Validation of Seakeeping CFD Simulations in Head and Oblique Waves Using the Naval Hydro Pack

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Outline

Objective

- Assess the reliability of the Naval Hydro pack for seakeeping and generally naval hydrodynamics simulations
- Address numerical uncertainties, including
  - **Temporal resolution uncertainty**
  - **Hydro–mechanical coupling uncertainty** (number of fluid–flow/6 DOF correctors)
  - **Grid resolution uncertainty**
  - **Periodic uncertainty**
- **Best practice guidelines**

Topics

1. Tokyo 2015 Workshop cases (KCS hull at design Froude number)
   - Head waves
   - Oblique waves
2. SHOPERA workshop cases (DTC hull at low Froude numbers)

Tokyo 2015 Head Waves

Overview of experimental and simulation set–up

- Towed ship in head waves at design Froude number: $F_n = 0.26$
- Model scale: $L_{PP} = 6.0702$ m
- 5 wave conditions (and a steady resistance test)
  1. C1; $\lambda/L_{PP} = 0.65$, $H = 0.062$ m
  2. C2; $\lambda/L_{PP} = 0.85$, $H = 0.078$ m
  3. C3 (resonant case); $\lambda/L_{PP} = 1.15$, $H = 0.123$ m
  4. C4; $\lambda/L_{PP} = 1.37$, $H = 0.149$ m
  5. C5; $\lambda/L_{PP} = 1.96$, $H = 0.196$ m
- Additional details and experimental data available at Tokyo Workshop On CFD in Ship Hydrodynamics website
- Experimentally measured
  1. Heave
  2. Pitch
  3. Total resistance
- No experimental uncertainty reports
- Comparison of `swenseFoam` and `navalFoam` solvers. Note: uncertainty assessment with `swenseFoam` only (presently)

Temporal Resolution Study, C5 Case

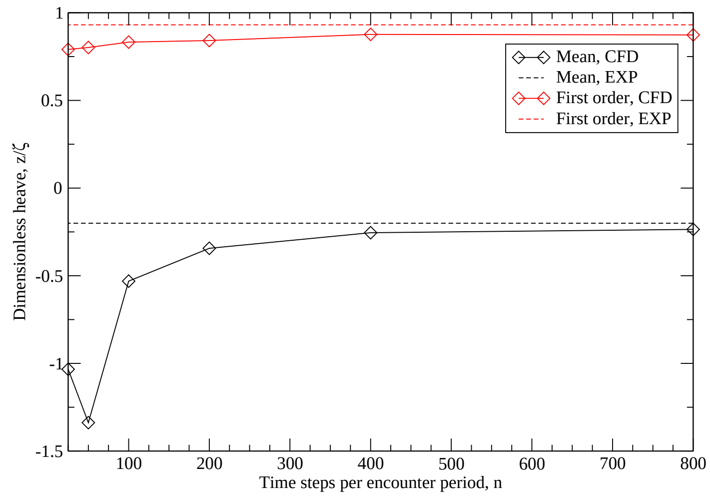
What is the best time step for seakeeping applications?

- Varying number of time steps per encounter period
  1. $n = 25$ (extremely large time step, $CFL = \mathcal{O}(10^2)$)
  2. $n = 50$
  3. $\vdots$
  4. $n = 800$
- Time steps larger than $T_e/25$ crashed due to 6 DOF solver (explicit fifth order Runge–Kutta with Cash–Karp parameters)
- *i.e.* flow solver **is stable** (as it should be considering the von Neumann stability analysis for implicit solvers!)
- Temporal resolution uncertainty assessment
- Periodic uncertainty assessment for each time step size via moving window FFT (30 encounter periods simulated)

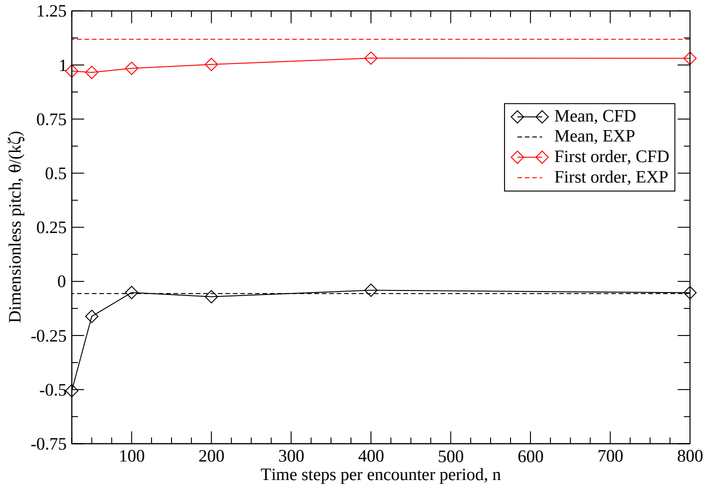
Harmonic Amplitudes

Temporal resolution uncertainties for amplitudes:

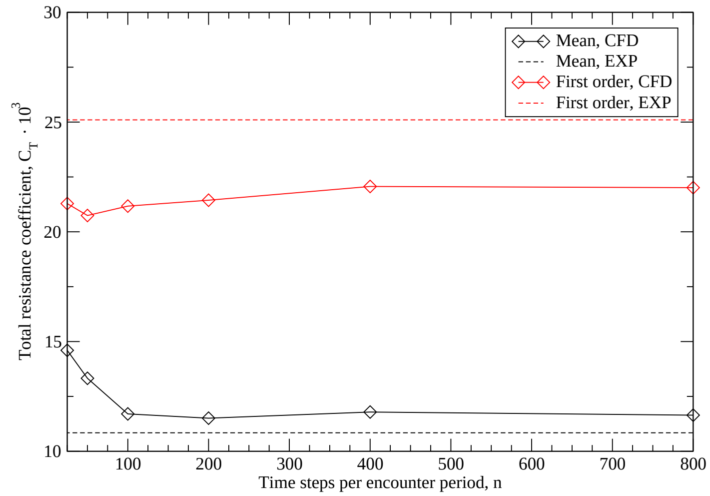
- Heave: $\approx 3.00\%$
- Pitch: $\approx 2.12\%$
- Resistance: $\approx 2.13\%$



Heave amplitudes



Pitch amplitudes



Resistance amplitudes

Hydro–Mechanical Coupling Study

Varying number of fluid–flow/6 DOF correctors (outer, PIMPLE correctors):

1. $n = 2$
2. $n = 4$
3. $n = 6$
4. $n = 8$

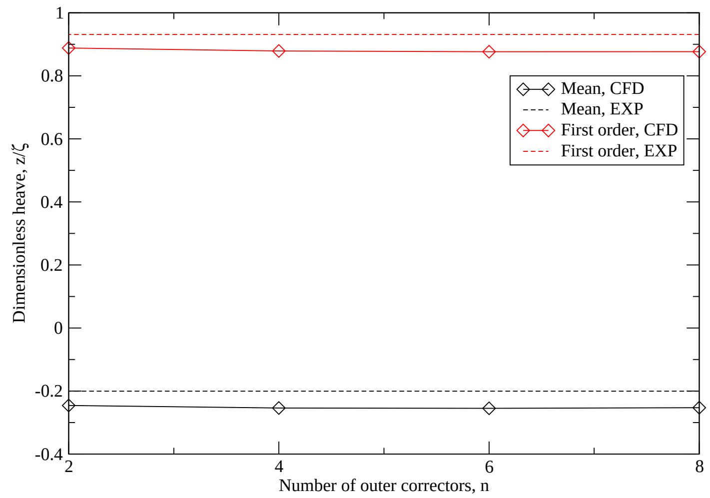
Improved hydro–mechanical coupling (planned for use in general pressure dominated FSI)

- 6 DOF motion equations are updated in each pressure correction step
  1. Tight pressure–6 DOF coupling
  2. Updating 6 DOF equations multiple times at negligible CPU expense
- Hydro–mechanical uncertainty assessment
- Periodic uncertainty assessment for each number of outer correctors via moving window FFT (30 encounter period simulated)

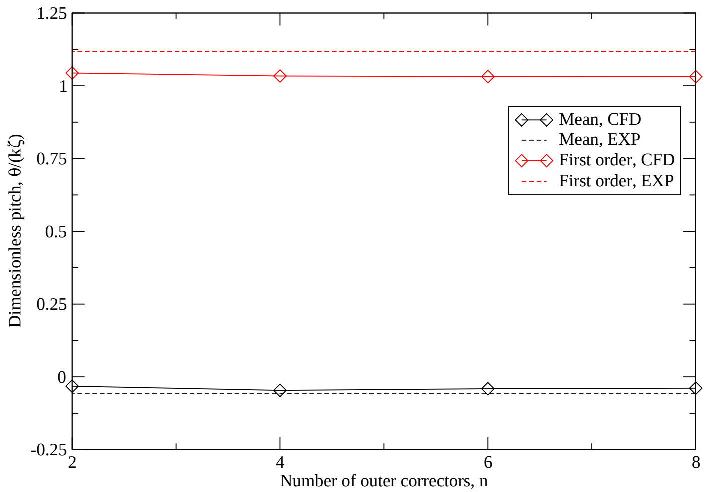
Harmonic Amplitudes

Hydro–mechanical coupling uncertainties for amplitudes:

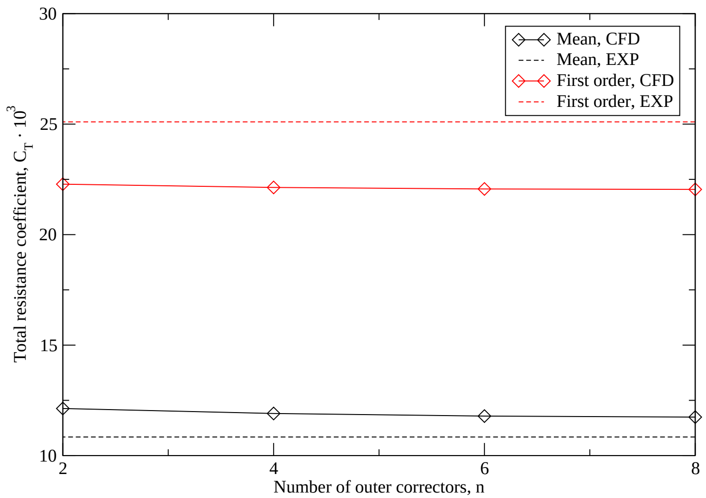
- Heave: $\approx 0.12\%$
- Pitch: $\approx 0.12\%$
- Resistance: $\approx 0.87\%$



Heave amplitudes



Pitch amplitudes



Resistance amplitudes

Grid Refinement Study

Three unstructured grids with

1. ≈ 600 000 cells (coarse)
2. ≈ 950 000 cells (medium)
3. ≈ 1 600 000 cells (fine)

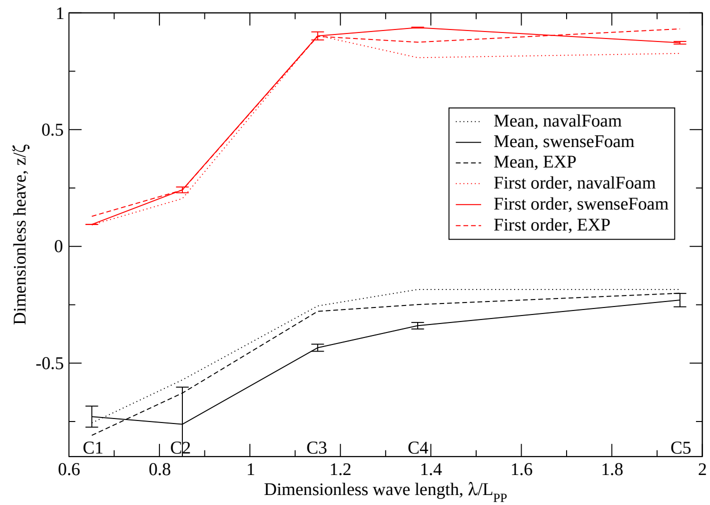
Notes

- Each case simulated with `swenseFoam` using all grids
- Grid refinement uncertainty assessment
- Only medium grid (950 000 cells) with `navalFoam`
- Periodic uncertainty assessment for each grid via moving window FFT (30 encounter periods simulated)
- **Grid uncertainty comparable to time step uncertainty**

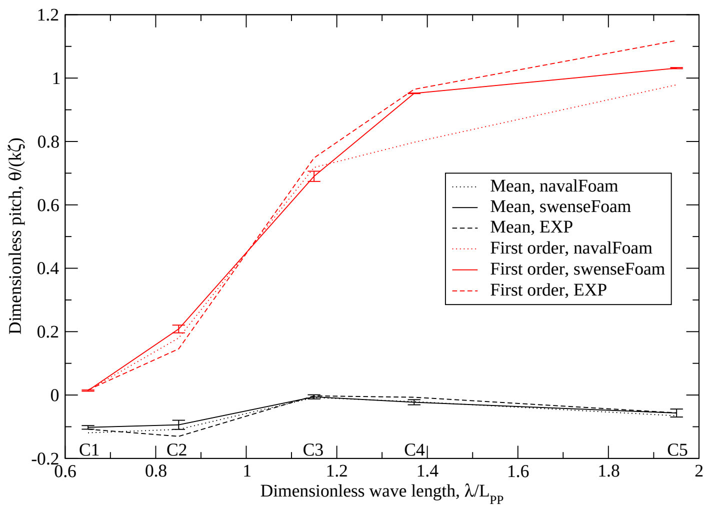
Harmonic Amplitudes

Average (cases C1 to C5) grid uncertainties for amplitudes:

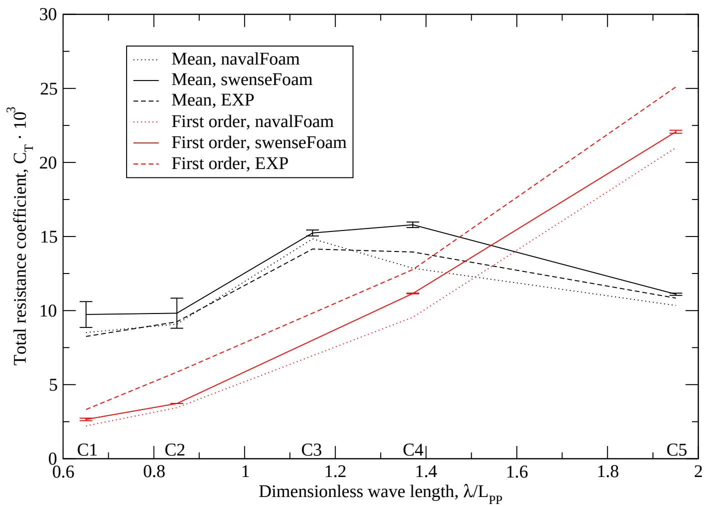
- Heave: $\approx 4.4\%$
- Pitch: $\approx 2.1\%$
- Resistance: $\approx 3.0\%$



Heave transfer function



Pitch transfer function

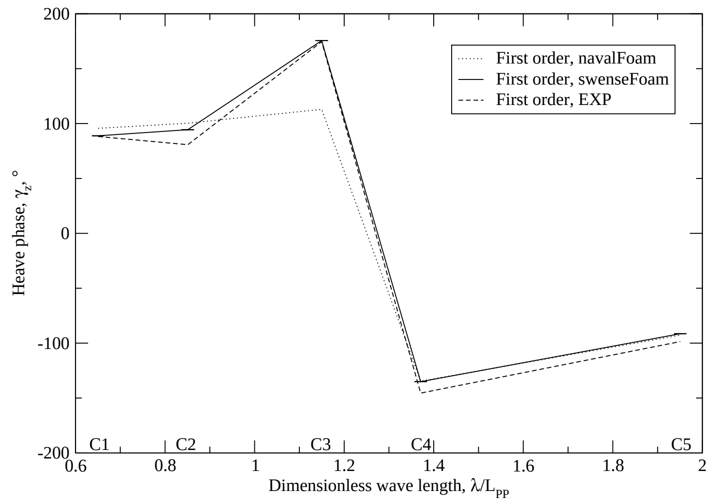


Resistance transfer function

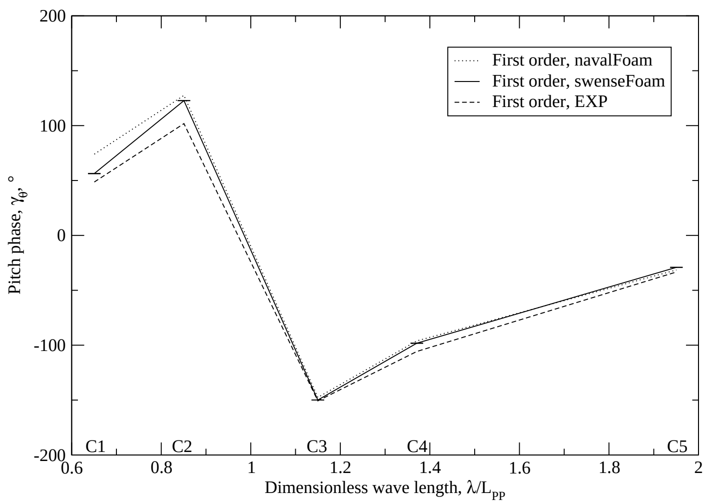
First Order Phases

Average (cases C1 to C5) grid uncertainties for phases:

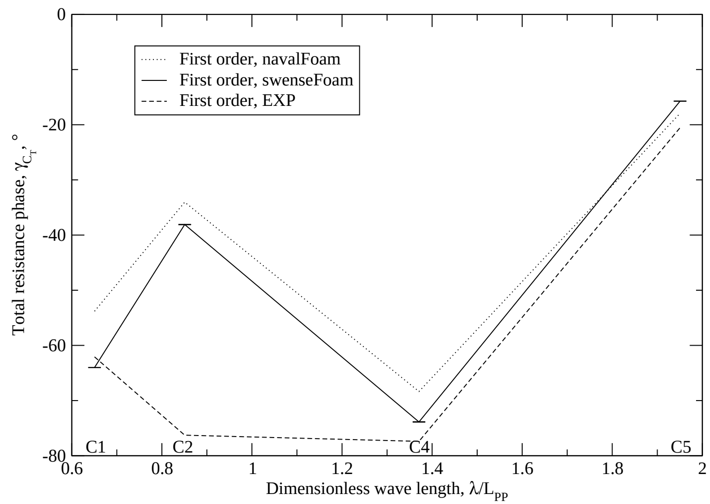
- Heave: $\approx 0.9\%$
- Pitch: $\approx 3.6\%$
- Resistance: $\approx 3.7\%$



Heave phases



Pitch phases



Resistance phases

Is Seakeeping with CFD feasible?

Feasibility estimate of head wave seakeeping study

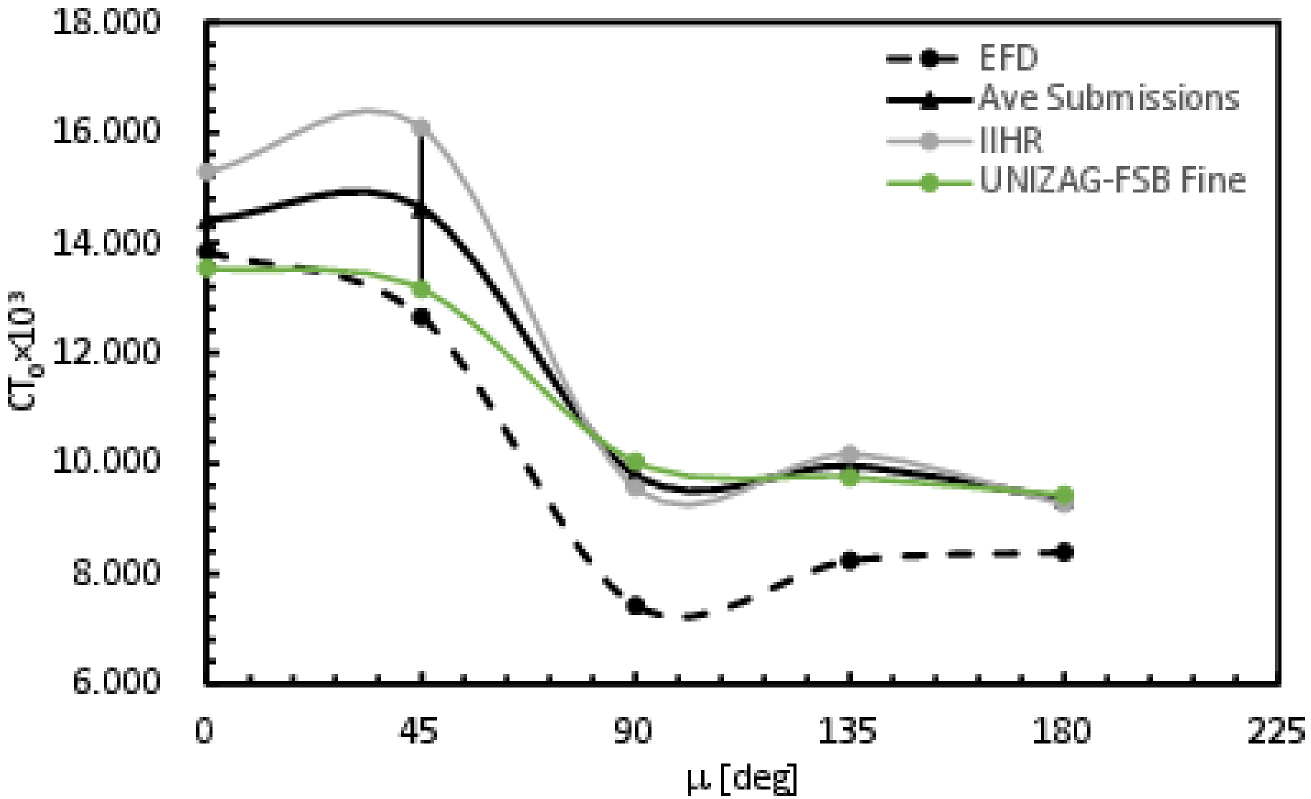
- Performed 33 simulations in total:
  - 6 simulations for the temporal resolution study
  - 4 simulations for the hydro–mechanical coupling study
  - 7 short simulations for parallel scaling test
  - 1 performance test
  - 15 simulations for grid refinement
- In approximately 2 weeks using 56 cores, one can get a good estimate of transfer functions at design Froude number, including numerical uncertainty assessment!
- Without uncertainty assessment, the transfer function can easily be obtained within a few days
- Albeit, the simulations are performed by an **experienced user**

Tokyo 2015 Oblique Waves

Overview of experimental and simulation set–up

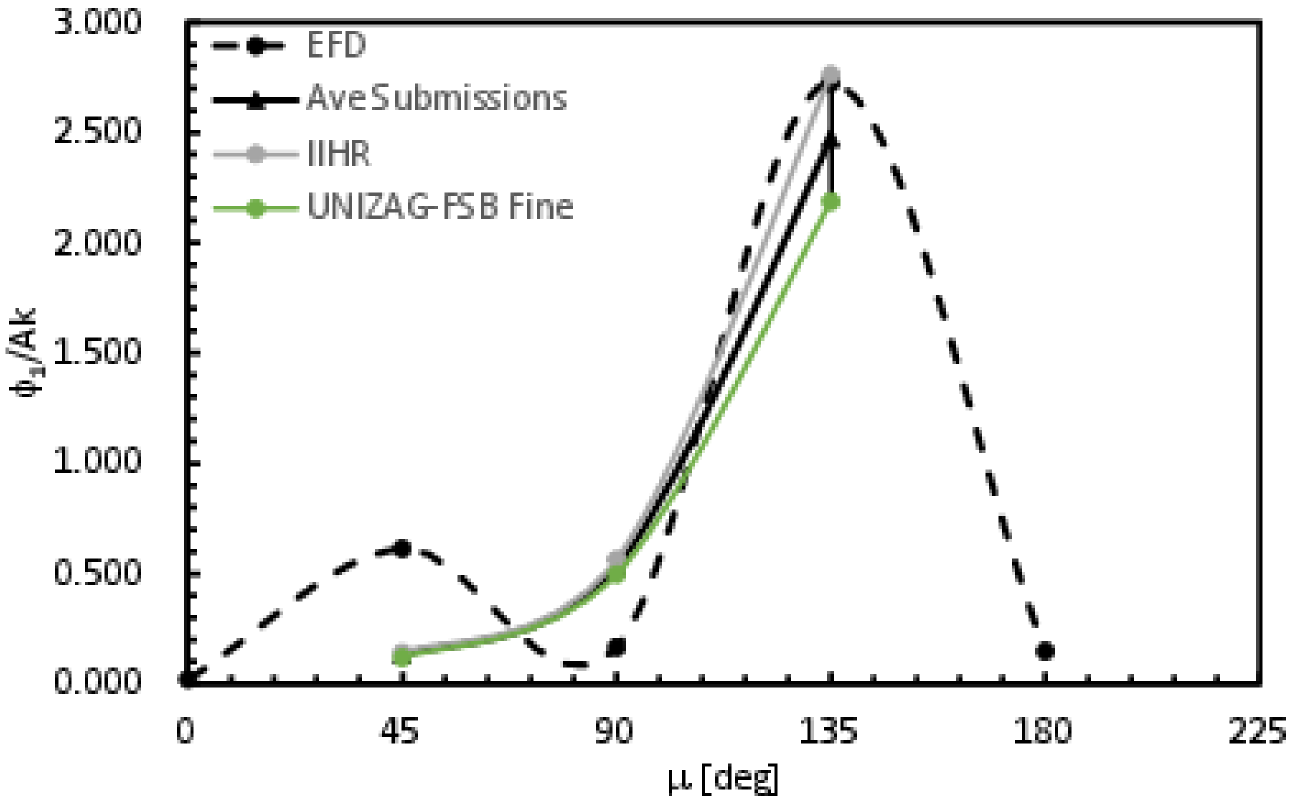
- Towed ship in head waves at design Froude number: $F_n = 0.26$
- Model scale: $L_{PP} = 2.7$ m
- Regular wave: $\lambda / L_{PP} = 1$, $H = 0.045$ m
- 5 wave encounter angles:
  1. C1: $\xi = 0^\circ$–head sea
  2. C2: $\xi = 45^\circ$–bow sea
  3. C3: $\xi = 90^\circ$–beam sea
  4. C4: $\xi = 135^\circ$–quartering sea
  5. C5: $\xi = 180^\circ$–following sea
- Experimentally measured: heave, **roll**, pitch and total resistance
- No experimental uncertainty reports
- Only two submissions: CFDShip-Iowa and us
- Combined post processing done by group of prof. Stern at IIHR, Iowa.
- `swenseFoam` solver with grid uncertainty assessment

Mean Total Resistance



Mean value of total resistance coefficient

Roll Amplitude



First harmonic amplitude of roll

CPU Times

Hardware and simulations times

- 7 nodes (56 cores):
  - CPU–2x Intel Xeon E5–2637 v3 4–core
  - 3.5 GHz
  - 15MB L3 Cache
  - DDR4–2133
- **CPU time: 40 min per encounter period** for:
  - C2 bow waves case
  - 3.2 million cells
  - 56 cores
  - 7 outer (PIMPLE, motion) correctors (before recent development of improved hydro–mechanical coupling strategy)
  - Approximately 225 time–steps per encounter period
  - Maximum CFL number from 55 to 70 during the simulation (fixed time step of 0.004 s)
  - 60 periods simulated (periodic uncertainty assessment)

SHOPERA Benchmark Outline

SHOPERA Benchmark Study

- All cases performed on three grids
- Low and zero forward speed
- Various wave parameters (**steep waves**):

  (6 head waves cases and 10 oblique waves cases

  \+ 1 irregular head waves case performed)

  $\times$ 3 grids

  = 51 simulations in total

Head waves cases:

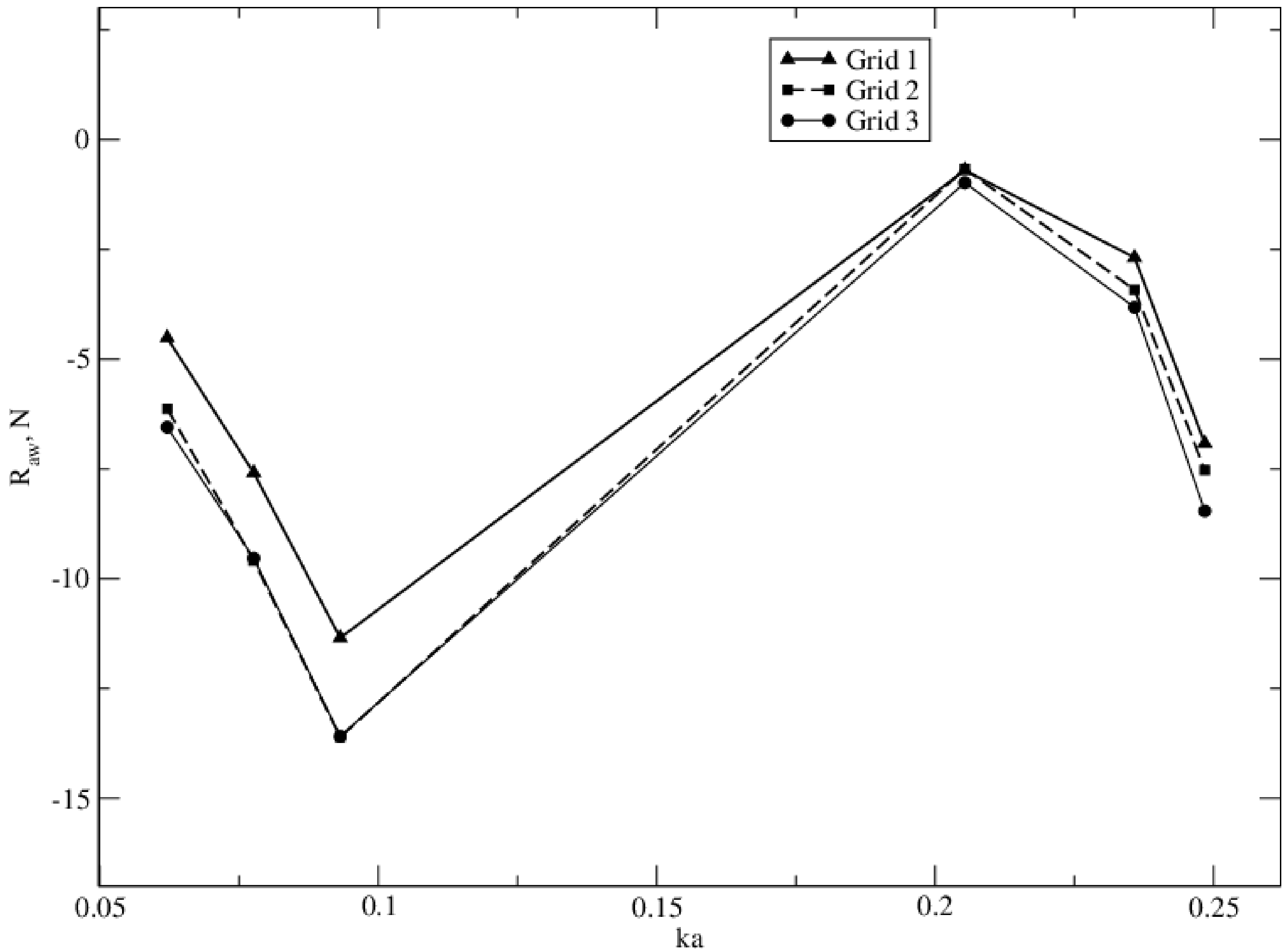
Run number	H, m	T, s	ka	λ, m	v, kt	F_r
3031	10	9	0.248	126.5	6	0.054
3041	7.5	8	0.235	99.9	6	0.054
3051	5	7	0.205	76.5	6	0.054
3700	9	13.94	0.093	303.5	6	0.054
3711	6	13.94	0.062	303.5	6	0.054
3720	7.5	13.94	0.078	303.5	6	0.054

Oblique Case Setups

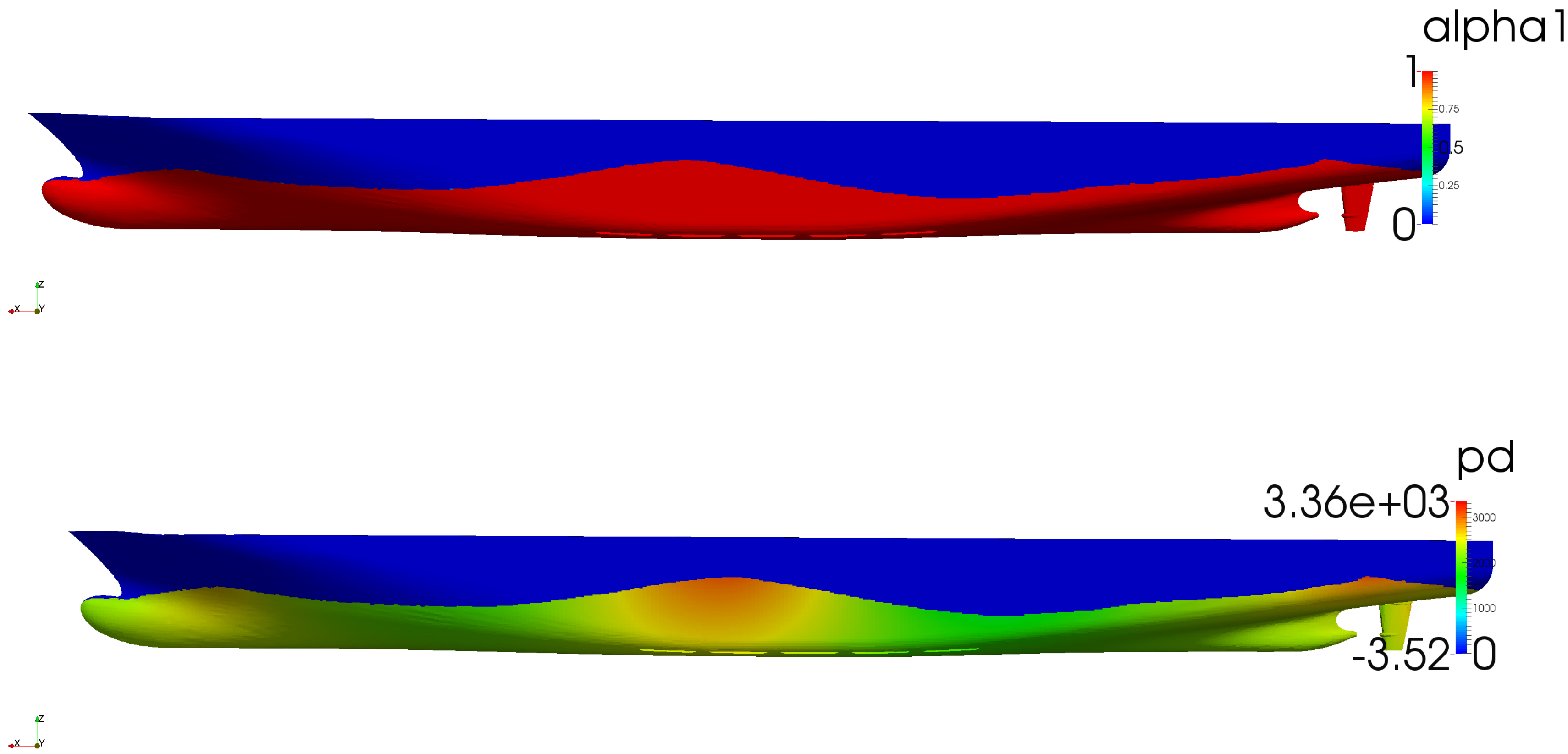
Oblique waves cases:

Run number	H, m	T, s	ka	λ, m	Encounter angle, ^{o}	F_r
2140	10	9	**0.248**	126.5	30	0
2250	10	9	**0.248**	126.5	60	0
2355	6	10	**0.121**	156.1	90	0
2480	7.5	8	**0.236**	99.9	120	0
2580	10	9	**0.248**	126.5	150	0
2690	10	9	**0.248**	126.5	180	0
3140	10	9	**0.248**	126.5	30	0.054
3250	10	9	**0.248**	126.5	60	0.054
3370	7.5	8	**0.236**	99.9	120	0.054
3460	6	10	**0.121**	156.1	150	0.054

Head Waves Resistance



Dynamic Pressure Resolution



Sharp, non–ventilating free surface

Concluding Remarks

Naval Hydro pack **thoroughly validated and verified** regarding seakeeping at design Froude number (Tokyo 2015 Workshop): `swenseFoam` and `navalFoam`

Extensive uncertainty assessment, including

- Periodic uncertainty assessment: a significant number of encounter periods (> 10) needs to be simulated in order to achieve truly periodic solution
- Temporal resolution study: a trade–off between performance and accuracy for **practical applications**
- Hydro–mechanical coupling: solution extremely insensitive to number of outer correctors
- Grid refinement study: good results can be obtained with relatively coarse grids ($< 1\,000\,000$ cells)

Established best practice guidelines regarding time–step, grid resolution, number of simulated periods and hydro–mechanical coupling resolution

TO-DO

- Turbulence modelling at low Froude and Brard numbers?
- Further V&V for oblique, short waves needed