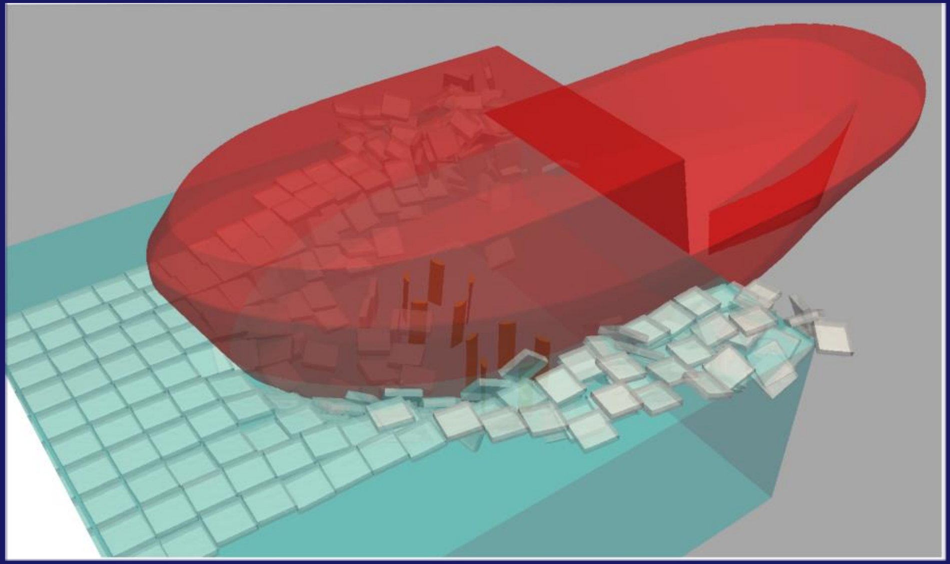
Validation of a GPU-Accelerated LBM Based Numerical Ice Tank for a Voith Schneider Propulsion System

M. Gehrke, D. Mierke, T. Rung and P. Hauer



TUHH Hamburg University of Technology
VOITH

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Fluid Dynamics and Ship Theory

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Structure

- **Introduction**
  - Ice Simulations using LBM
  - VSP Kinematics
- **Rainflow-Counting Algorithm / Fatigue Analysis**
- **Generic Test Case**
- **Real Application Test Case**
- **Summary and Outlook**

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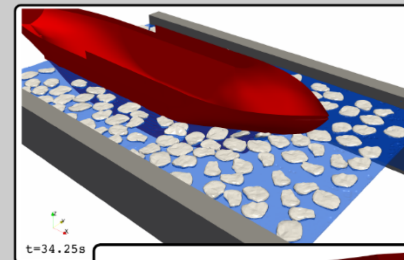
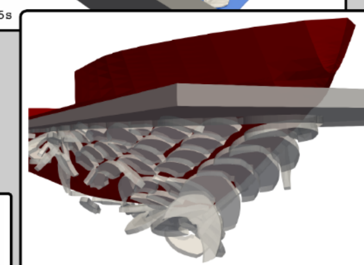
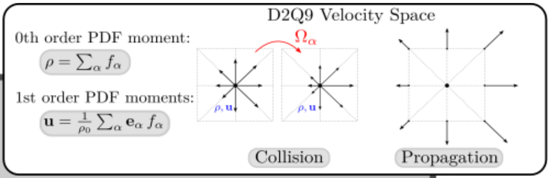
Introduction

- **TUHH / FDS** - Ice related Research Projects
  - Development of a Numerical Ice Tank (`ProEis`)
    - FSI of pre-broken ice floes modeled as rigid bodies → Mierke, Gehrke
  - Modeling of Icebreaking (`PrICE`) → Huisman





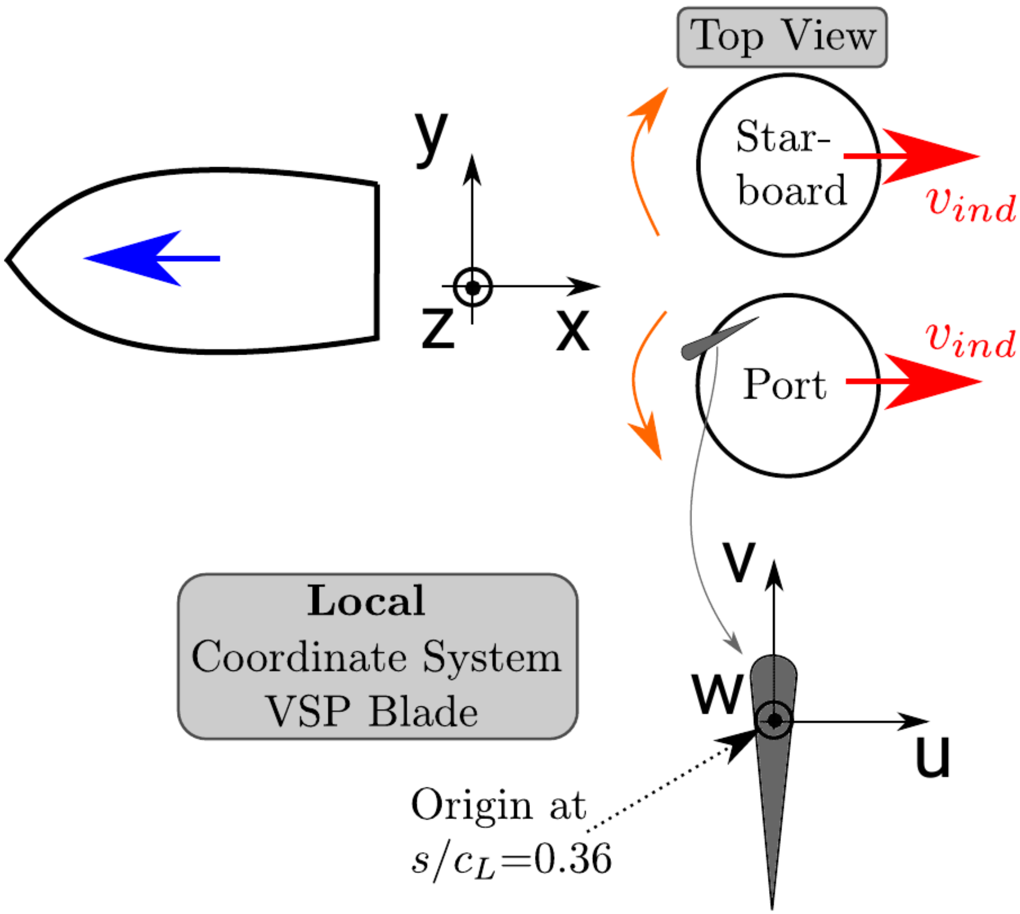
- `elbe` → 'efficient lattice boltzmann environment'
  - GPU accelerated solver for singlephase and free surface flows
  - Involving fluid structure interaction (rigid bodies, coupled to ODE)

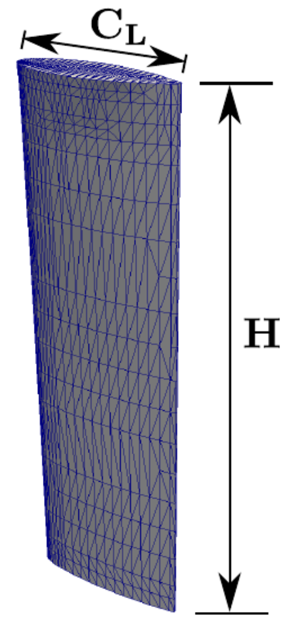


Lattice Boltzmann Equation (LBE) $\rightarrow$ PDF

- $$f_\alpha\,(t + \Delta t, \mathbf{x} + \Delta t\, \mathbf{e}_\alpha) - f_\alpha(t, \mathbf{x}) = \Omega_\alpha$$
  - Left-hand side: transient change and particle advection
  - Right-hand side: modeling the particle interaction
- **Strictly local** collision step $\rightarrow$ extremely well suited for GPU accelaration
  - Aims at short simulation times (ideally **overnight**) of comprehensive test case scenarios
  - Preferably runs in a shared memory GPU standard desktop PC system (e.g. using NVIDIA TitanX, 12GB)

VSP Blade Geometry and Coordinate Systems

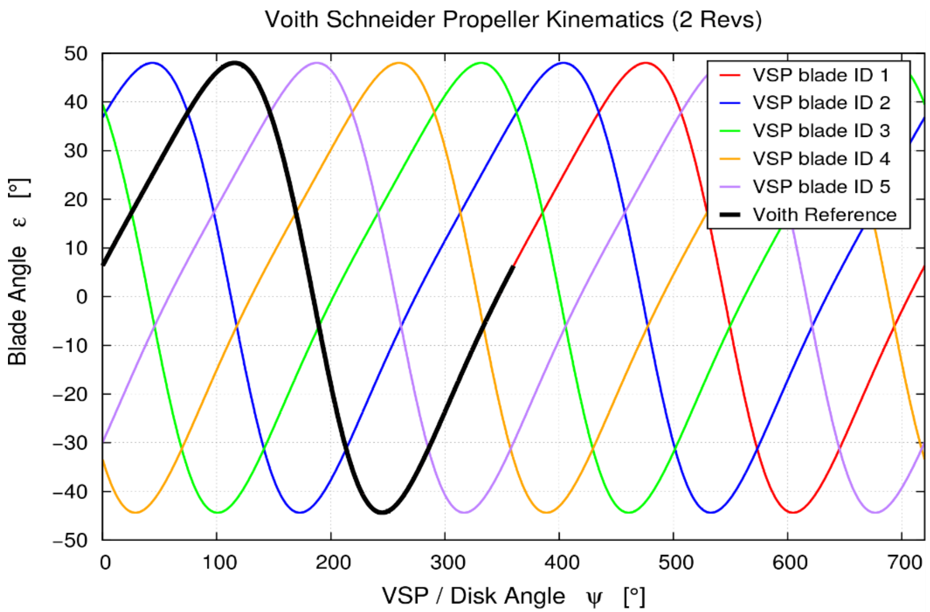


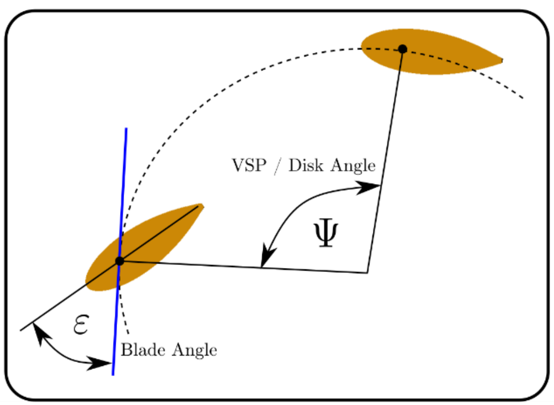


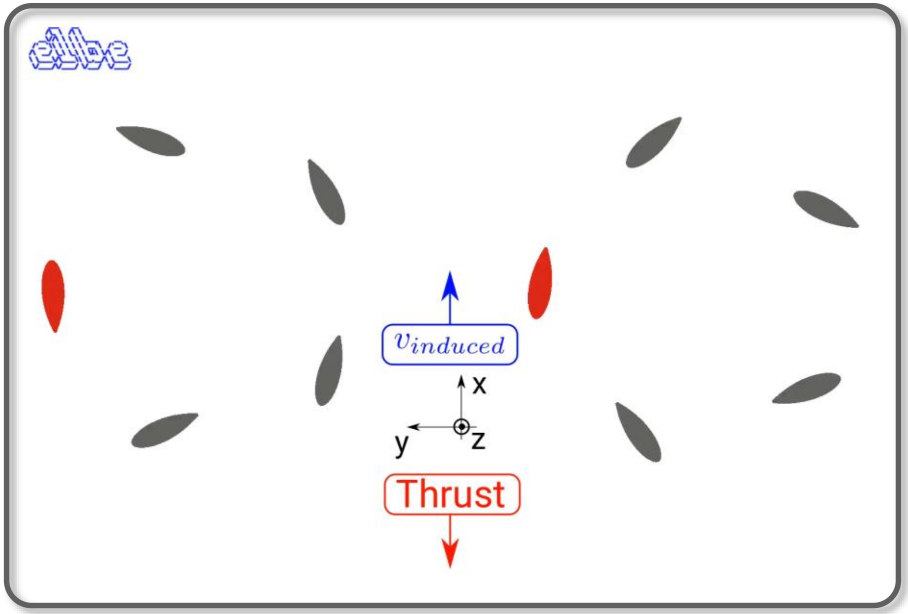
VSP Blade Geometry (model scale)

- Trailing Edge cutted to match Δx
- SI Dimensions: $0.11 \times 0.325 \times 0.04\ m^3$ (Chord Length $\times$ Height $\times$ Max Thickness)

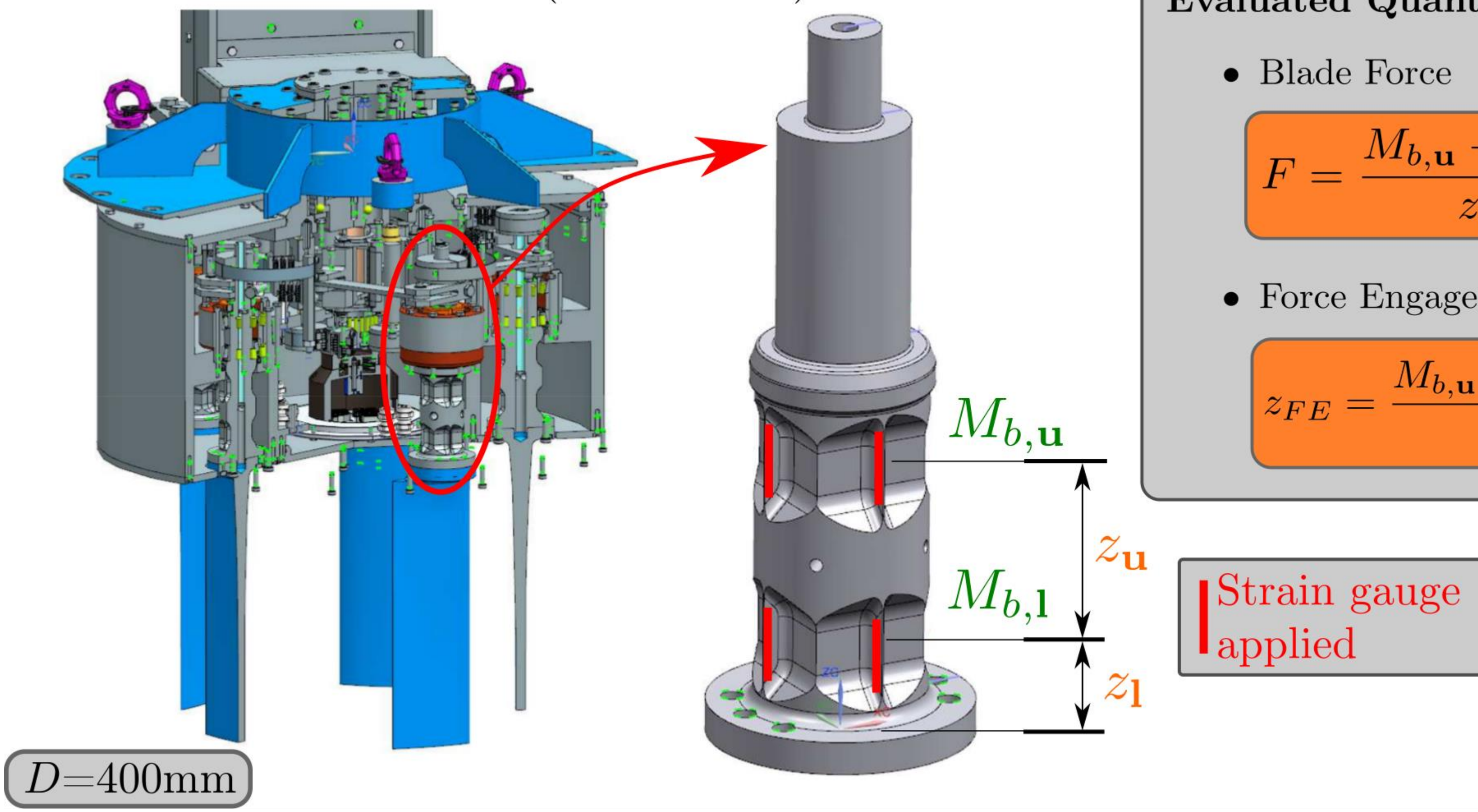
VSP Kinematics







Instrumented VSP (Model Scale)



Evaluated Quantities:

- Blade Force

$$F = \frac{M_{b,\mathbf{u}} - M_{b,\mathbf{l}}}{z_u}$$

- Force Engagement Point

$$z_{FE} = \frac{M_{b,\mathbf{u}}\, z_l - M_{b,\mathbf{l}}\, (z_l + z_u)}{M_{b,\mathbf{u}} - M_{b,\mathbf{l}}}$$

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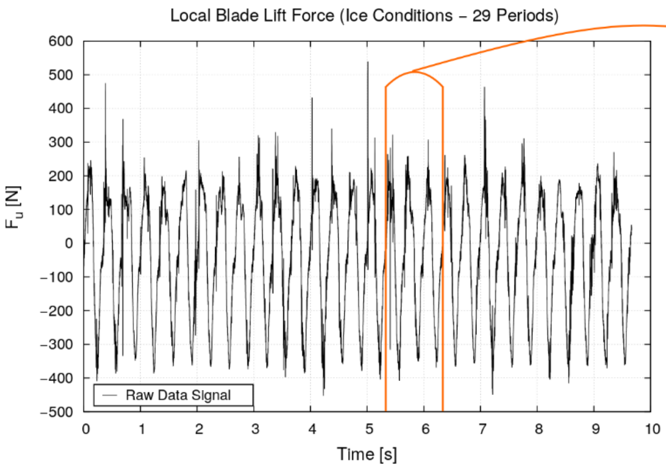
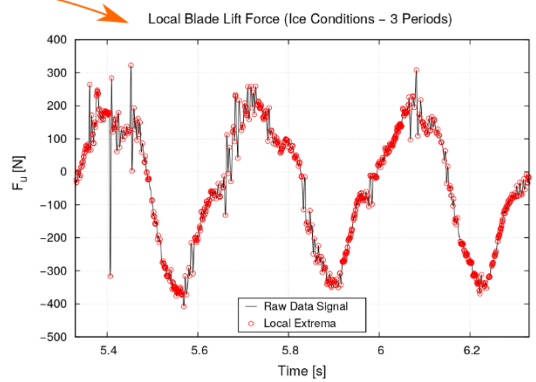
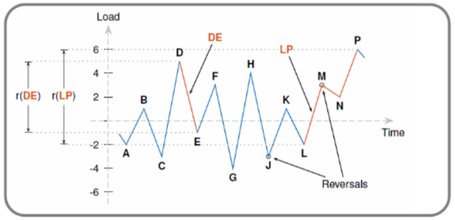
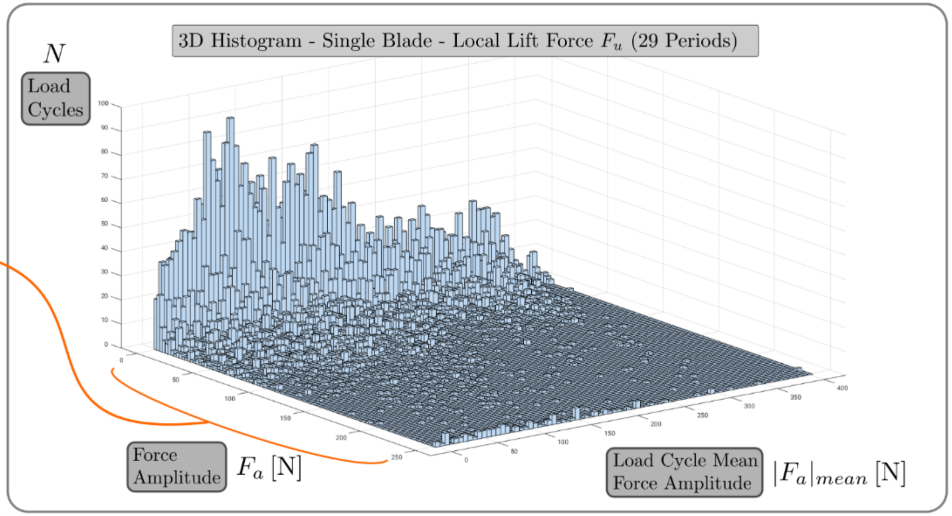


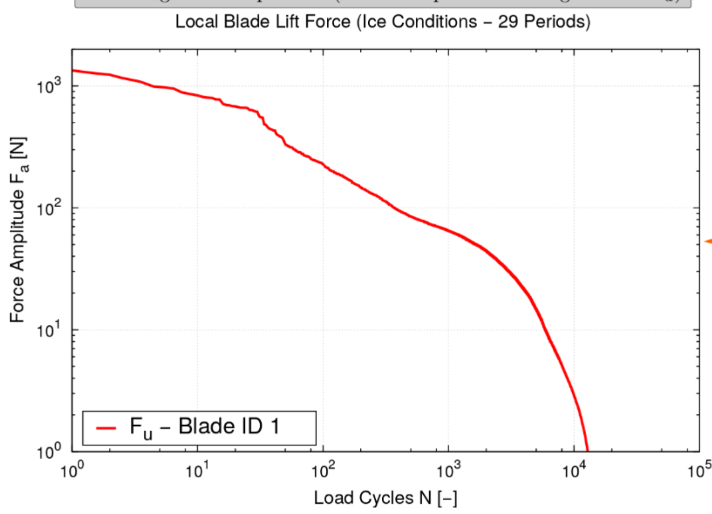


Matlab Postprocessing - Rainflow Counting Algorithm

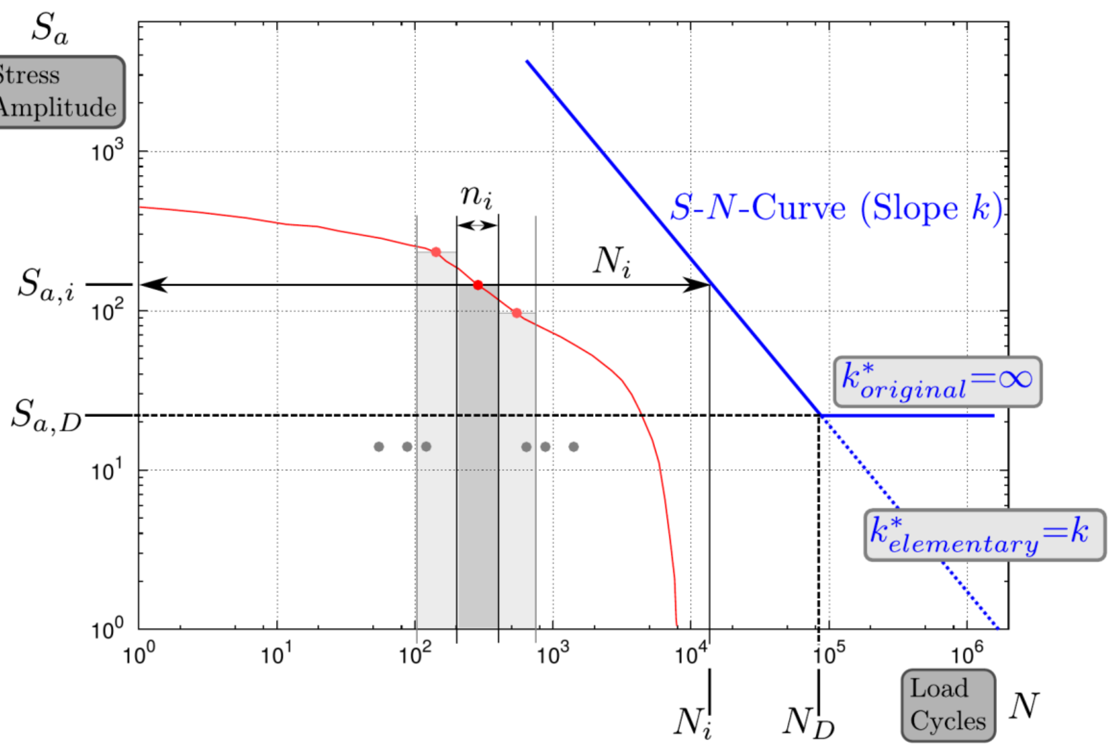




2D Histogram - Amplitudes (N added up in descending order of S_a)



Linear Damage Accumulation / Fatigue Analysis



Original Palmgren-Miner rule:

$$S_{a,i} \geq S_{a,D} : N_i = N_D \left(\frac{S_{a,i}}{S_{a,D}}\right)^{-k}$$

$$S_{a,i} < S_{a,D} : N_i \rightarrow \infty$$

Elementary Palmgren-Miner rule:

$$N_i = N_D \left(\frac{S_{a,i}}{S_{a,D}}\right)^{-k}$$

Damage sum for n_i load cycles in bin:

$$D_i = \frac{n_i}{N_i} = \frac{n_i}{N_i(N_D, S_{a,i}, S_{a,D}, k)}$$

Total damage sum for k bins / steps:

$$D = \sum_{i=1}^{k} D_i = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

- Stress-Cycle Curve rates the performance of a component (depending on material and geometric properties, manufacturing processes etc.)
- ***LDA*** to assess the influence of a load spectrum on the durability of a component (match e.g. **DNV GL** class rules proof of operational strength)

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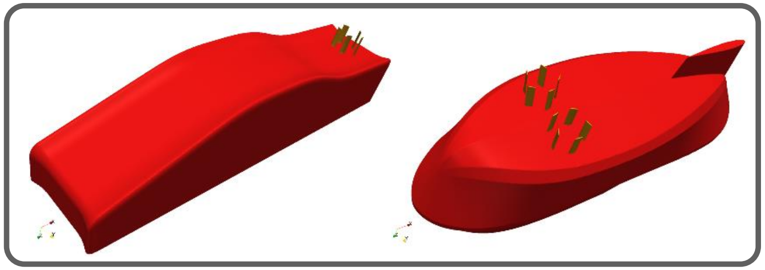
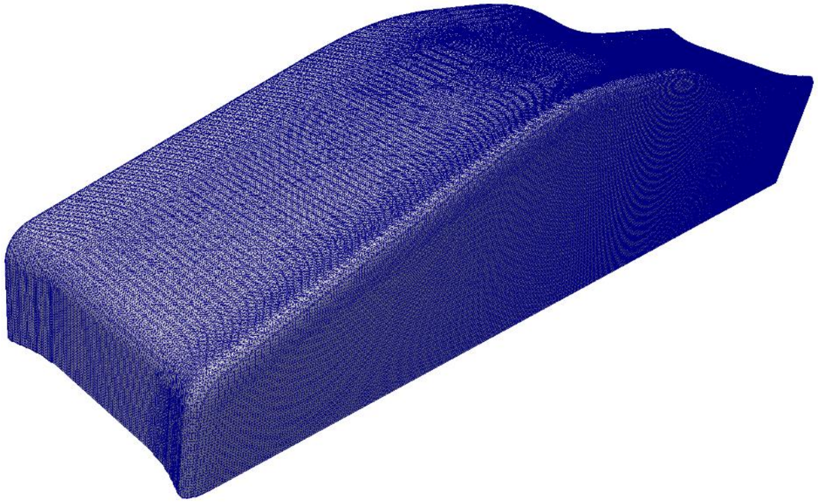
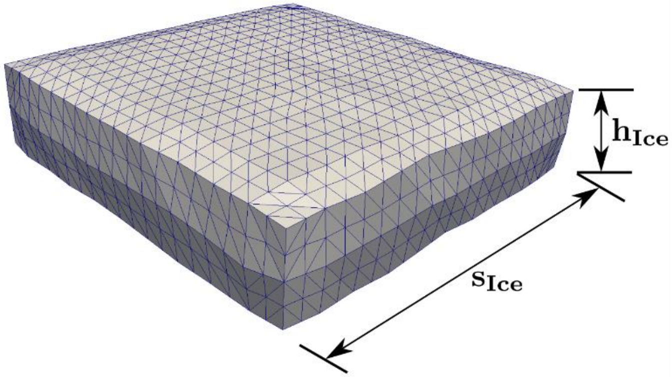
Test Case Introduction

Single and **double** VSP propelled hulls analyzed in model tests and simulations







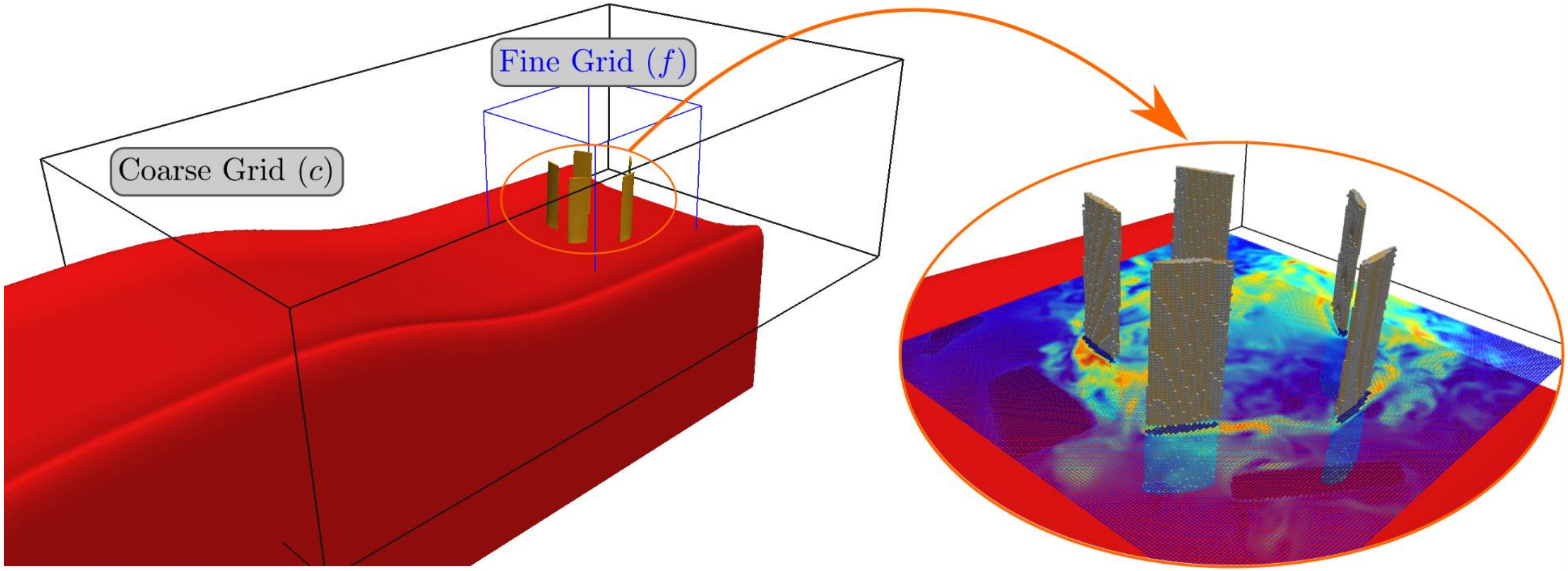
Generic ***Feeding*** Hull Geometry (model scale)

- Aims at maximizing the amount of ice floes approaching the propulsor
- SI dimensions: $5.7 \times 1.3 \times 1.25\ m^3$ $(\mathrm{L} \times \mathrm{B} \times \mathrm{H})$

Generic Ice Floe Geometry (model scale)

- Derived from the characteristic breaking pattern of the underlying hull geometry
- SI dimensions vary between:
  - edge length: $\mathbf{s_{Ice}} \in \{0.175, 0.35\}\mathrm{m}$
  - ice thickness: $\mathbf{h_{Ice}} \in \{0.05, 0.075, 0.1\}\mathrm{m}$

Generic *Feeding* Hull – Domain Discretization



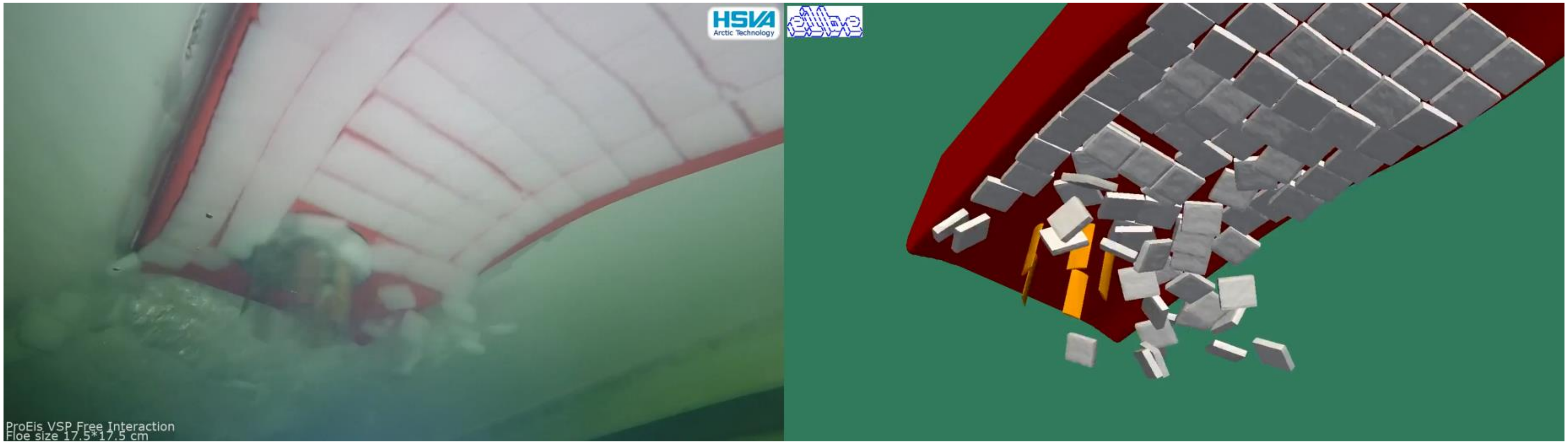
Far Field / Coarse Grid (c) discretization:

- 3.3m×1.8m×1.0m
- 425×232×129 Nodes (**12.72** million)
- $\Delta x_c \approx 7.8$mm, $\Delta t_c \approx 0.1$ms

Propulsor Zone / Fine Grid (f) discretization:

- 0.7m×0.7m×0.66m
- 182×182×170 Nodes (**5.63** million)
- $\Delta x_f \approx 3.9$mm, $\Delta t_f \approx 0.05$ms
- Nodes on c_L (Shaft Root) ≈ 30

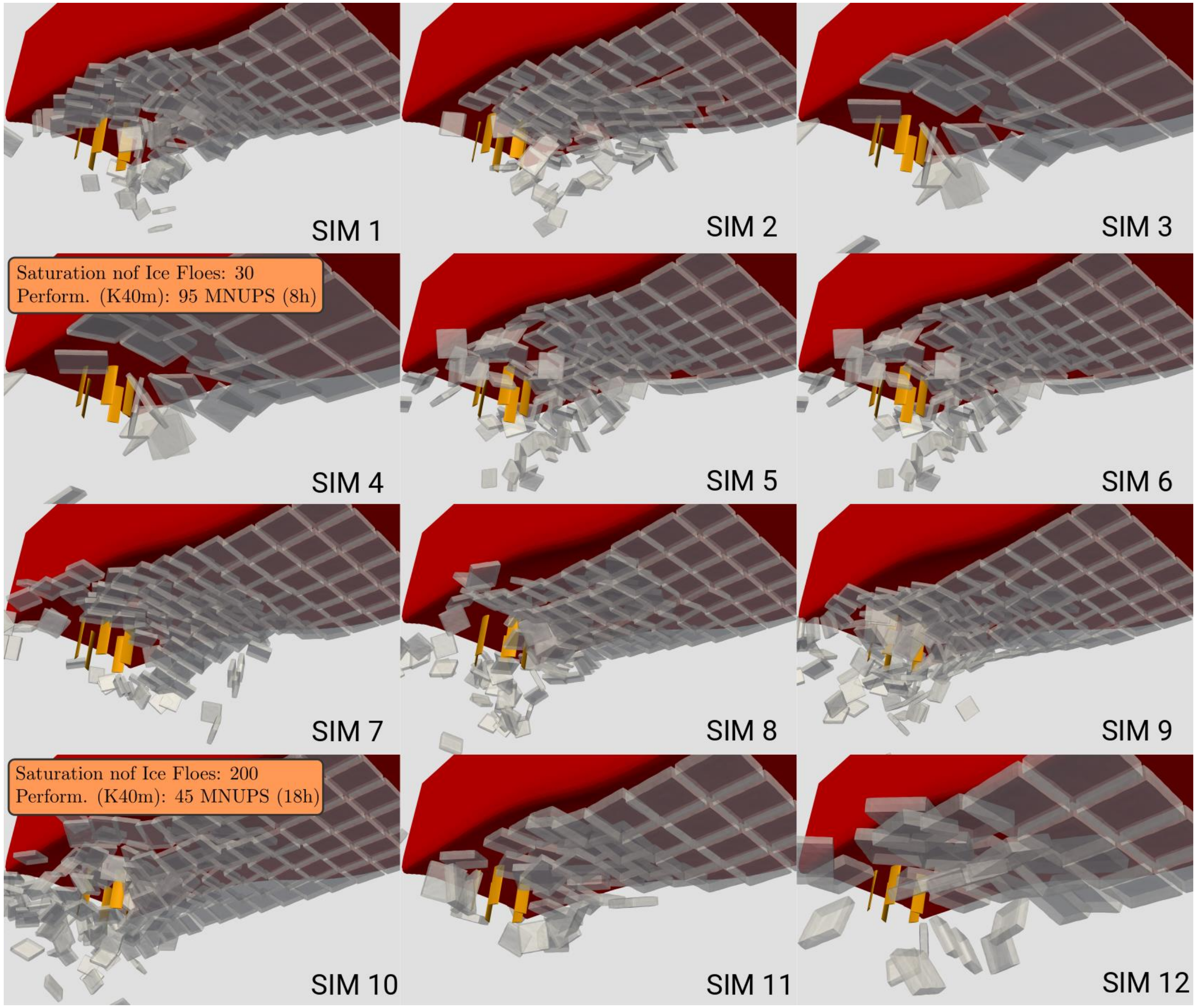
Model Test vs. Simulation Animation



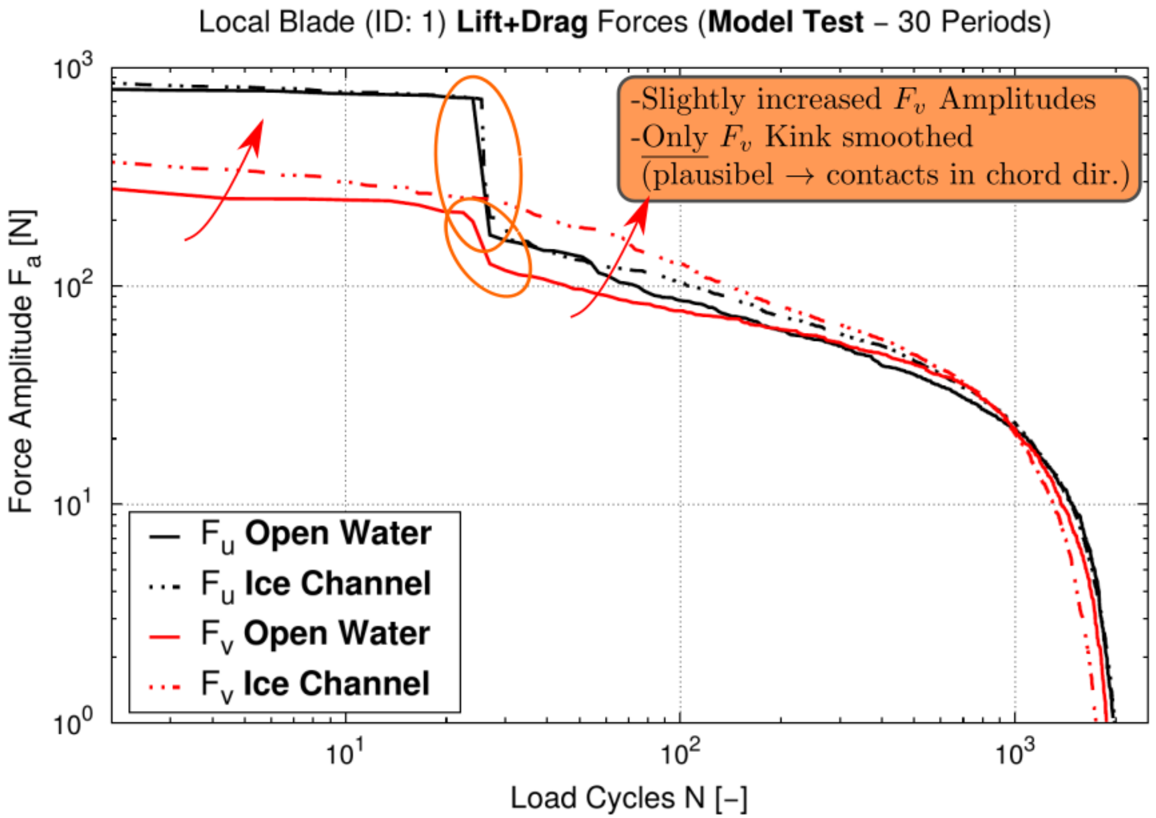
- Homogeneous ice floe inflow approaching the propulsor
- Partial ***Milling*** in model test (splitting up pre-brokes floes to [*very*] small pieces)
- Fairly good agreement between model test and sim. with respect to floe dynamics

Sim.-No.	n [Hz]	v_∞ [m/s]	J [−]	h_{Ice} [m]	s_{Ice} [m]	Remark
1	3.00	0.45	0.119	**0.05**	**0.1750**	HSVA Model Test Configuration (**BL**)
2	2.25	0.34	0.119	0.05	0.1750	HSVA Model Test Configuration
3	3.00	0.45	0.119	0.05	0.3500	HSVA Model Test Configuration
4	2.25	0.34	0.119	0.05	0.3500	HSVA Model Test Configuration
5	**4.00**	0.45	0.090	0.05	0.1750	Increased Rotational Frequency
6	**3.50**	0.45	0.102	0.05	0.1750	Increased Rotational Frequency
7	**2.25**	0.45	0.159	0.05	0.1750	Decreased Rotational Frequency
8	3.00	0.90	**0.239**	0.05	0.1750	Increased Advance Ratio ($v_\infty \uparrow$)
9	3.00	1.35	**0.358**	0.05	0.1750	Increased Advance Ratio ($v_\infty \uparrow$)
10	3.00	1.80	**0.477**	0.05	0.1750	Increased Advance Ratio ($v_\infty \uparrow$)
11	3.00	0.45	0.119	**0.75**	**0.2625**	Increased Ice Thickness + Edge Length
12	3.00	0.45	0.119	**0.10**	**0.3500**	Increased Ice Thickness + Edge Length

Simulations under Ice Conditions

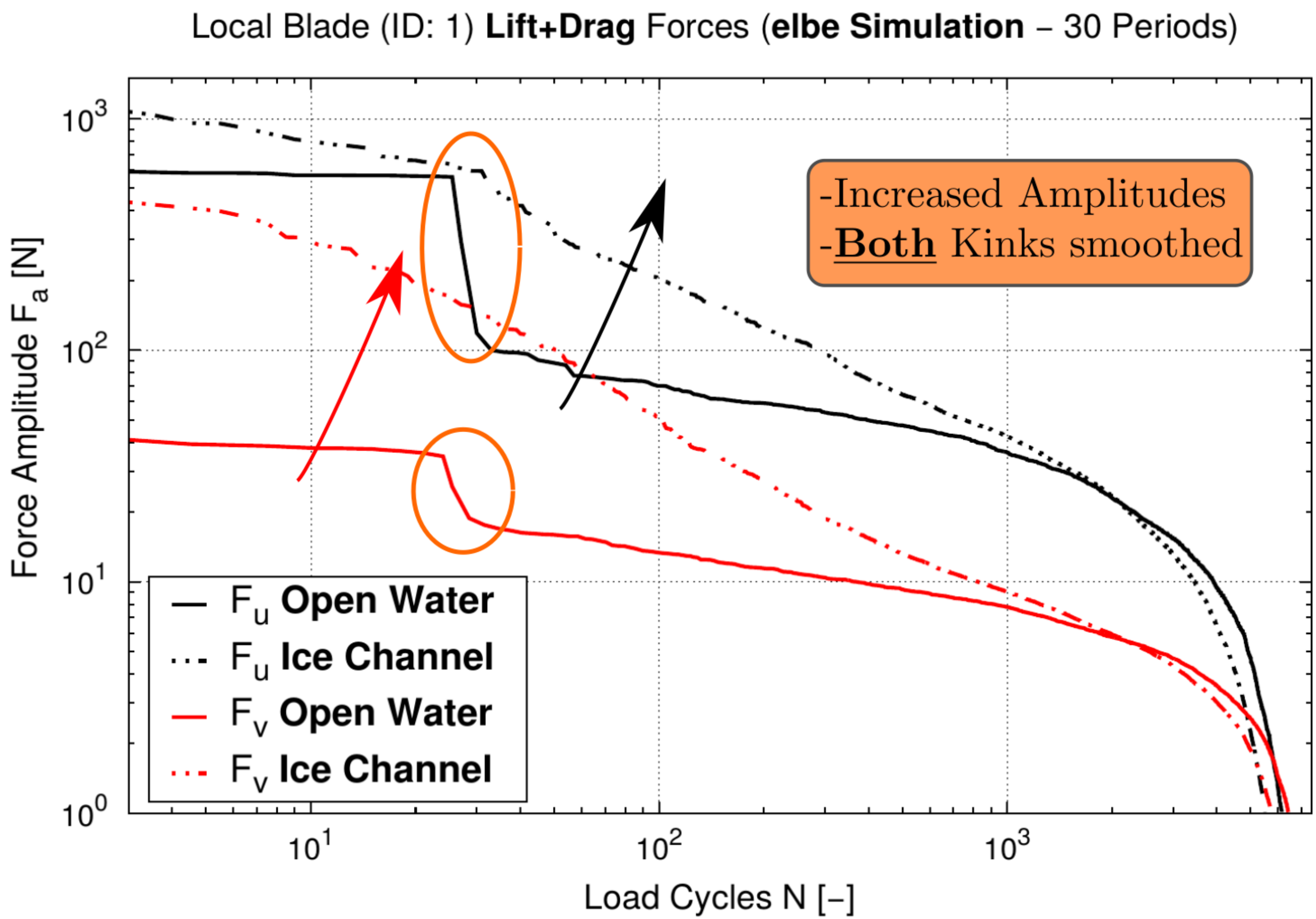


Open Water vs. Ice Conditions – **HSVA**

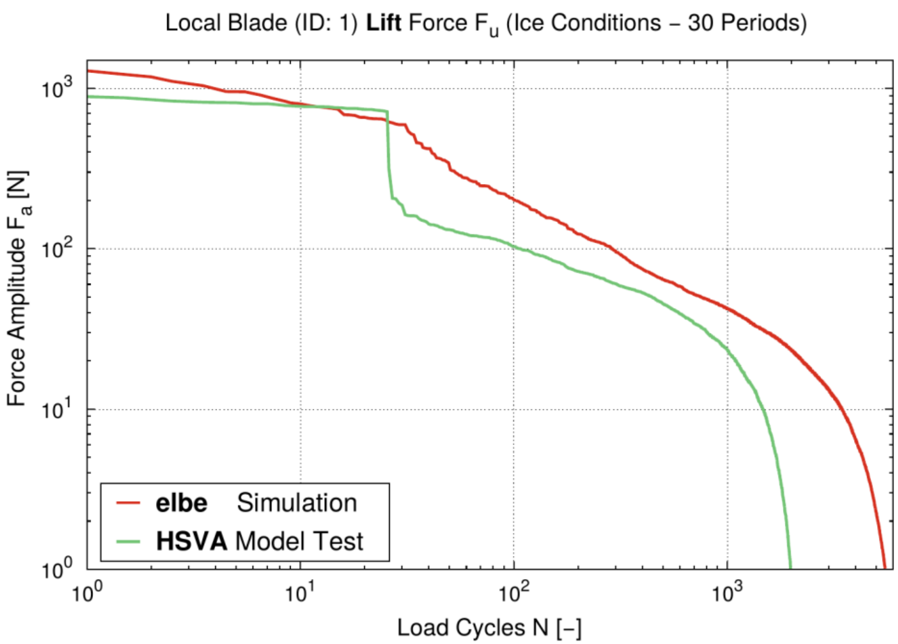


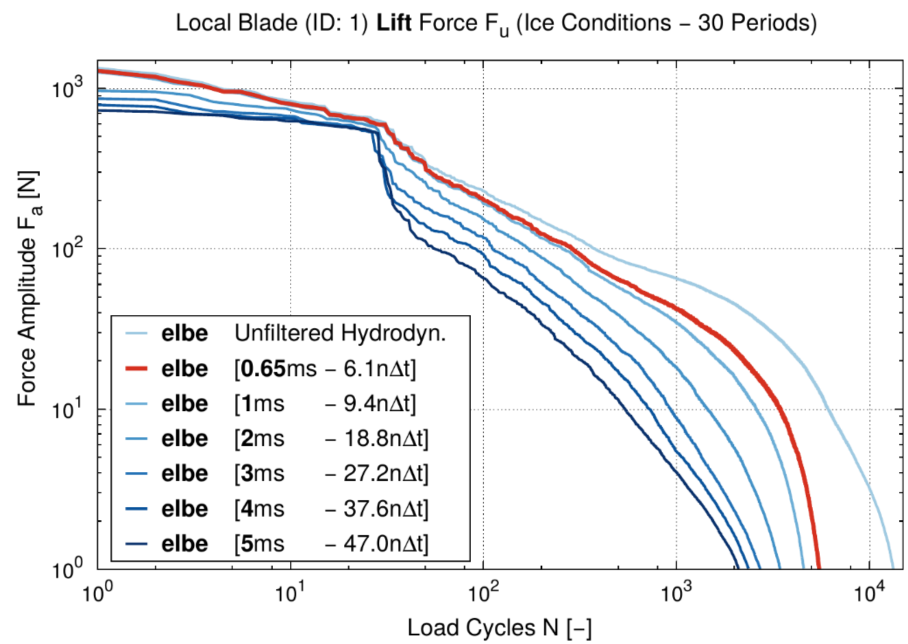
- Reasonable shift in **Local Drag** Force
  - Increased Amplitudes as added resistance due to ***Milling***
  - Contacts occur at the profiles leading egde along the chord axis

Open Water vs. Ice Conditions – **TUHH**

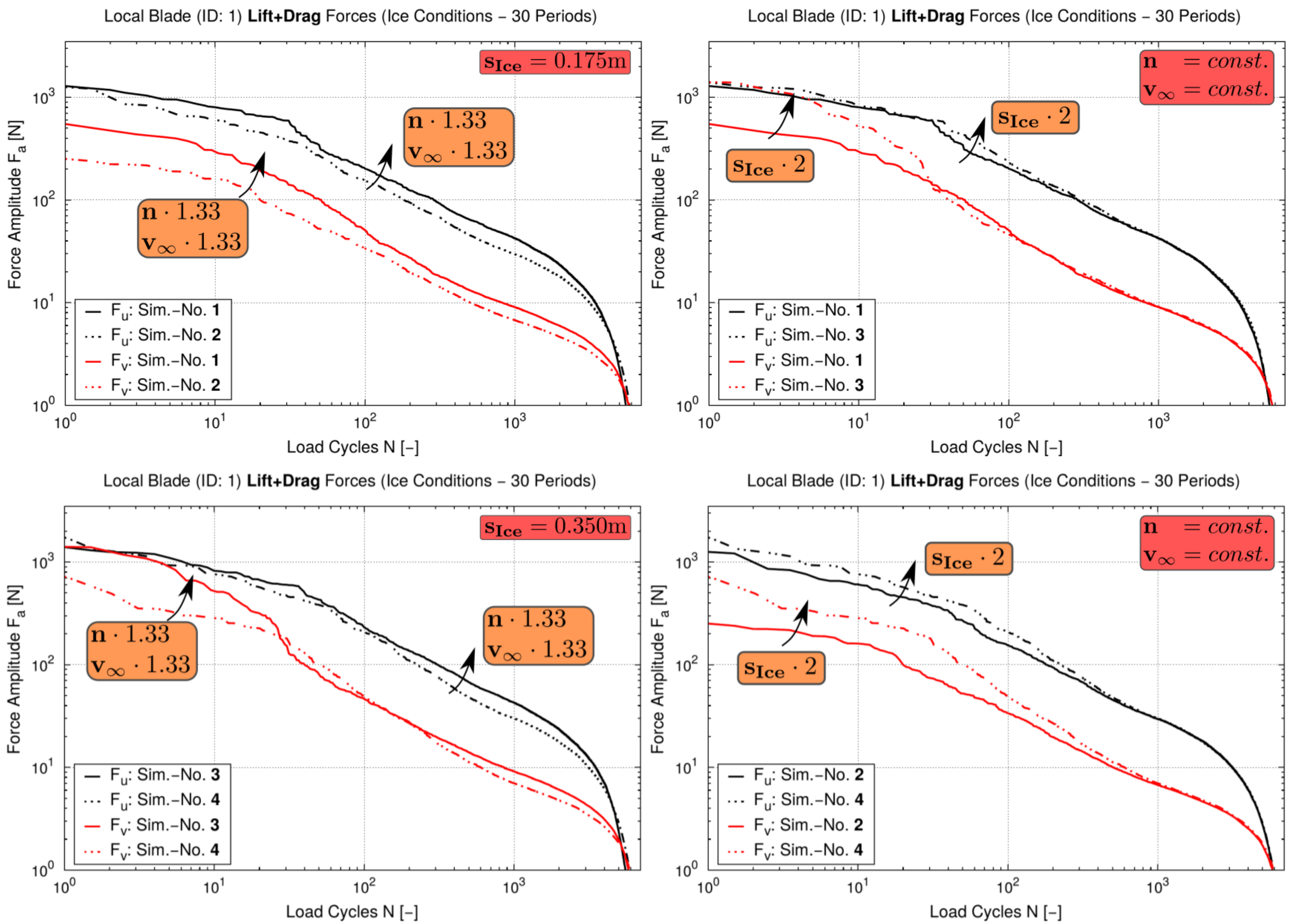


Ice Conditions – Case No. 1 – **HSVA** vs. **TUHH**



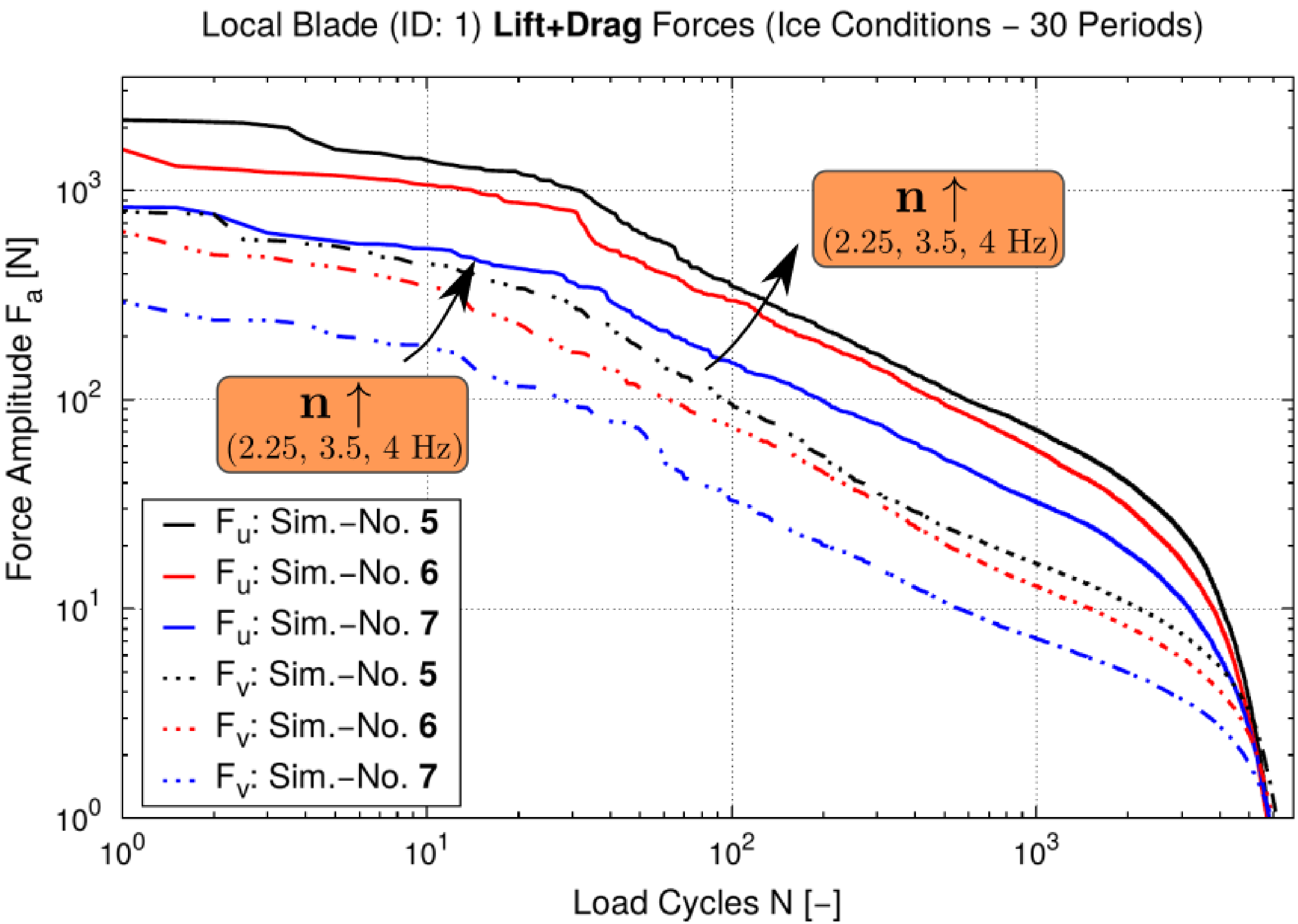


- Significant filter (***moving average***) influence
  - Applied to hydrodynamic signal (smooth numeric oszillations)
  - Currently chosen to match model test sampling rate (0.65ms)

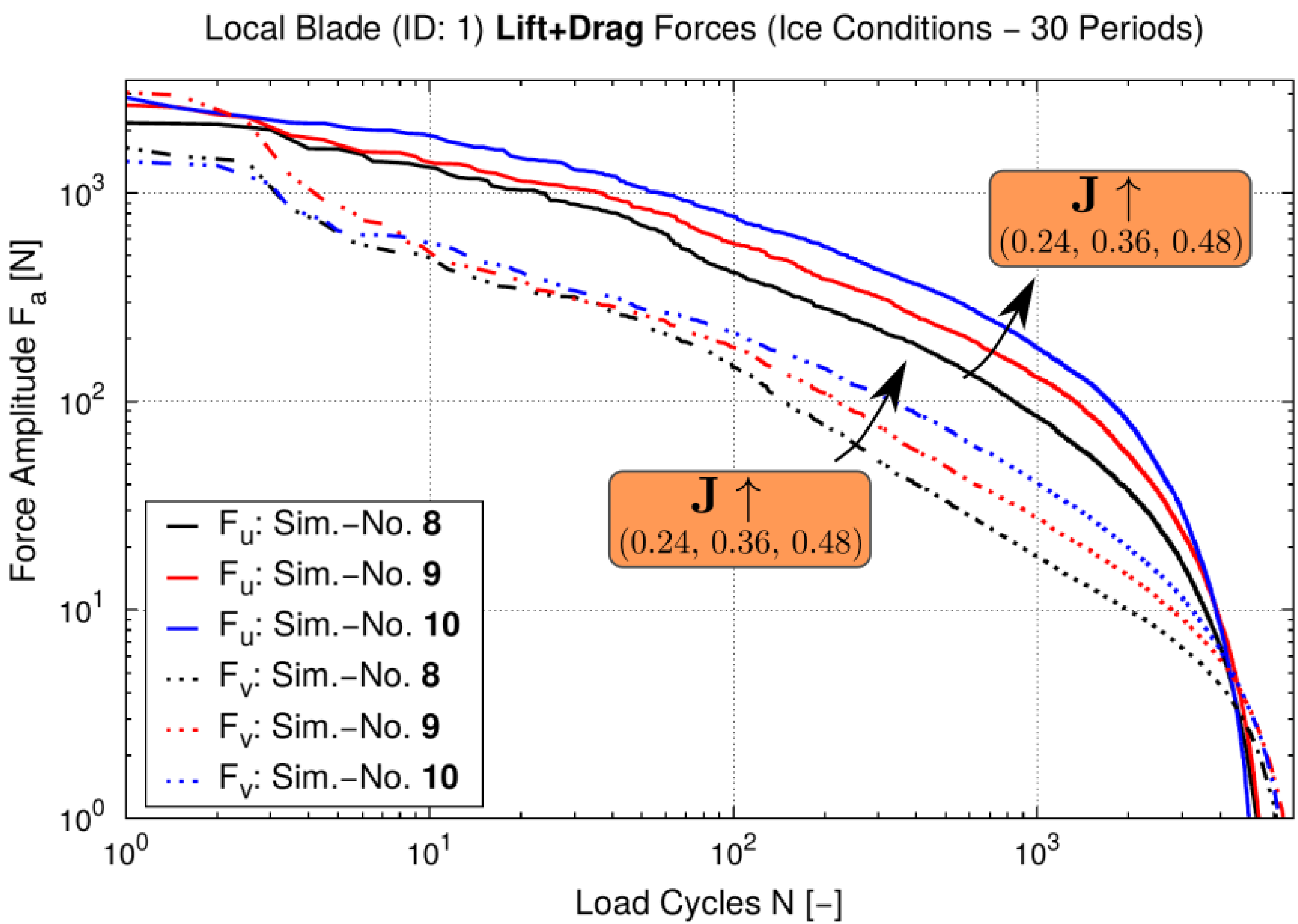

Local Blade (ID: 1) Lift+Drag Forces (Ice Conditions – 30 Periods)
$s_{Ice} = 0.175m$
n · 1.33
v_∞ · 1.33
n · 1.33
v_∞ · 1.33
Force Amplitude F_a [N]
Load Cycles N [–]
F_u: Sim.–No. 1
F_u: Sim.–No. 2
F_v: Sim.–No. 1
F_v: Sim.–No. 2
Local Blade (ID: 1) Lift+Drag Forces (Ice Conditions – 30 Periods)
n = const.
v_∞ = const.
s_{Ice} · 2
s_{Ice} · 2
F_u: Sim.–No. 1
F_u: Sim.–No. 3
F_v: Sim.–No. 1
F_v: Sim.–No. 3
Local Blade (ID: 1) Lift+Drag Forces (Ice Conditions – 30 Periods)
$s_{Ice} = 0.350m$
n · 1.33
v_∞ · 1.33
n · 1.33
v_∞ · 1.33
F_u: Sim.–No. 3
F_u: Sim.–No. 4
F_v: Sim.–No. 3
F_v: Sim.–No. 4
Local Blade (ID: 1) Lift+Drag Forces (Ice Conditions – 30 Periods)
n = const.
v_∞ = const.
s_{Ice} · 2
s_{Ice} · 2
F_u: Sim.–No. 2
F_u: Sim.–No. 4
F_v: Sim.–No. 2
F_v: Sim.–No. 4

- **HSVA**
  - Plausible results with regard to ***Milling*** process
    - Vanishing influence of ice floe edge length
    - Mass influence might exist for varying ice thickness (*not tested so far*)
- **TUHH**
  - Plausible results with regard to the ***Rigid Body*** model
    - Amplitudes increase whilst increasing momentum by either varying the VSPs frequency or the ice floe mass (edge length)

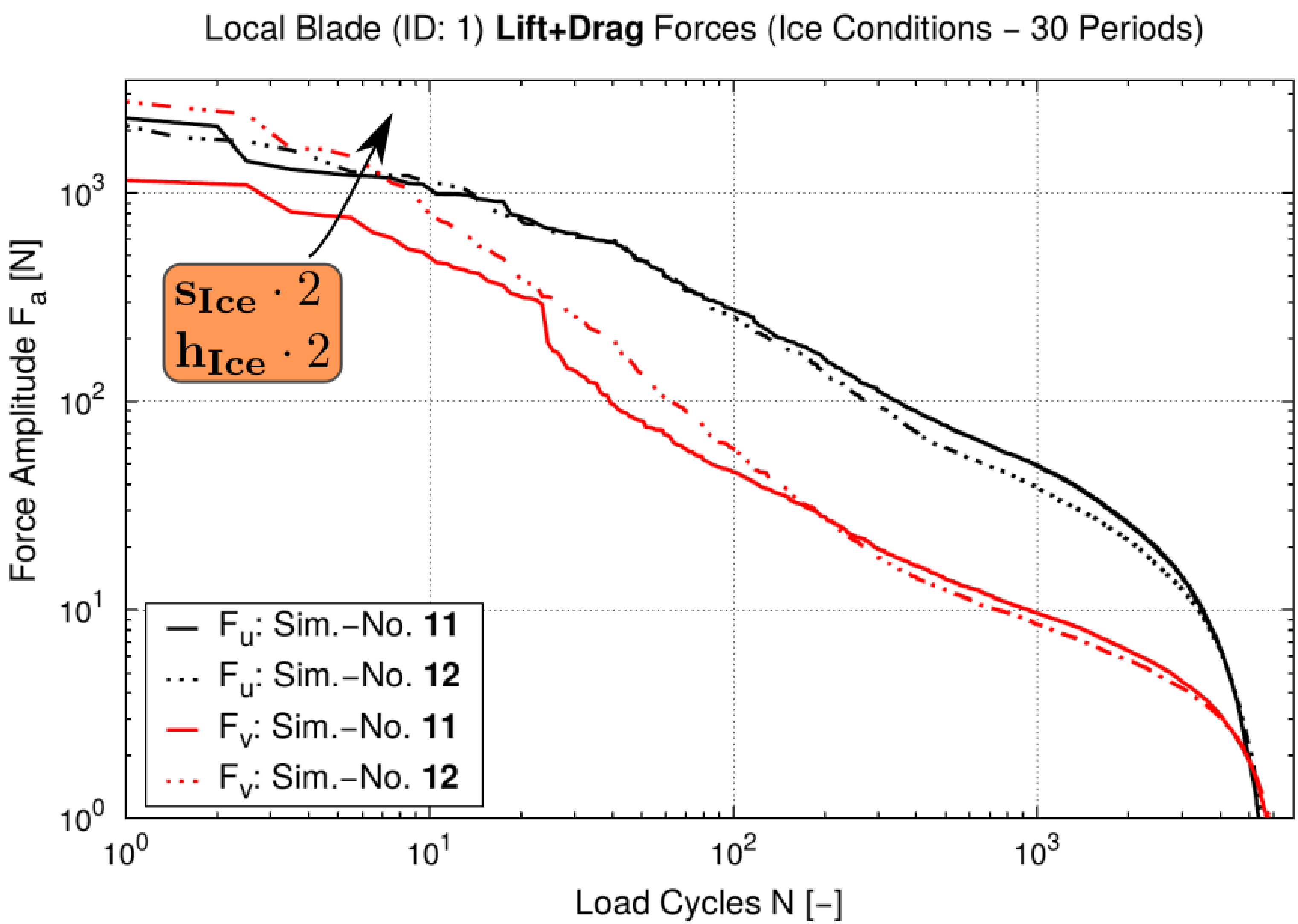
Ice Conditions – **TUHH** Parameter Study I



Ice Conditions – **TUHH** Parameter Study II



Ice Conditions – **TUHH** Parameter Study III



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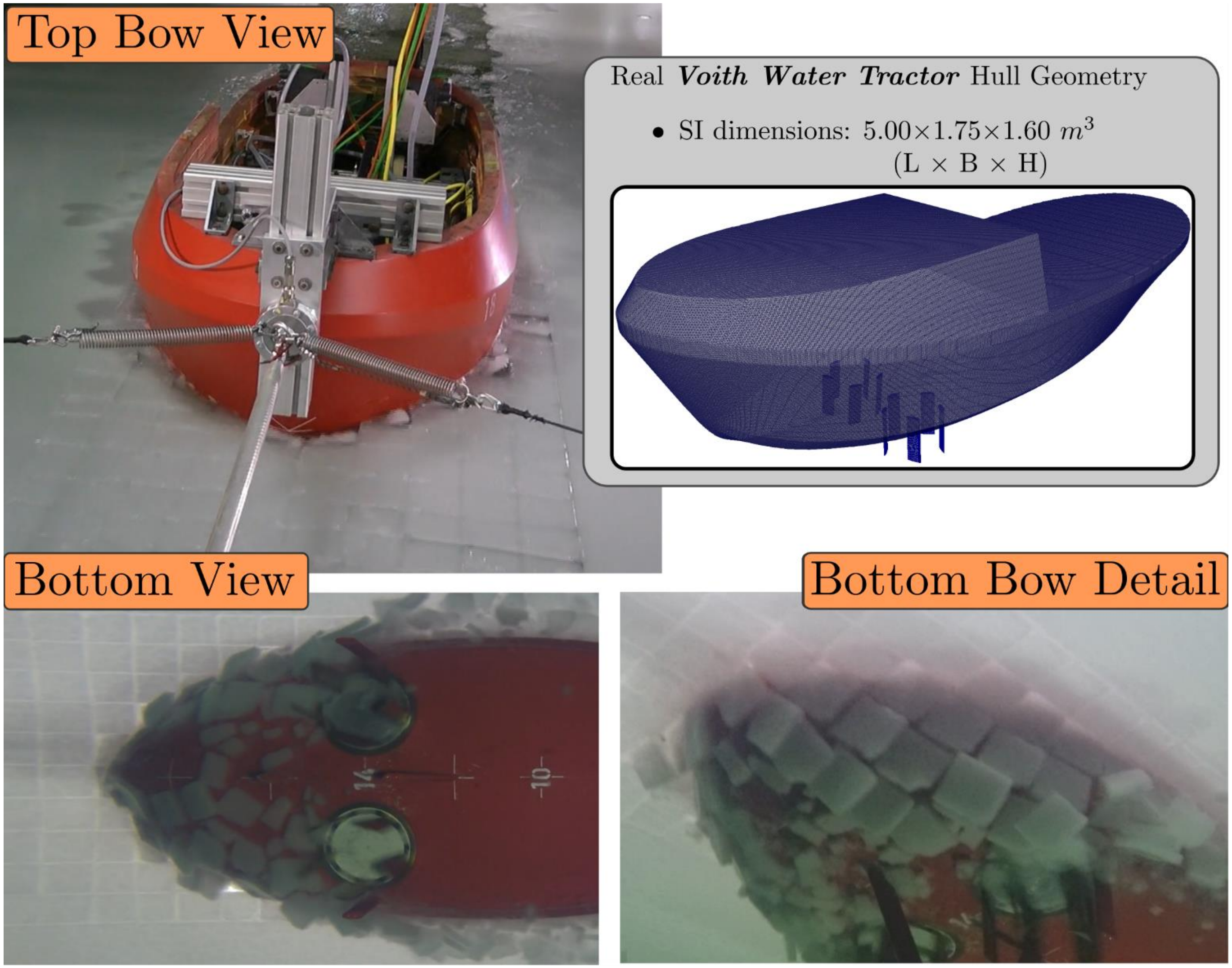
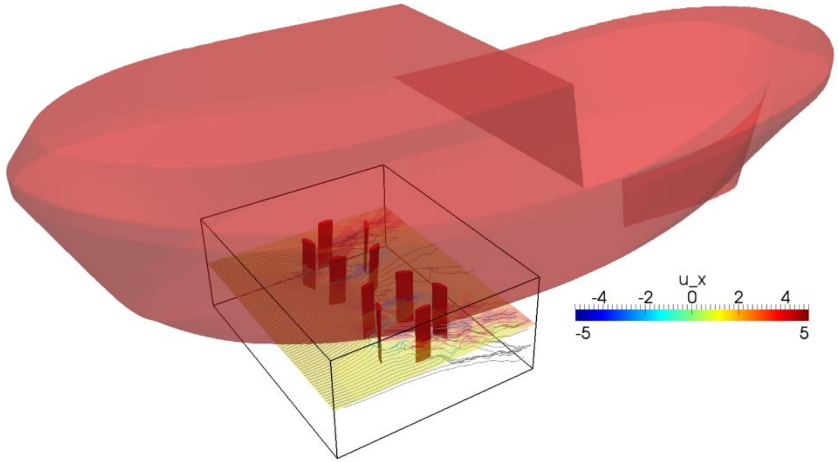
Voith Water Tractor – **HSVA** Model Test



Voith Water Tractor – **TUHH** Simulation

Overview - 2 VSP Disks arranged in Bow Region



Far Field / Coarse Grid (c) discretization:

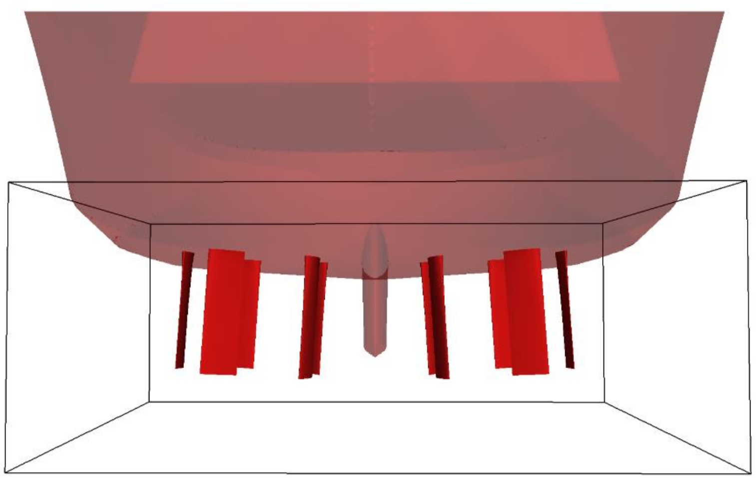
- $3.3\text{m}\times3.0\text{m}\times1.2\text{m}$
- $400\times364\times146$ Nodes (**21.26** million)
- $\Delta x_c \approx 8.27\text{mm} \quad \Delta t_c \approx 0.15\text{ms}$

Propulsor Zone / Fine Grid (f) discretization:

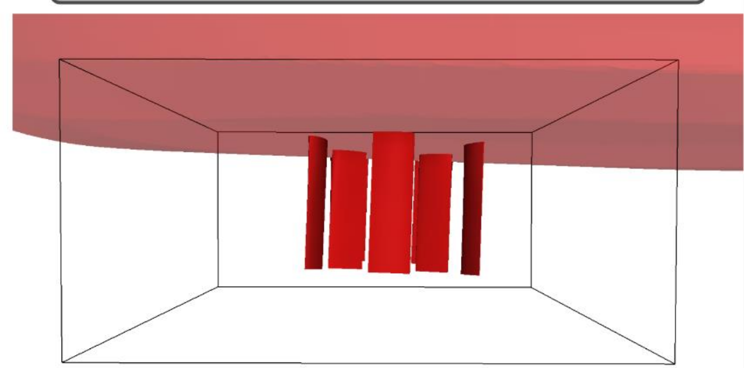
- $1.2\text{m}\times1.5\text{m}\times0.6\text{m}$
- $292\times370\times144$ Nodes (**15.56** million)
- $\Delta x_f \approx 4.14\text{mm} \quad \Delta t_f \approx 0.075\text{ms}$

Performance Aspects:

- Simulated Real Time: **30s**
- GPU / Computational Time: **42h**
- Average Performance: **50** MNUPS (domain saturation: **280** ice floes)

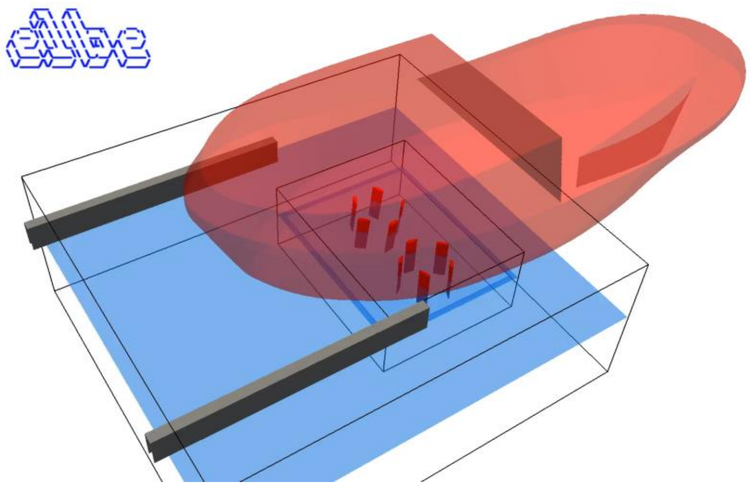


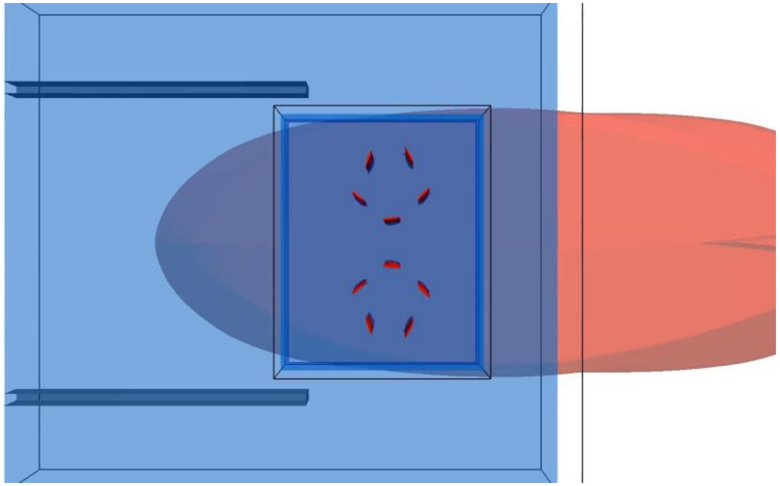
Bow View

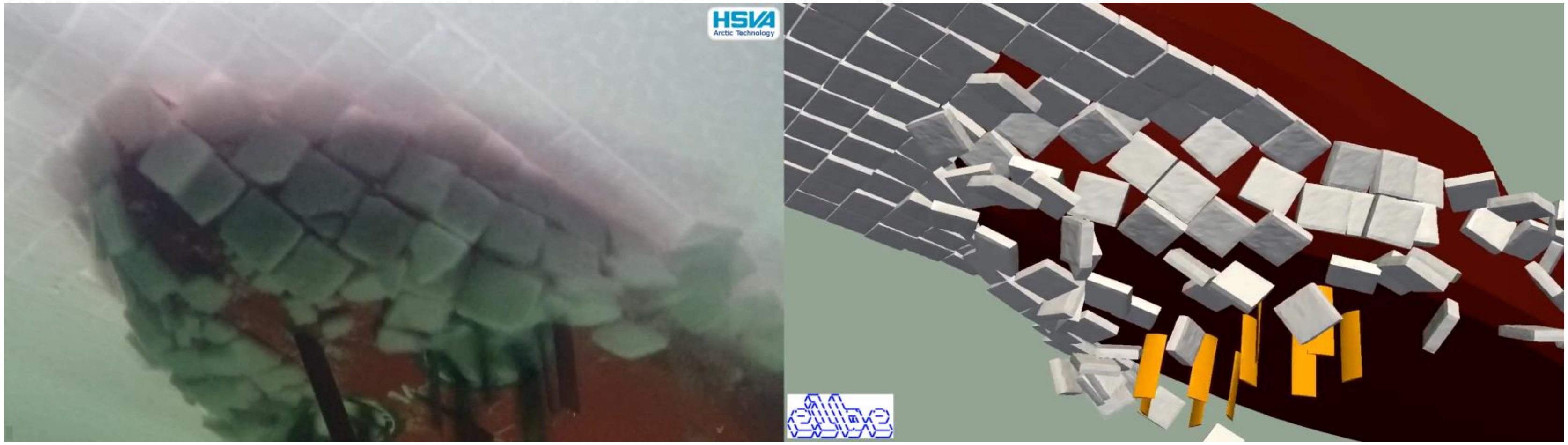


Side View

Model Test vs. Simulation Animation







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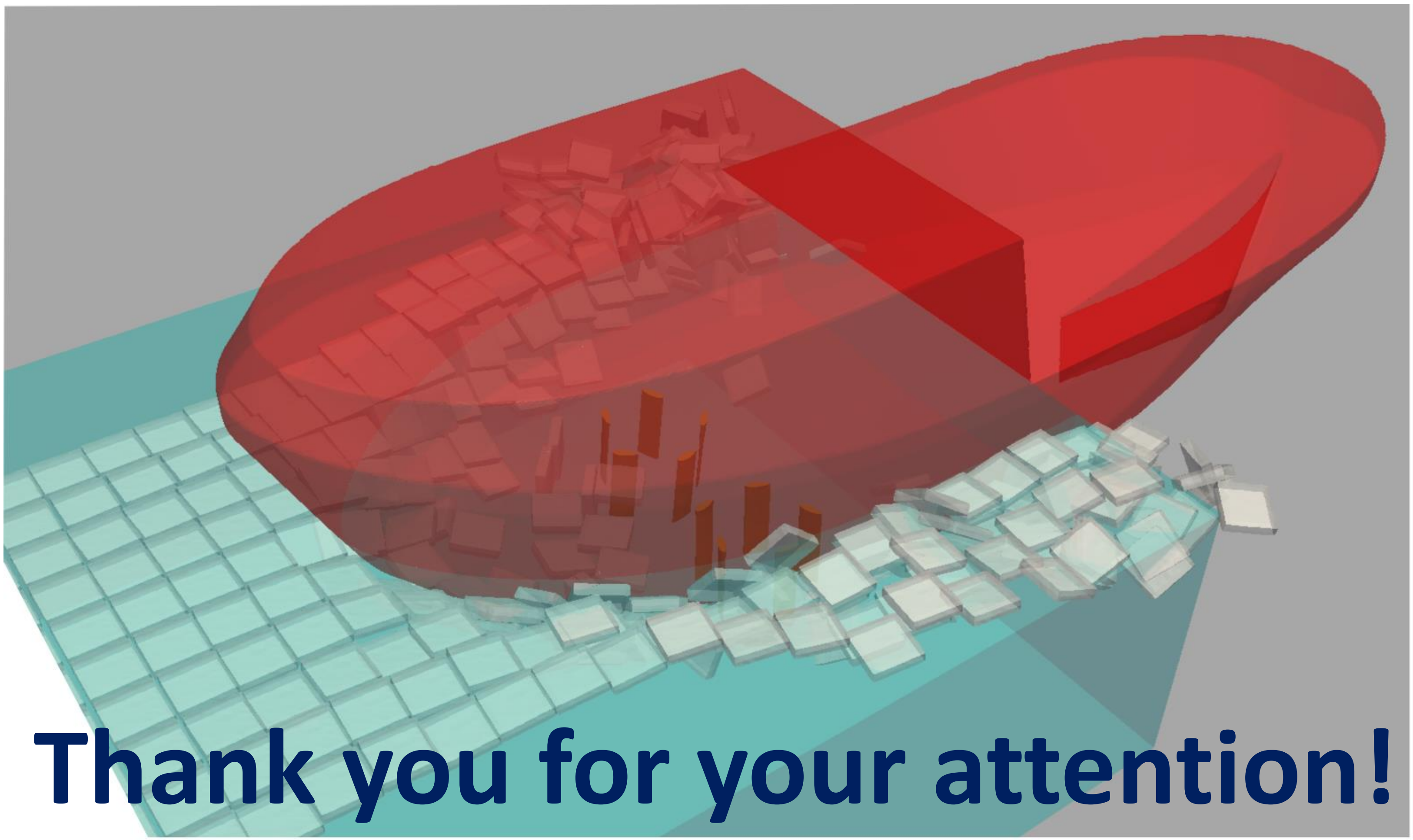
Summary and Outlook

- **Summary**
  - *Implemented* VSP kinematics for single and double VSP arrangement
  - *Validated* hydrodynamic signal based on RANS and model test data
  - *Applied* Rainflow-Counting algorithm
    - Prepare data according to class rules (e.g. **DNV GL**) for the proof of operational strength
- **Ongoing and future work**
  - *Construct* realistic load scenarios / spectra for the life cycle of a VSP propelled ship (prescribe open water / ice cond. ratio)
    - Run further simulations of extensive paramater studies (Variables: frequency, inflow velocity, ice conditions, take icebreaking into account, etc.)
  - *Define* **S-N** curve for the underlying VSP
  - *Accomplish* **LDA** and assess the VSPs operational strength

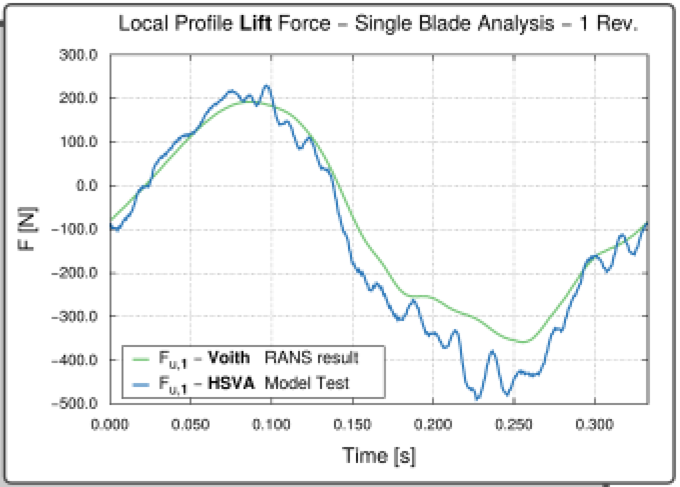


Thank you for your attention!

Appendix

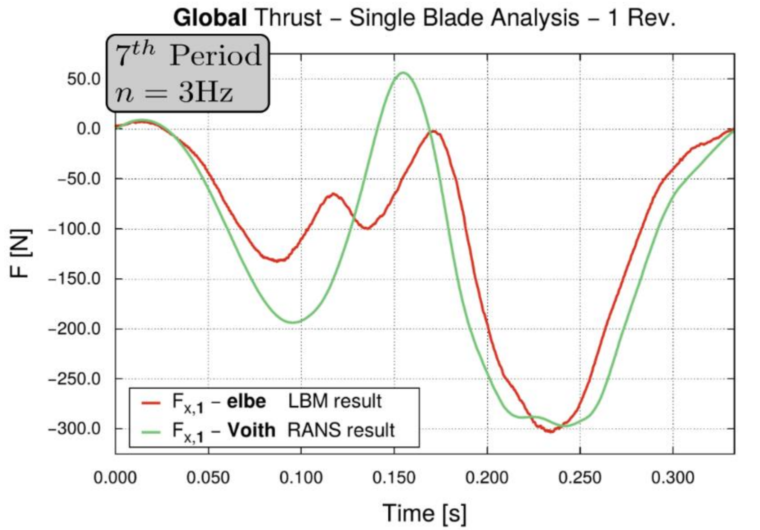
Validation Sequence

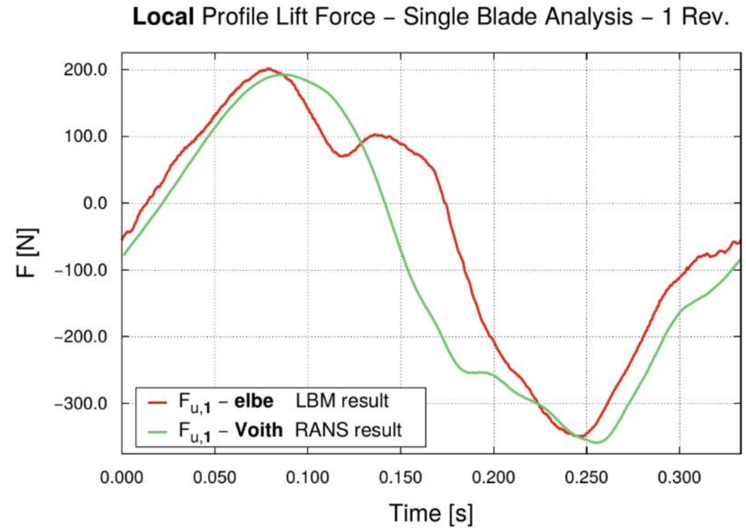
- Data to be used for the Validation of `elbe`
  - HSVA Model Test data
  - Voith RANS simulation CFD data (used for VSP dimensioning)

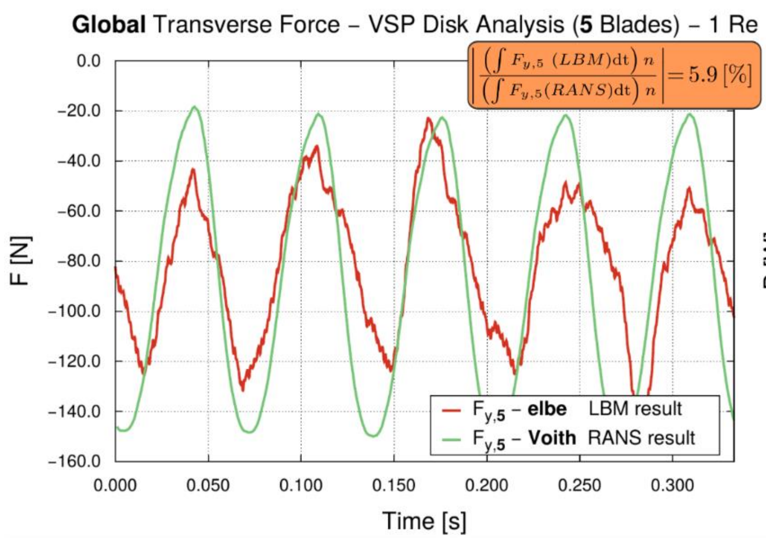


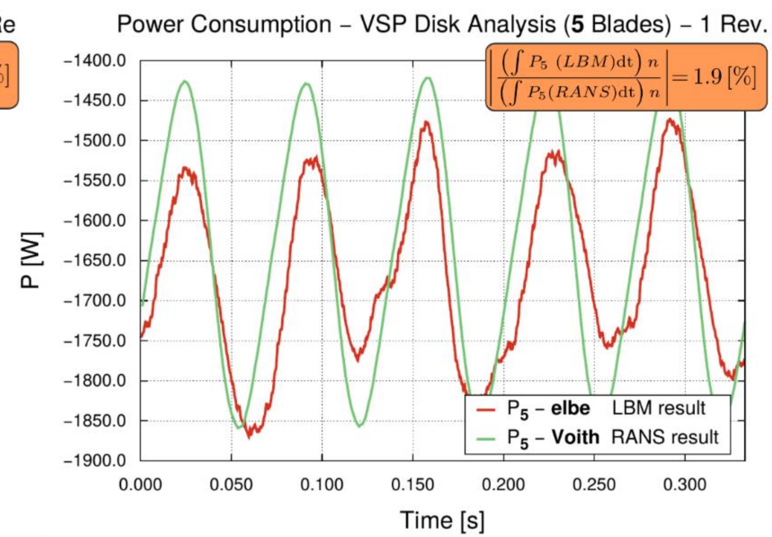
- **Validation Sequence**:
  - *Open Water* → *Hydrodynamic* - Validation (**wo** ice)
    - → Single operational point considered:
      90° VSP Pitch Angle, $J = 0.12$ $[n = 3\text{Hz},\ v_\infty = 0.45\text{m/s}]$
    - Compare LBM, RANS and Model Test data
  - *Ice Conditions* - Validation
    - Compare LBM to Model Test data
      for 4 operational points (n, v_∞ and floe size variation)
    - Run LBM Parameter Study to derive trends

Hydrodamic Validation of decisive Quantities

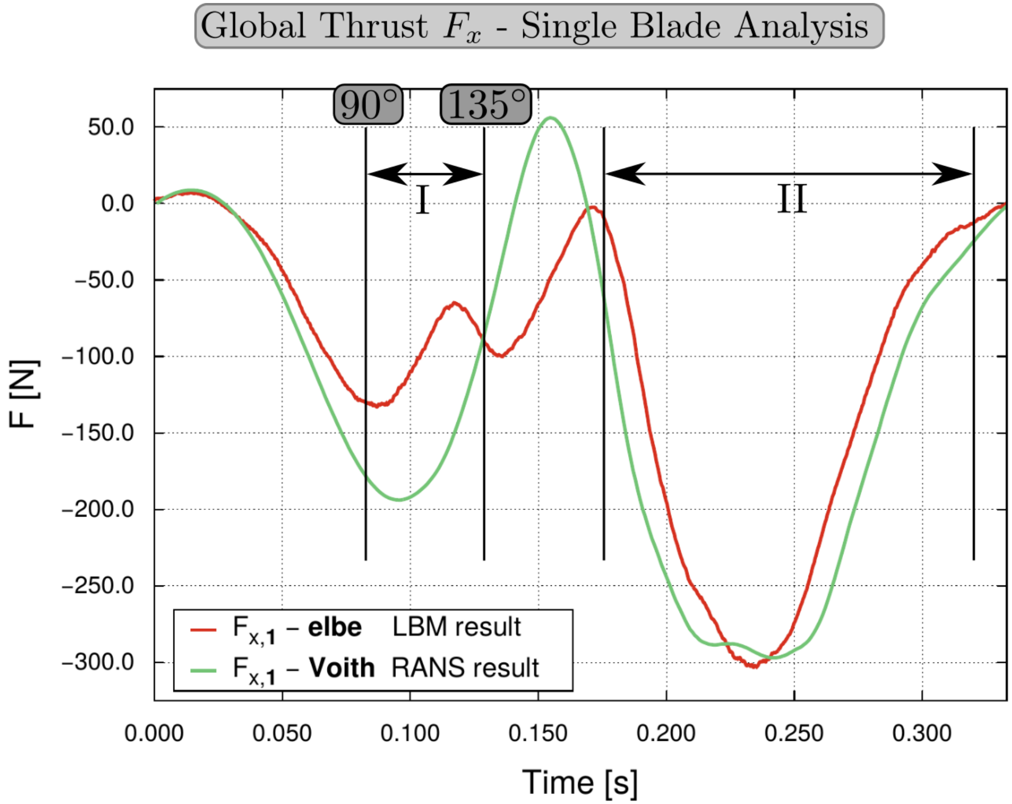


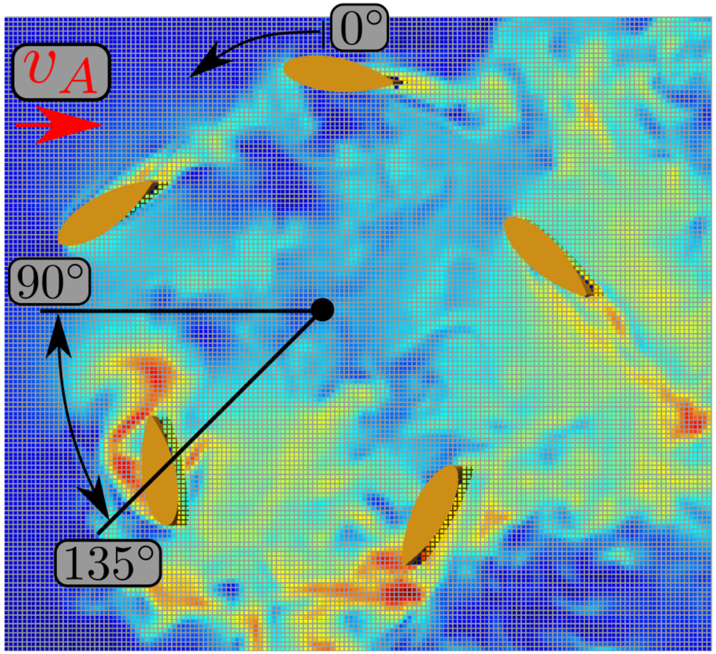




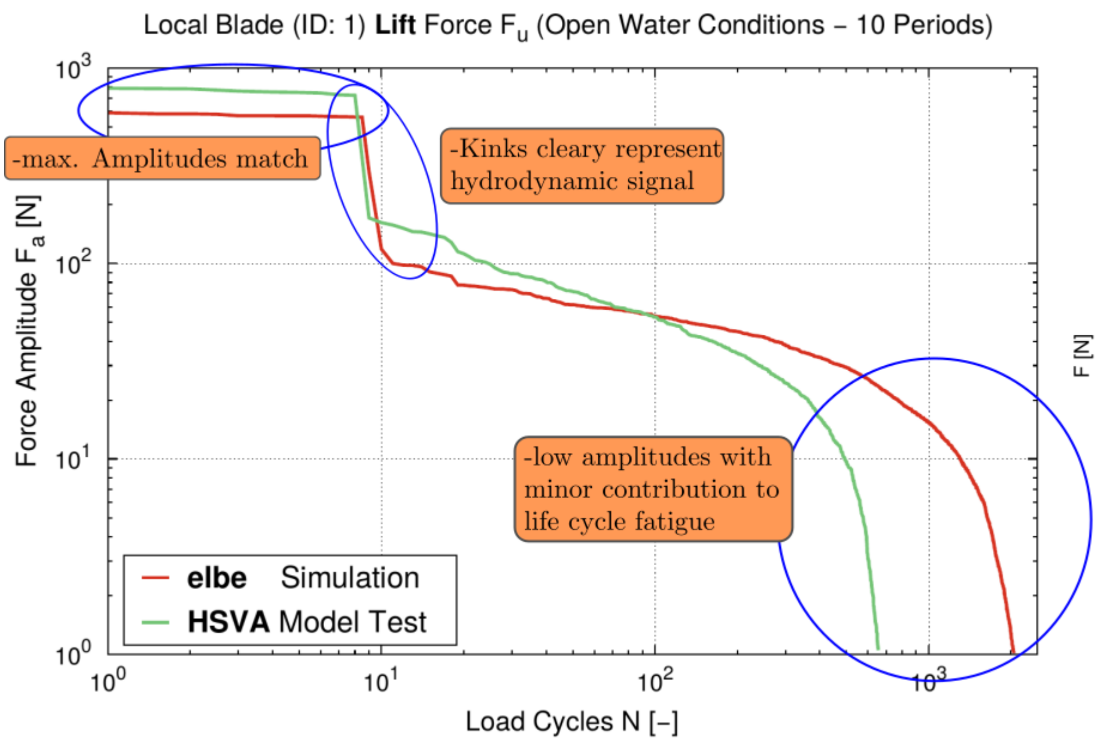


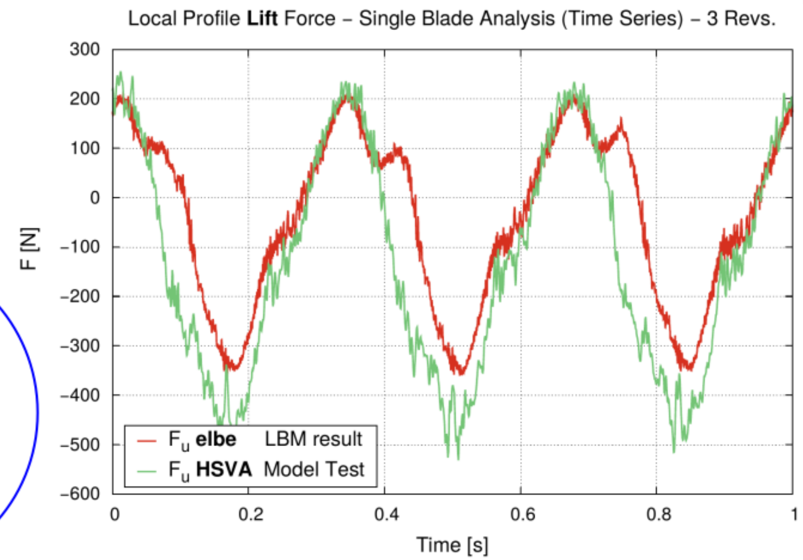
Deviations between RANS and LBM result



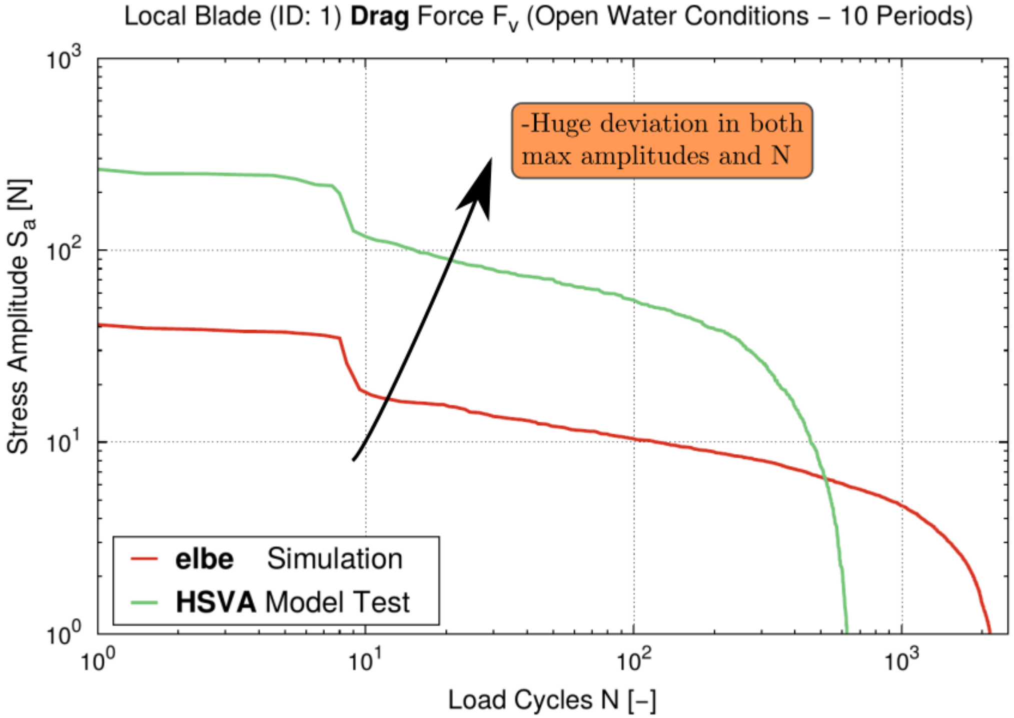


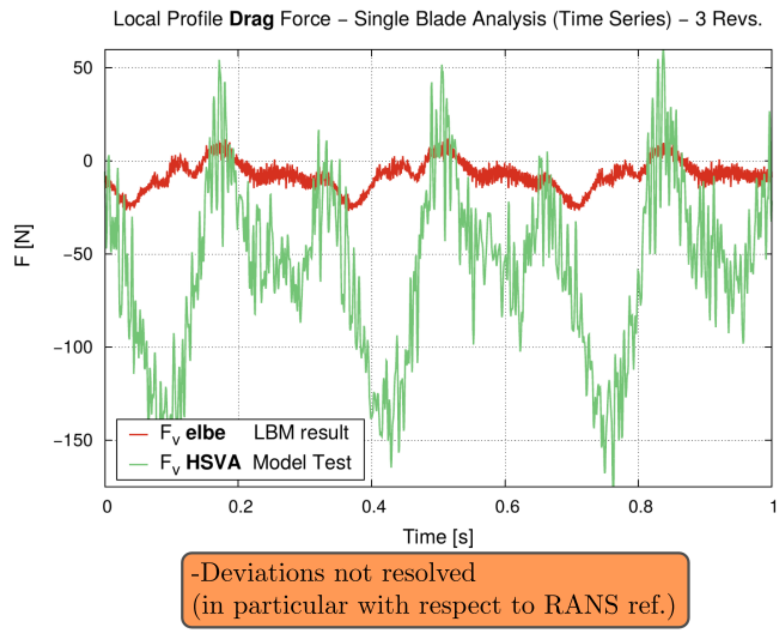
Open Water Validation – Rainflow Analysis (**Lift**)



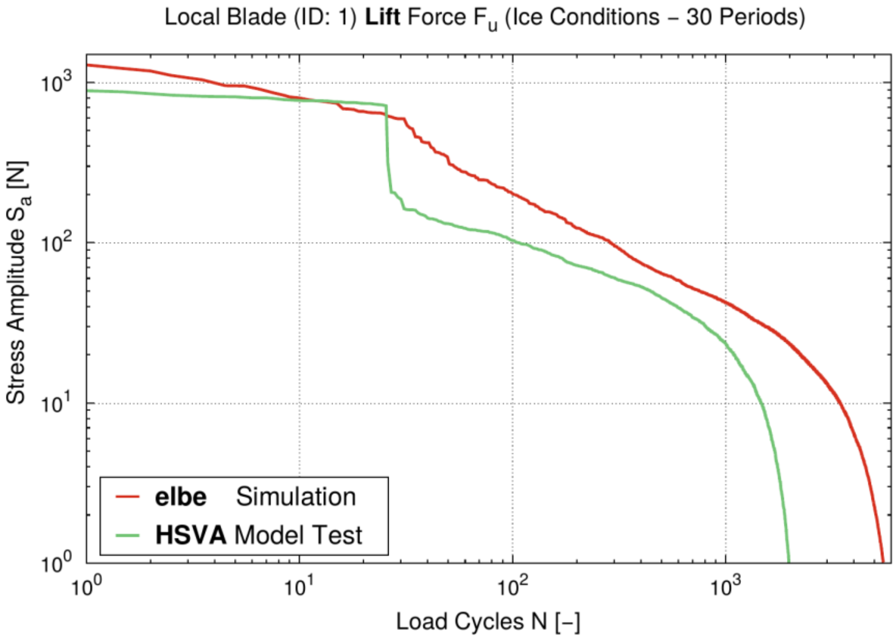


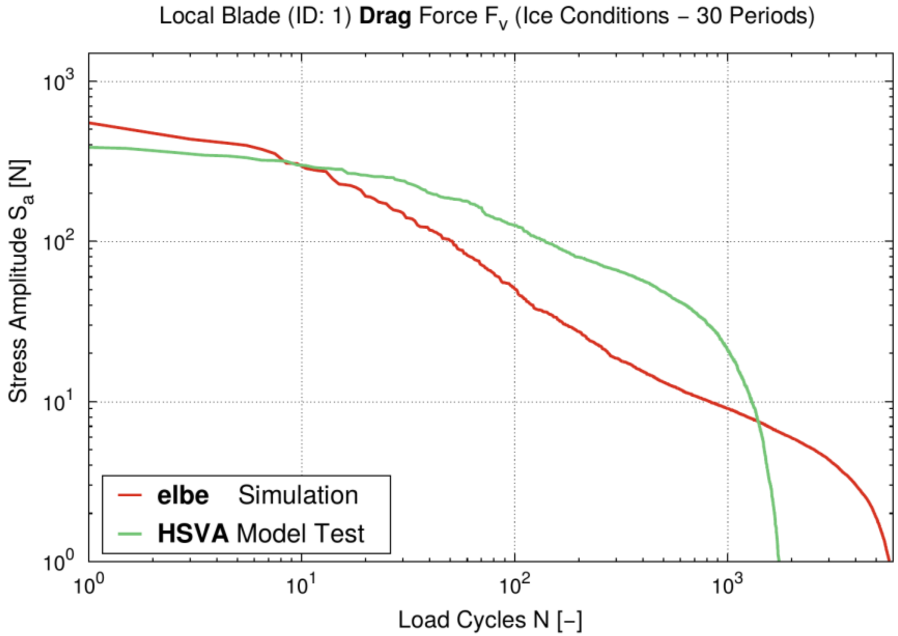
Open Water Validation – Rainflow Analysis (**Drag**)





Ice Conditions – Case No. 1 – **HSVA** vs. **TUHH (Lift+Drag)**





Ice Conditions – 4 HSVA Model Test Configurations