Physics-Based Modeling of Hydrodynamics around Surface Ships

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Acknowledgement

- **CREATE-SHIPS Program - Dr. Doug Post, Mr. Myles Hurwitz**
- **Computational Hydromechanics Division (Code 5700) at NSWCCD**

Outline

- Background
- Overview of NavyFOAM
- Validations
  - Canonical problems
  - Gothenburg 2010 workshop
- Applications
  - JHSS
  - DDG-1000
- Conclusions

Background

- The ultimate goal is to simulate powering, maneuvering and seakeeping performance of surface ships in real seaways
- Among the challenges are:
  - Numerically capturing air-water interface with a large jump in density often involving liquid sheets, droplets, and bubbles
  - Environment (e.g., sea states, winds)
  - Very large ship motions involving 6-DOF
  - Tracking ship motion for a long time to predict "rare events" like capsizing
  - Many parameters and their combinations defining a "safe operating envelop"
- A long shot, yet can be tackled in a staged manner…
  - Surface ships cruising on calm water (resistance and powering)
  - Hydrodynamic force/moment due to incident waves ("diffraction" problem)
  - Forced oscillations (radiation problem) to provide "hydrodynamic coefficients" for 6-DOF motion solver.

NavyFOAM Technical Specification

- Three top-level solvers – sRansFoam, sRansSRFFoam, turbFSFoam, turbSRFFSFoam, turbWaveFoam
- Second-order FVM-based spatial discretization for arbitrary polyhedral elements
- Projection method for velocity-pressure coupling
- Solution-adaptive mesh refinement
- Second-order temporal discretization schemes
- Fully implicit solution algorithms
- A suite of RANS turbulence models including k-ε and k-ω families of EVMs and Reynolds-stress models
- LES and hybrid RANS/LES models
- Interface-capturing using volume-of-fluid (VOF) method
- GCL-compliant ALE approach with moving/deforming mesh
- Body-force model for propulsors
- 6-DOF solver with option for users to constrain modes of choice
- Domain decomposition and message passing (MPI) based parallelism

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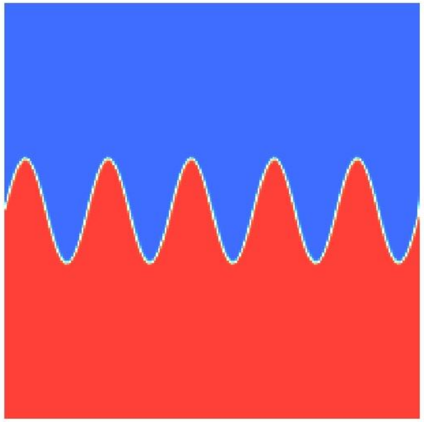
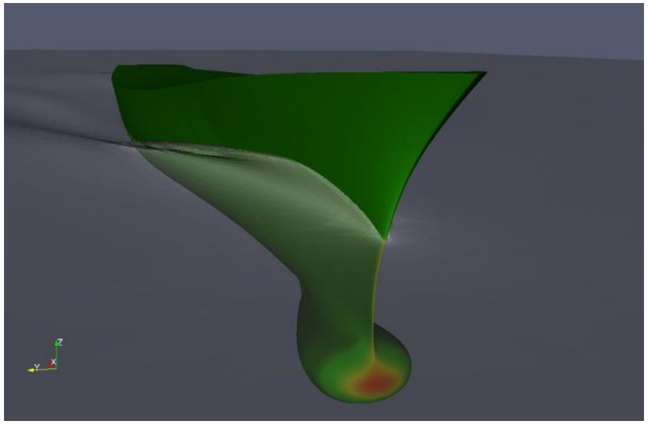
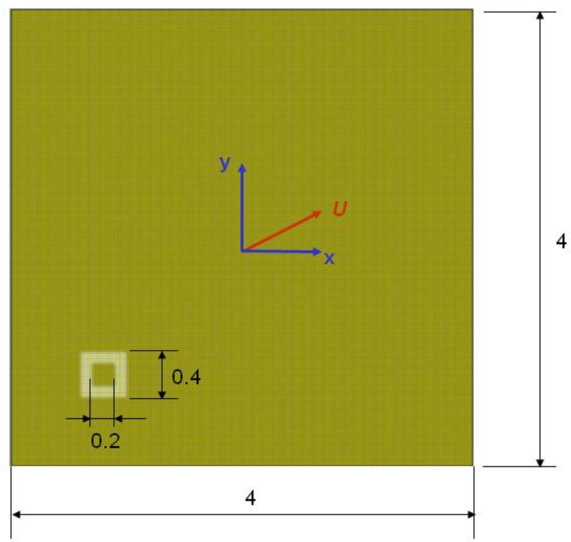
Advection Schemes for VOF Equation

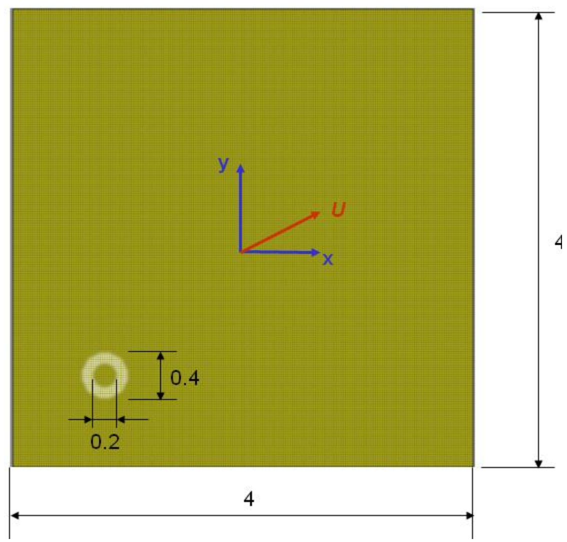
- **Critical for solution accuracy and stability**
- **New advection schemes (CICSAM, HRIC, MHRIC, interGamma, InterGammaM) for volume-fraction equation have been implemented and validated.**

Numerical Experiments

Advection of hollow square and circle





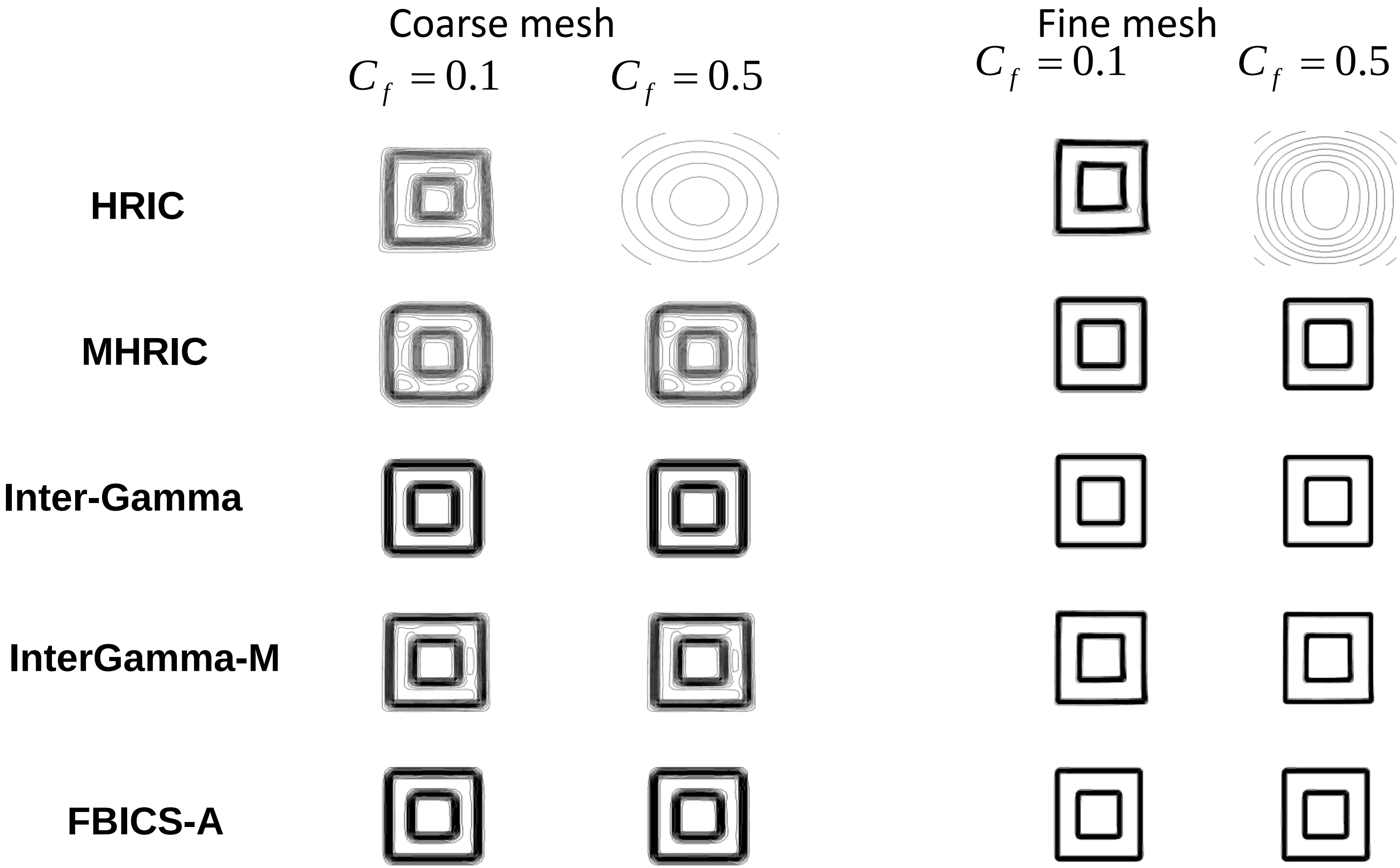
Uniform coarse mesh: 200 × 200

Uniform fine mesh: 400 × 400

Uniform velocity field: U = (2, 1)

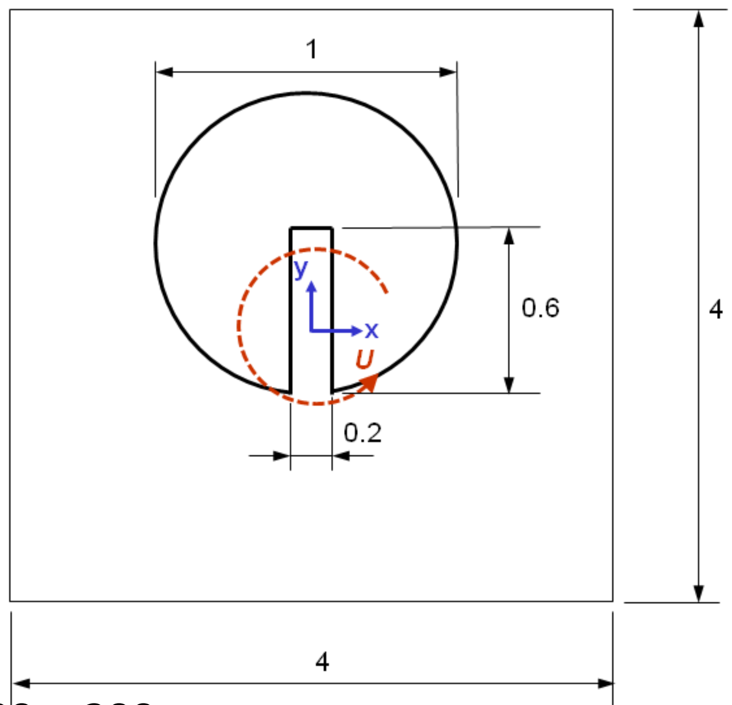
Volume fraction equation solved implicitly

Numerical Experiments



γ contours (range: 0.05-0.95 in intervals of 0.05) at t=1.2

Numerical Experiments - Zalesak's rotating slotted disk



Uniform coarse mesh: 200×200

Uniform fine mesh: 400×400

Uniform velocity field: $U = (-2\pi y, 2\pi x)$

Volume fraction equation solved explicitly at two fixed Co numbers: $C_f = 0.1$ $C_f = 0.5$

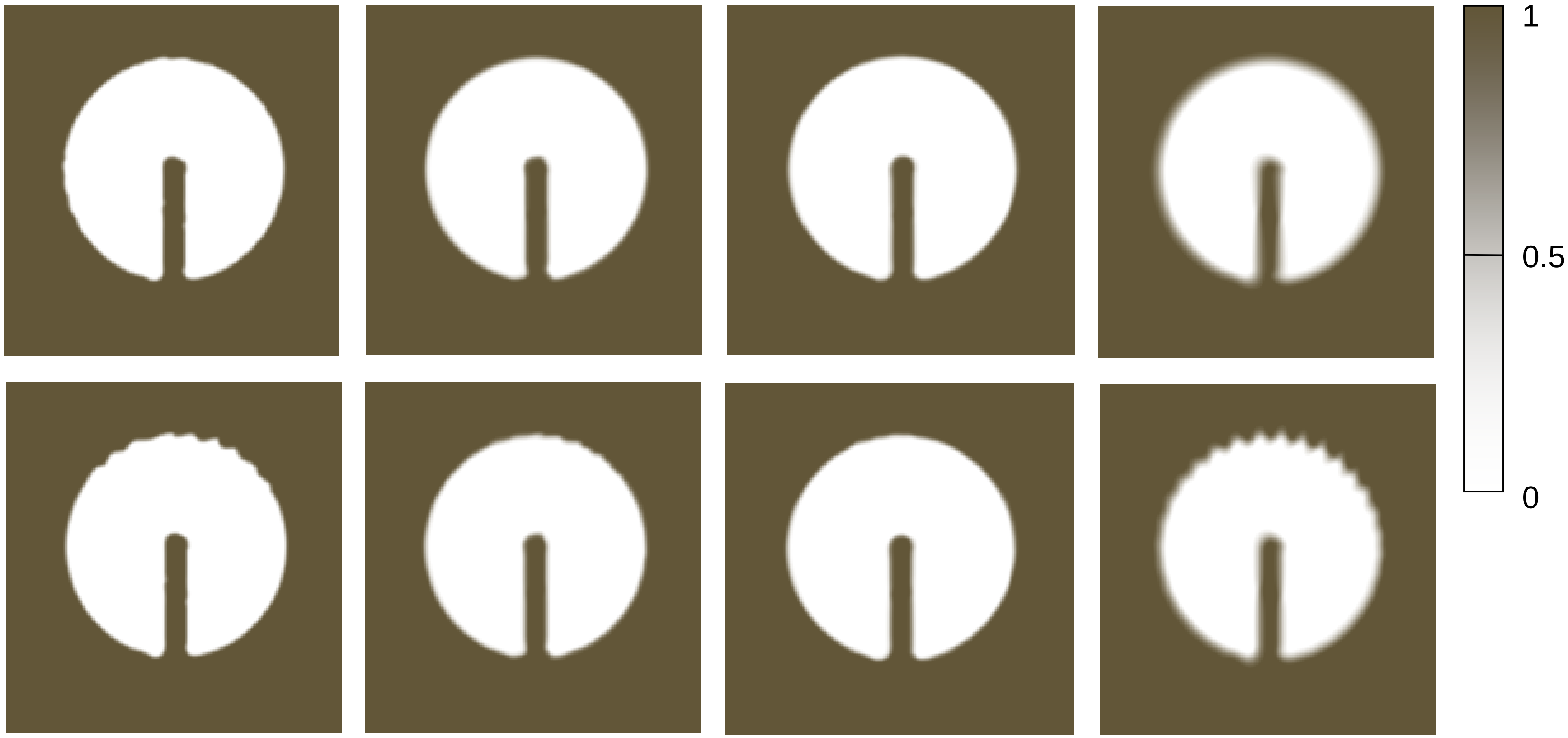
Zalesak's rotating disk

Coarse mesh: 200 x 200

CICSAM **HRIC** **MHRIC** **QUICK**

CFL = 0.1

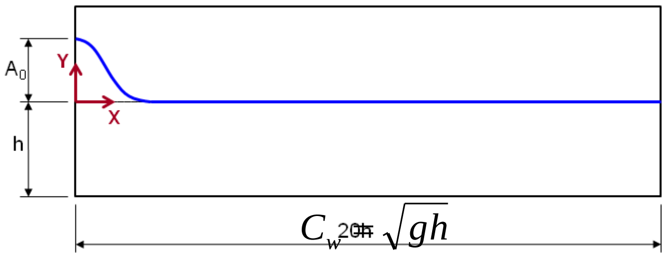
CFL= 0.5



Contours of volume fraction ⍰ after one revolution

Numerical Experiments
A Traveling Solitary Wave

Traveling solitary wave



Wave speed:

Initial free surface profile:

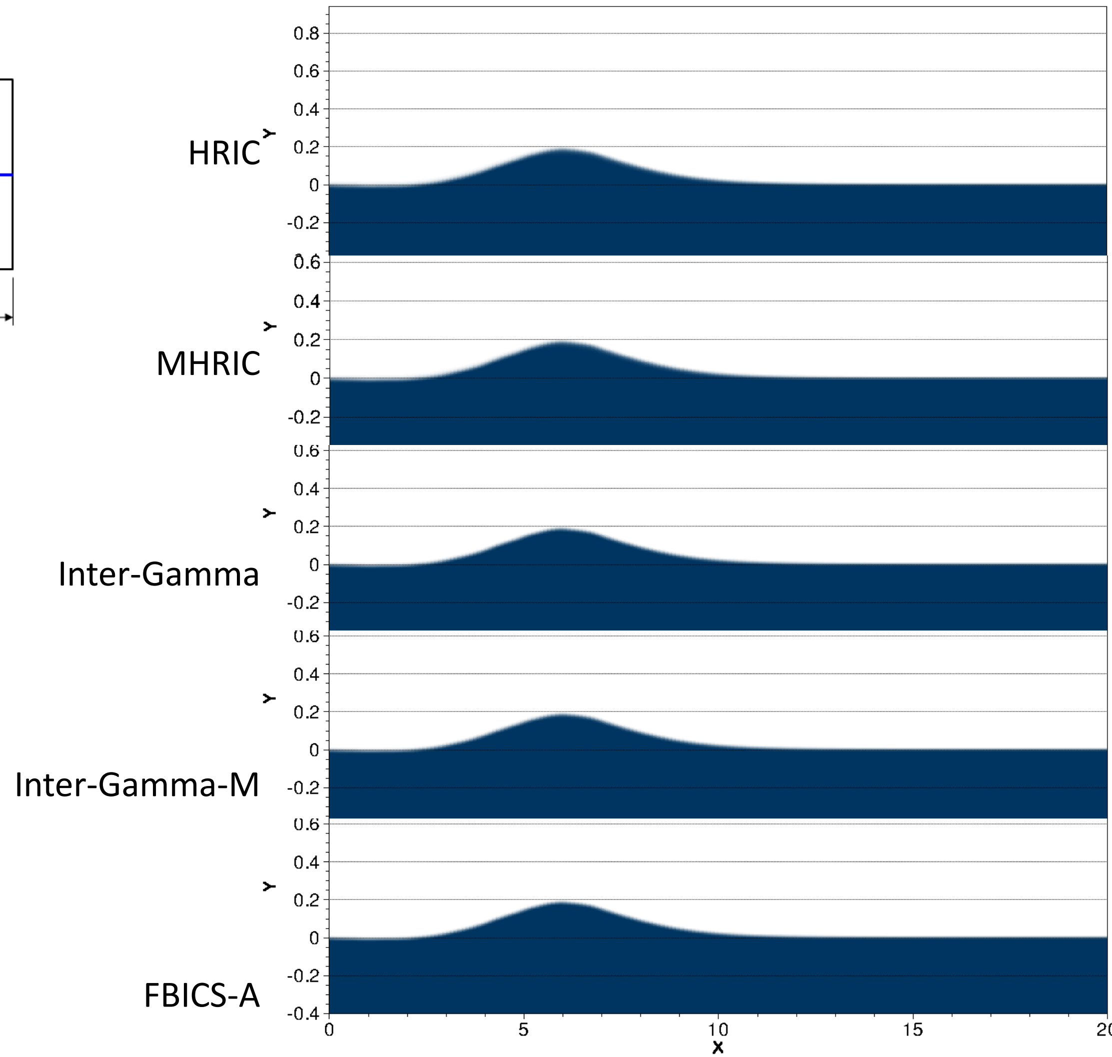
$$A(x,0) = \frac{A_0}{\cosh^2(\sqrt{3A_0}/2x)}$$

$$A_0 / h = 0.4$$

Mesh: 200×136

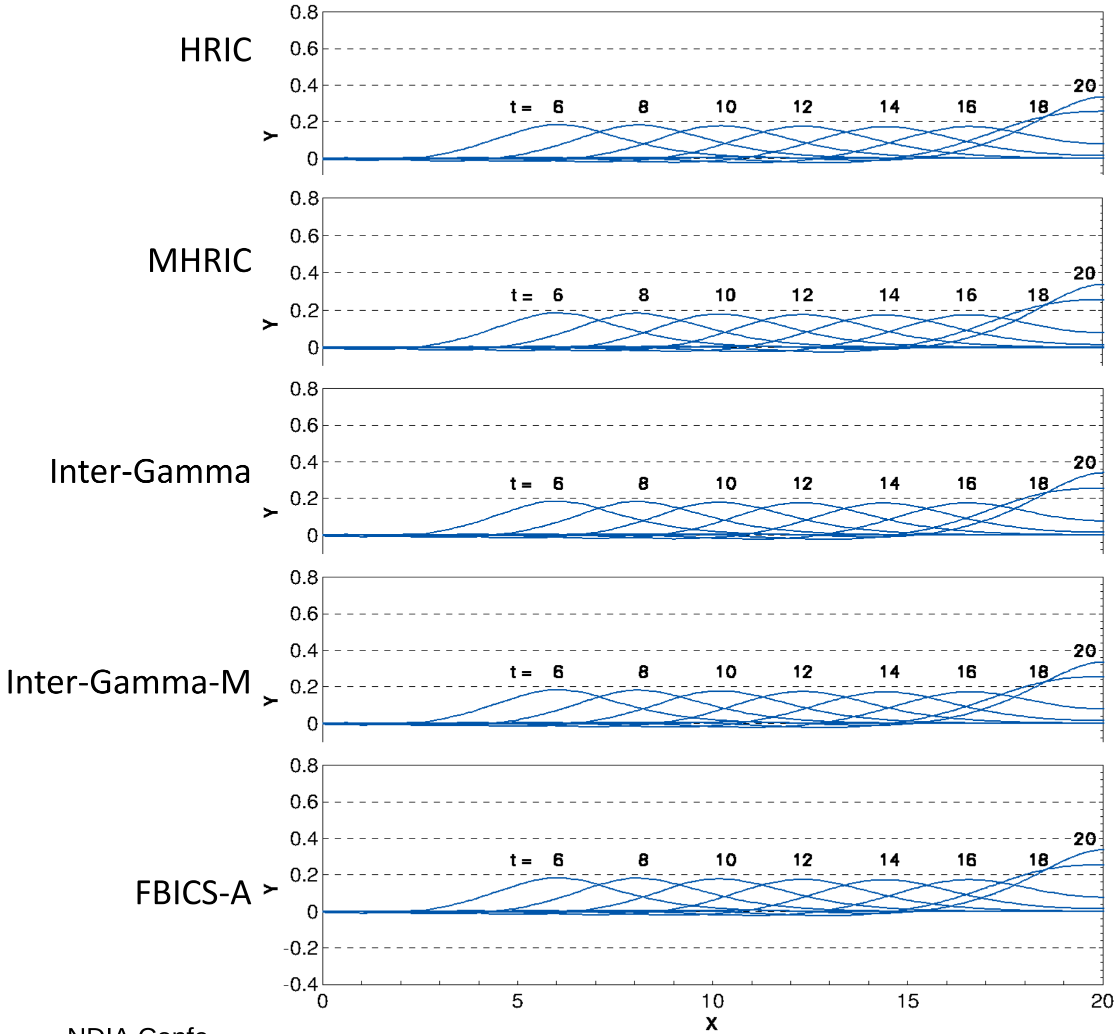
$$C_f = 0.1$$

Volume fraction equation solved implicitly at

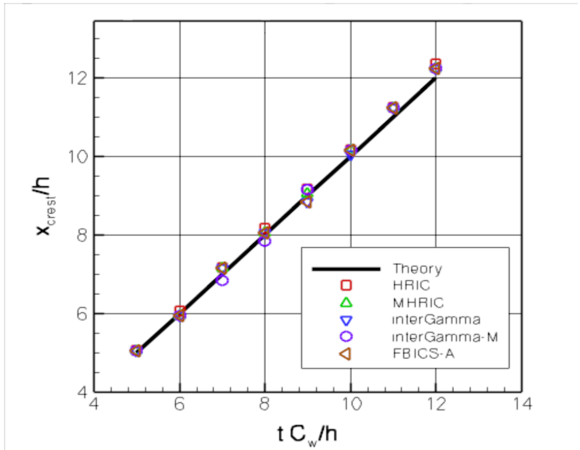


γ contours at t = 6

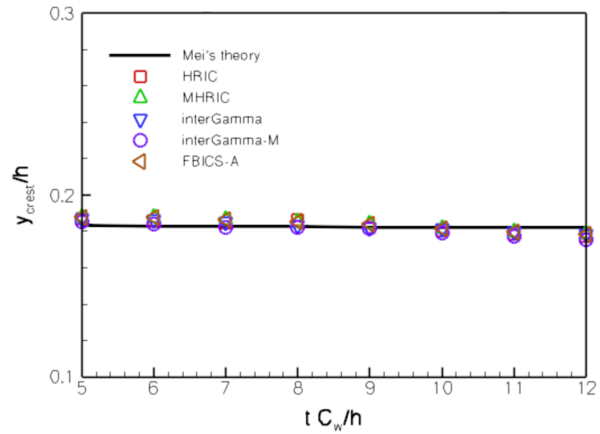
Numerical Experiments
A Traveling Solitary Wave (cont'd)



Traveling wave train



Wave crest position vs. time



Wave amplitude vs. time

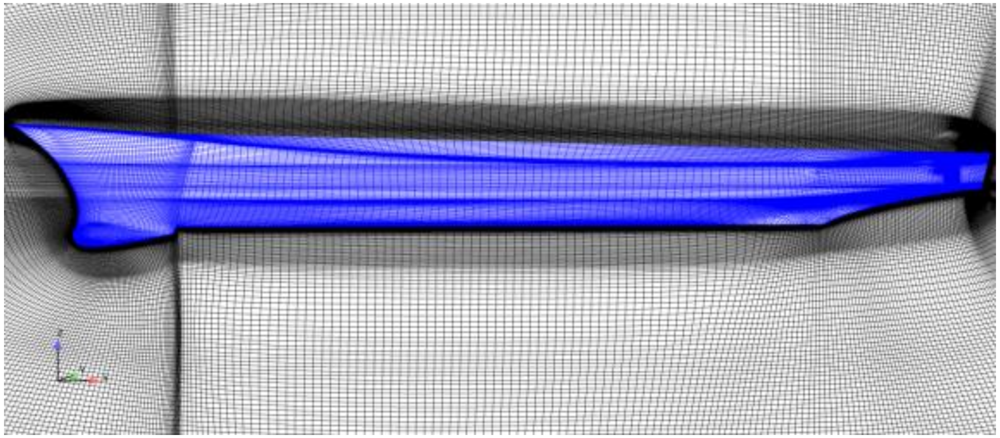
Gothenburg 2010 Workshop

- **An international workshop series started in 1990 to evaluate the state of the art in CFD for ship hydrodynamics**
- **Held in Gothenburg, Sweden in December 2010.**
- **For G2.01K, three ships have been selected for test case**
  - **KVLCC2 (tanker)**
  - **DTMB 5415 (destroyer)**
  - **KCS (container ship)**
- **A total of 82 entries from roughly 40 organizations worldwide – the largest ever**
- **Our entries with NavyFoam**
  - **KVLCC2 (case 1.1 – double-body)**
  - **DTMB 5415 (cases – 3.1a, 3.1b, 3-5, fixed and free sinkage and trim)**

Gothenburg 2010 Workshop

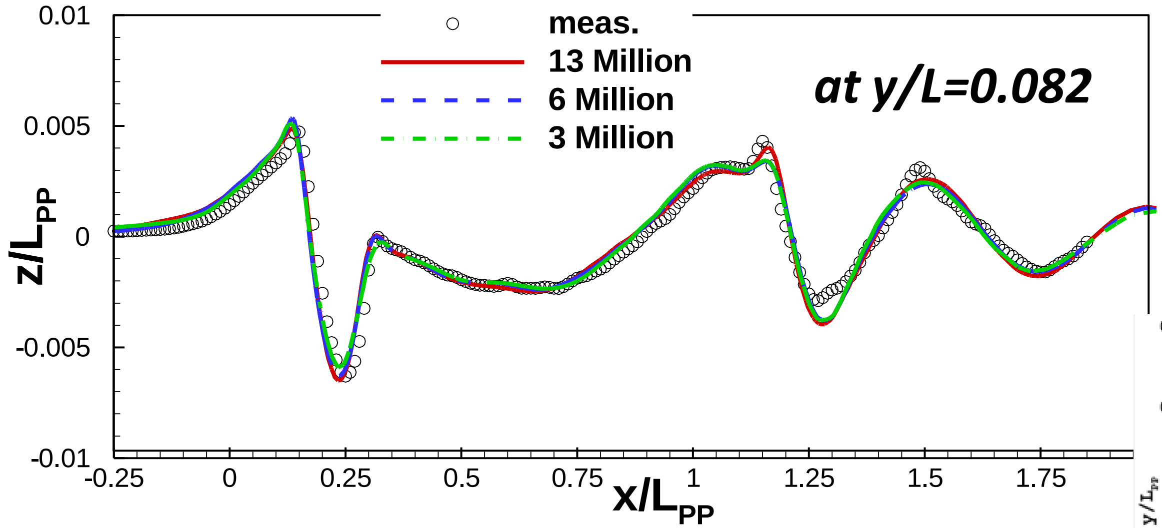
- Three hull forms
  - U.S. Navy Combatant DTMB 5415
  - The Korean VLCC KVLCC2
  - The Korean container ship KCS
- Types of test cases
  - Local flow at fixed sinkage and trim
  - Local flow at dynamic sinkage and trim

Description of DTMB 5415

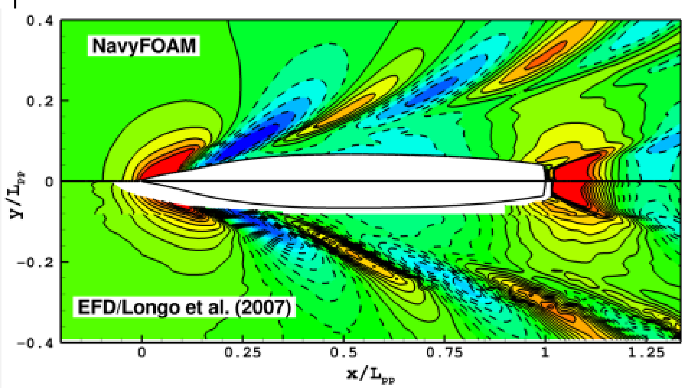


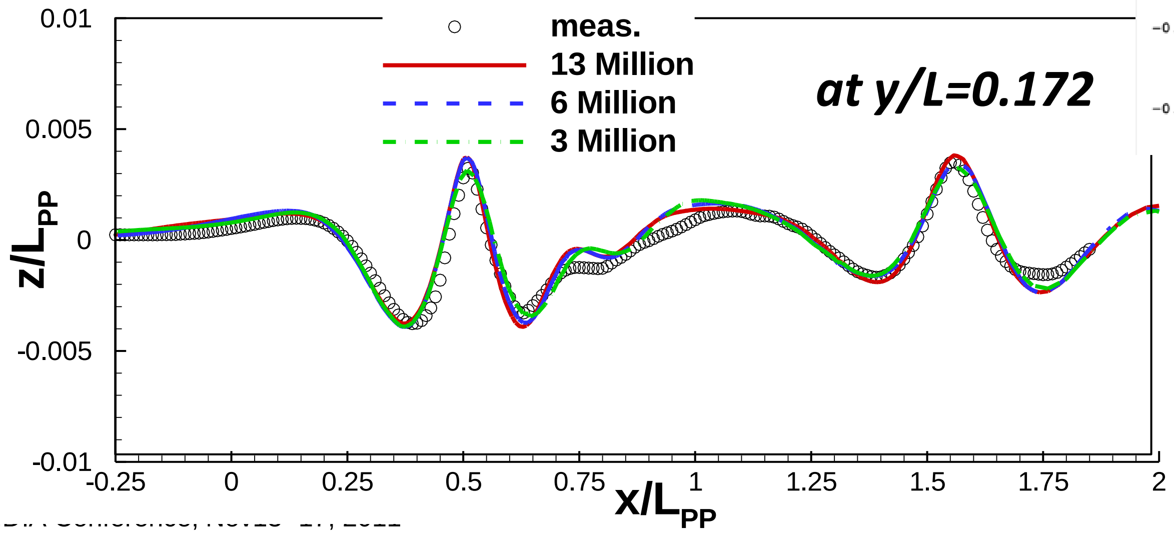
- Re_L = 5.1 x 10^6 , Fr = 0.28
- Fixed and free sinkage and trim (Case 3.1a and 3.1b)
- Two-phase (VOF) RANS computations using an implicit solver
  - Mesh dependency (3M, 6M 13M cells)
  - Advection schemes (HRIC, MHRIC, van Leer, interGammaM)
  - Turbulence models
- Run on SGI Altix cluster at ARL

DTMB 5415 - Fixed sinkage and trim
Mesh-dependency of Solutions



Case 3.1b

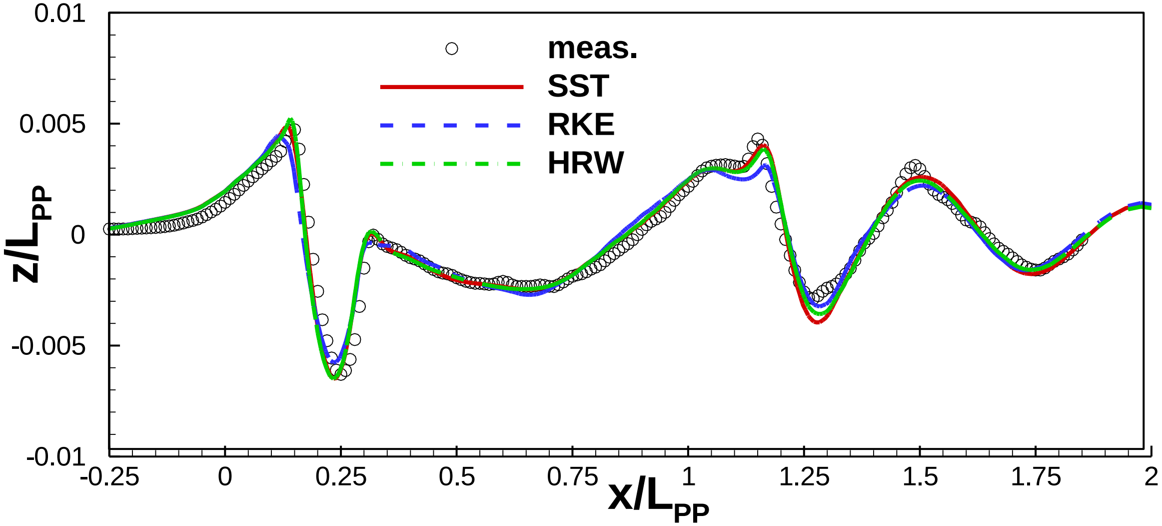


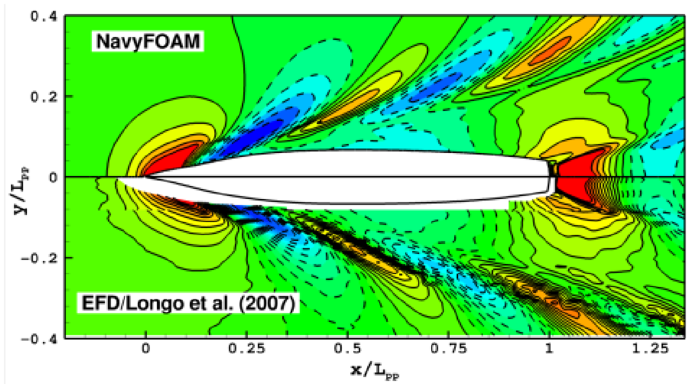


DTMB 5415 - Fixed sinkage and trim
Impacts of turbulence modeling

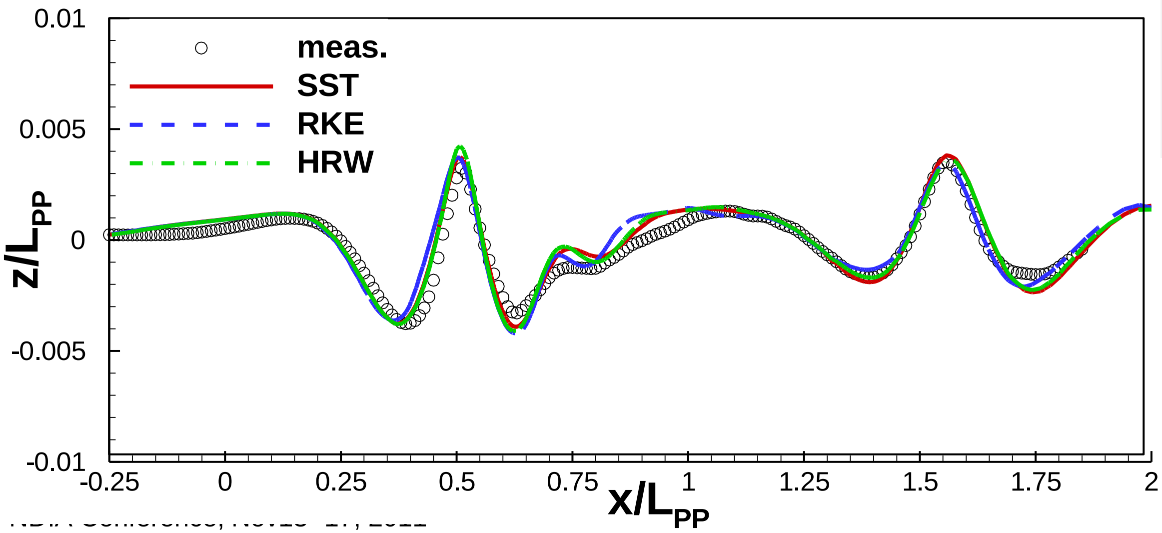
Case 3.1b

at y/L=0.082

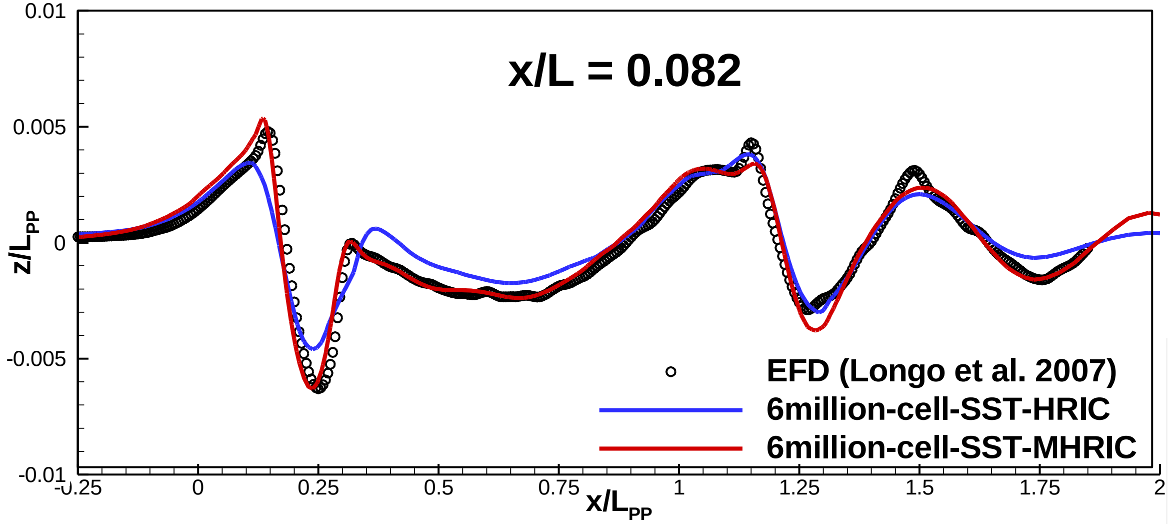




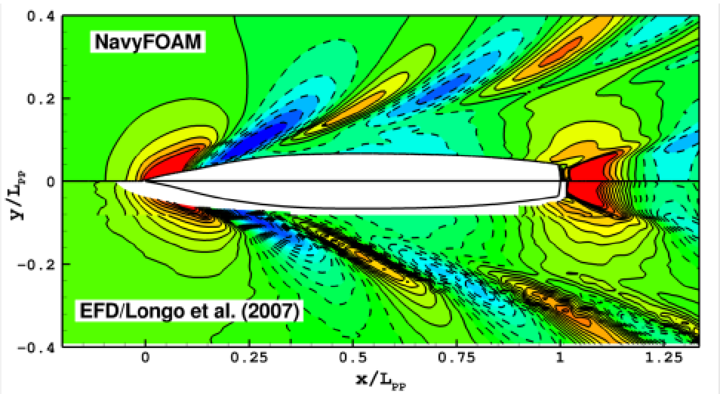
at y/L=0.172

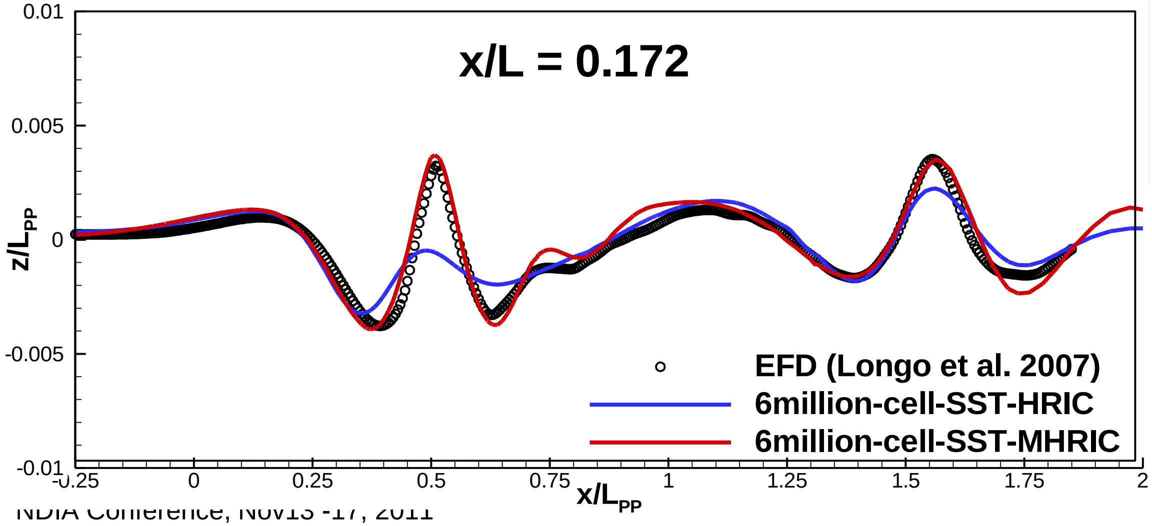


DTMB 5415 - Fixed sinkage and trim
Impacts of convection schemes



Case 3.1b

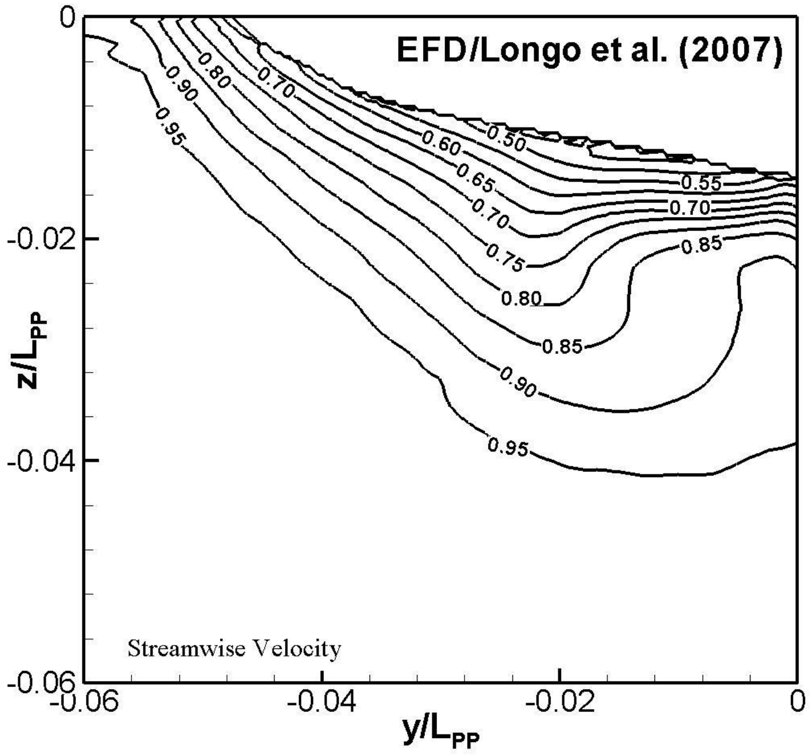




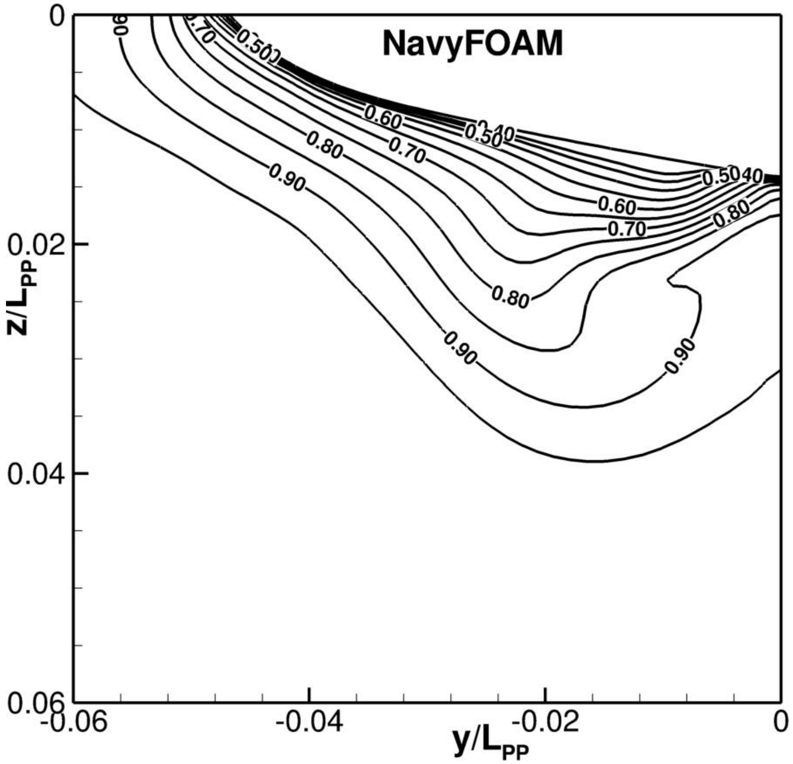
DTMB 5415 – Streamwise velocity contour

Case 3.1b

Meas.



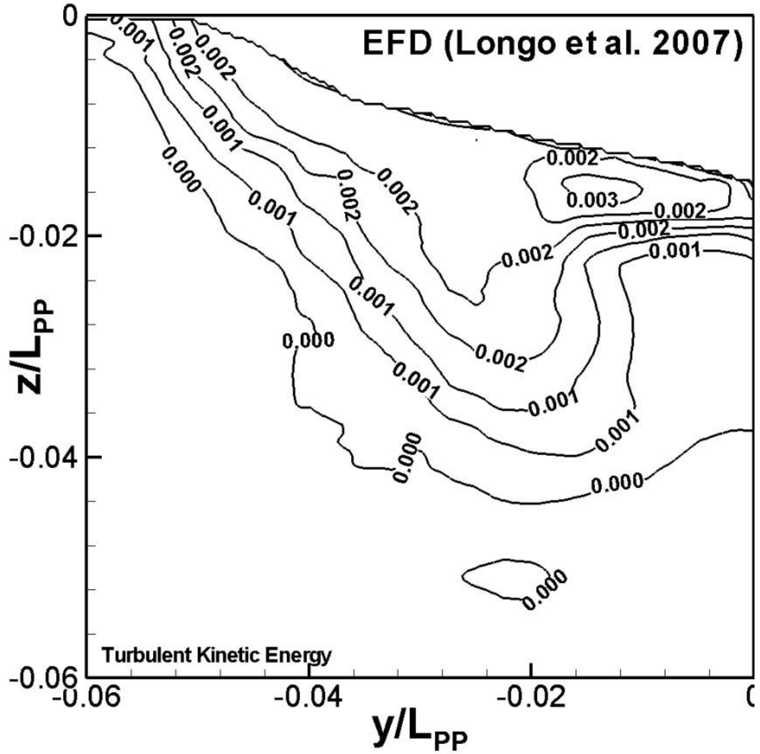
Comp.



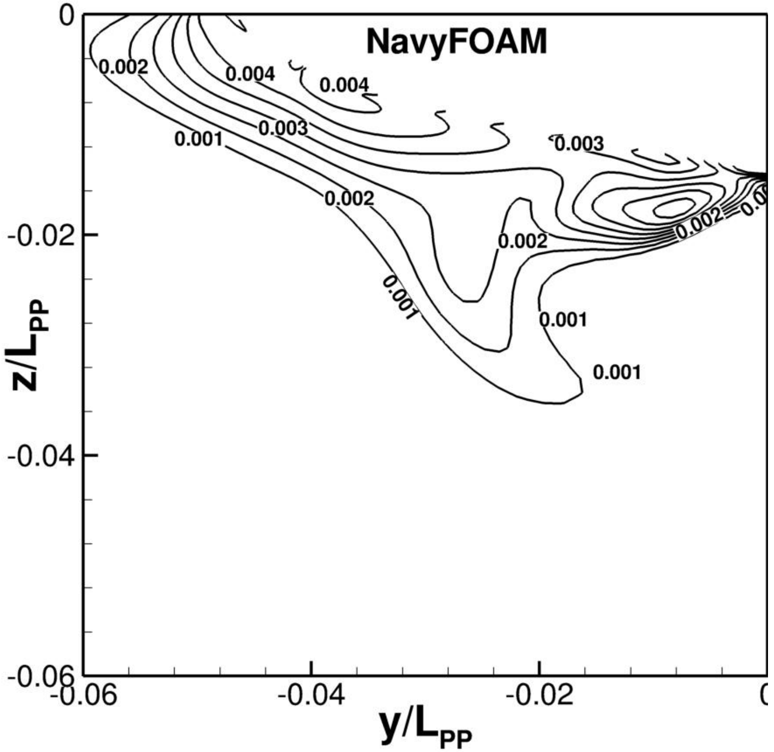
DTMB 5415 – Turbulent Kinetic Energy contour

Case 3.1b

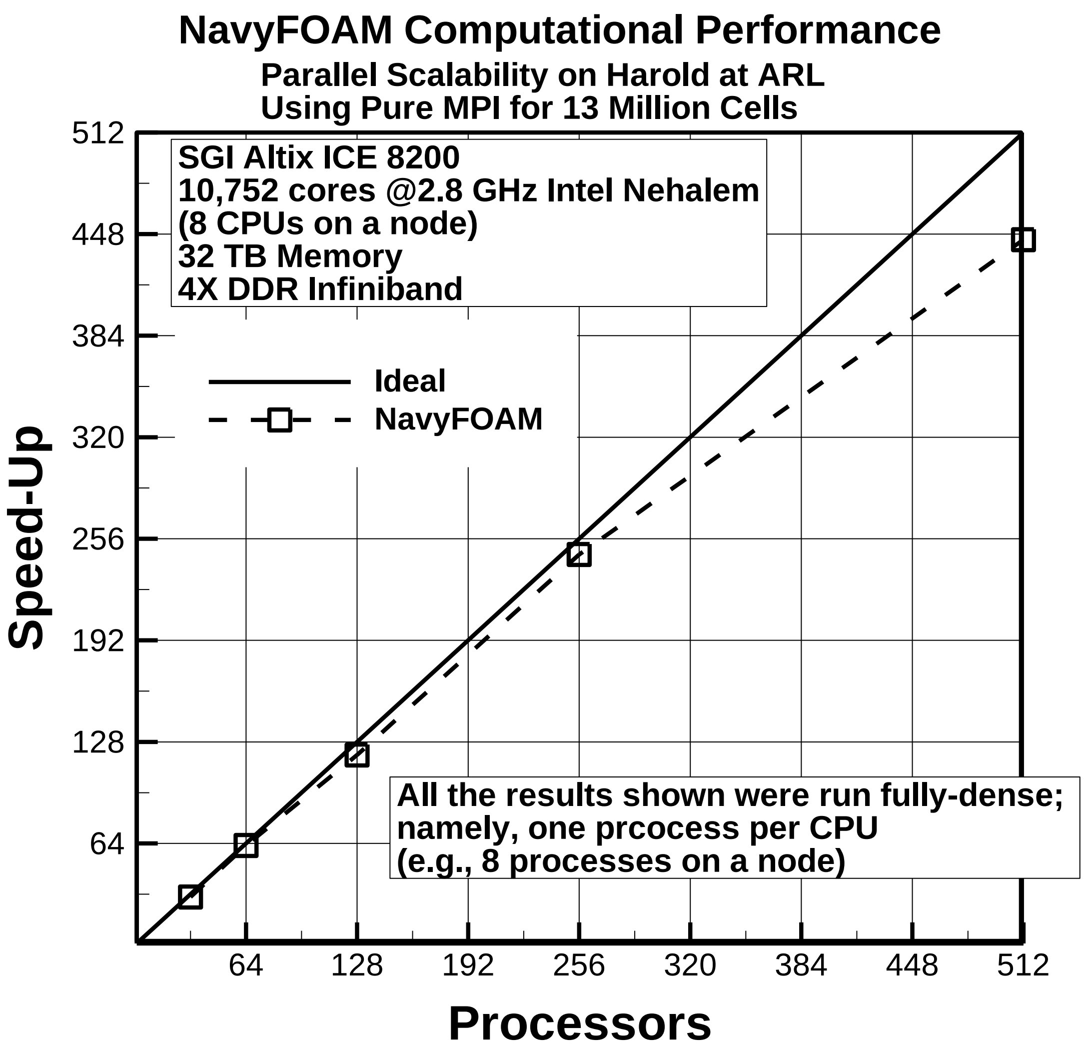
Meas.



Comp.



Parallel scalability – DTMB 5415



DTMB 5415 – Fixed sinkage and trim

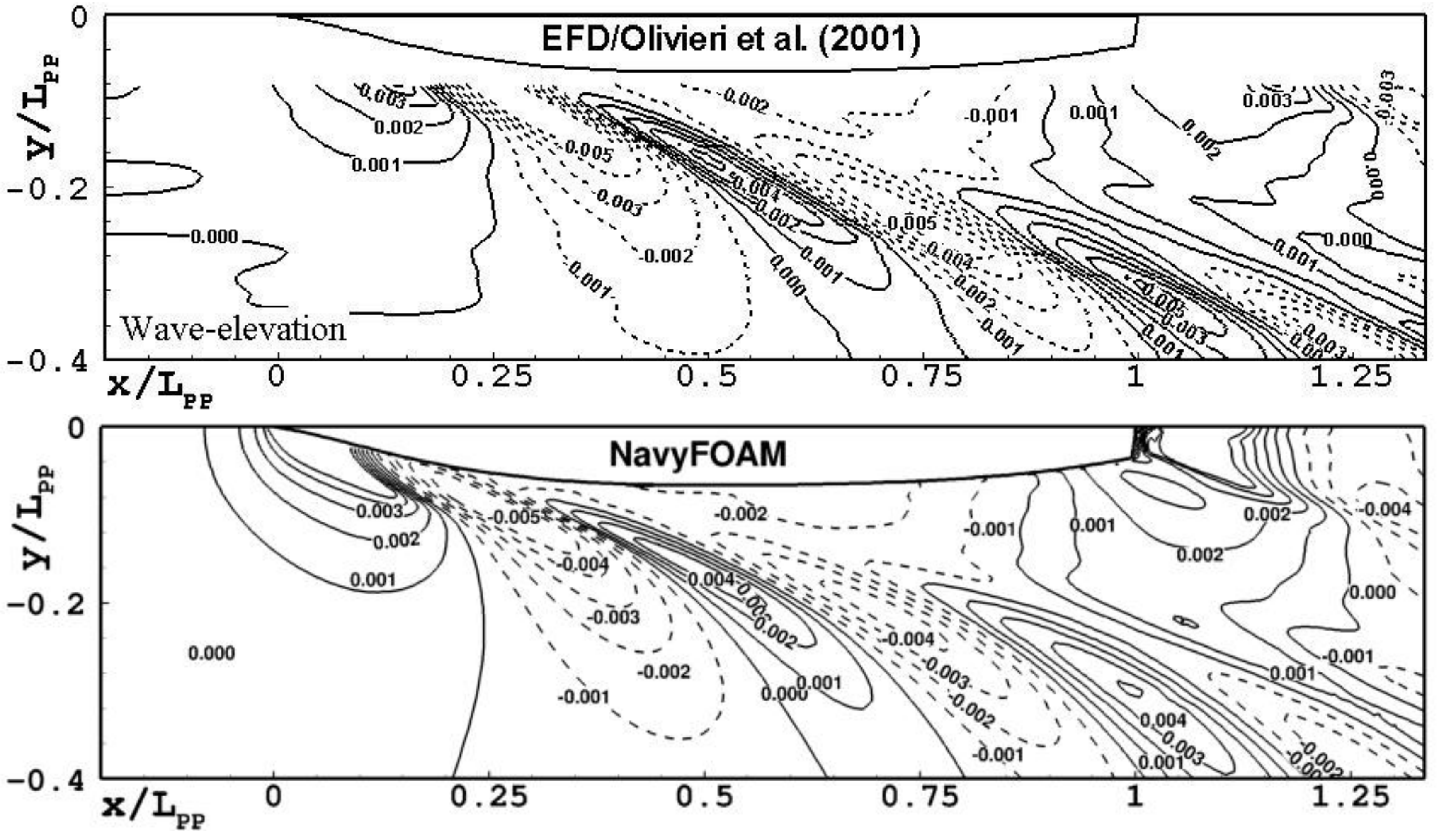
Case 3.1a -

Calm water conditions

Fixed sinkage: -1.82×10^{-3}, trim: -0.108^{o}

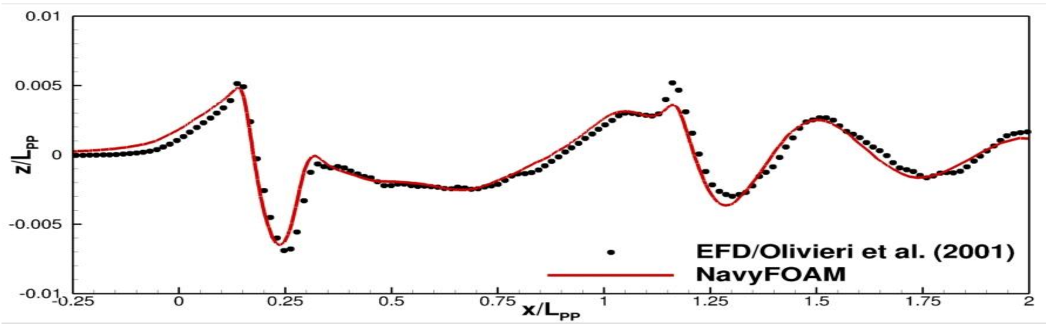
$Re_L = 1.19\times10^{7}$, $Fr = 0.28$

DTMB 5415 – Fixed sinkage and trim

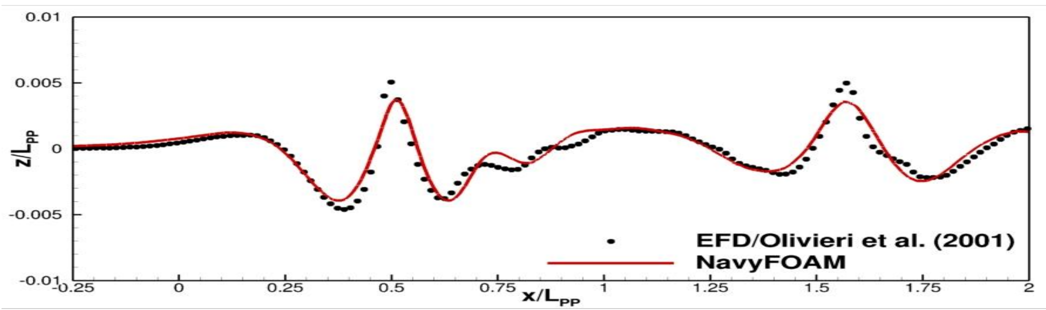


Wave elevation contour

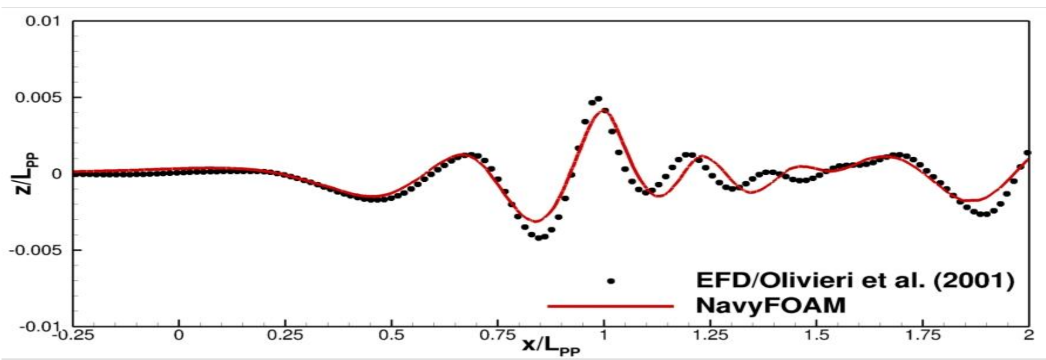
DTMB 5415 – Fixed sinkage and trim



Wave cut at y/L = 0.0082

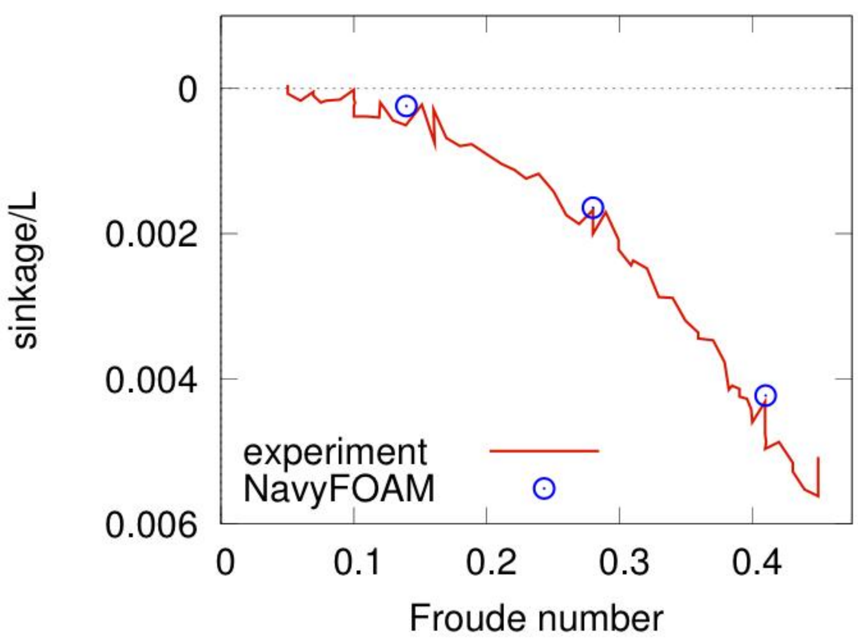


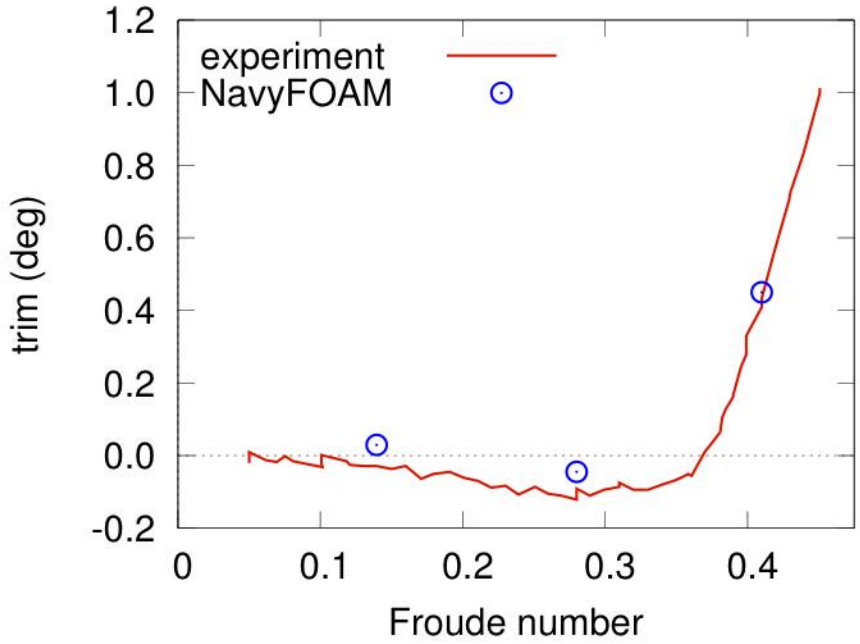
Wave cut at y/L = 0.172



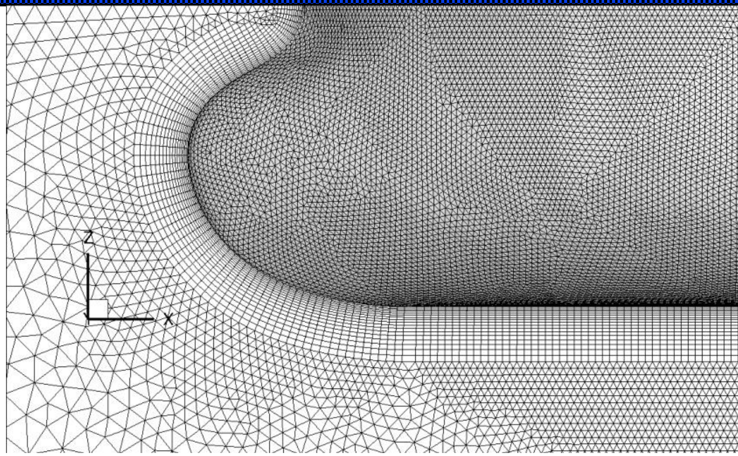
Wave cut at y/L = 0.301

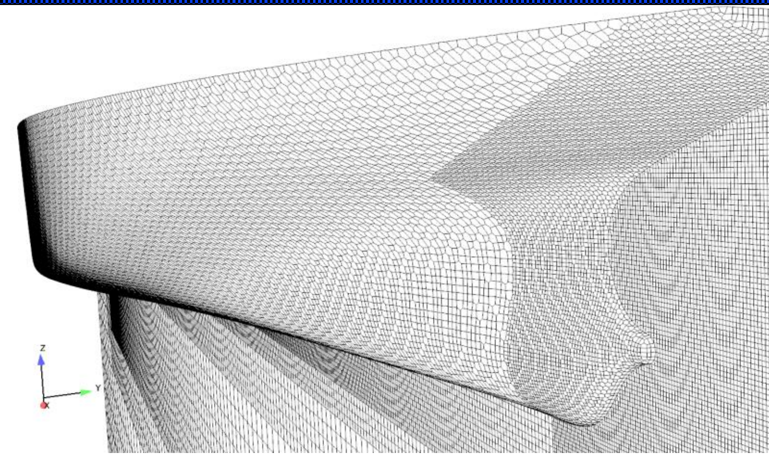
DTMB 5415 – Free to sink and trim





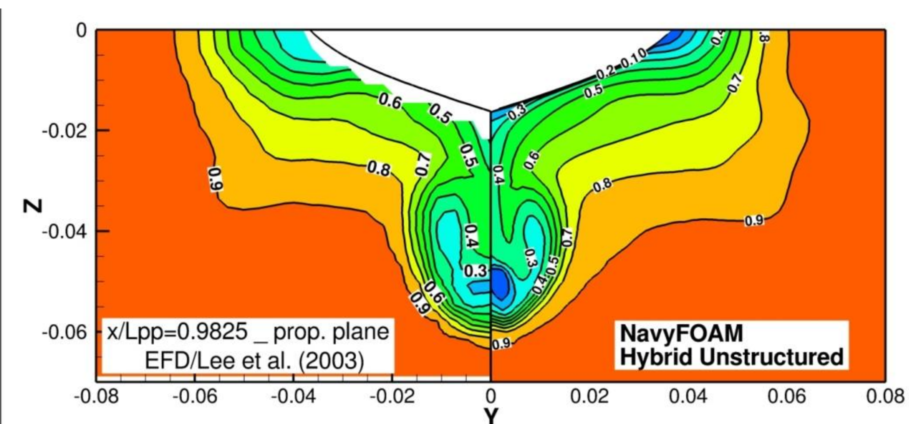
KVLCC2 – Double-Body Tanker Model

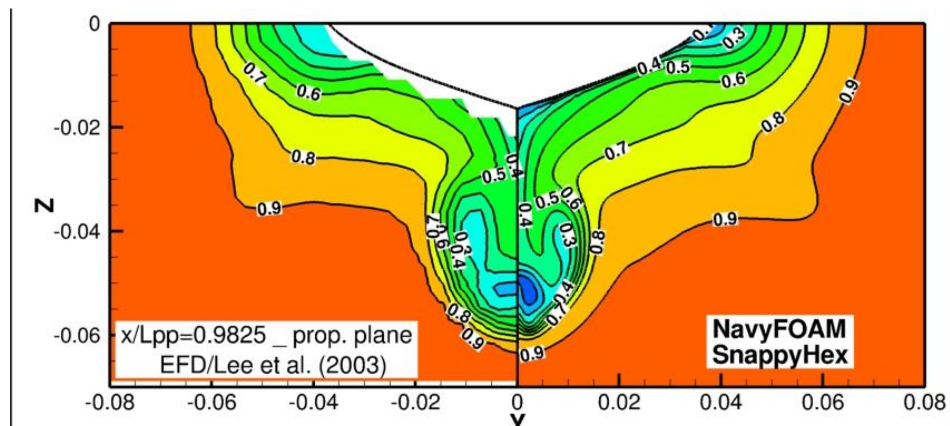




Hybrid unstructured mesh

Automatic hex-dominant mesh



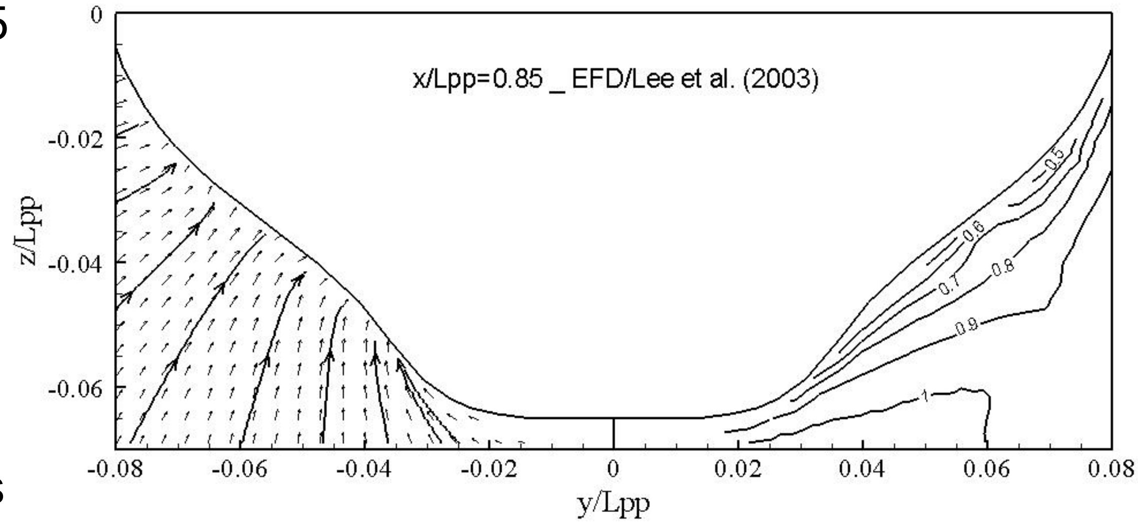


Contour of axial velocity at the propeller plane

Can we accurately predict propeller Inflow using unstructured meshes?

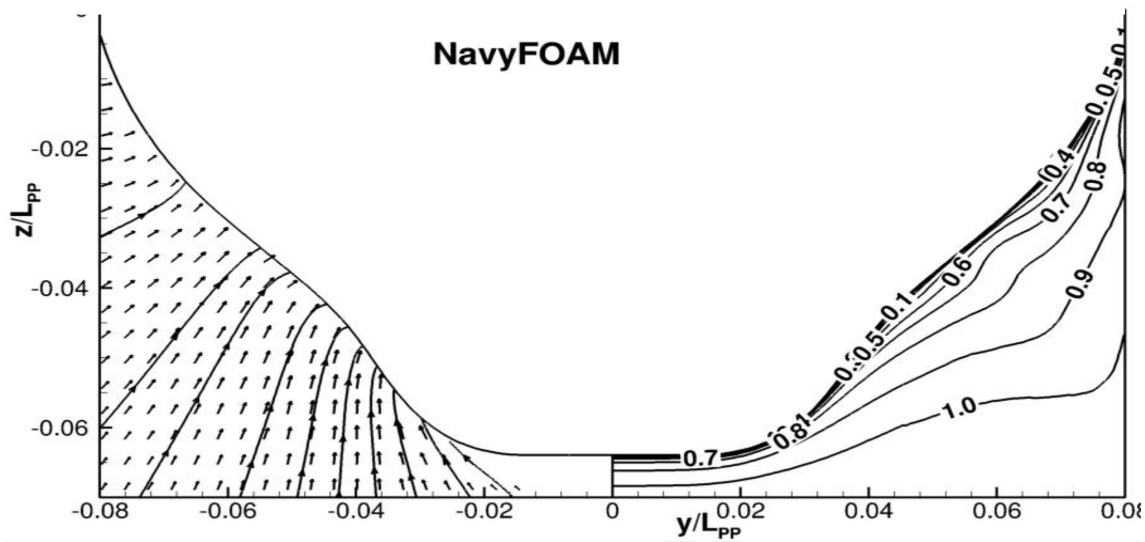
KVLCC2 – Double-Body Tanker Model

At X/Lpp = 0.85



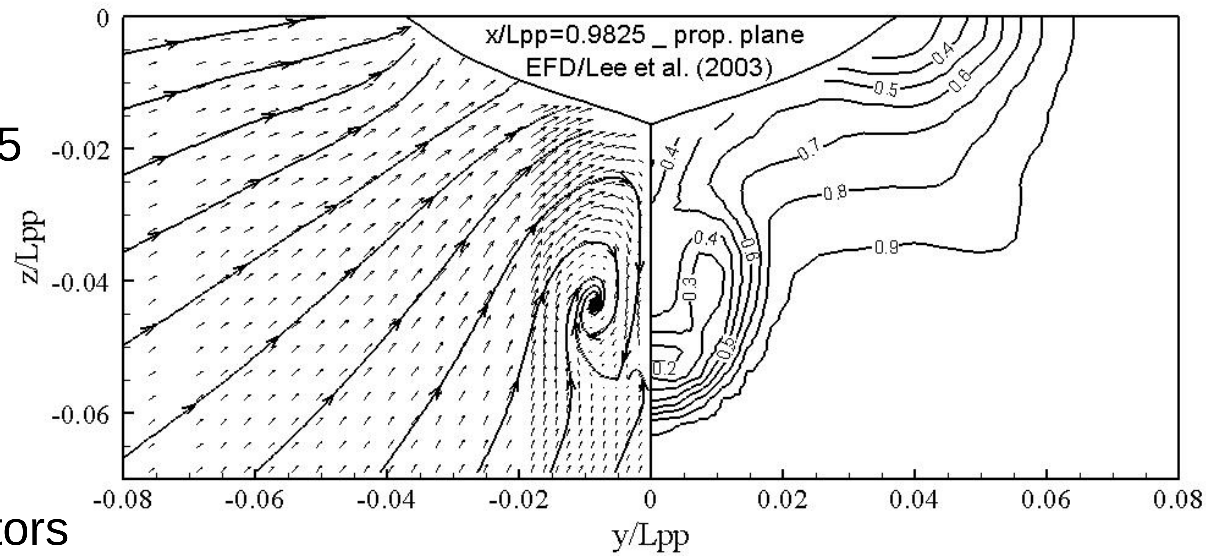
Cross flow vectors and streamlines

U contours



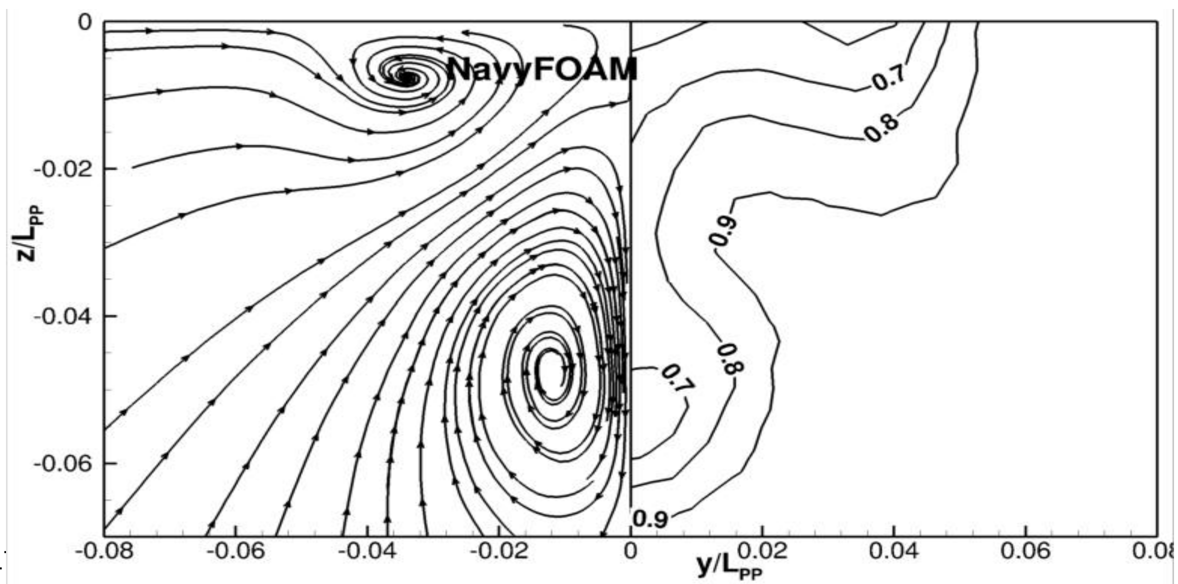
KVLCC2 – Double-Body Tanker Model

At x/Lpp = 0.9825



Cross flow vectors and streamlines

U contours



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JHSS – Description of experiment

- **Joint High Speed Sealift (JHSS) is a naval concept vehicle with axial-flow waterjets.**
- **Detailed flow measurements were conducted in the towing basins at NSWCCD (Jessup et al., 2008).**
- **The model configurations were tested:**
  - **Bare hull with four propellers and strut appendages**
  - **Bare hull with axial-flow waterjets**
  - **Bare hull with mixed-flow waterjets**
- **Three hull variants were designed with a gooseneck bow and different transoms**

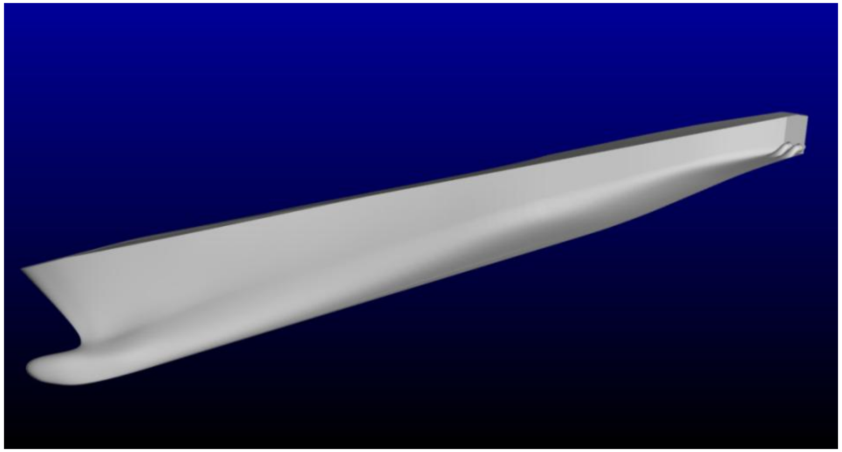
JHSS – Computational approach

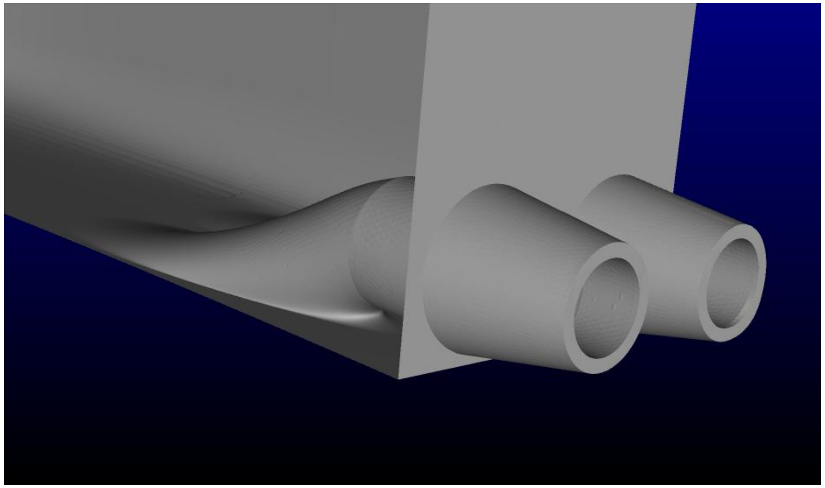
Simulation Approach:

RANS calculations done with TENASI (UT-Chattanooga), and Navy's version of OpenFOAM (NavyFOAM)

Unstructured grids generated using SolidMesh/Aflr3 (Mississippi State University)

Structured grids generated using Gridgen





Modeling Notes:

Port/Starboard symmetry is assumed

TENASI Free surface modeled as a symmetry plane

Free surface effects are included in NavyFOAM calculations

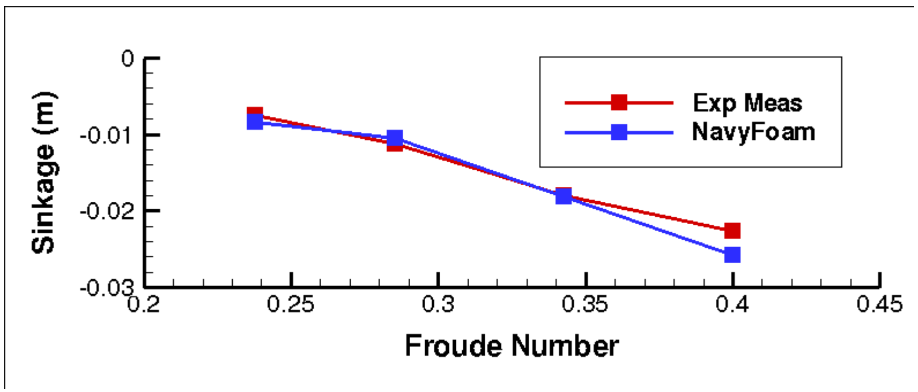
Propelled calculations use a Body Force Propulsor model to simulate waterjet pump

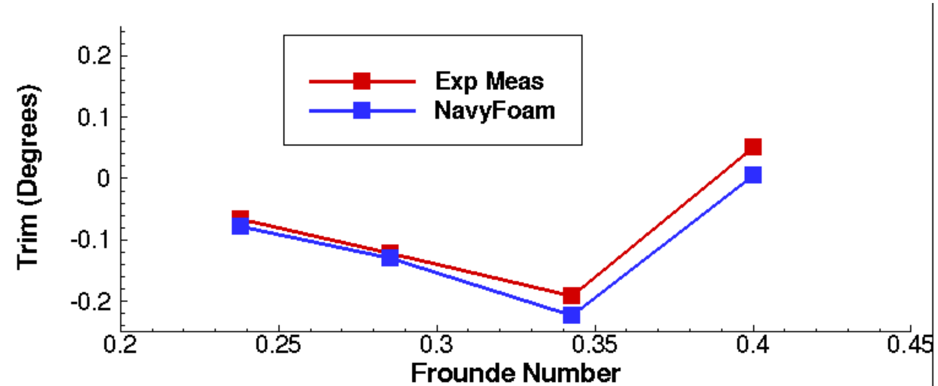
JHSS – Bare hull sinkage and trim

NAVSEA CARDEROCK Surface Warfare Center Division

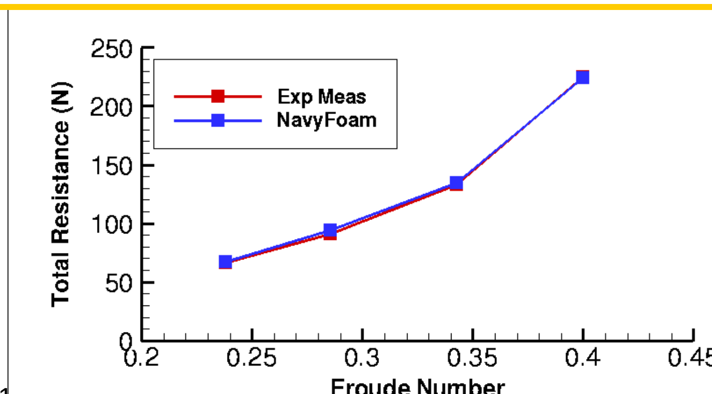
(-) **Computed sinkage and trim values agree well with experimental measurements**

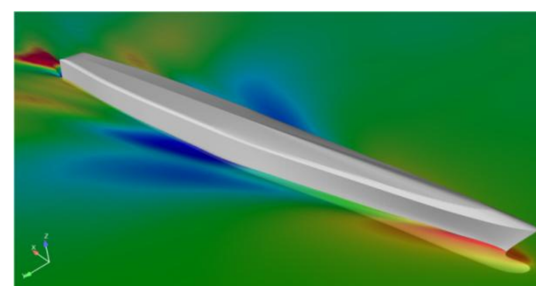
(-) **At the highest Froude Number there is a slight disagreement in the results, but the trend is captured well**



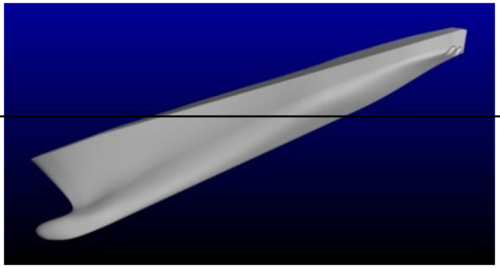


(-) **The computational resistance agrees with well with experimental measurements**

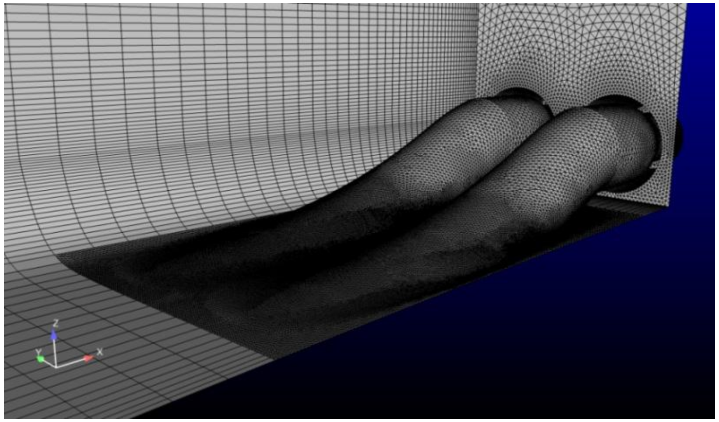


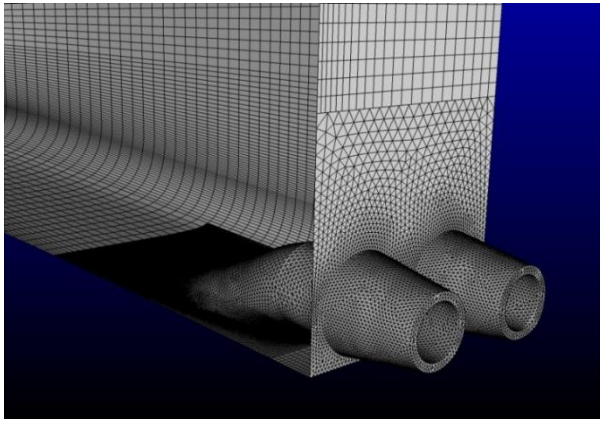


JHSS –
Powering fixed sinkage and trim

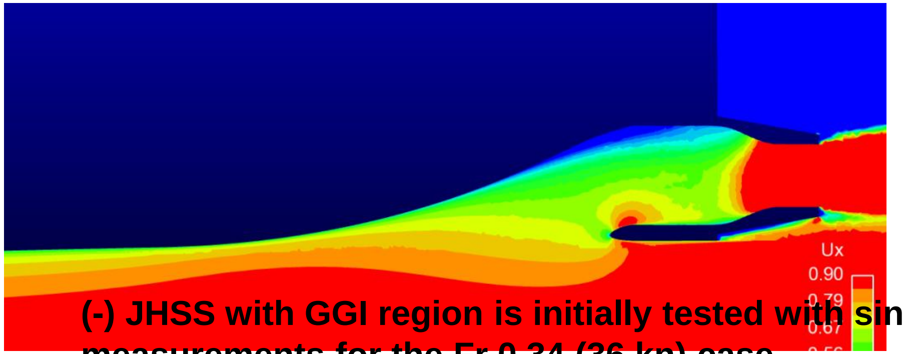


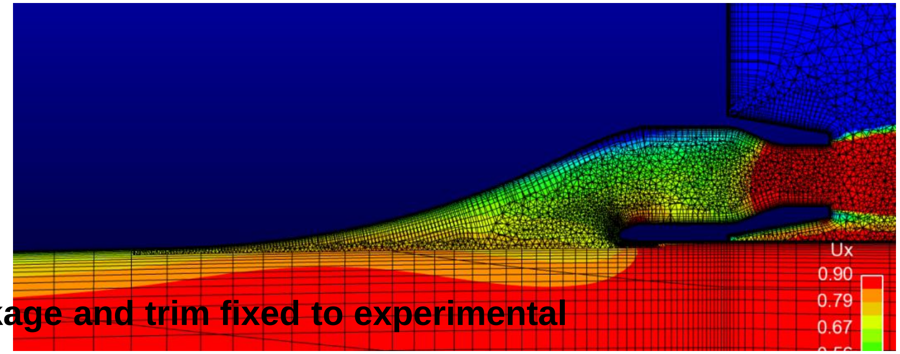
Surface Mesh on the Stern





Axial velocity contours through the inlet stay smooth and match experiment and previous computations well



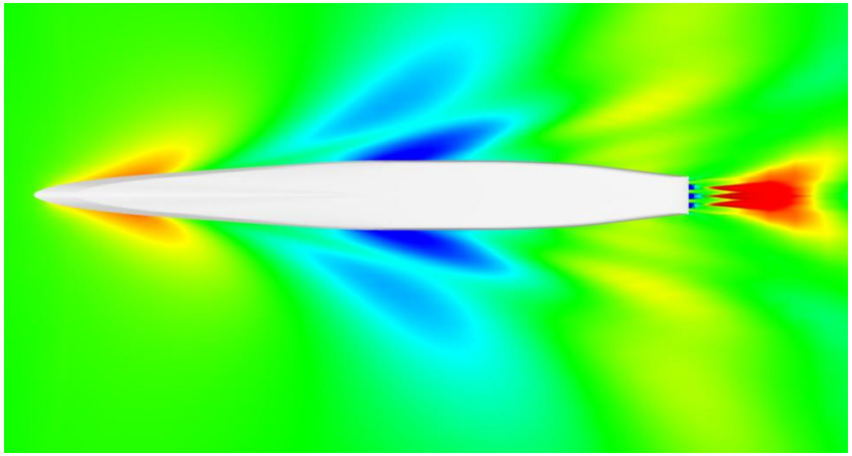


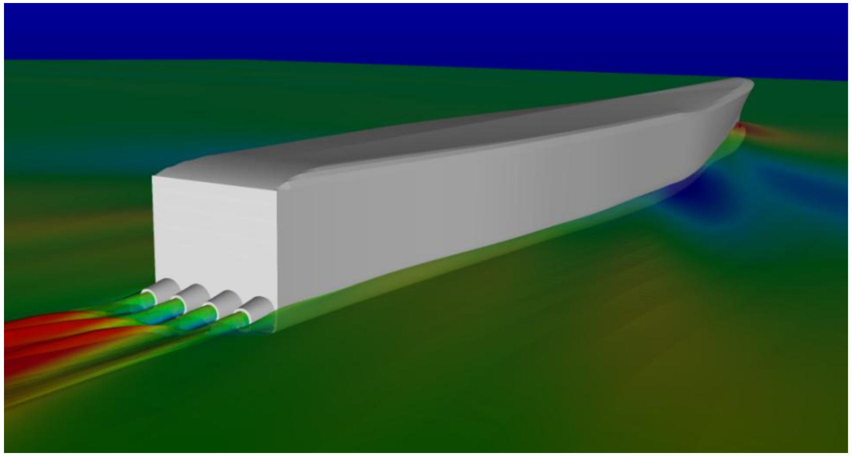
(-) JHSS with GGI region is initially tested with sinkage and trim fixed to experimental measurements for the Fr 0.34 (36 kn) case

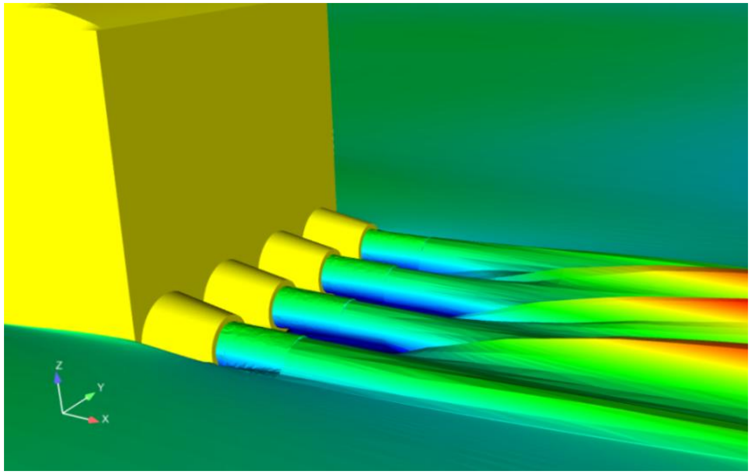
(-) Previous multiphase solver had to be adjusted to accommodate Body Force implementation

JHSS – Power prediction fixed sinkage and trim

Top View of Free Surface Colored by Elevation | **View of Stern with Transparent Surface**







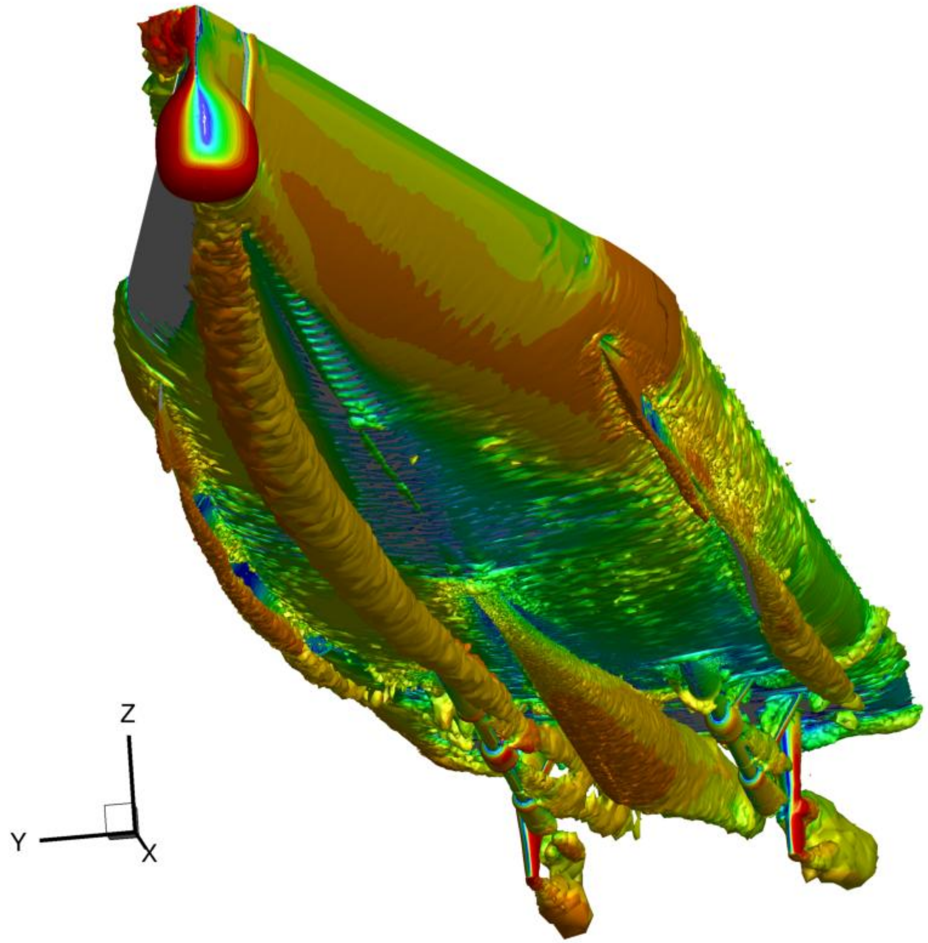
Cusanelli, Carpenter & Powers
NSWCCD-50-TR-2007/076

Flow Exiting the Waterjets: Experiment (left) & Computation (right)

Fully Appended DDG-1000

- Fully appended configuration includes bilge keels, skeg, shafts, struts, and rudders.
- Forces and moments from RANS simulations were used to provide hydrodynamic coefficients for TEMPEST.
- RANS run matrix:
  - Straight ahead case: different speeds with various drift angles
  - Constant turning case: turning radius = 3*body length (L), 4L, 5L, 10L
- Grids used: unstructured 18 million cells including prism layers and tetrahedra.

Fully Appended DDG-1000



Isosurface Q contour plot

Summary & Conclusions

- Surface ship applications involve complex flow physics such as turbulence, two-phase flow phenomena near the air-water interface, 6-DOF motion, and environments.
- NavyFOAM has been validated for free-surface problems ranging from canonical problems to model ships.
- NavyFOAM was among the best performing RANS solvers to accurately predict resistance, wave profiles, and local flow at Gothenburg 2010 Workshop.
- We've also developed best practices in numerical algorithms, discretization schemes, and turbulence modeling for surface ship applications.
  - Fully implicit solution algorithm
  - RANS turbulence modeling
  - Advection schemes for VOF equation