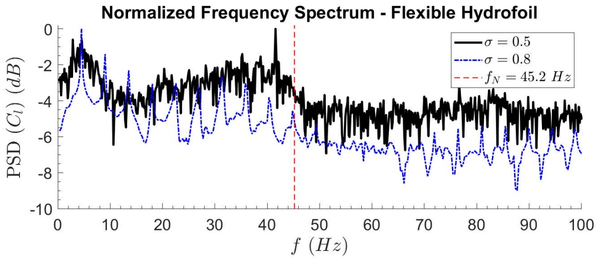
Cheng & J, OMAE 2024

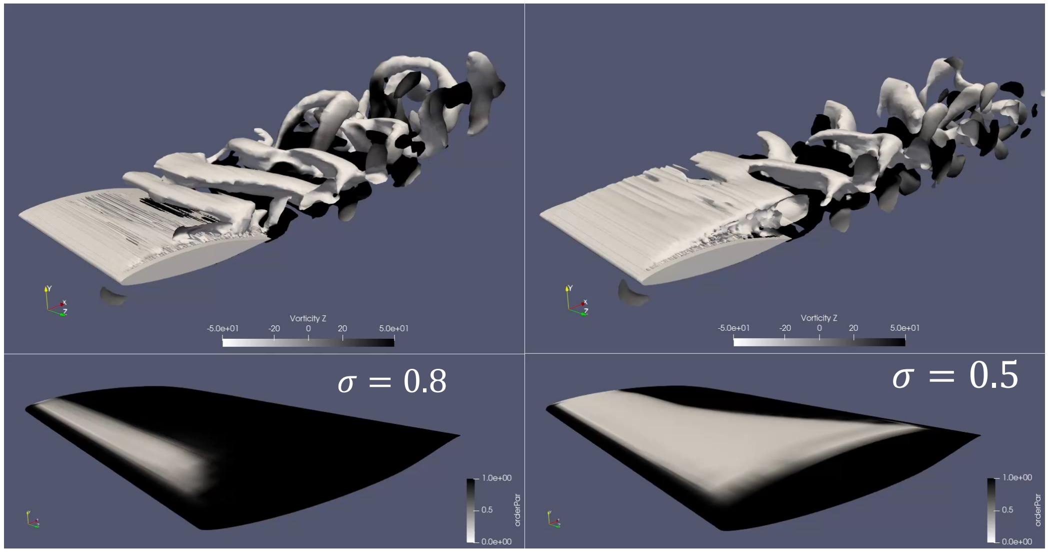
Flexibility Effect on Sheet Cavitation

Propeller/rudder system
(Seaspan Corporation)

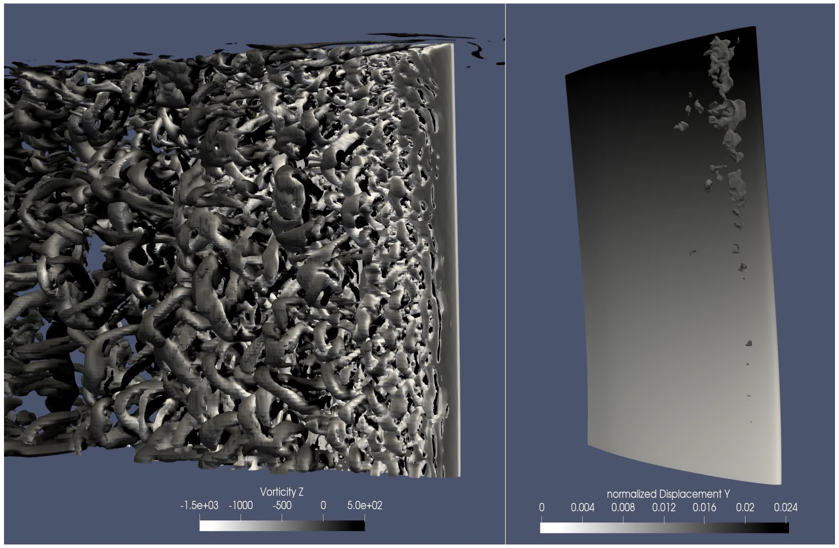
- Sheet cavitation on suction side of blades/rudder
    - Occurs at off-design angle of incidence
    - Results in large suction pressure at leading edge
- Flexibility adjusts pressure fluctuations
    - Cavitation cycle adopts subharmonic frequencies of propeller blade
    - Proper adjustment of flexibility and trailing edge can reduce cavitation and noise







Vortex dynamics and cloud cavitation



Coupled bending-torsional synchronization

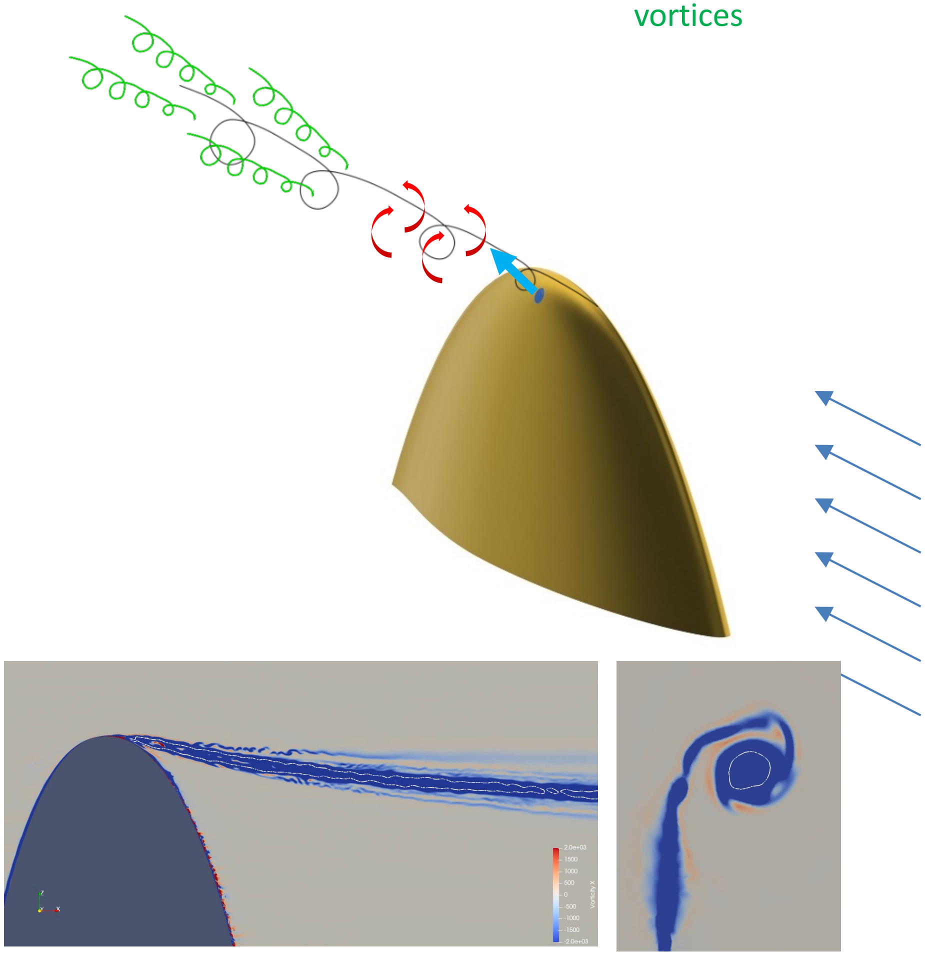
Darbhamulla & J., CAF 2023

Active Jet and Passive Morphing Techniques

Active → Jet Injection

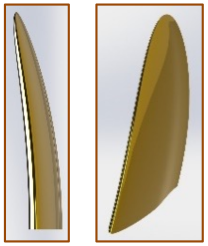
Mixing up the tip vortex flow

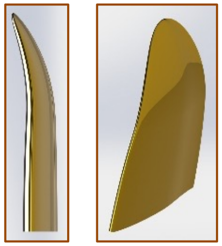
Splitting the tip vortex to smaller vortices



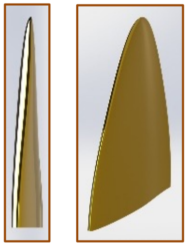
Passive → Holes from Pressure Side to Suction Side

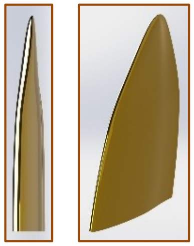
Bending


Entire Span


Partial

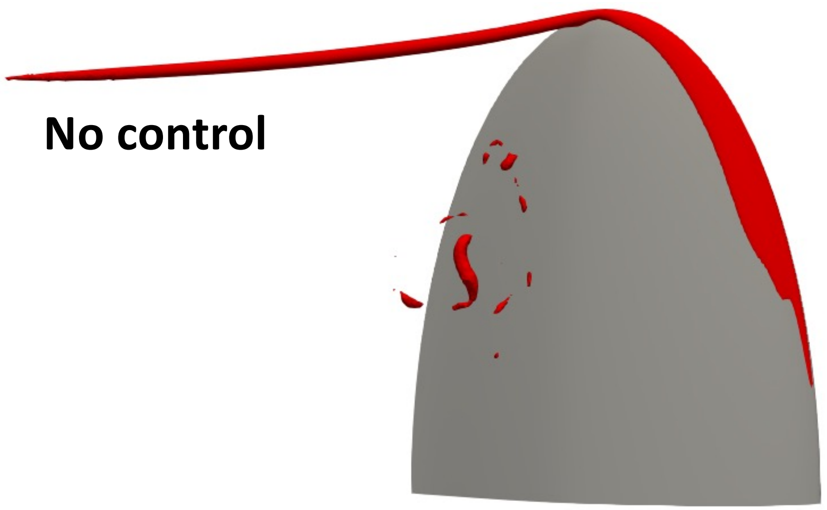
Twisting


Entire Span

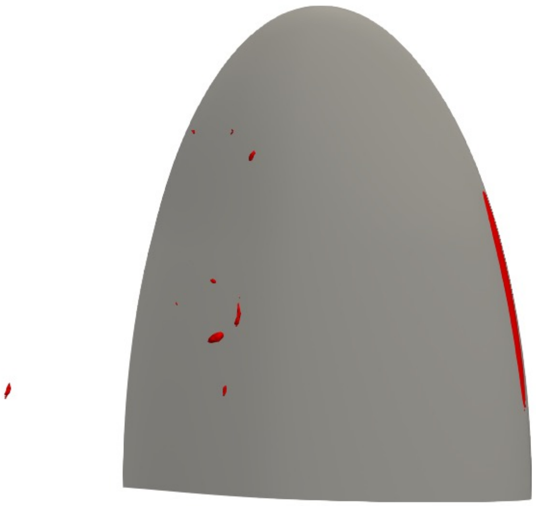

Partial

Confidential: Not published

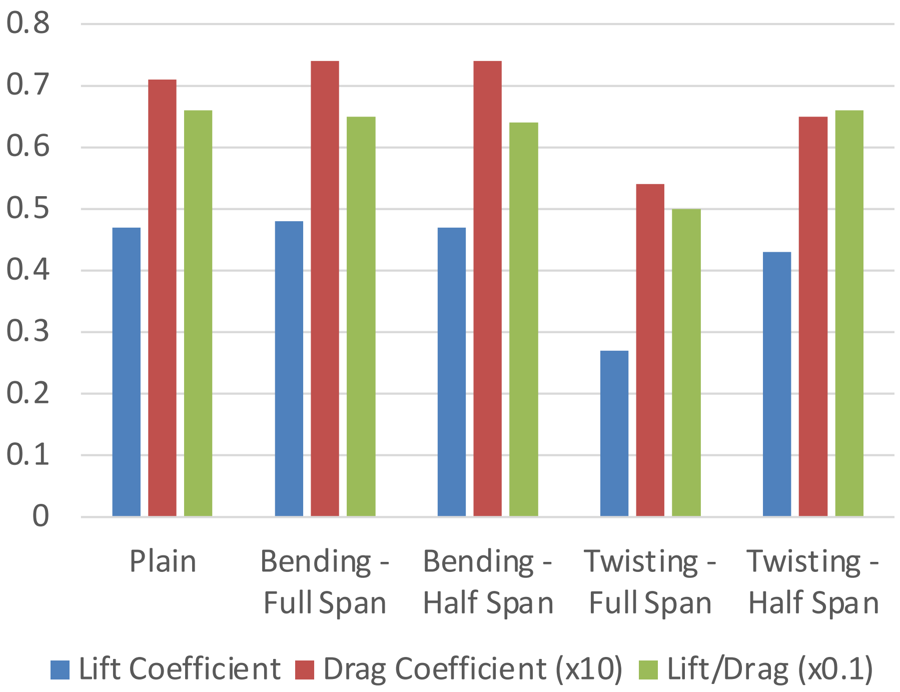
Effect of Twisting on Tip Vortex Cavitation: Preliminary Results



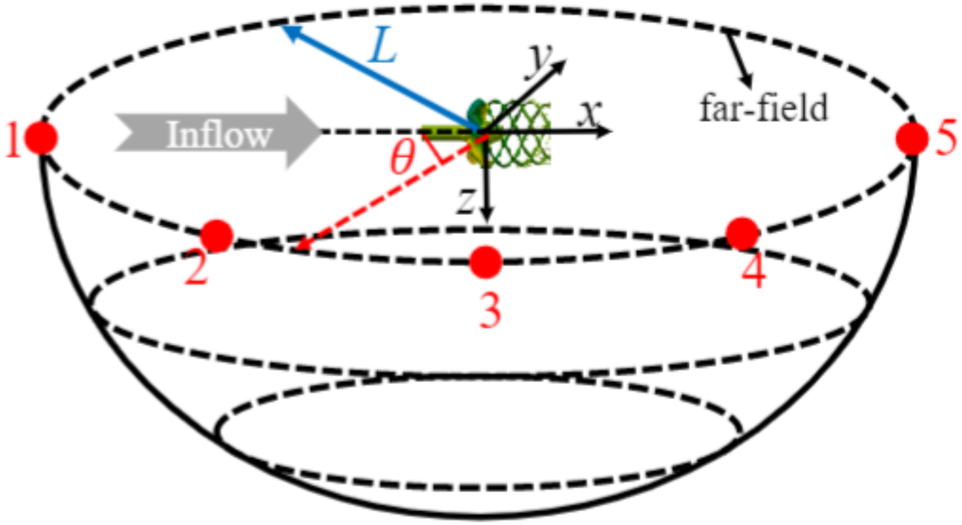
No control



Control with continuous twisting



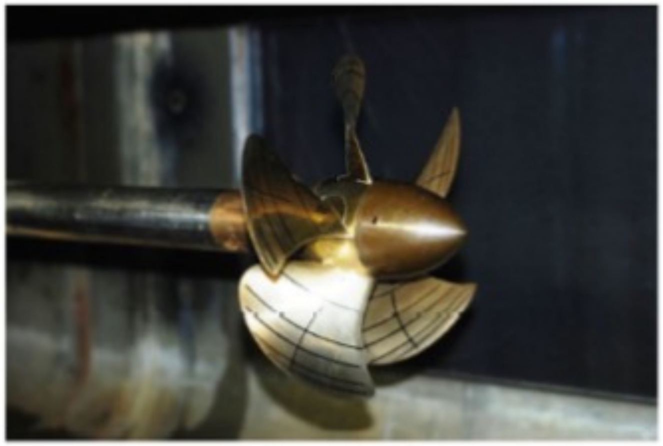
Confidential: Not published



FULL SCALE PROPELLER VALIDATION AND URN PREDICTIONS

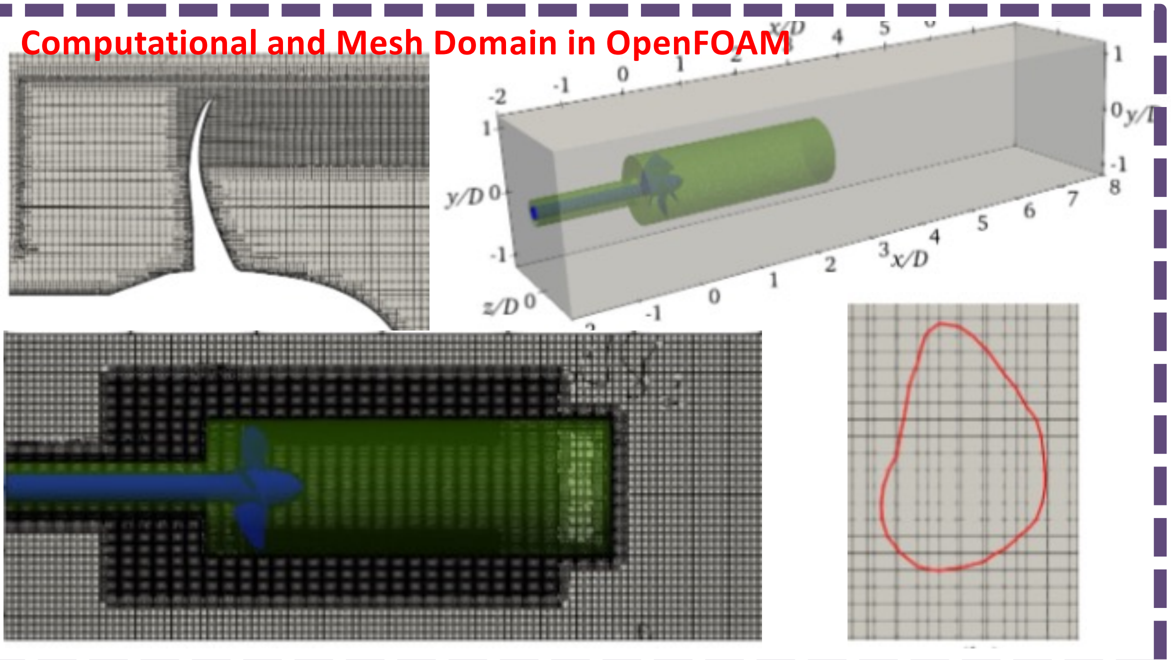
Near-field wake dynamics of full propeller

Potsdam Propeller Test Case (VP1304）



J	σ_n	n	D	Hub ratio
1.019	2.024	25 rps	0.25 m	0.3

Computational and Mesh Domain in OpenFOAM

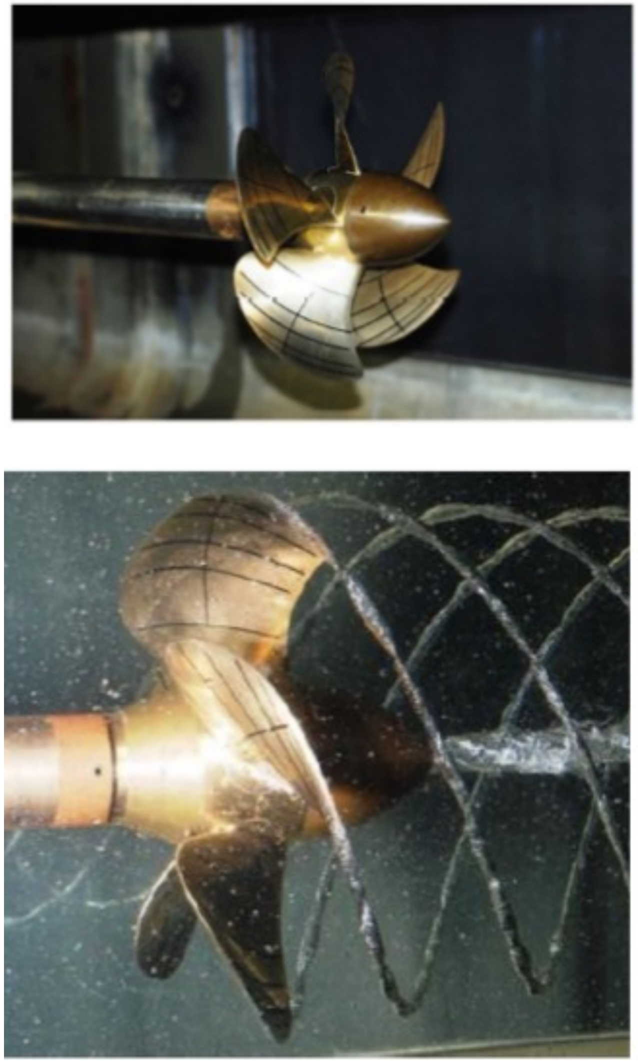


Mesh Dependency and Model Validation

	Total cells number (millions)	Rotor region (millions)	Stator region (millions)	$K_{T,rms}$	$10K_{Q,rms}$	y^+	$\hat{x}_{tv}$
Experiments [18]				0.374	0.9698		
Other simulation [37]				0.380	0.9680		
Mesh 1	18.0	15.0	3.0	0.361	1.0398	92	0.004
Mesh 2	26.9	22.5	4.5	0.375	0.9710	40	0.006
Mesh 3	40.4	33.7	6.7	0.378	0.9648	19	0.009

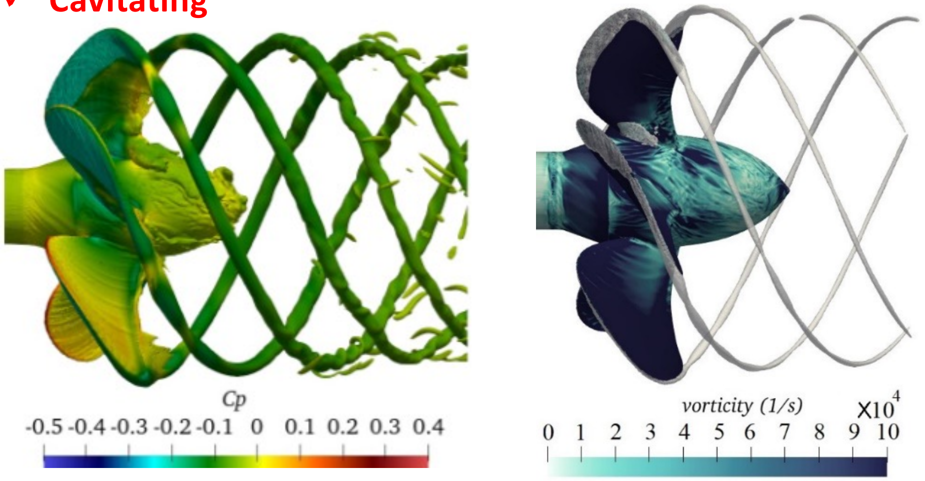
➢ Near-field wake dynamics of full propeller

✓ **Potsdam Propeller Test Case (VP1304）**

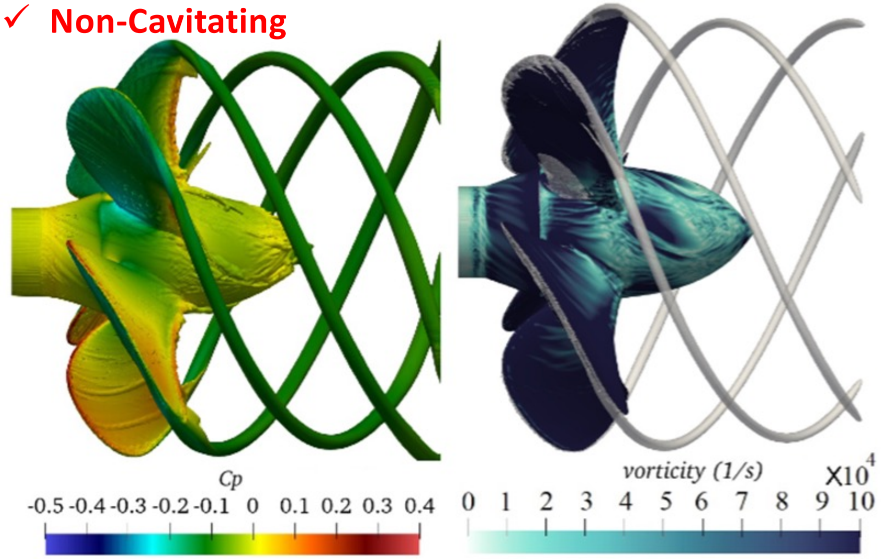


Simulation Results

✓ **Cavitating**

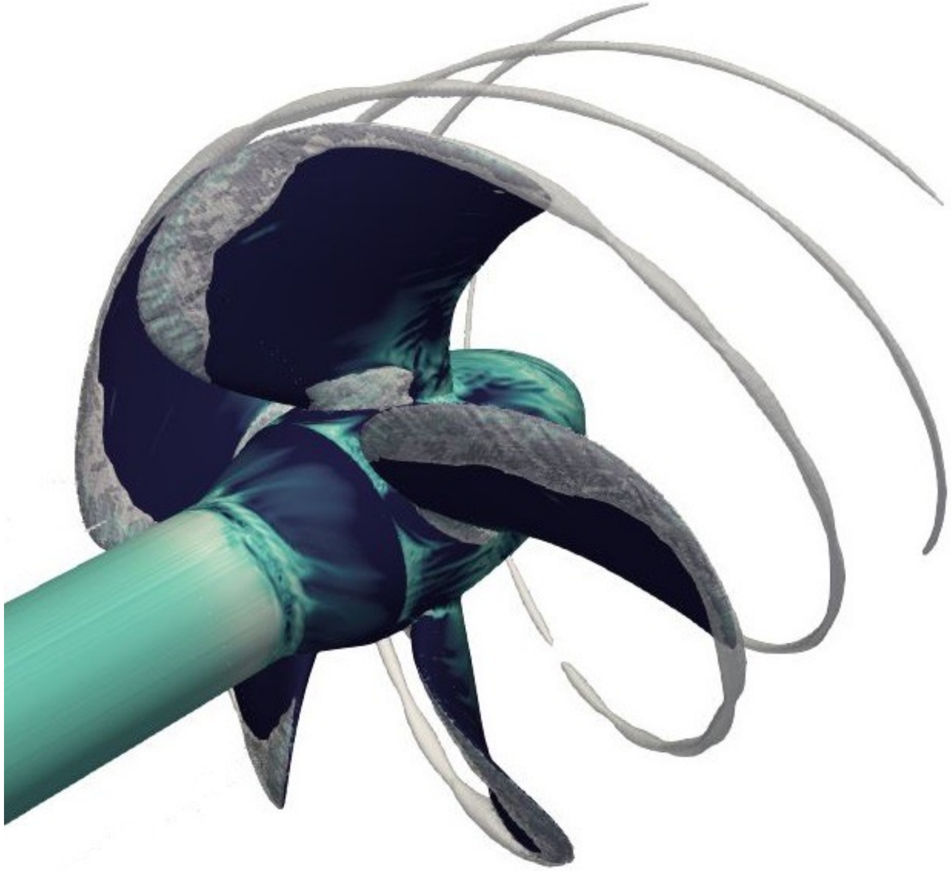


✓ **Non-Cavitating**

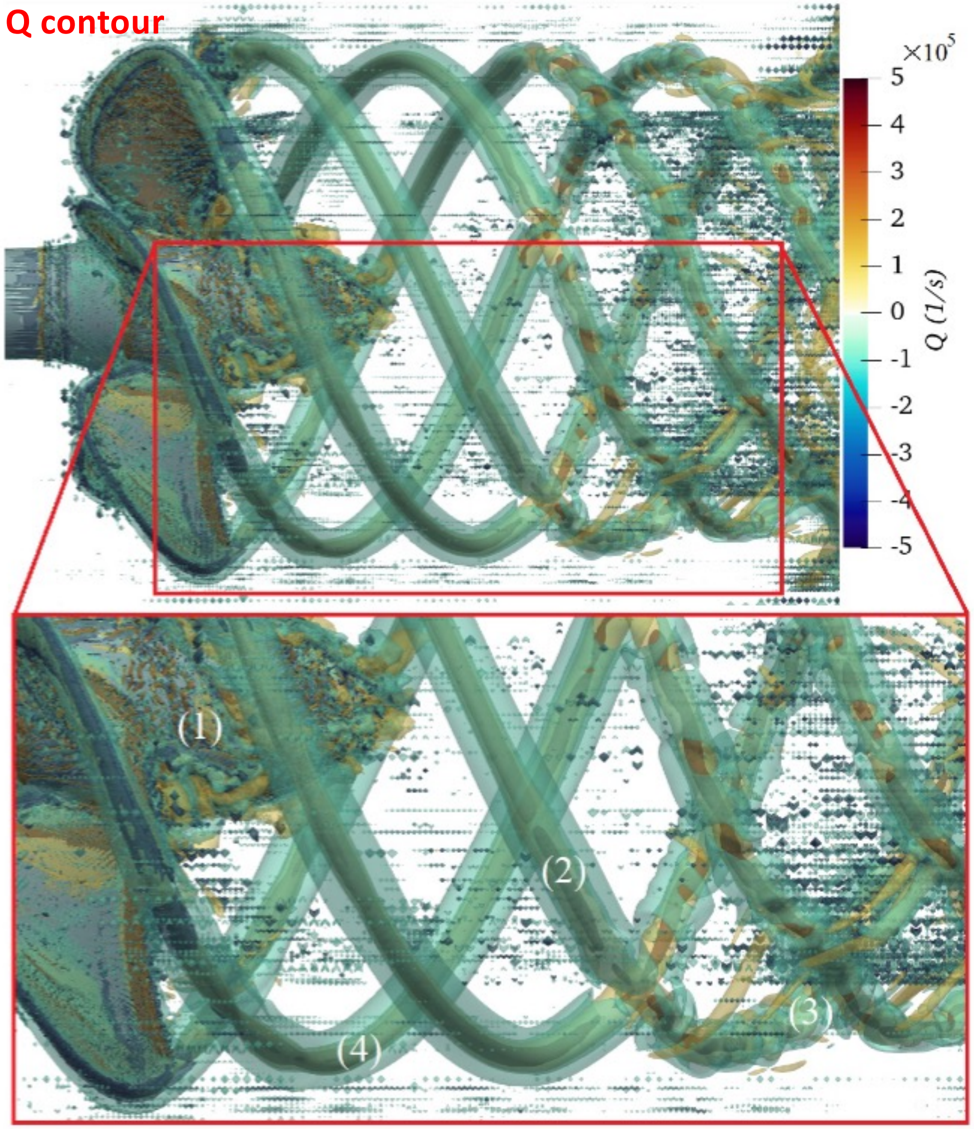


➢Near-field wake dynamics of full propeller

Cavitation contour

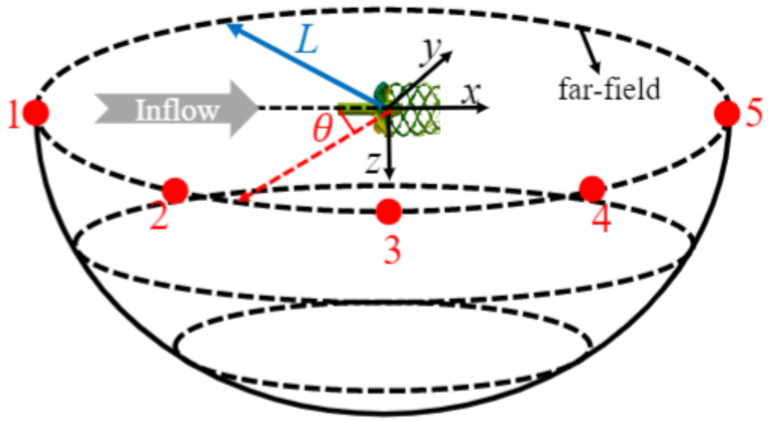


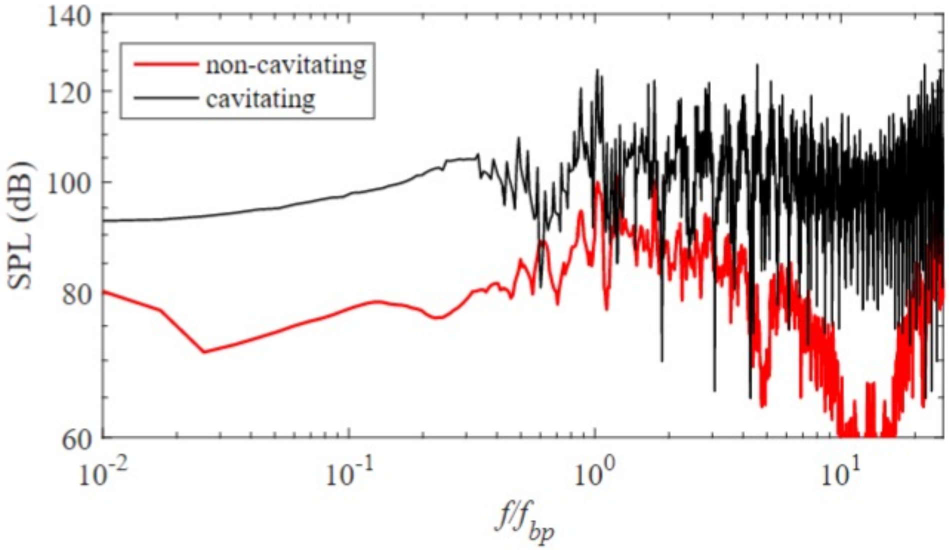
Q contour

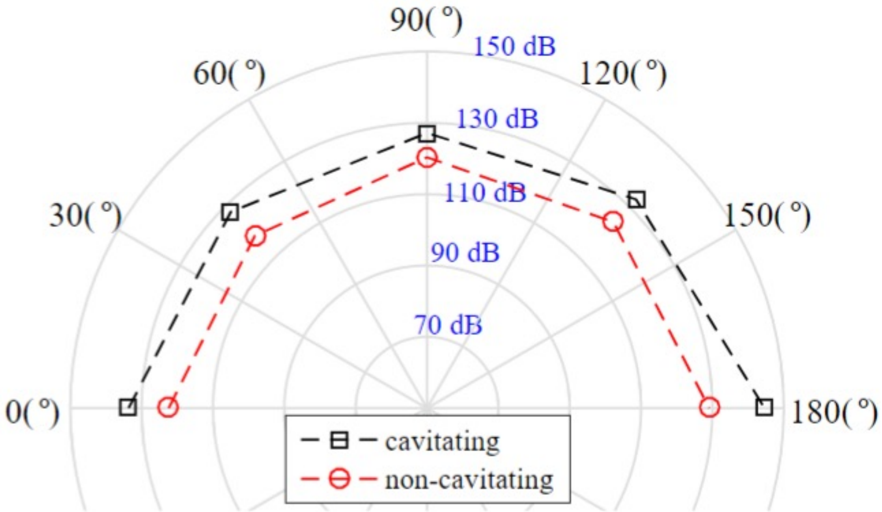


➢ Near-field noise prediction of full propeller

✓ **SPL directivity**

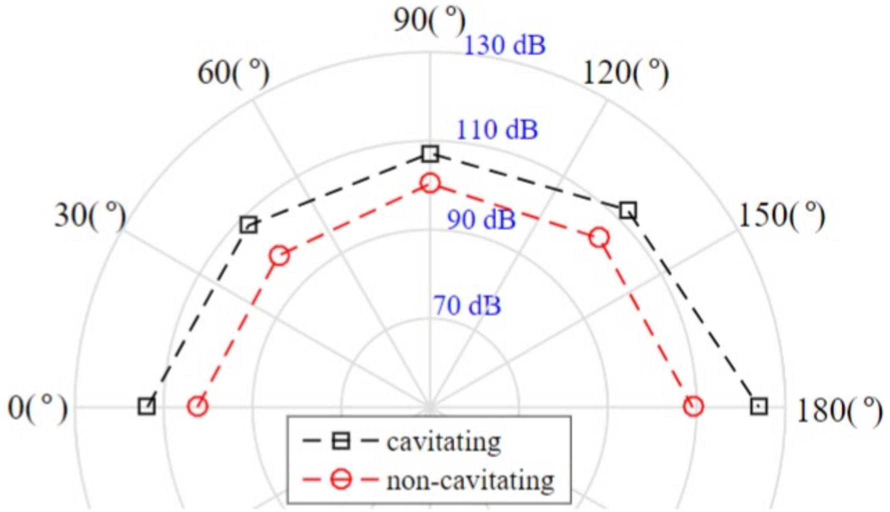






L = 100 m

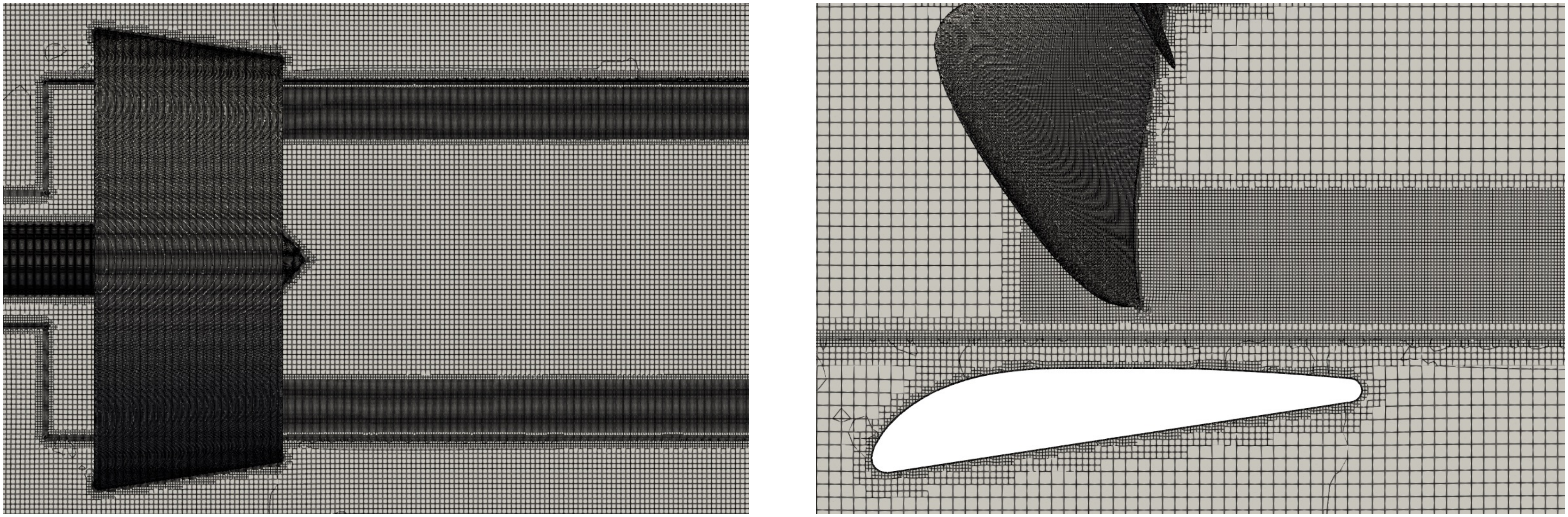
(a)



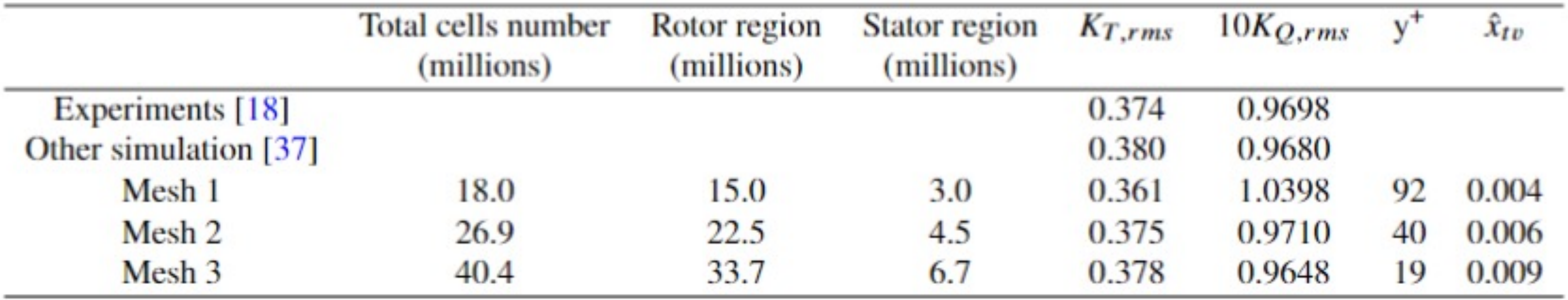
(b)

L = 1000 m

Ducted Propeller: Effect of Nozzle



Mesh Dependency and Model Validation



	Total cells number (millions)	Rotor region (millions)	Stator region (millions)	$K_{T,rms}$	$10K_{Q,rms}$	y^+	$\hat{x}_{tv}$
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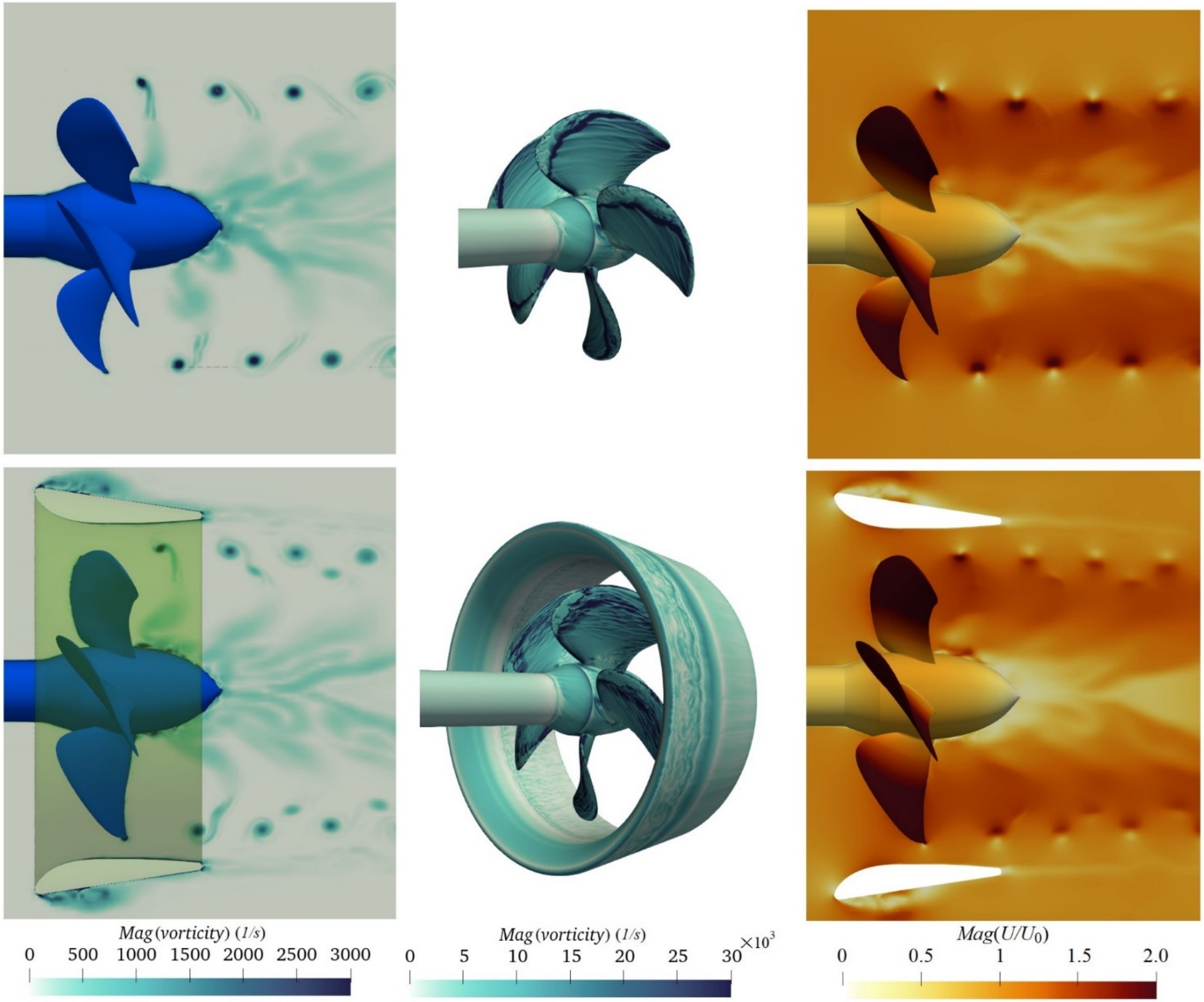
Mesh 3	40.4	33.7	6.7	0.378	0.9648	19	0.009

Comparison of Flow Fields (1)

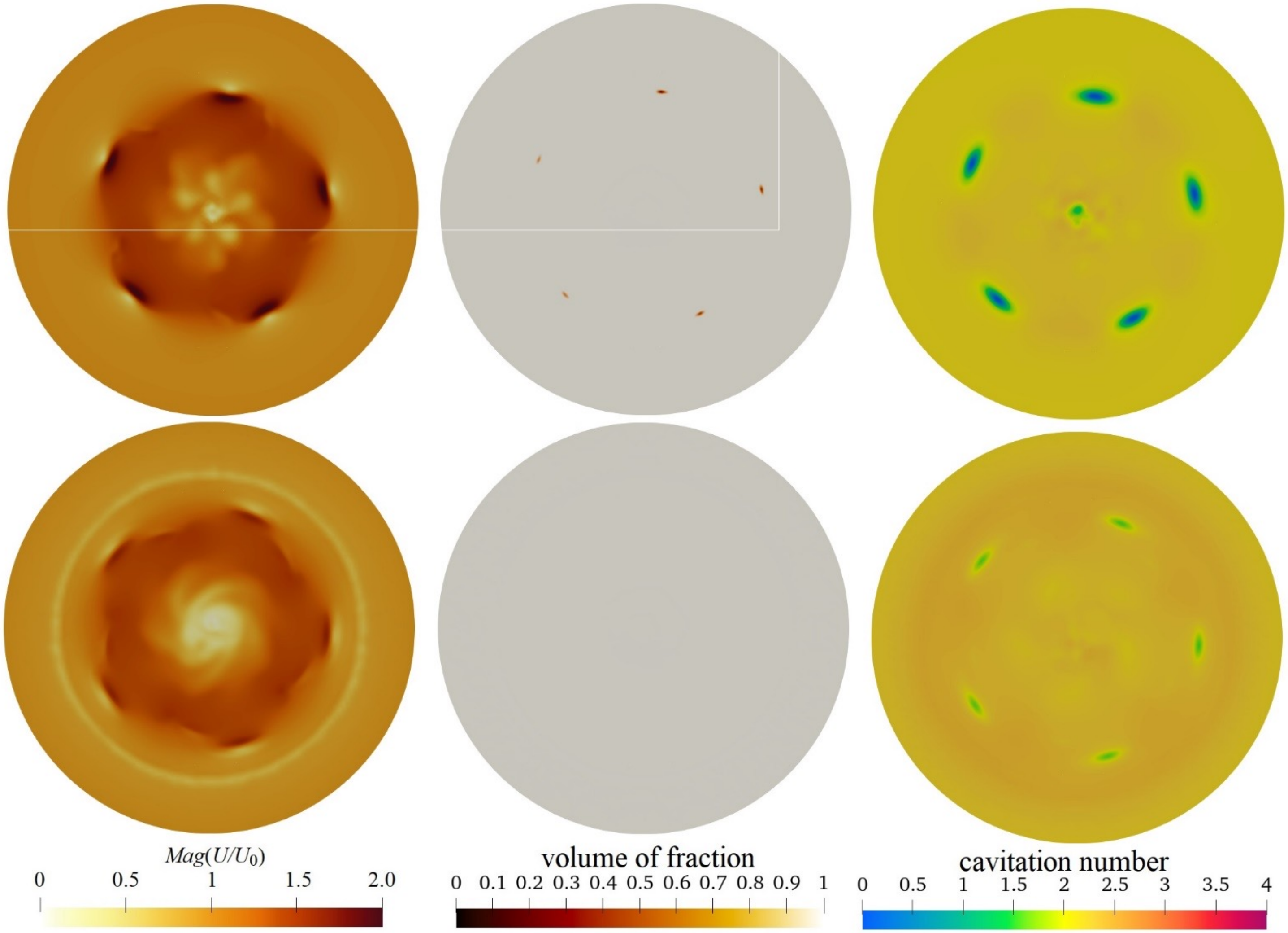
- ✓ Non-ducted
- ✓ Ducted



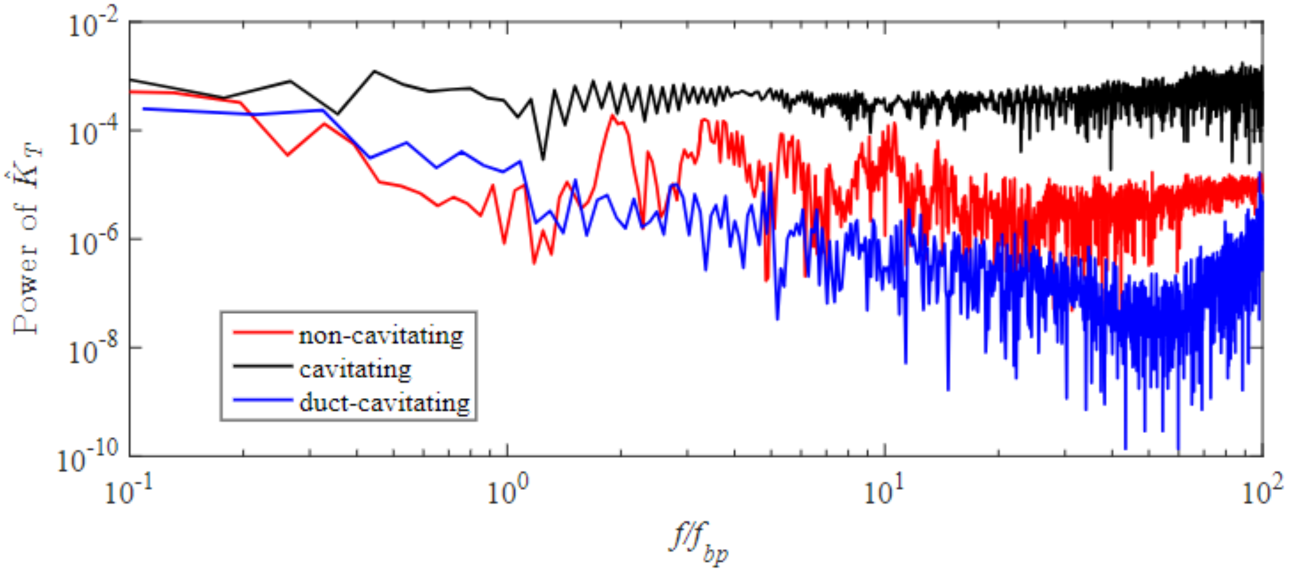
Comparison of Flow Fields (2)

- ✓ *y*-*z* planes at $x/D = 0.4$

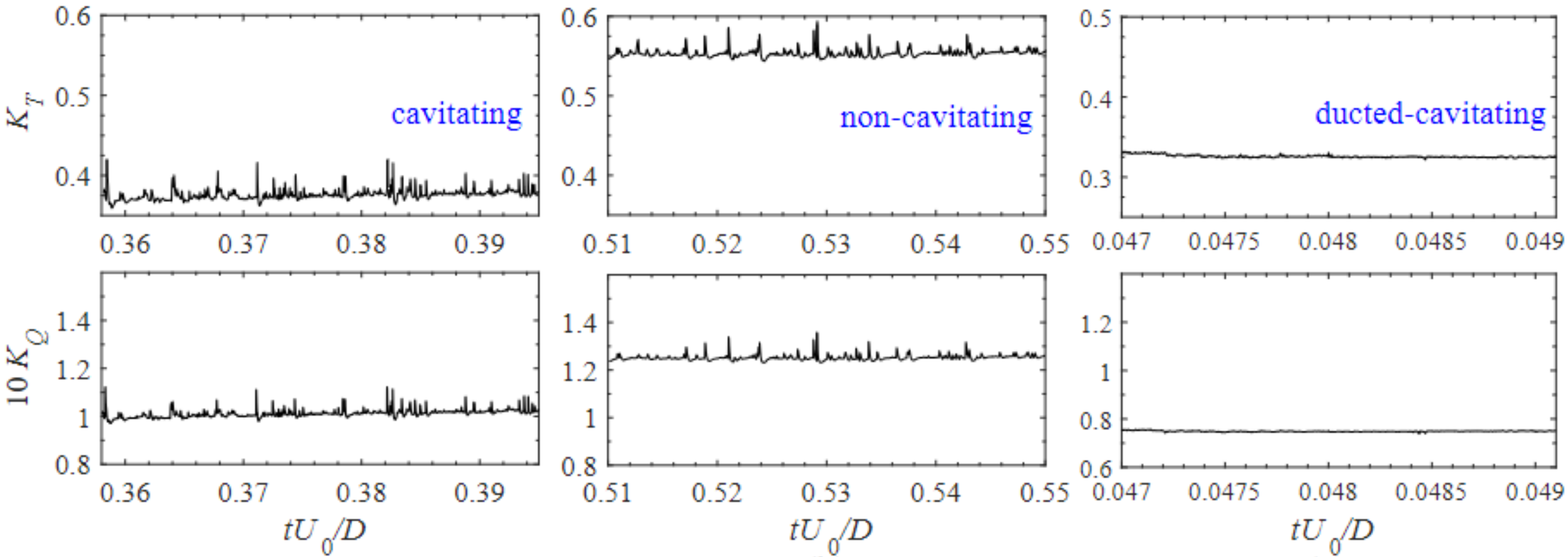
  - ✓ Non-ducted
  - ✓ Ducted



Effect of Nozzle on Noise Spectra



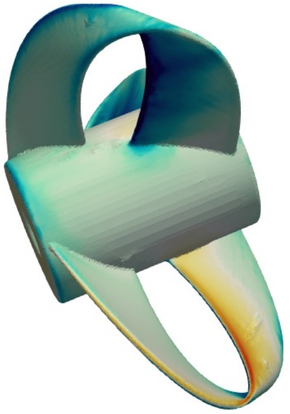
	$K_{T,rms}$	$10K_{Q,rms}$
Non-cavitating	0.542	1.2421
Cavitating	0.378	0.9648
Ducted-Cavitating	0.326	0.7488

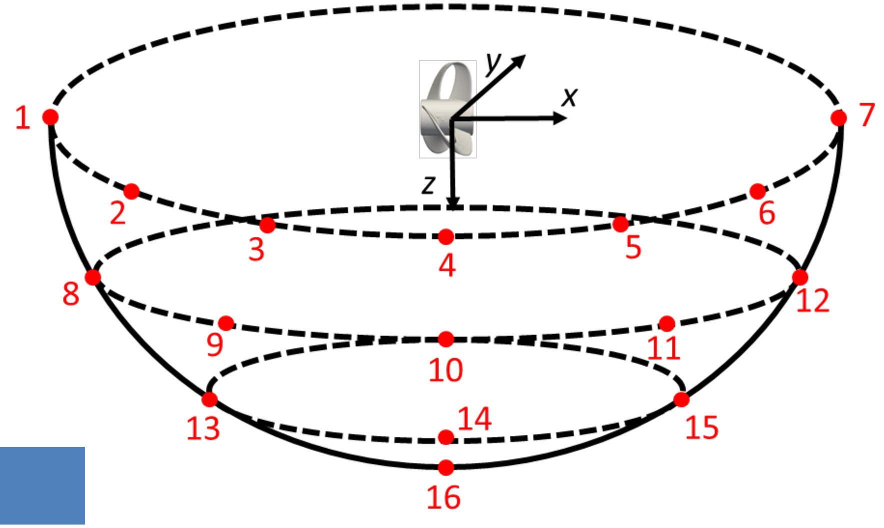


(a) (b) (c)

Toroidal Propeller

- Turbulence model: *k*-*w* SST DES
- Hydroacoustics: FW-H



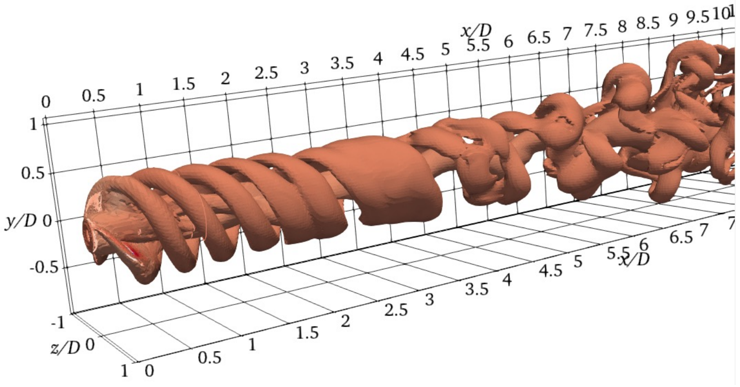


SPL (dB) at the monitor location-Traditional propeller

L: 100 m	1: 165.0	4: 166.3	7: 165.4	16: 166.4
L: 1000 m	1: 145.0	4: 146.4	7: 145.4	16: 146.4

SPL (dB) at the monitor location-Toroidal propeller

L: 100 m	1: 166.5	4: 167.3	7: 167.0	16: 167.3
L: 1000 m	1: 146.6	4: 147.3	7: 147.0	16: 147.3

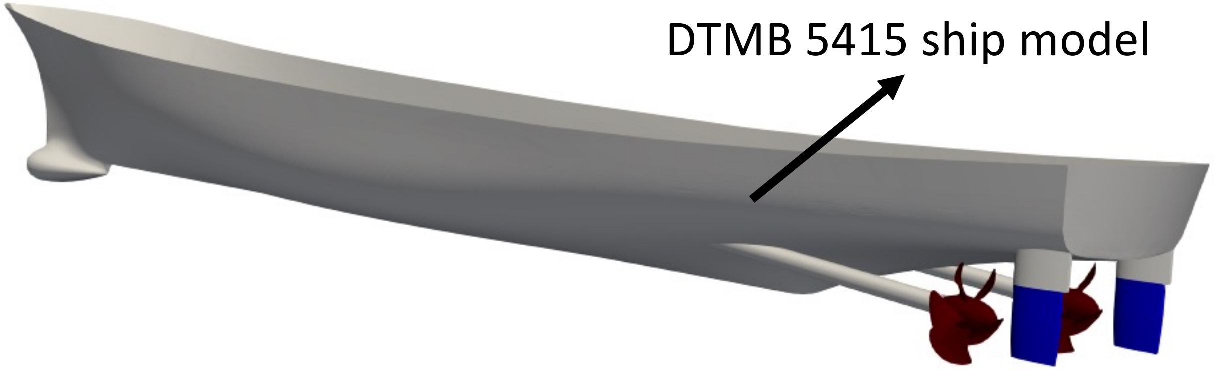


Vorticity distribution

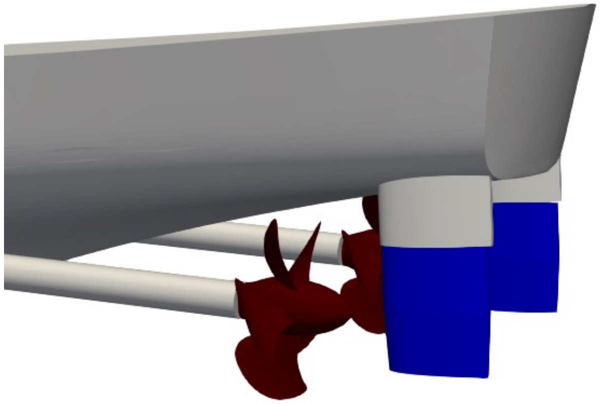
Zhi & Jaiman, 2023

Propeller Wake Interaction with Hull and Rudder

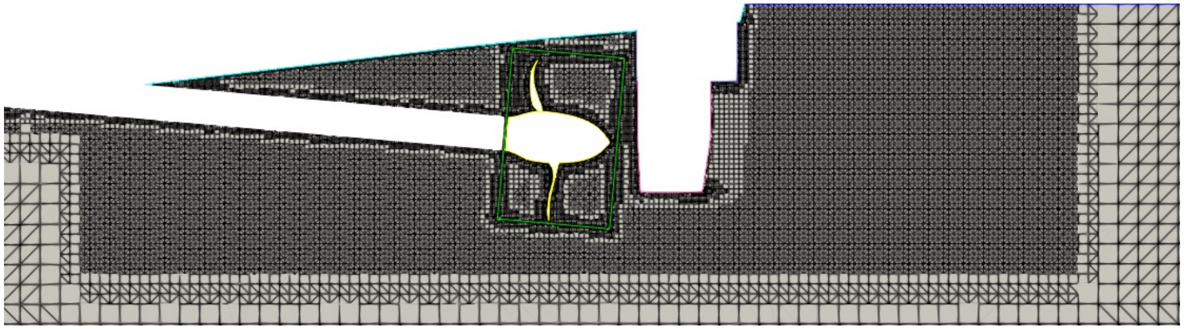
- ❑ Breaking of vortex and cavitation structures (colliding with hull and rudder)
- ❑ Wake-induced vibration of rudder
- ❑ Accompanied generation of noise sources



DTMB 5415 ship model

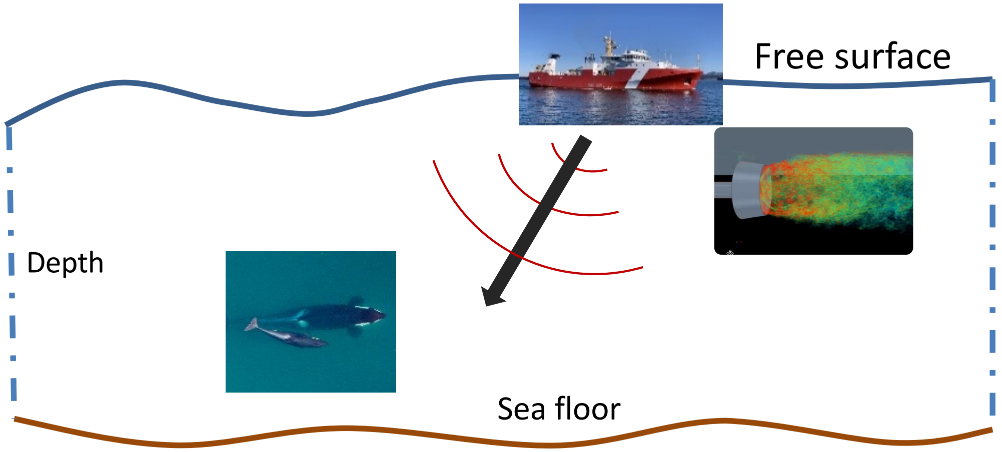


VP 1304 propeller model



MELO: An Adaptive Physics-Based MachinE Learning Framework for Anthropogenic Noise and Ocean Soundscape

- ❑ Develop a new AI-based toolbox to reduce ship noise impact on marine mammals
- ❑ Can we predict the evolution of acoustics in ocean environment over long horizons
  - ▶ Physics-based machine learning (PBML) algorithms using simulation and measurement datasets
- ❑ Demonstrate the applicability of adaptive operational strategy using PBML toolkit
  - ▶ Realistic ocean bathymetry
  - ▶ Ship voyage parameters



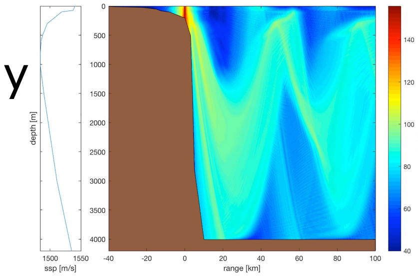
Monopole (Cavitation)
Dipole (Vortex/Wake)

Free surface

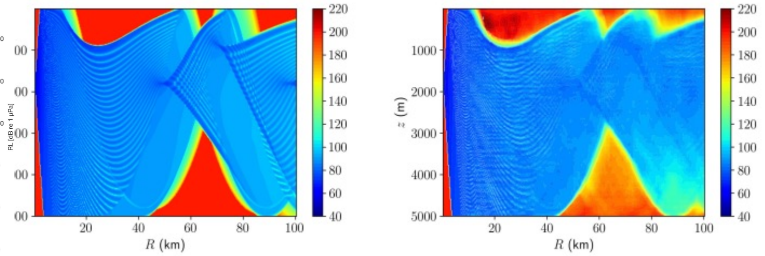
Depth

Sea floor

Transmission loss $\left(-20\ \log\frac{p}{p_0}\right)$ of acoustic wavefront



Field measurement



(a) Truth

(b) CRAN prediction

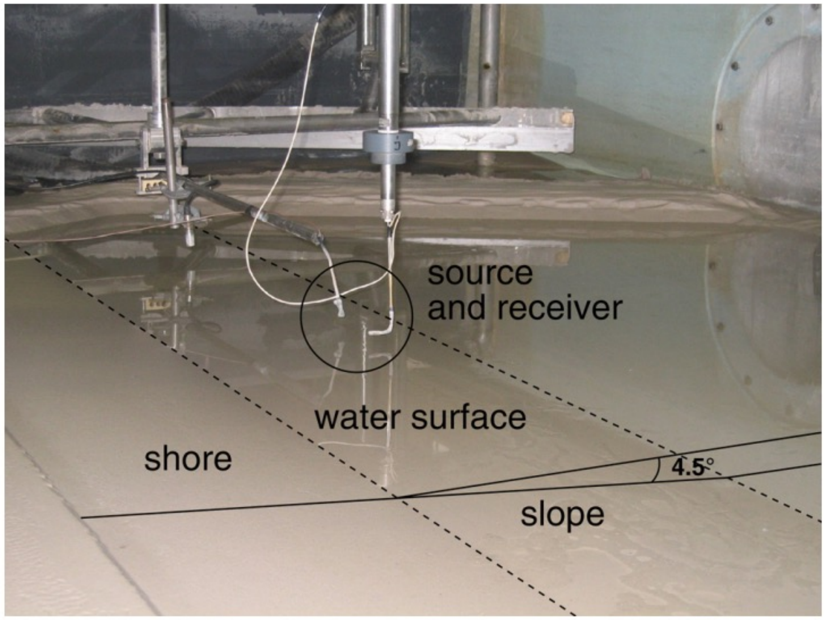
Wrik et al., JASA 2022

ClearSeas

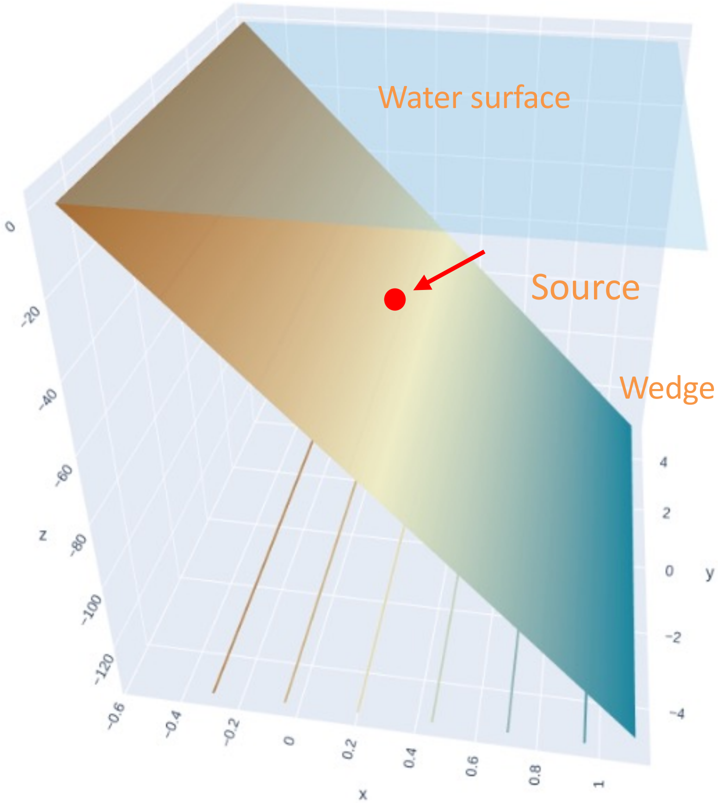
Transport Canada

Canada

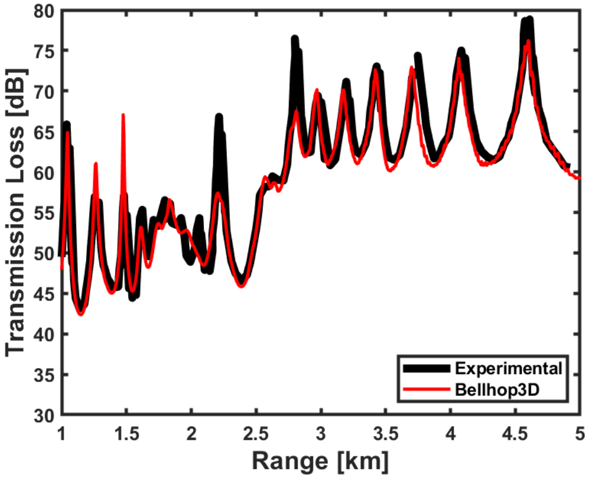
Far-Field Noise Validation



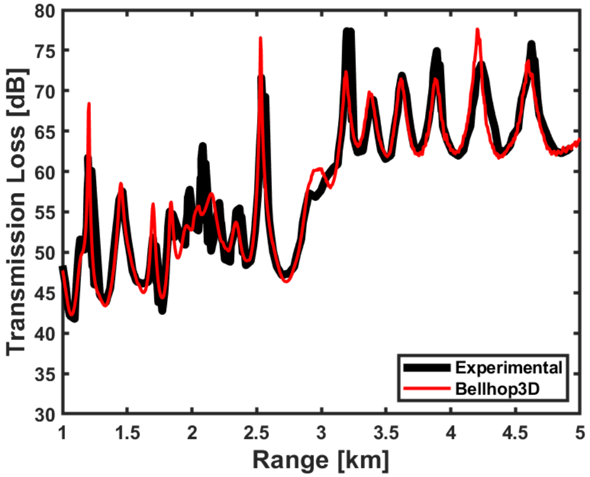
Experimental setup (CNRS France)



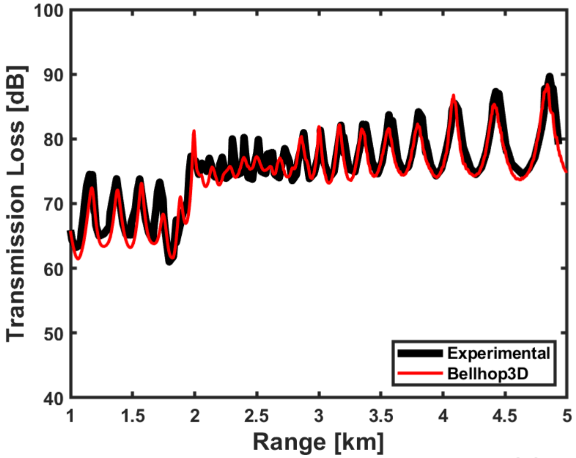
Computational acoustics modeling
(ray-tracing)



H1, 122 Hz



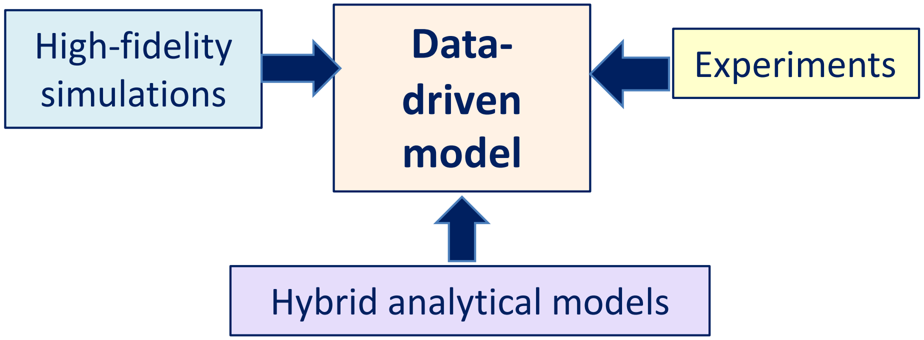
H1, 141.6 Hz



H3 = 25.4mm, 150 Hz

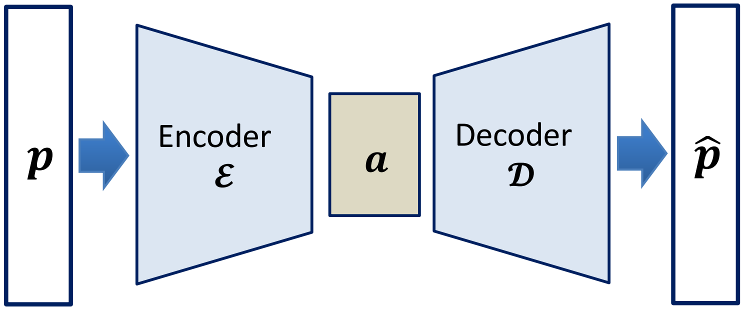
Data-Driven Learning of Underwater Radiated Noise

- ☐ Learning from data
  - ▶ Agnostic to how data is obtained
  - ▶ Data usually abundantly available



- ☐ Challenges
  - ▶ Accuracy: generalized prediction
  - ▶ Scalability: dimensionality reduction
  - ▶ Interpretability

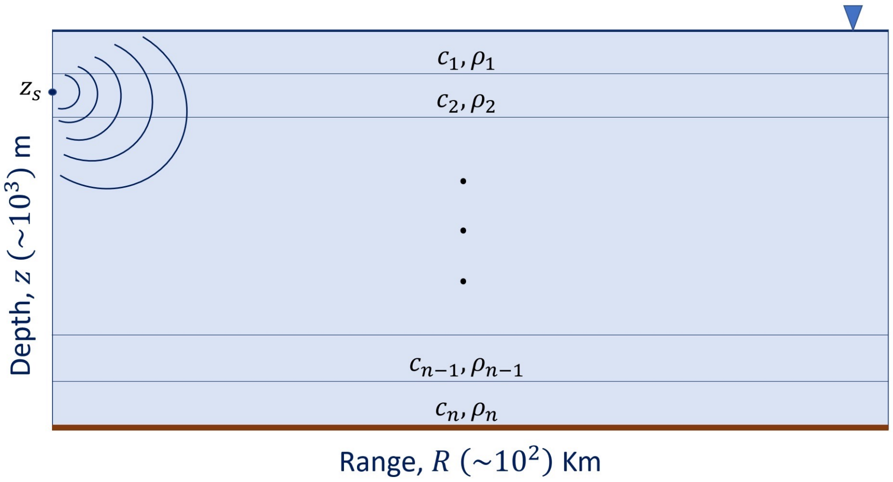
- ☐ Proposed solution: Convolutional Recurrent Autoencoder Network (CRAN)
  - ▶ Convolutional autoencoders + recurrent neural network
  - ▶ Sequence-to-sequence prediction

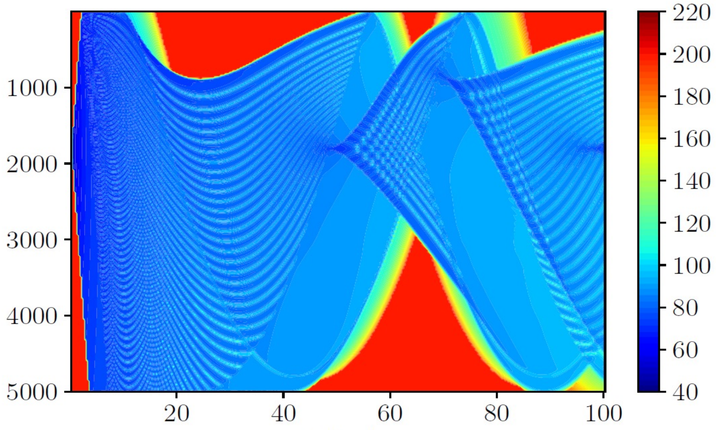


Wrik et al., JASA 2022

Data-Driven Learning of Ocean Acoustics

- Depth-dependent ocean environment
  - Losses due to geometric spreading, reflection from bottom and top
  - Complex wave interference
  - Several parameters: ocean bed, source depth, water temperature and salinity



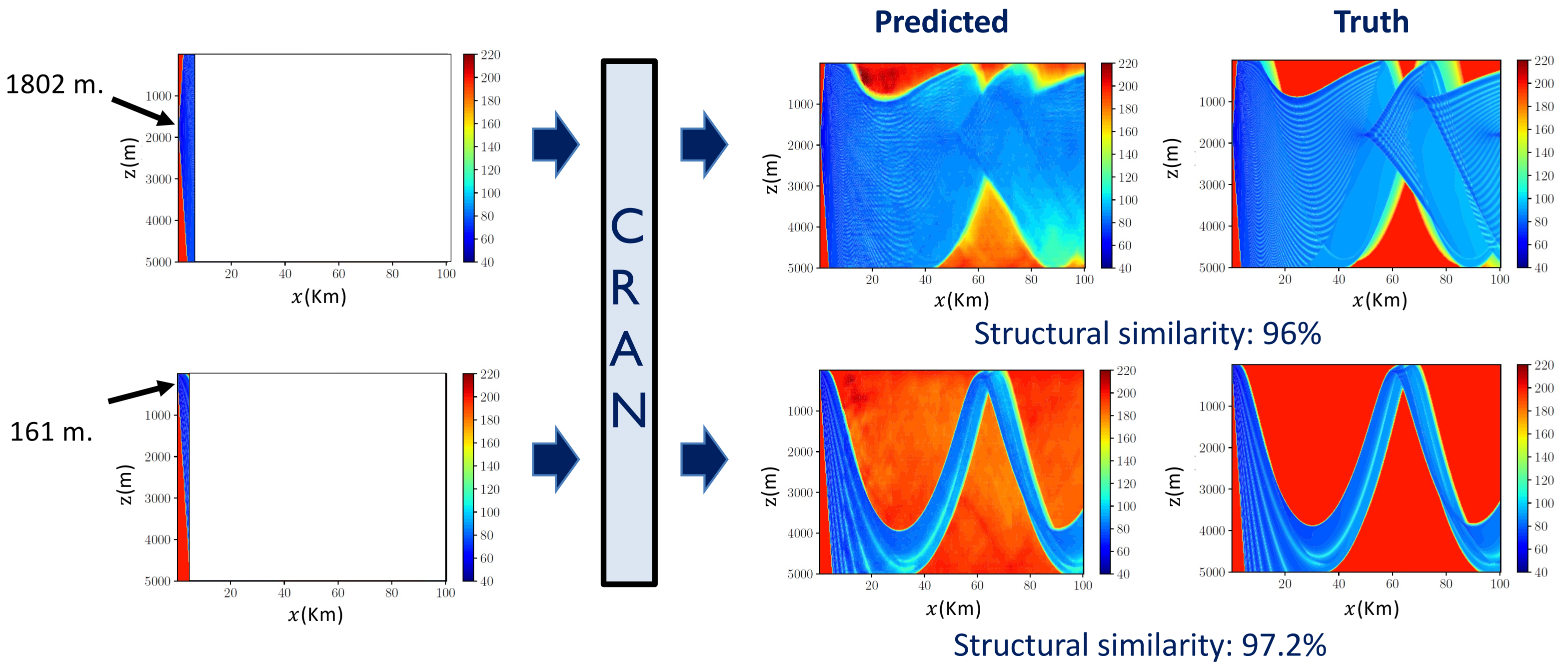


Transmission loss $\left(-20\ \log\frac{p}{p_0}\right)$ of acoustic wavefront

- Training data
  - Transmission loss for randomly sampled source depths
- CRAN prediction of far-field TL
  - Source depths outside training range

CRAN Generalization Capability

❑ Far-field sound propagation: depth-dependent sources


1802 m.

161 m.

Predicted

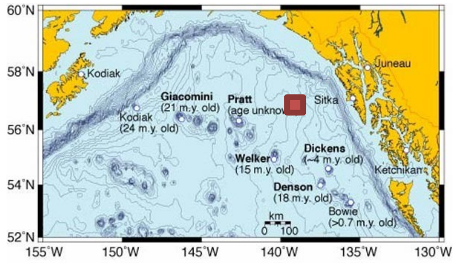
Truth

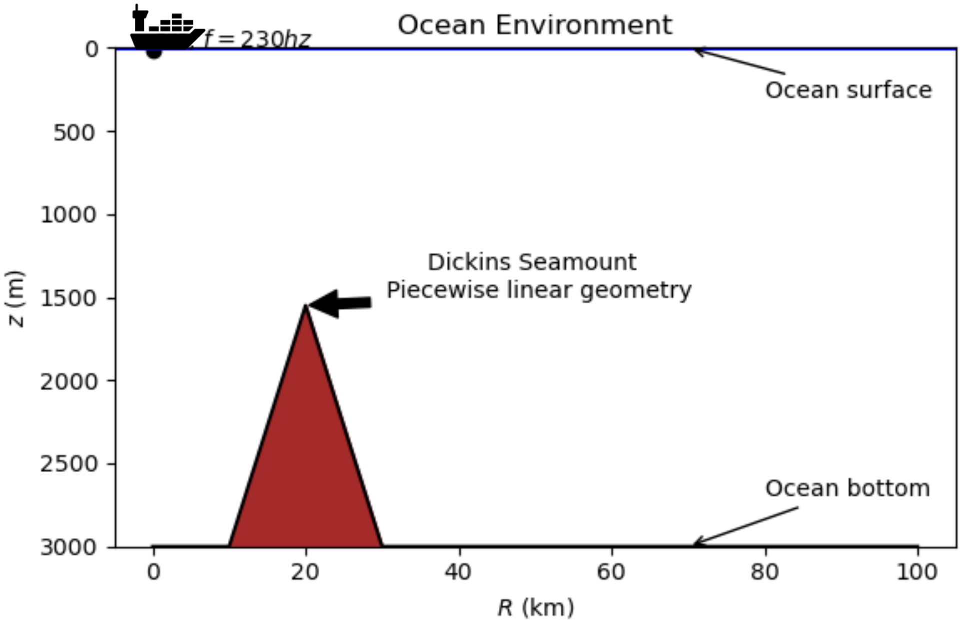
Structural similarity: 96%

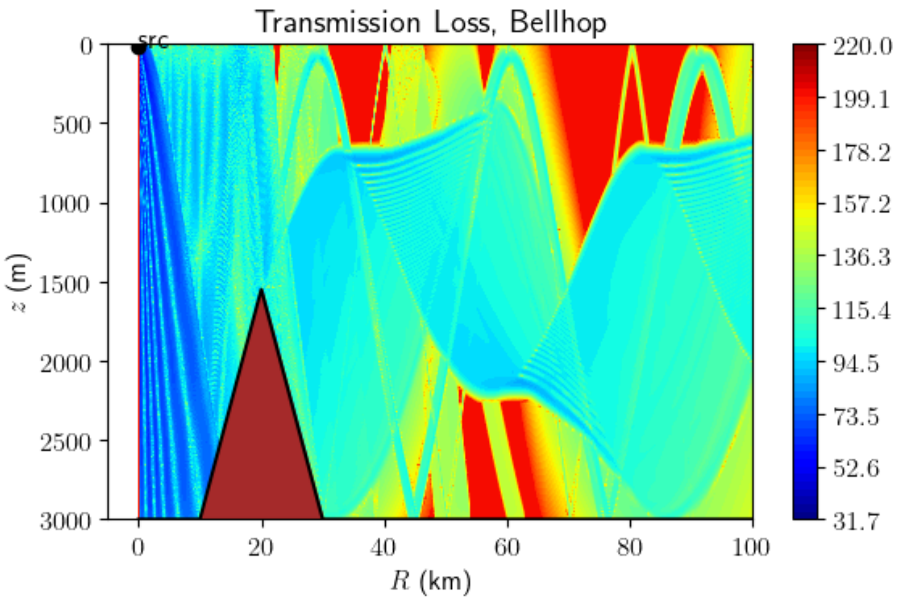
Structural similarity: 97.2%

❑ Acoustic wavefront patterns predicted accurately

CRAN for Varying Bathymetry

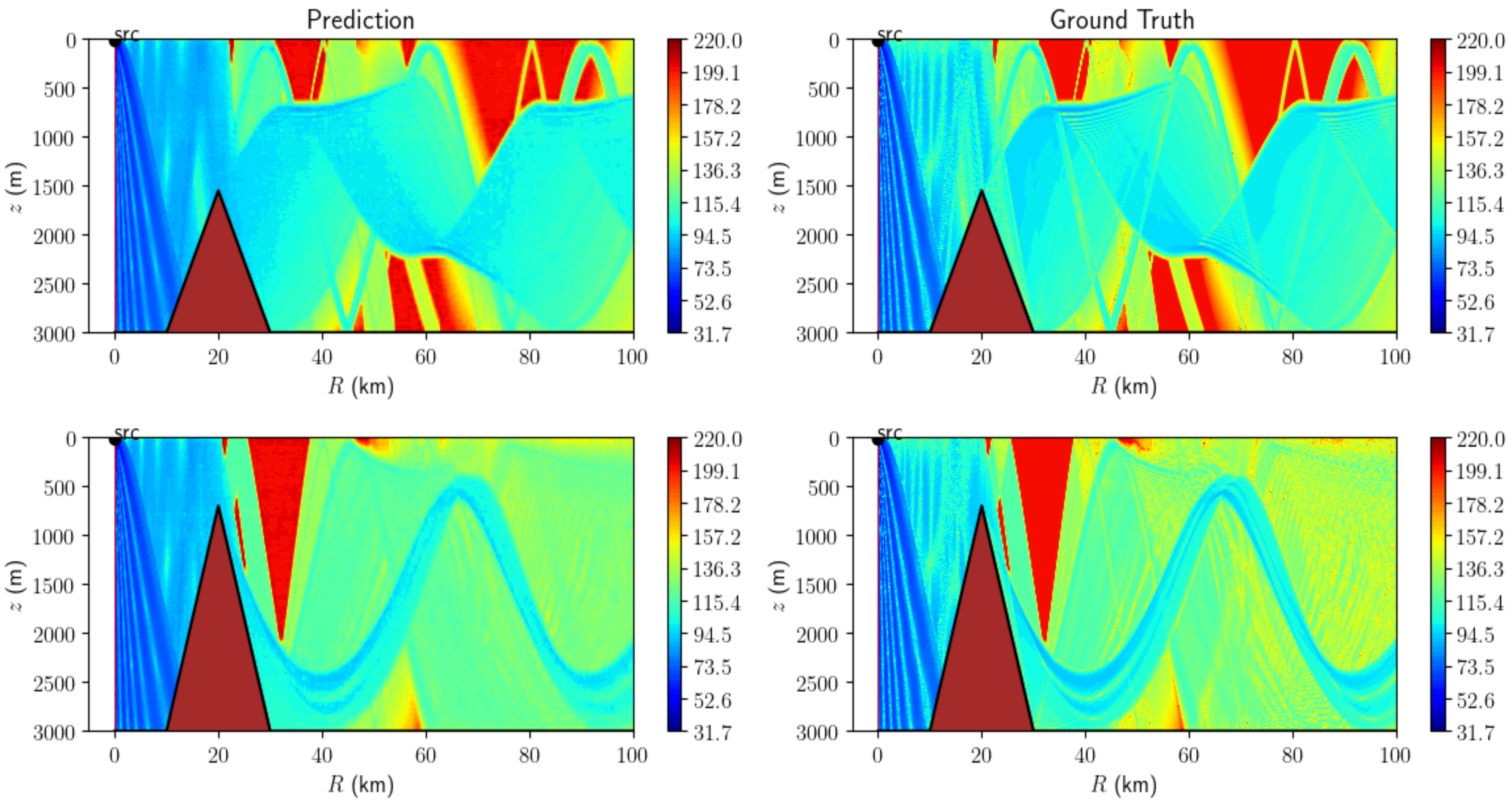






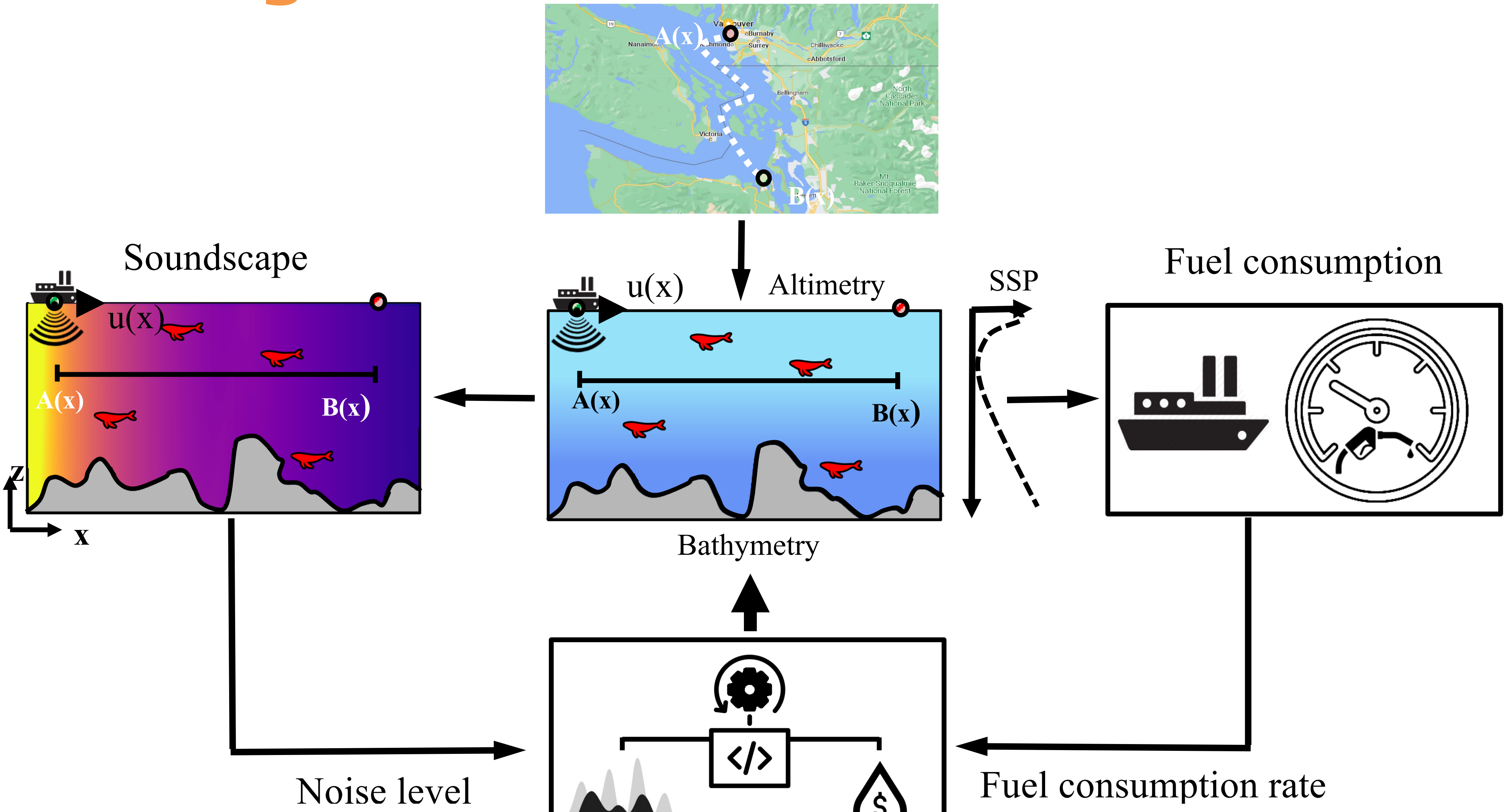
- ☐ Complex wave interference patterns
  - ► Large spatial dimensions
  - ► Computationally expensive

CRAN Prediction for Varying Bathymetry



SSIM = 90%

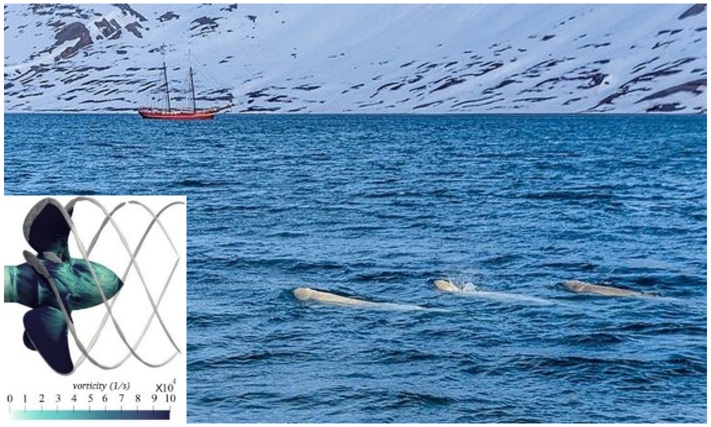
Case Study: Adaptive URN Management

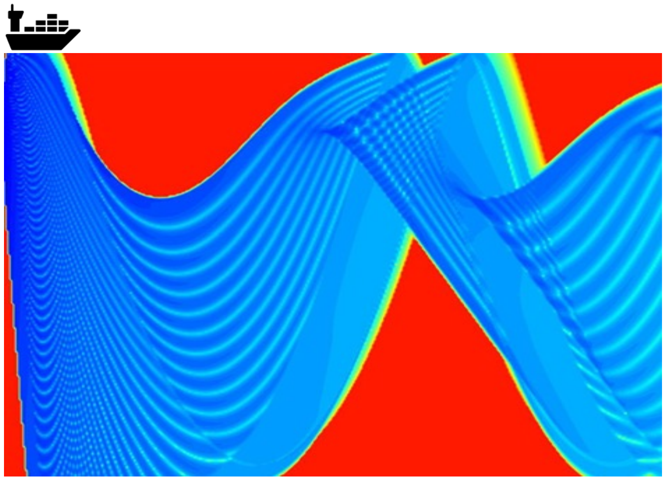


$$\mathcal{J}_1 = \sum_{i=1}^{n-1}\sum_{j=1}^{m}\sum_{f}(NL_{ij}(v_i, f; \phi) - \alpha_j(f))\, df$$

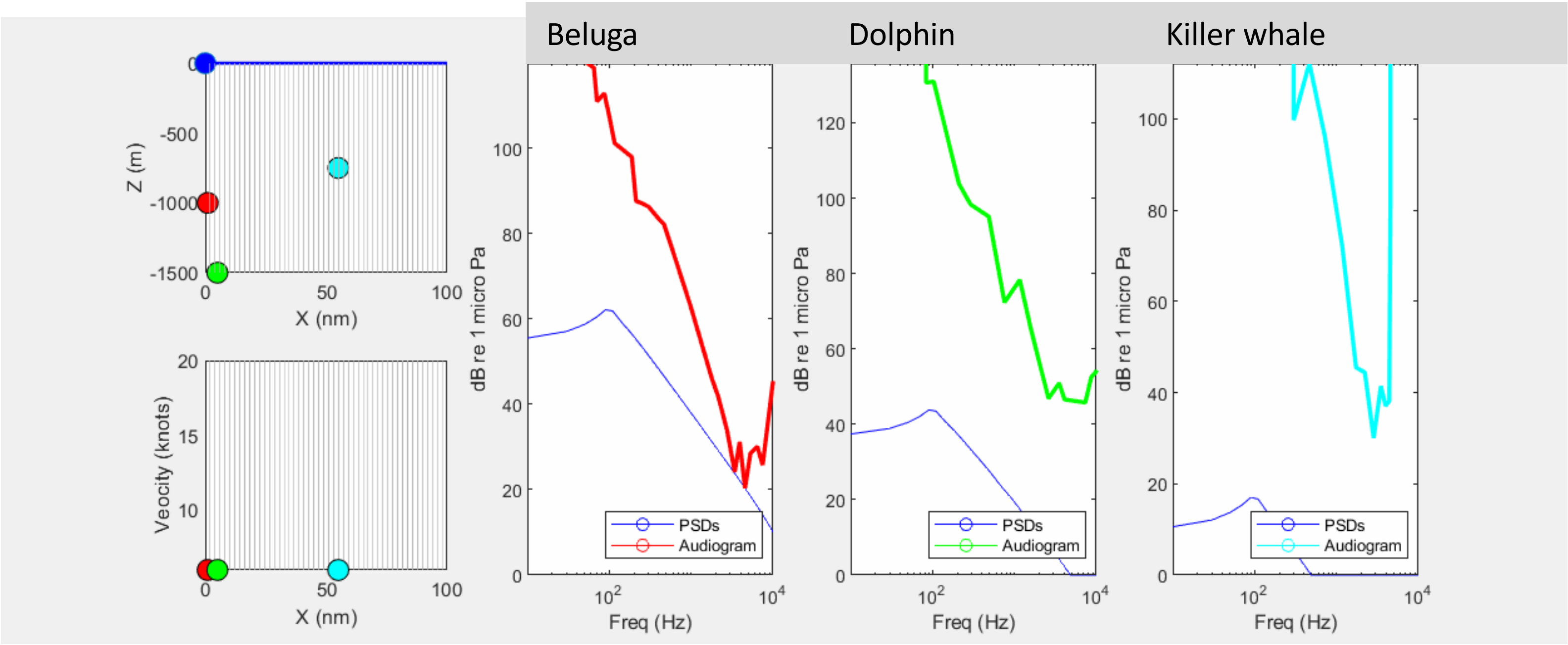
$$\mathcal{J}_2 = \sum_{i=1}^{n-1}\frac{d_i}{v_i}F(v_i; \phi)$$

Intelligent ship operation





- Physics-based machine learning for underwater radiated noise
- Multi-objective optimization of ship noise and fuel consumption



Summary

- Propeller modeling with cavitation and hydro-acoustics
  - Established validation and best practices for in-house CFD modeling
  - Explored physical mechanisms and mitigation technologies for near-field noise suppression

- Demonstrated physics-based machine learning toolkit with adaptive speed optimization
  - AI-driven slowdown and distancing measures can be more effective
  - Optimal combination of technological measures with URN management

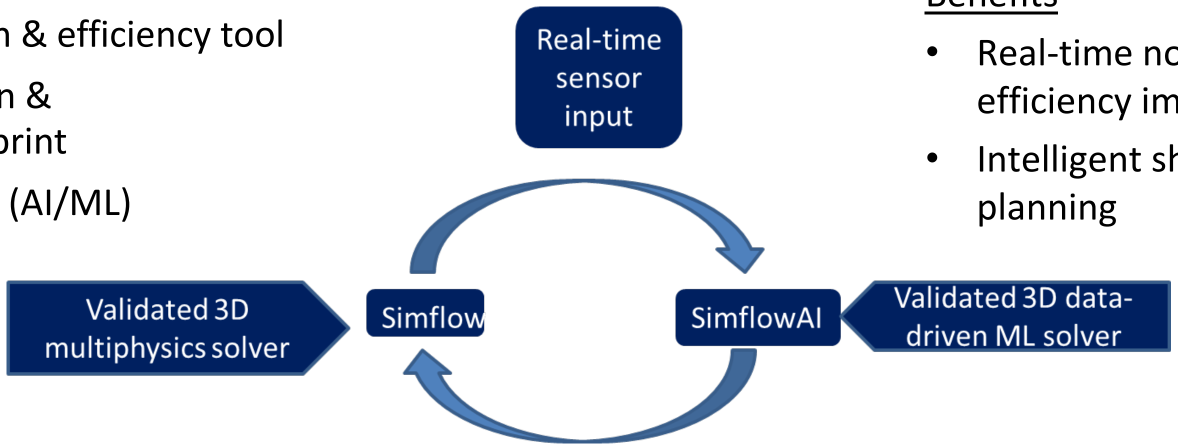
- Ongoing development:

Features

- Operational decision & efficiency tool
- Ship noise mitigation & environmental footprint
- Smart ship assistant (AI/ML)

Benefits

- Real-time noise reduction, efficiency improvement
- Intelligent ship path planning



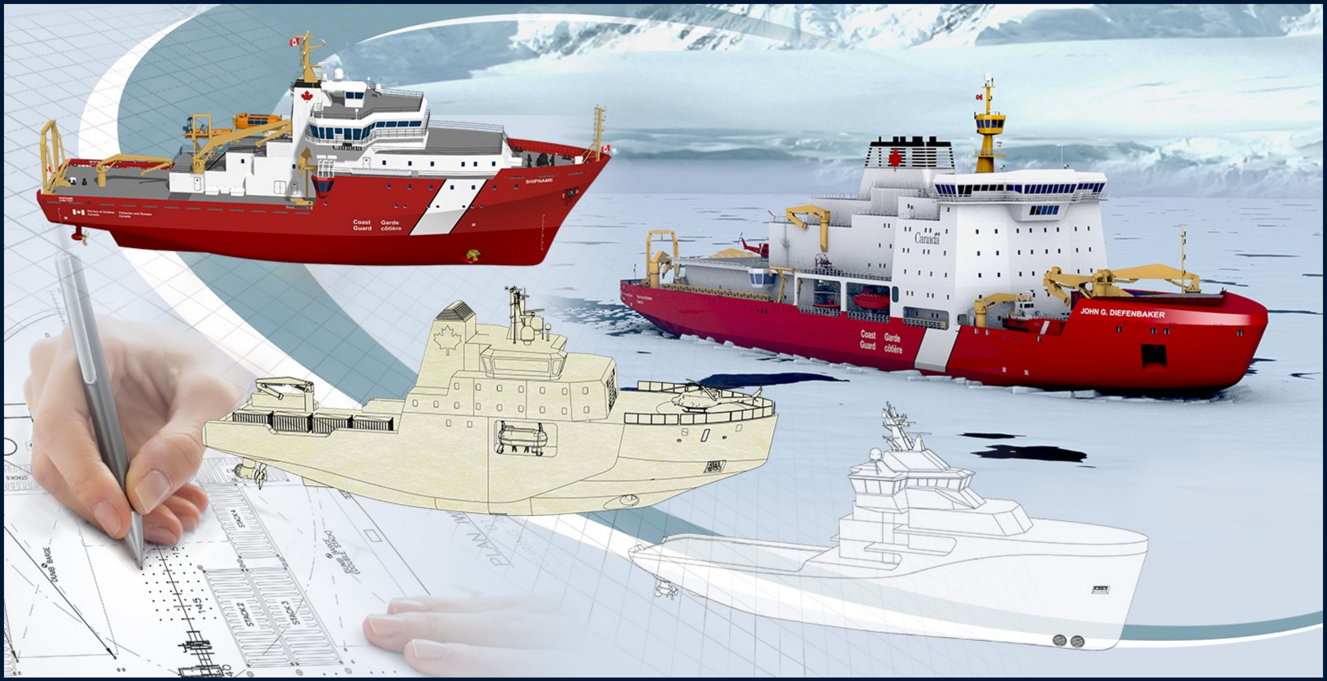
Real-time sensor input

Validated 3D multiphysics solver

Simflow

SimflowAI

Validated 3D data-driven ML solver



Thank you for your attention

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Transport Canada

Canada

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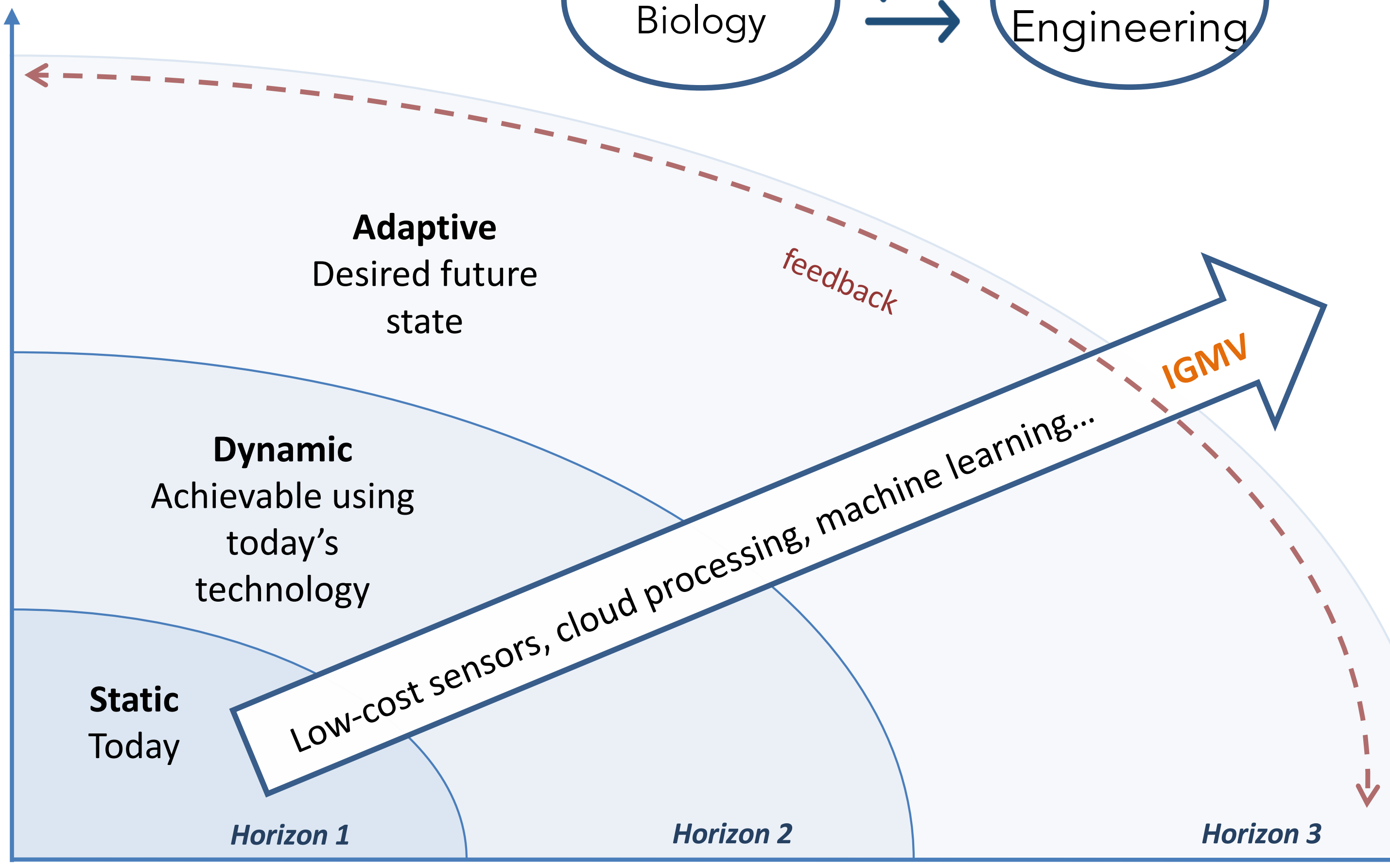
"IGMVs as a Symphony to Marine Mammals"

Marine Biology ⇄ Marine Engineering

Improved Vessel Mitigation

- Smart system controls
- Tunable materials
- Route planning
- Cavitation detection
- Antifouling measures
- Prop pitch/RPM/speed adjustment
- Report sightings
- Vessel slow downs
- Keep out zones



- Migration patterns
- Seabed hydrophones
- Real-time detection and identification
- Ship-based sensors and UAVs
- Behaviour Interpretation

Improved Animal Understanding

Clear Seas