Sea-Swallows Engineering Tool (SeaSwallowsTool) and Methodology

Presented by Haoyu Ding

University of Bath

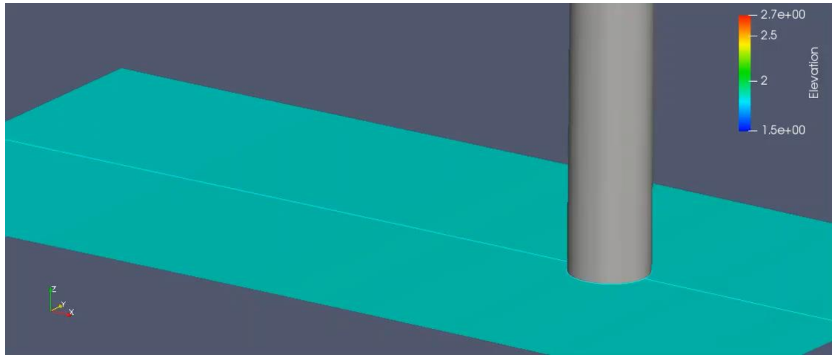
Sea-Swallows | Engineering and Physical Sciences Research Council | University of Bath | University of Oxford | University of Strathclyde Glasgow

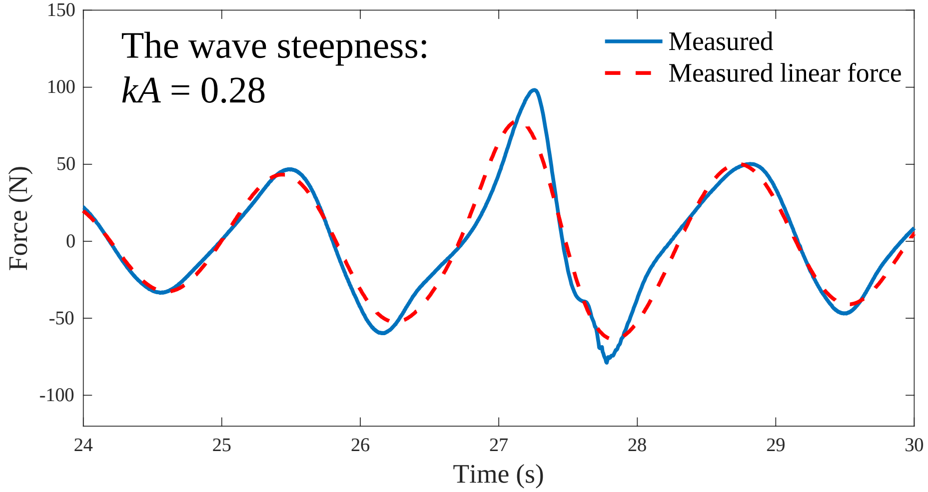
Background

Under severe wave conditions, **nonlinear force components are crucial**, as shown in the figure.

Thus, we develop a new method providing
fast and accurate prediction of nonlinear wave forces.

In this research, a **focused wave** type, generated by the **NewWave theory** for a **JONSWAP** sea-state, is used to represent a short-duration extreme wave.





Individual harmonics

Obtained using phase decomposition

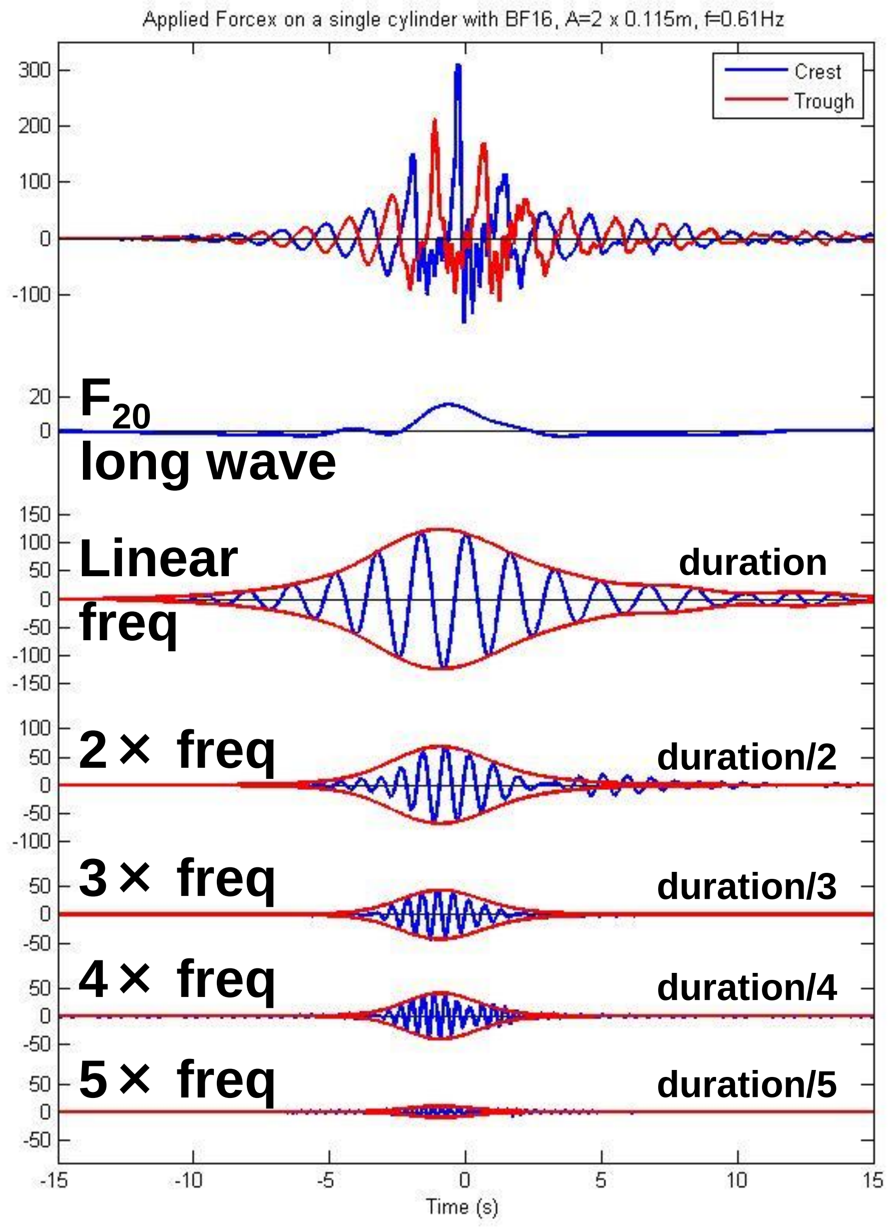
Envelopes reflect the correlations between linear and nth-order harmonics:

- **Linear force envelope:**
  Obtained using the Hilbert Transform.

- **nth-order harmonics envelopes (n > 2):**

Predicted by the (linear force envelope) ^{n}

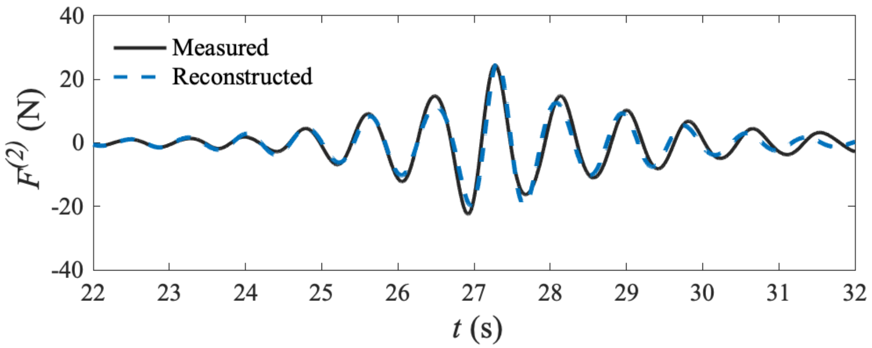
Chen, L.F., Zang, J., Taylor, P.H., Sun, L., Morgan, G.C.J., Grice, J., Orszaghova, J., Tello Ruiz, M. An experimental decomposition of nonlinear forces on a surface-piercing column: Stokes-type expansions of the force harmonics (2018) J. Fluid Mech., 848, 42-77.

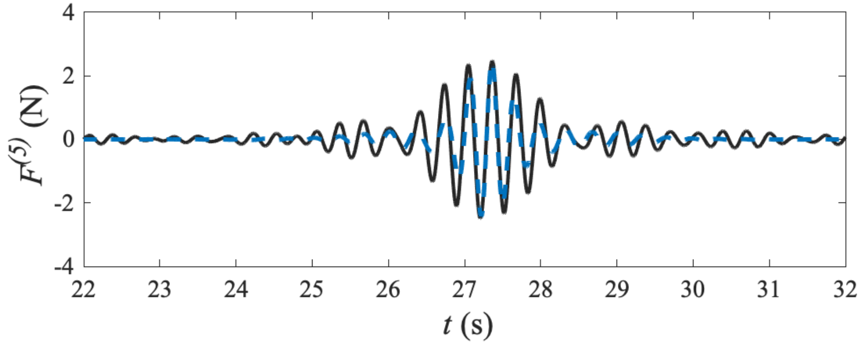


Force reconstruction – Stokes-type force model

$$F^{total} = \mathcal{F}_1[f_1] + \mathcal{F}_2\left[\alpha_{FF2}({f_1}^2 - f_{1H}^2) + \beta_{FF2}(2f_1 f_{1H})\right] + \mathcal{F}_3[\alpha_{FF3}(f_1(f_1^2 - 3f_{1H}^2)) + \beta_{FF2}(f_{1H}(3f_1^2 - f_{1H}^2))] + \cdots$$

with $\mathcal{F}_\mathrm{n}$: amplitude coefficient, $\phi_n = \arctan(\beta_{FFn}/\alpha_{FFn})$





Linear force

+

2nd harmonic

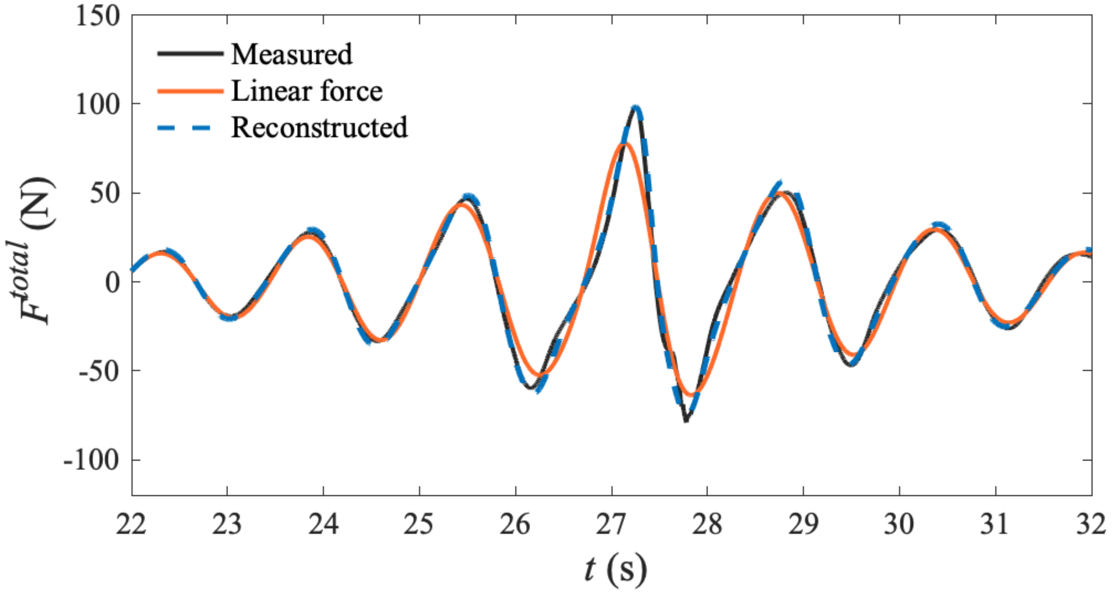
+

⋮

+

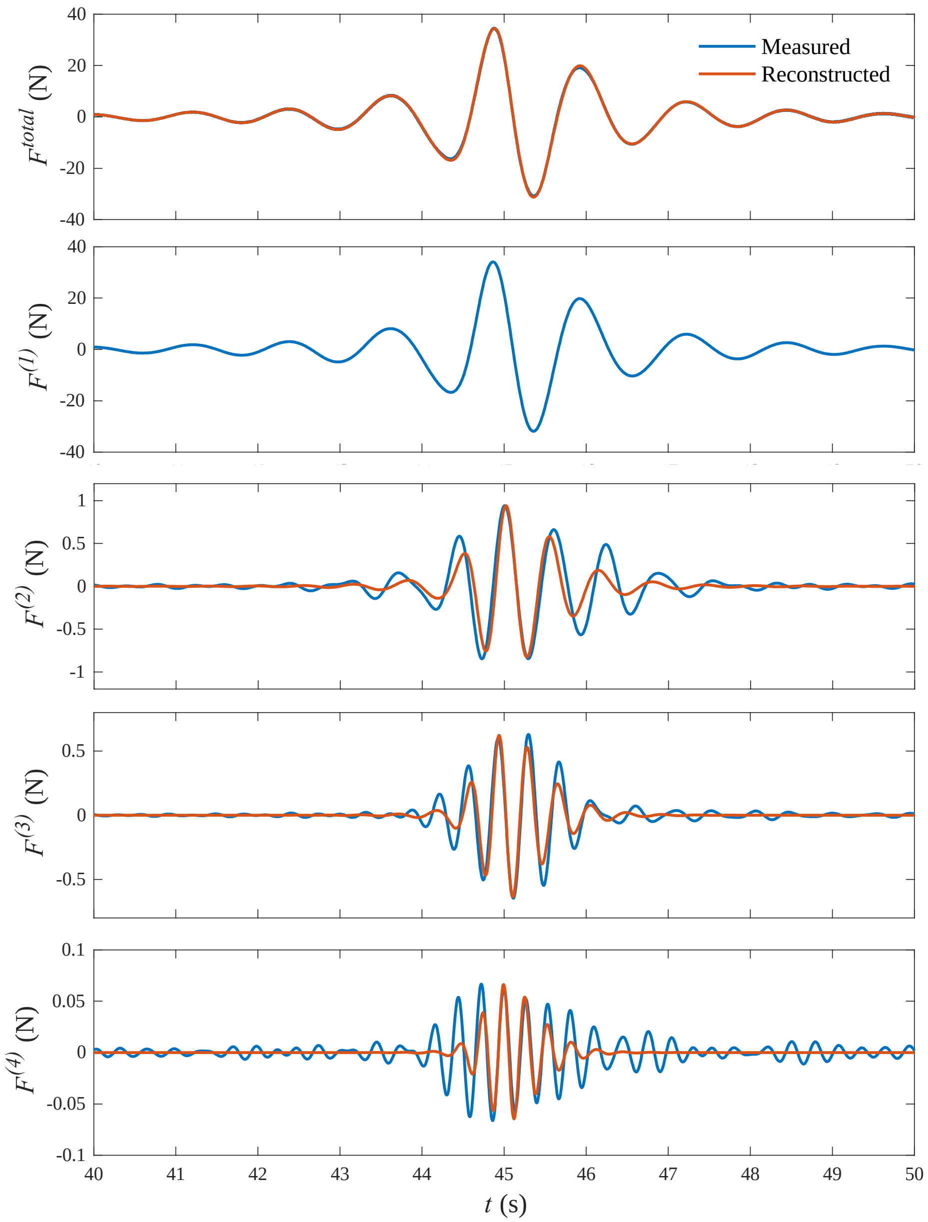
5th harmonic

Linear *vs.* Total *vs.* Reconstructed total



- **Force harmonics change with wave amplitude**

$A = 0.046$ m



Scaling from linear wave amplitude: 0.065/0.046 = 1.41

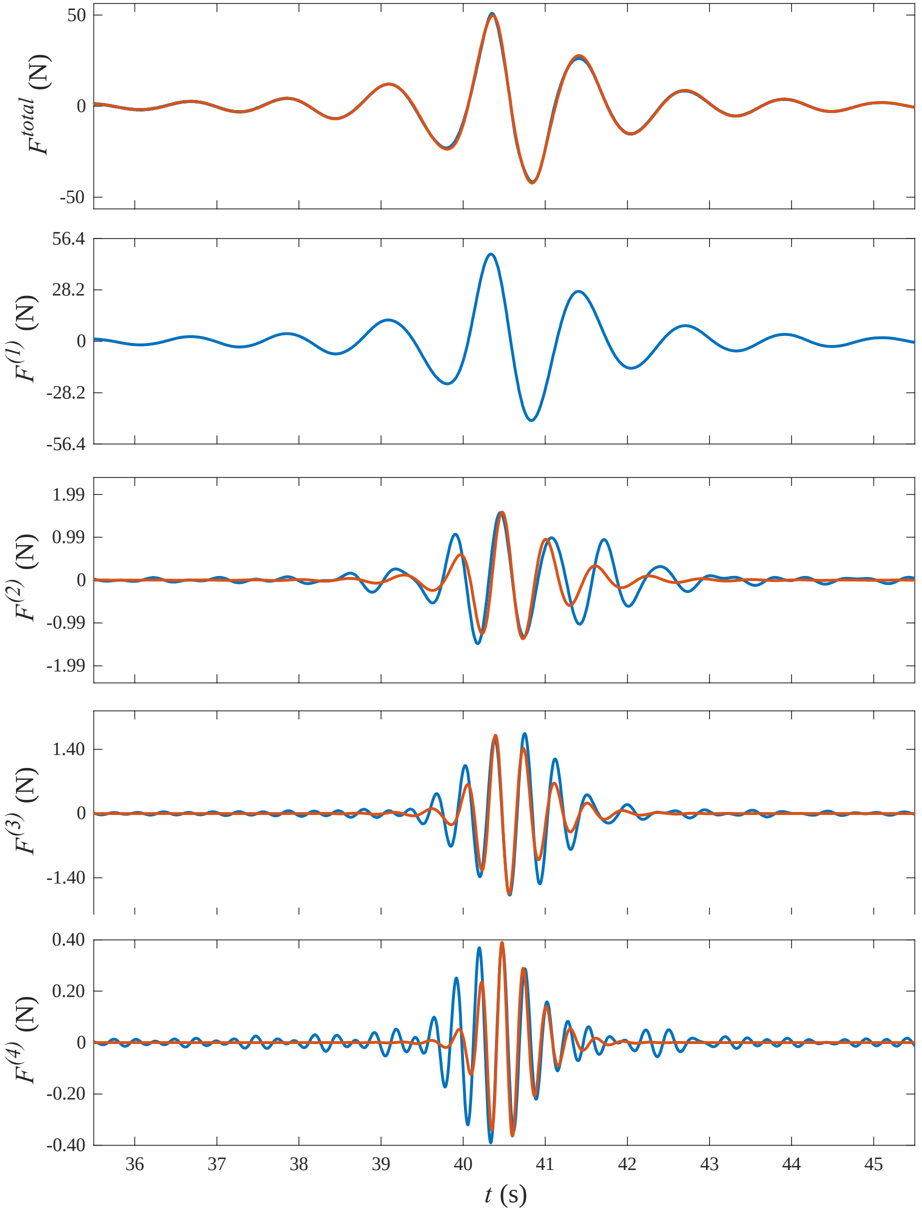
Y-axis scaled by 1.41

Y-axis scaled by 1.41^2

Y-axis scaled by 1.41^3

Y-axis scaled by 1.41^4

$A = 0.065$ m



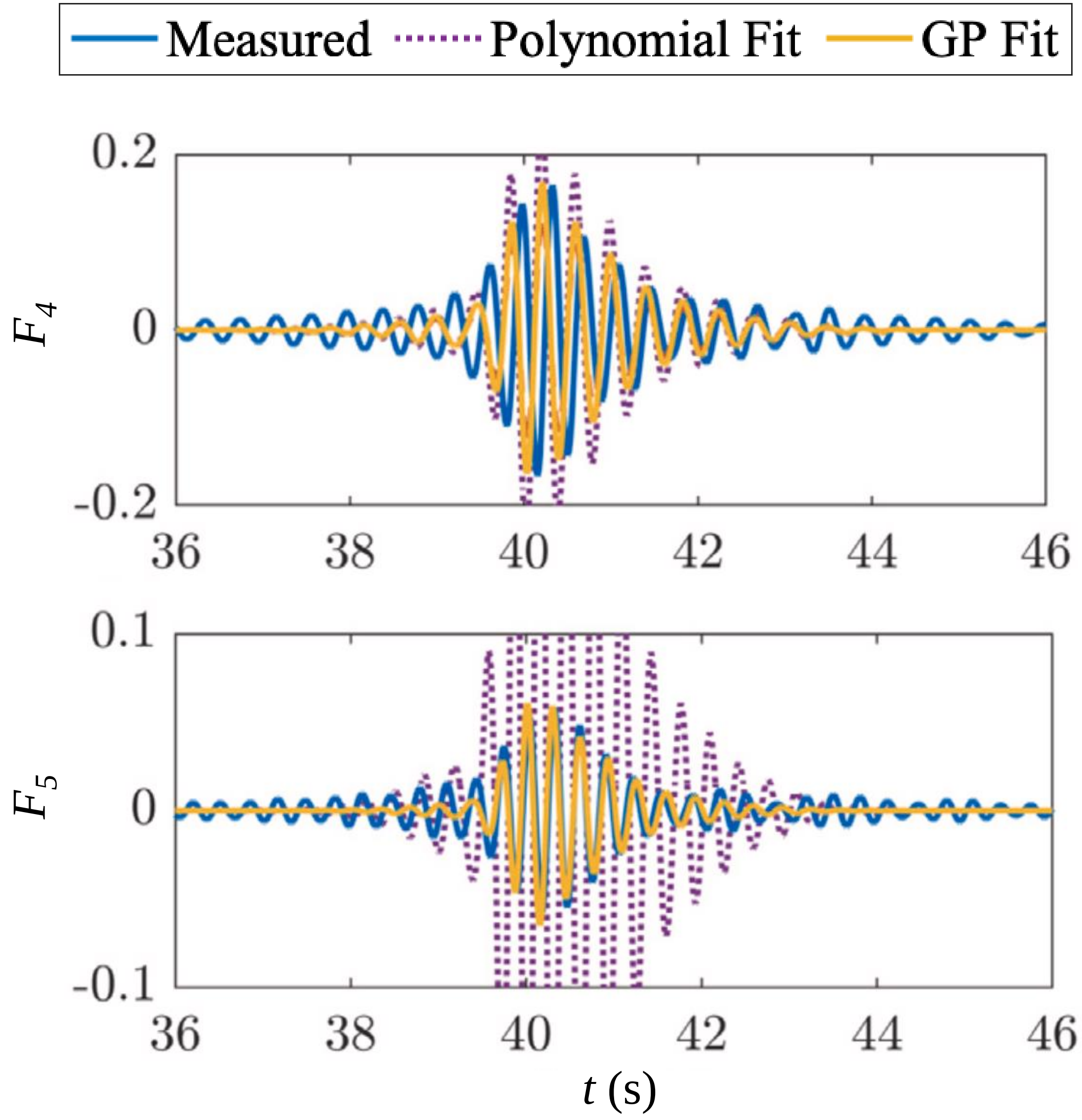
Gaussian Process model – fitting coefficient

Machine Learning-based digital tool

$\mathcal{F}_n \ or \ \phi_n \sim \mathcal{GP}(m(x), C_F(x, x^*)), \ x \in (kA, kR, kd)$

GP Fit is better than Polynomial Fit at:

- **Showing its uncertainty**
  Every prediction has a trusted confidence band.
- **No manual tweaking**
  Kernels adapt to the data's shape rather than a fixed polynomial order.
- **Keeping it simple**
  Marginal-likelihood tuning maintains complexity only where necessary.
- **Behaves at the edges**
  Smooth interpolation, cautious extrapolation.

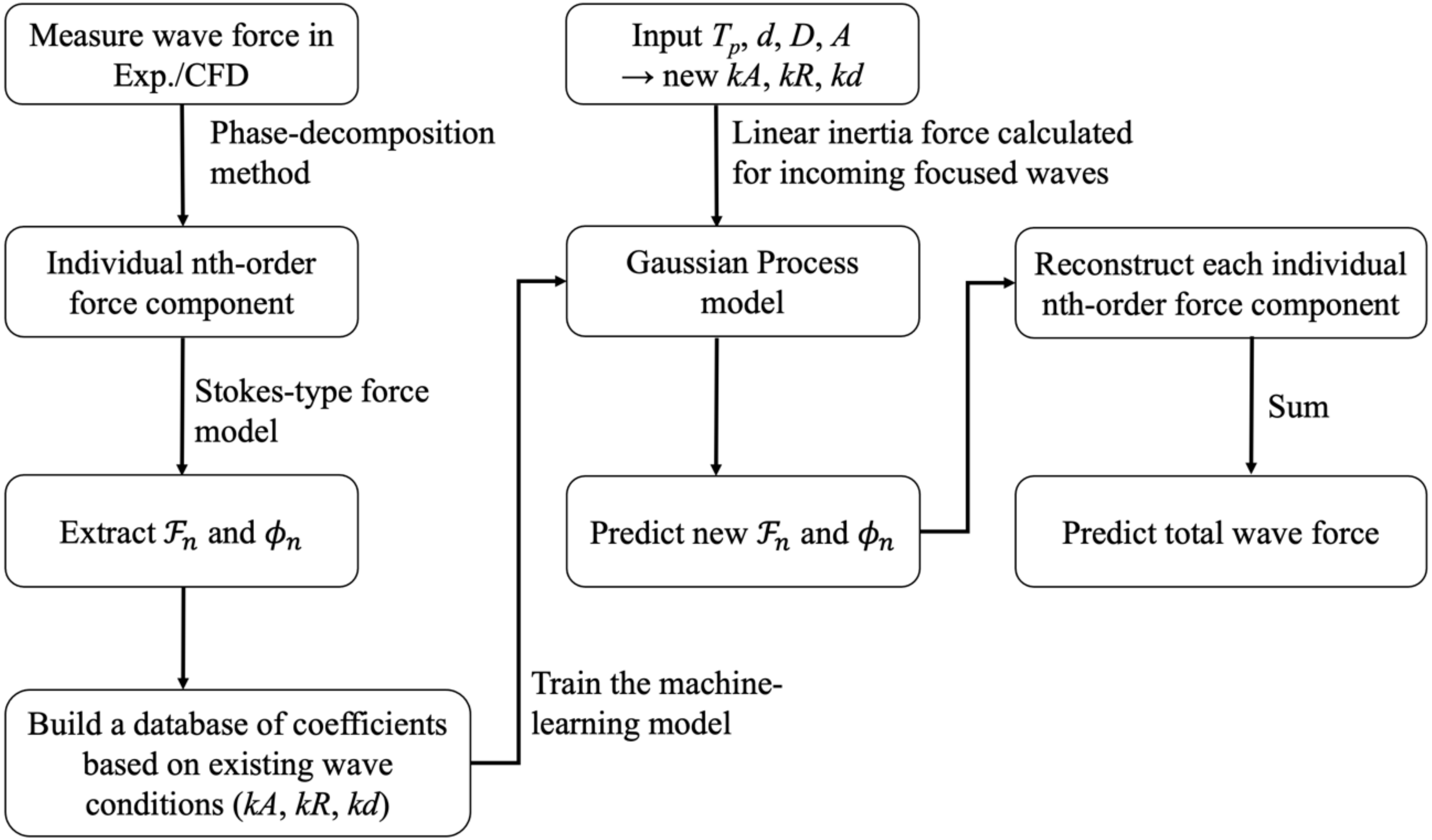


Tang, T., Ryan, G., Ding, H., Chen, X., Zang, J., Taylor, P. H., & Adcock, T. A. A. (2024).
A new Gaussian Process based model for non-linear wave loading on vertical cylinders.
Coastal Engineering, *188*, Article 104427.

Stokes-GP model

Stokes-GP model – Stokes-type force model + Gaussian Process (GP) Fit

Flow chart for model:

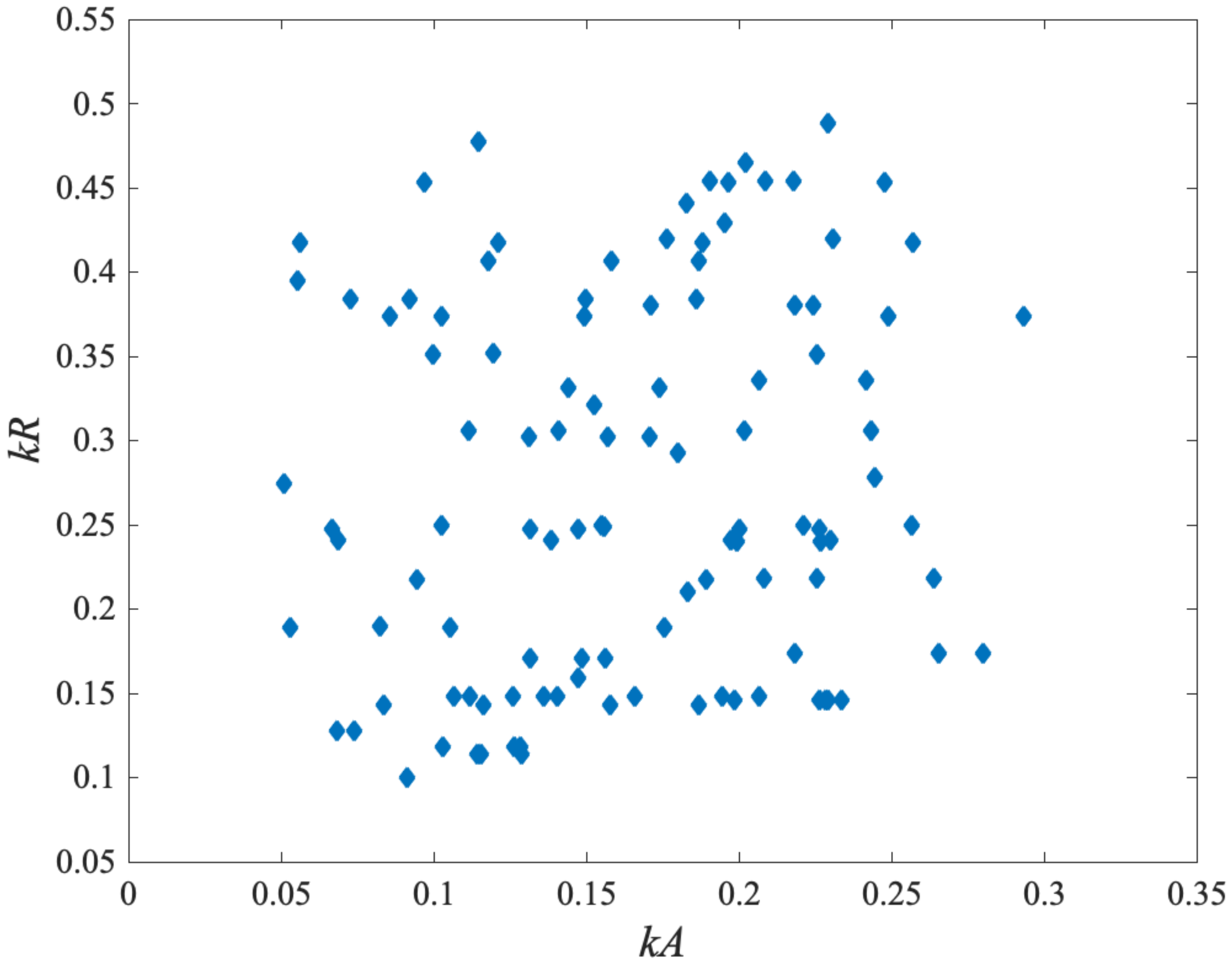


- **Experimental data for GP model training**

$0.05 \le kA \le 0.30, \quad 0.10 \le kR \le 0.49$

> 150 groups of wave tests conducted at 3 labs:
(each group with 2 or 4 phase shifts)

- **DHI**
  Danish Hydraulic Institute
- **KHL**
  Kelvin Hydrodynamics Laboratory
- **DUT**
  SKLCOE, Dalian Univ of Tech



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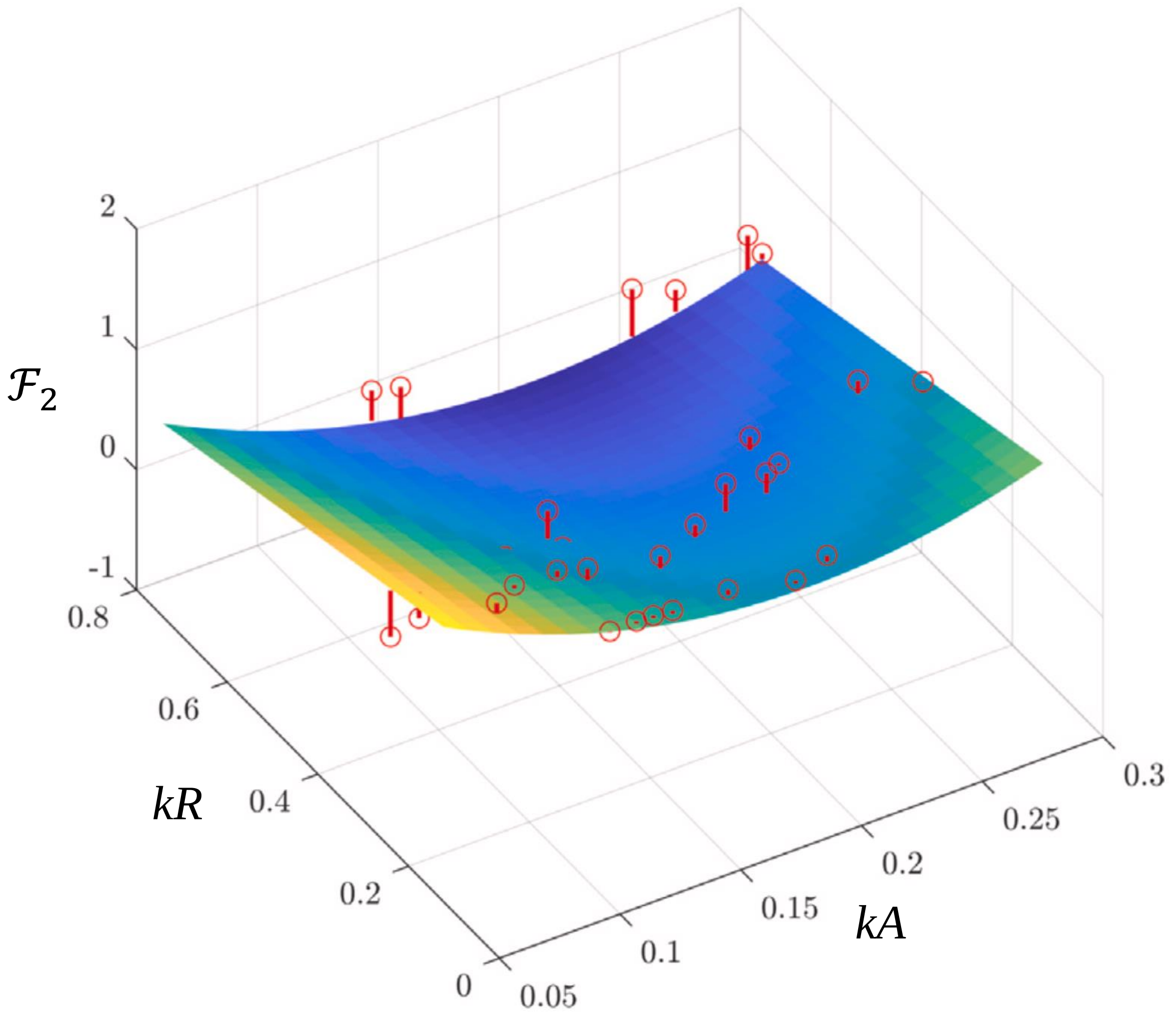
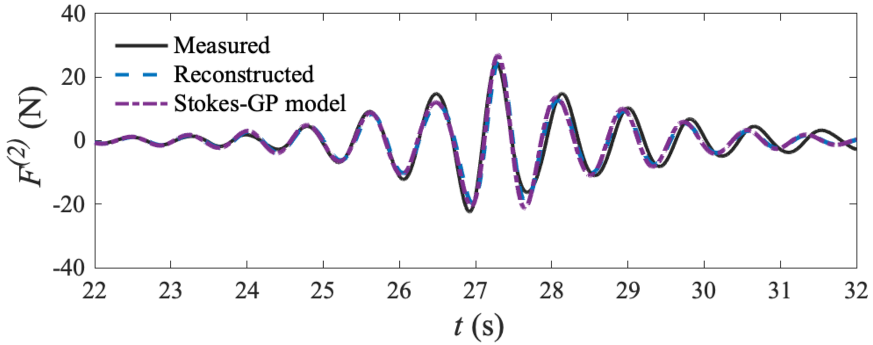
GP fit for 2nd order amplitude Coef. (KHL)

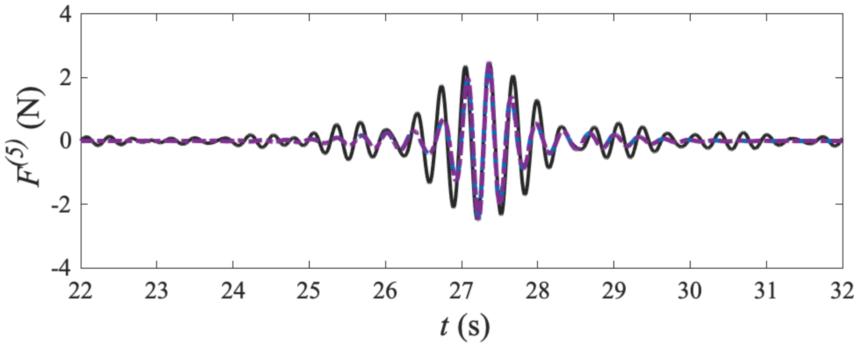


- **Results by Stokes-GP model**

Stokes-GP model trained by KHL data (in 2022)

Predict DUT test case (in 2023):





Linear force

+

2nd harmonic

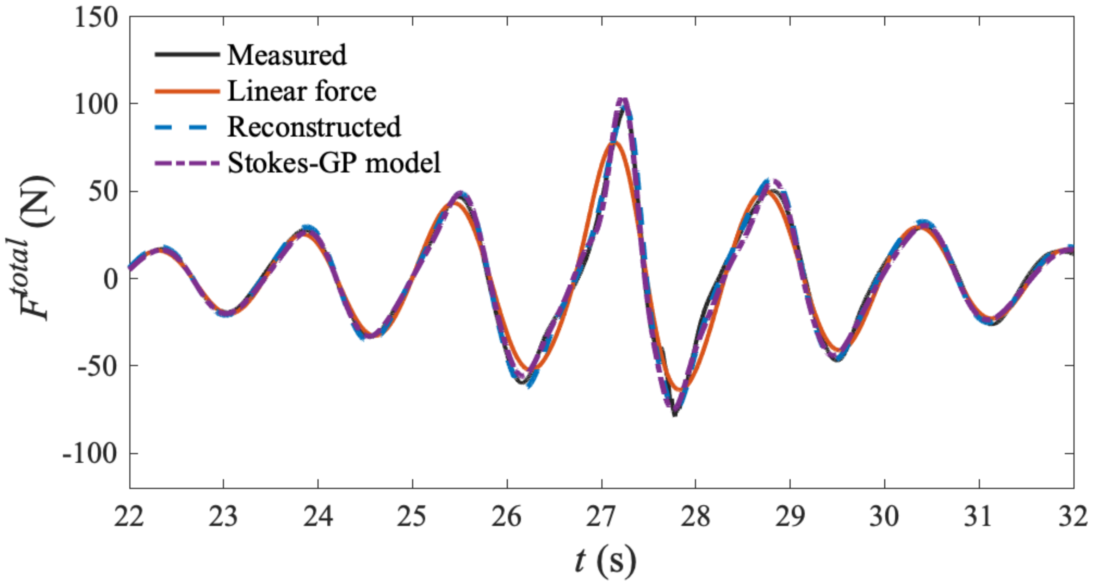
+

⋮

+

5th harmonic

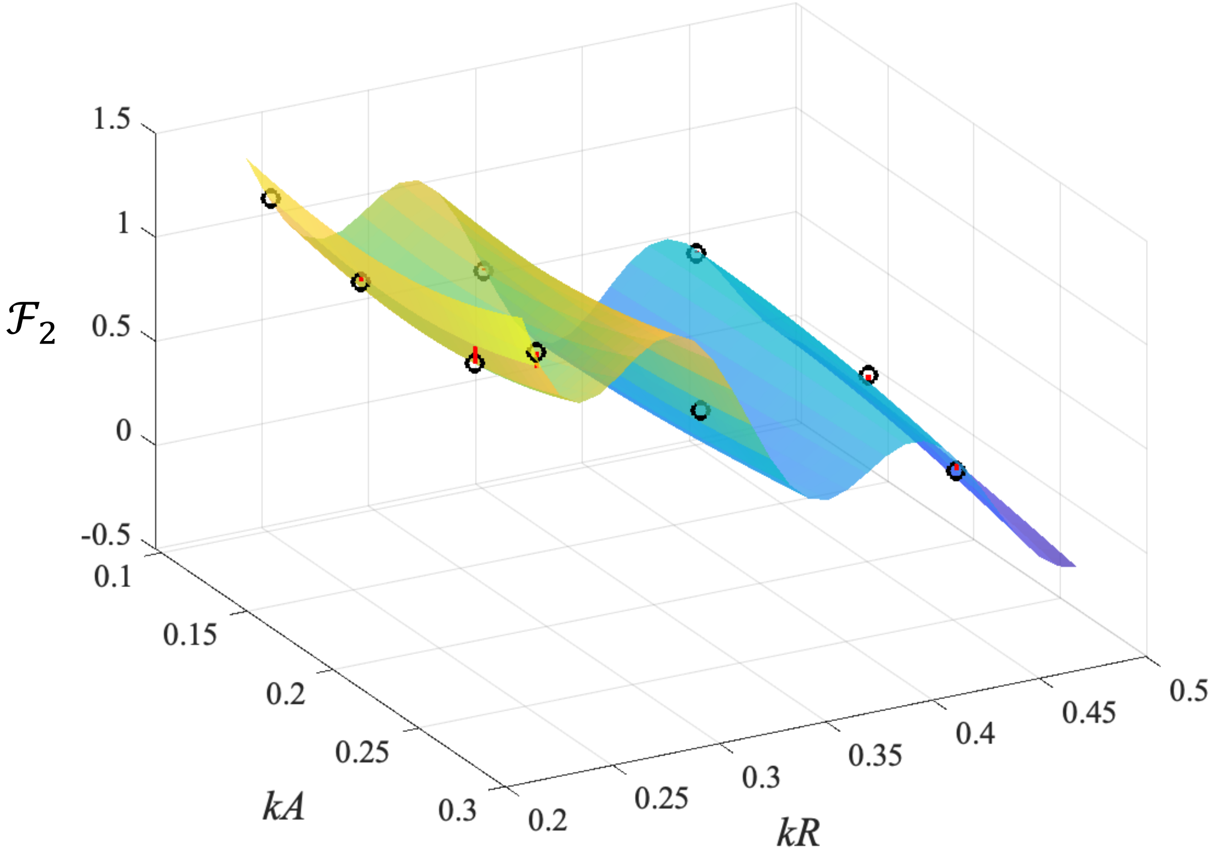
Linear *vs.* Total
vs. Reconstructed total
vs. Stokes-GP model prediction



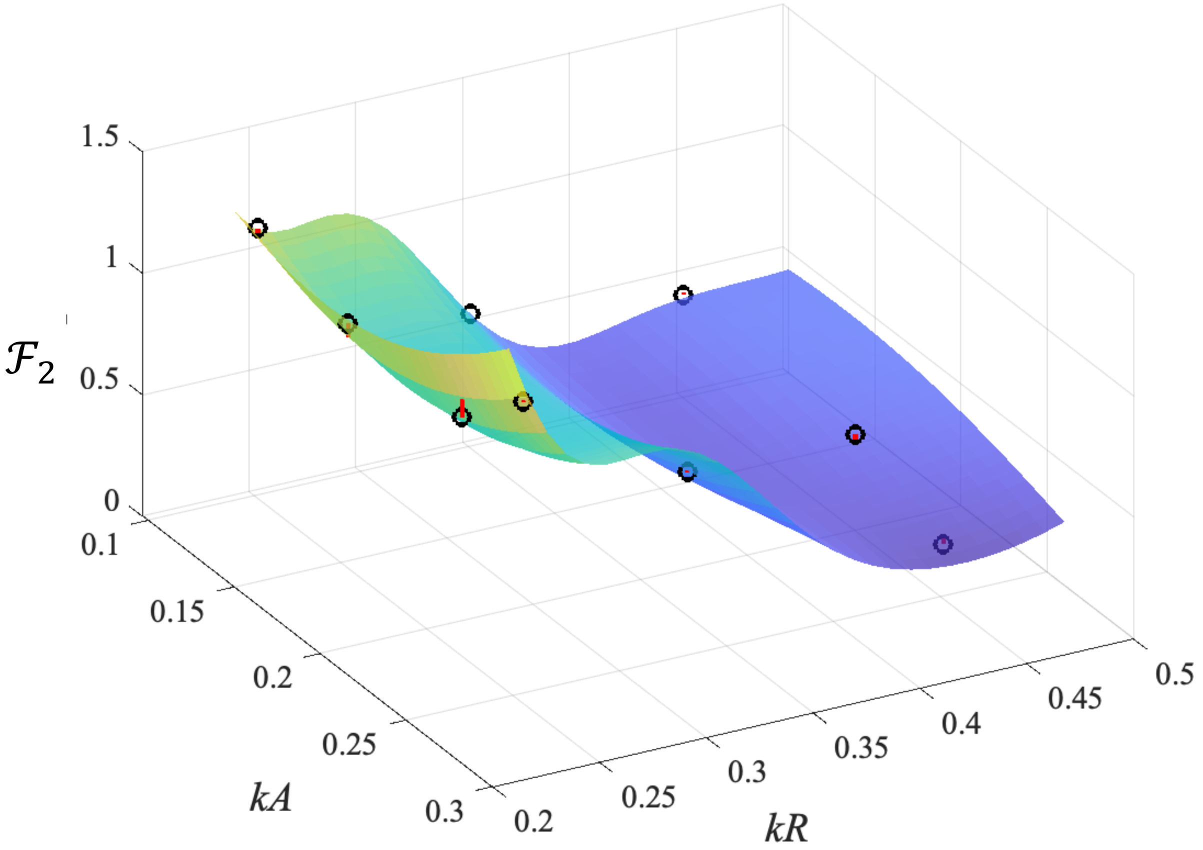
- **GP method improvement**

Original Stokes-GP model	New in SeaSwallowsTool
Data Pre-processing	
No or minimal data normalisation.	*Z*-score normalisation for both inputs and outputs. Consistent scaling – optimiser and stabiliser of predictions.
Kernel Function	
Standard kernel (isotropic squared exponential, covSEiso).	Adoption of an ARD kernel (covSEard) – different length scales for each input dimension.
Hyperparameter	
• Single random initialisations. • Local unstable hyperparameter estimates.	• Multiple random restarts to avoid local minima. • Iterations lead to a lower negative log marginal likelihood.

- **DUT data**: Water depth *d* = 0.7 m, Cylinder radius *R* = 0.125, *d/R* = 5.6.



Original GP model setup



New GP model setup
Locally smoother plane
expected as the KHL plane earlier

- **CFD supplementary data**

Computational Fluid Dynamics (CFD)
– Fully nonlinear viscous model

Accurately calculate nonlinear components

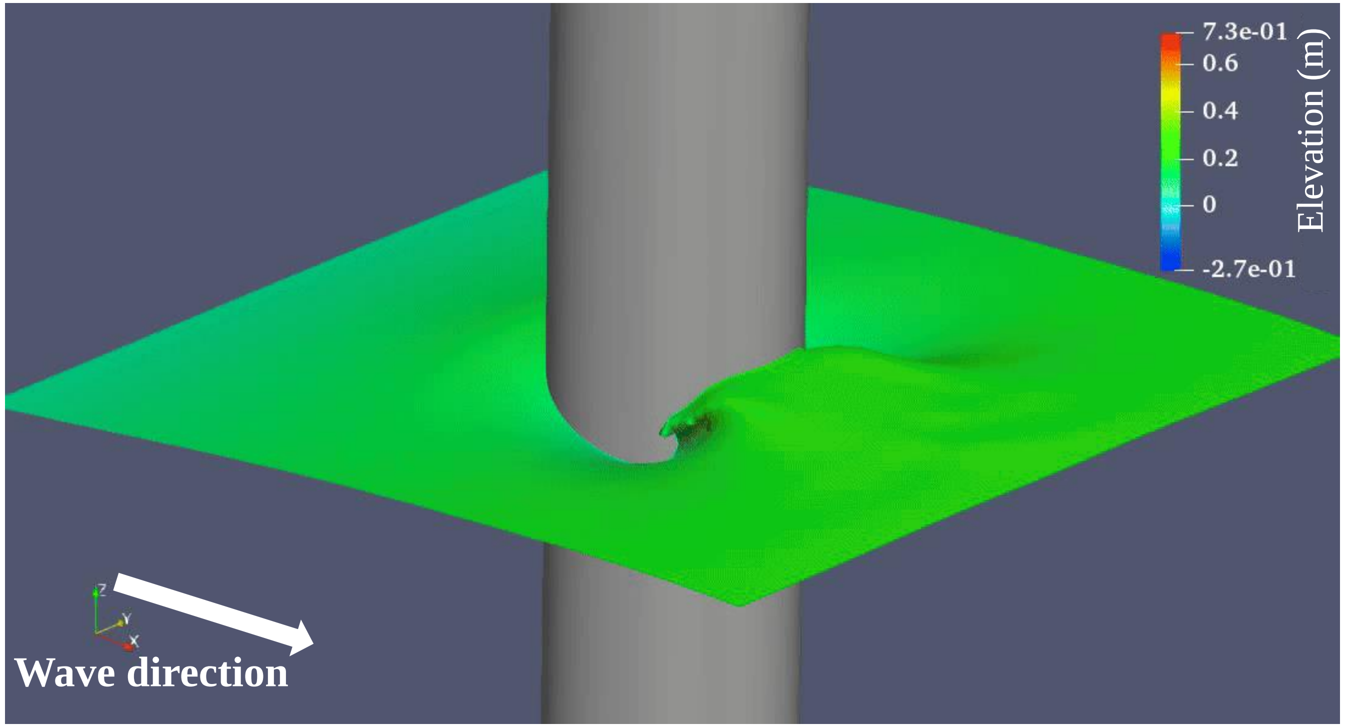
Two models are used:

- **OpenFOAM**

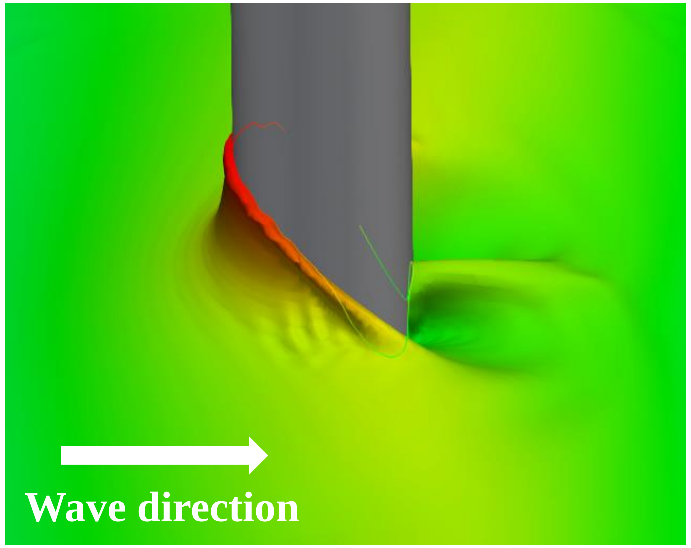
Open-source, Mesh-based Eulerian method

- **Particle-In-Cell (PIC) model**

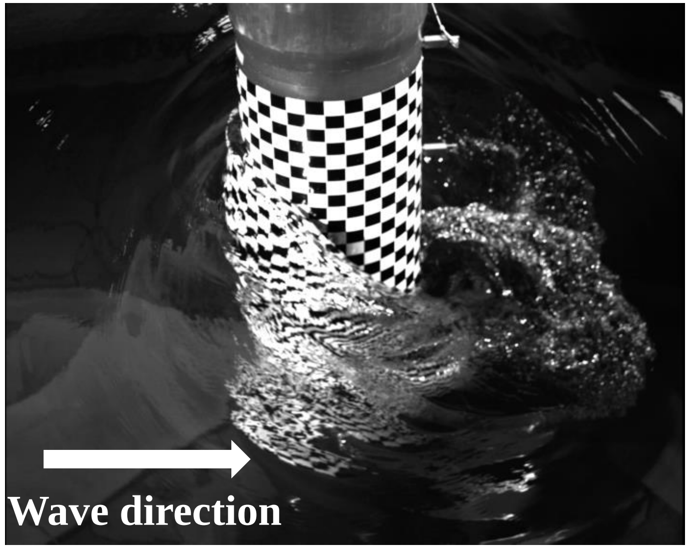
In-house,
hybrid (Eulerian + Lagrangian for advection term)



CFD



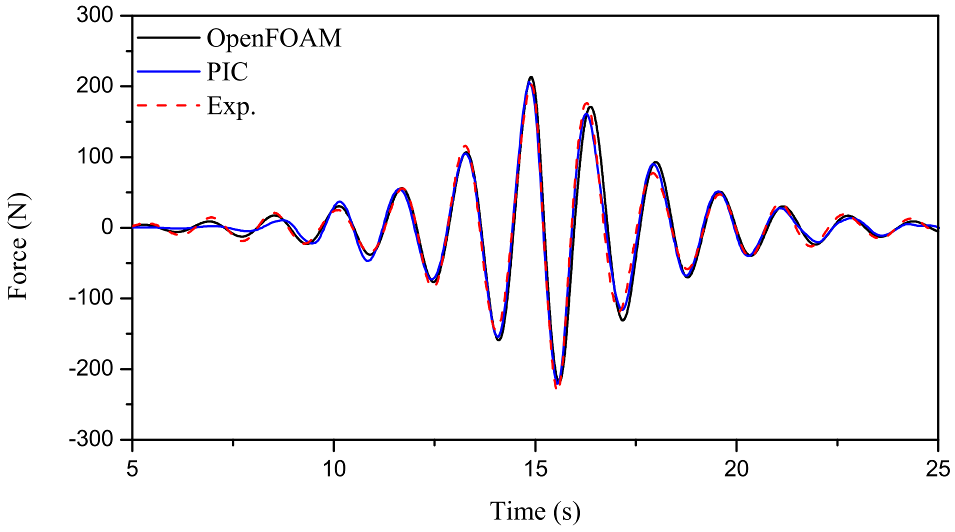
KHL exp.



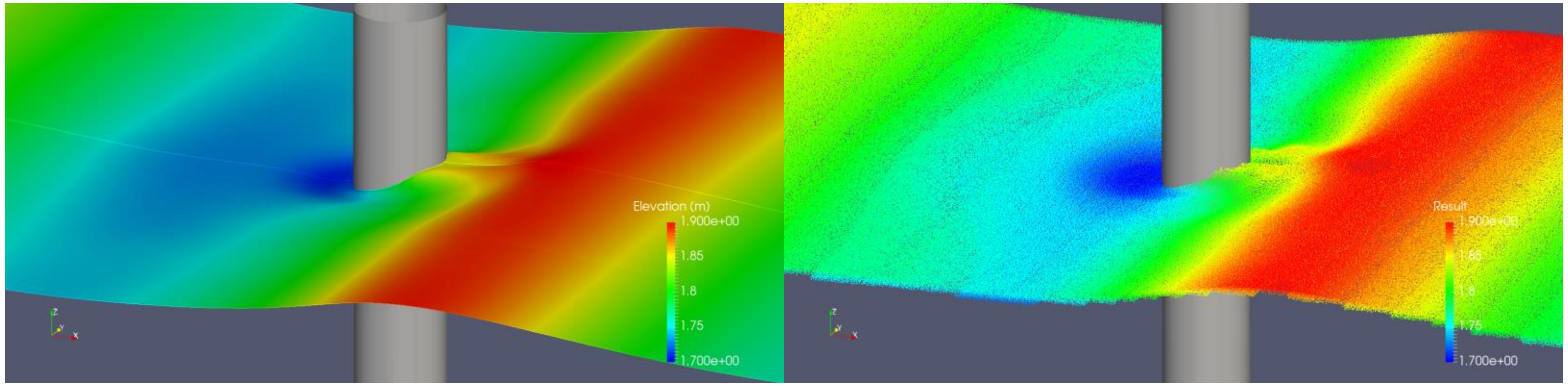
- **CFD supplementary data**

Validations

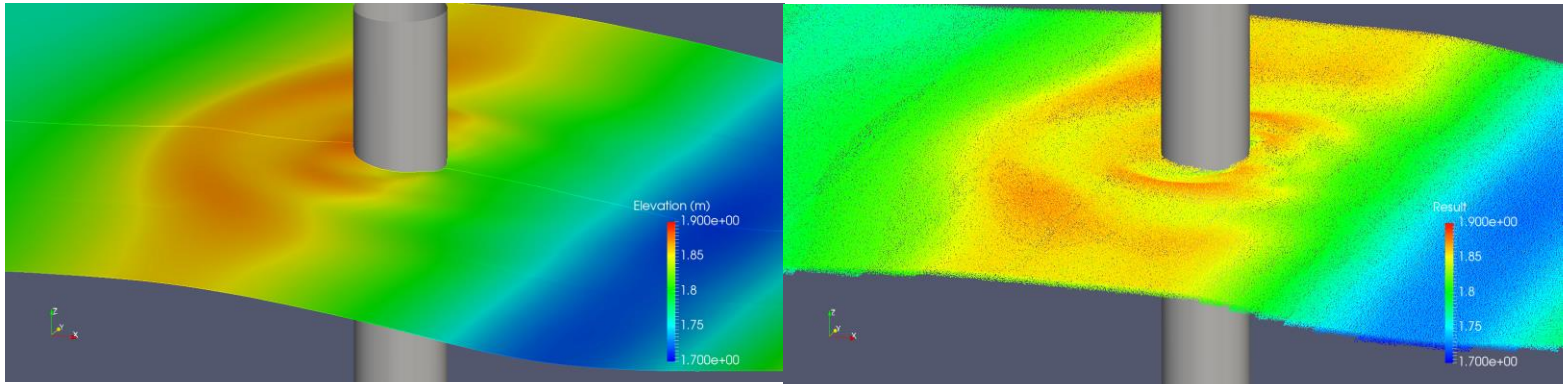
$kA = 0.16$, $kR = 0.32$



OpenFOAM PIC



The peak crest passes the cylinder



The next crest after the main crest passes the cylinder

- **CFD supplementary data**

Predictions for scattering wave field, illustrating:

[1] linear harmonic,

[2] 2nd harmonic,

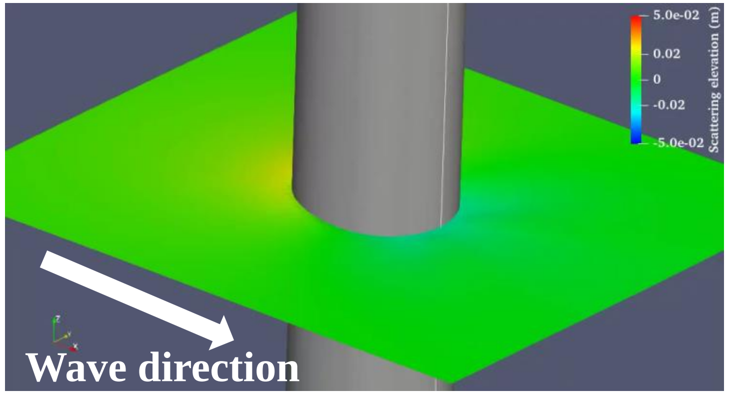
[3] 3rd harmonic,

[4] 4th harmonic,

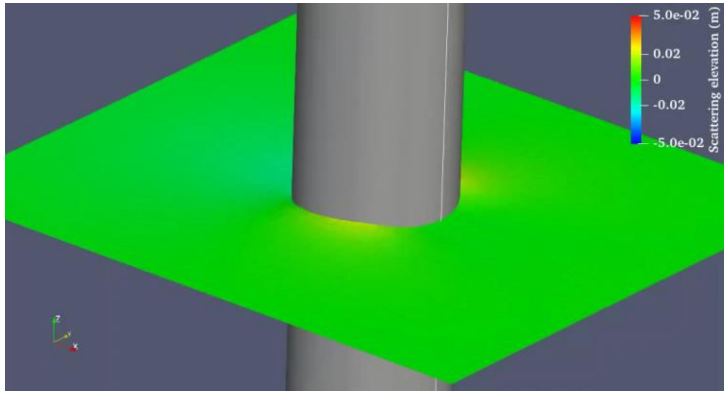
[5] 5th harmonic,

[>5] harmonics > 5th.

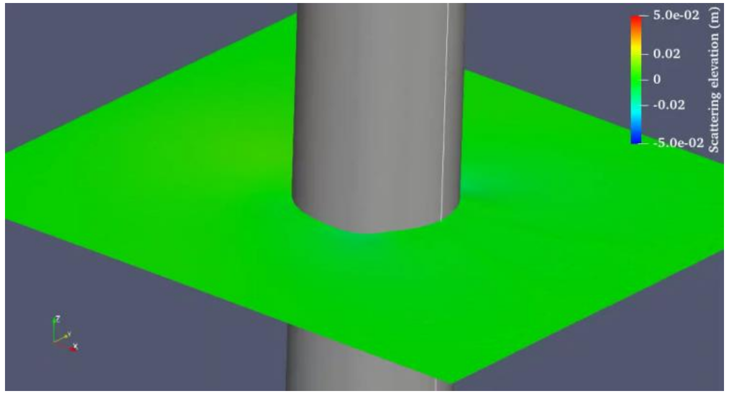
[1]



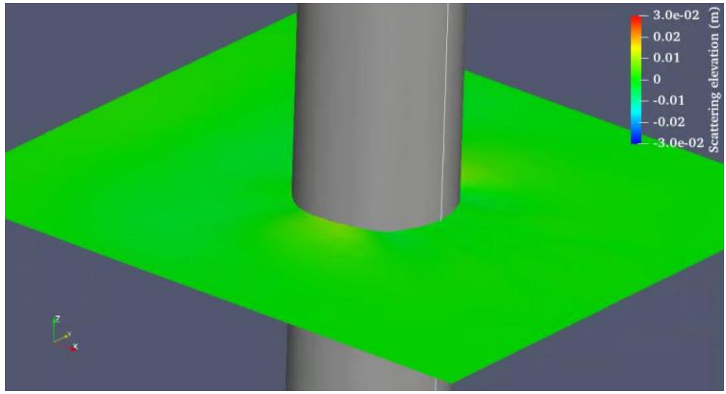
[2]



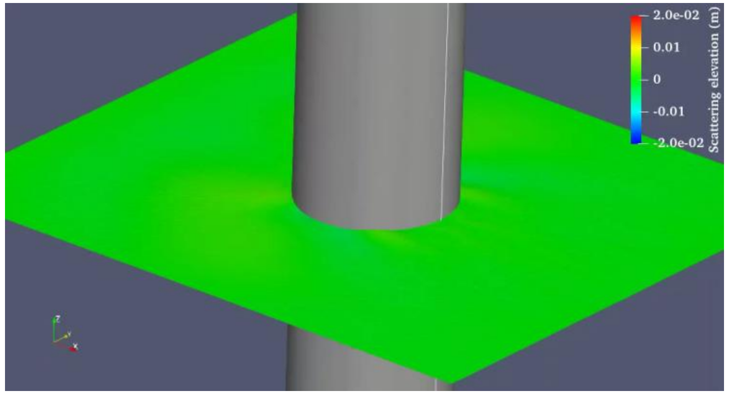
[3]



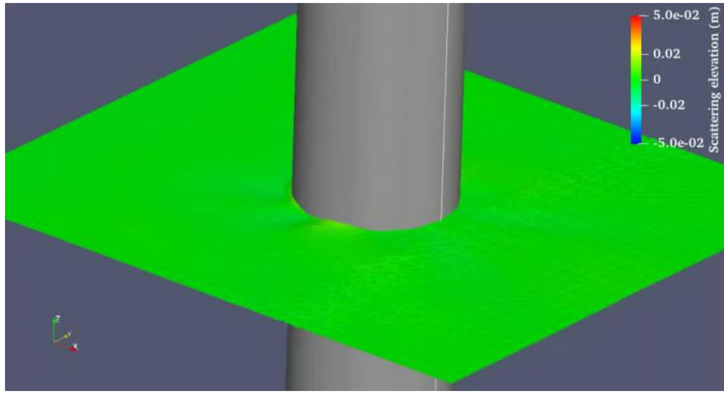
[4]



[5]



[>5]



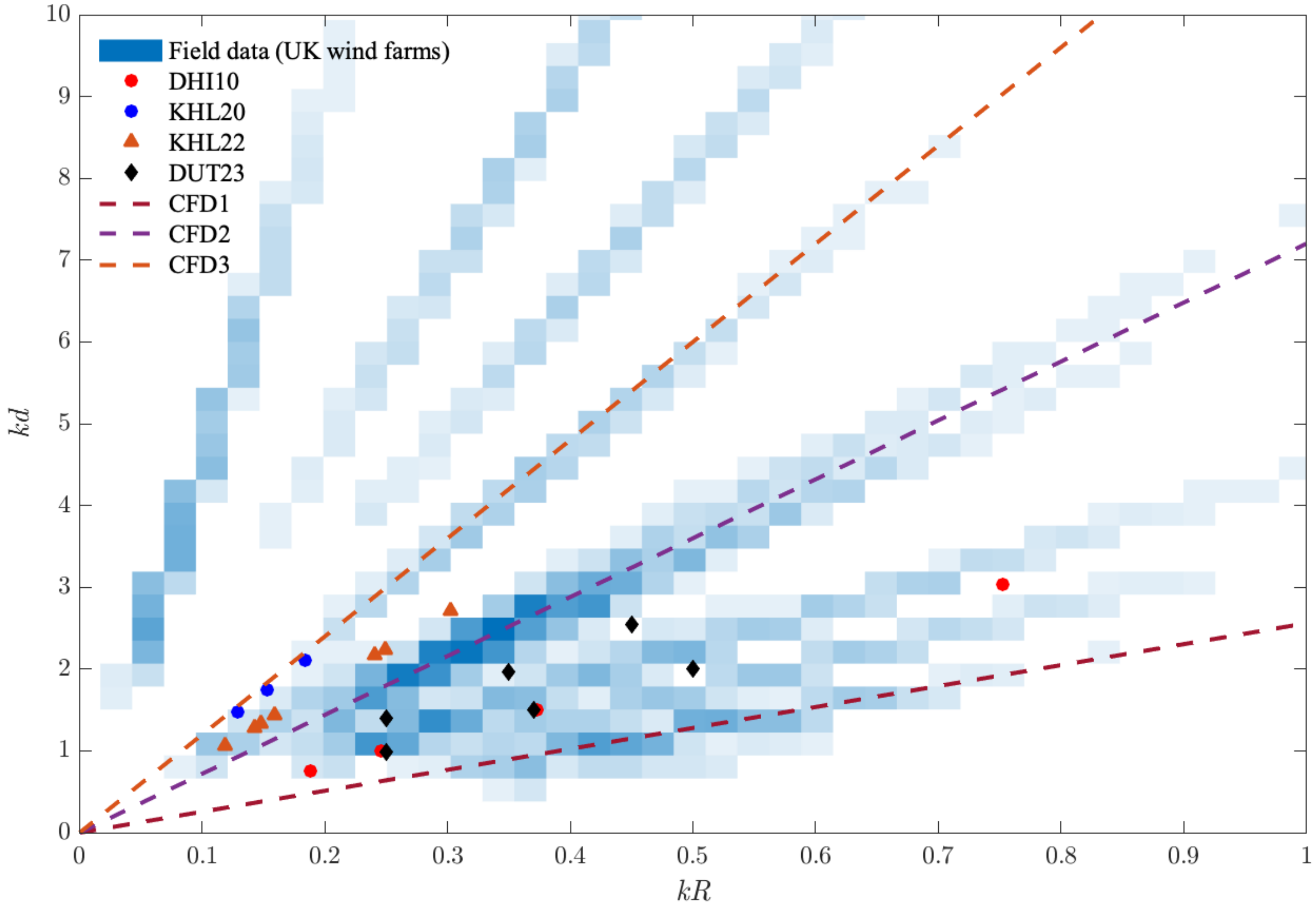
- **CFD supplementary data**

Field data:
Hourly sea-state parameters across all 36 UK offshore wind farm locations

DHI18, KHL20, KHL22, DUT23:
Previous physical experimental tests

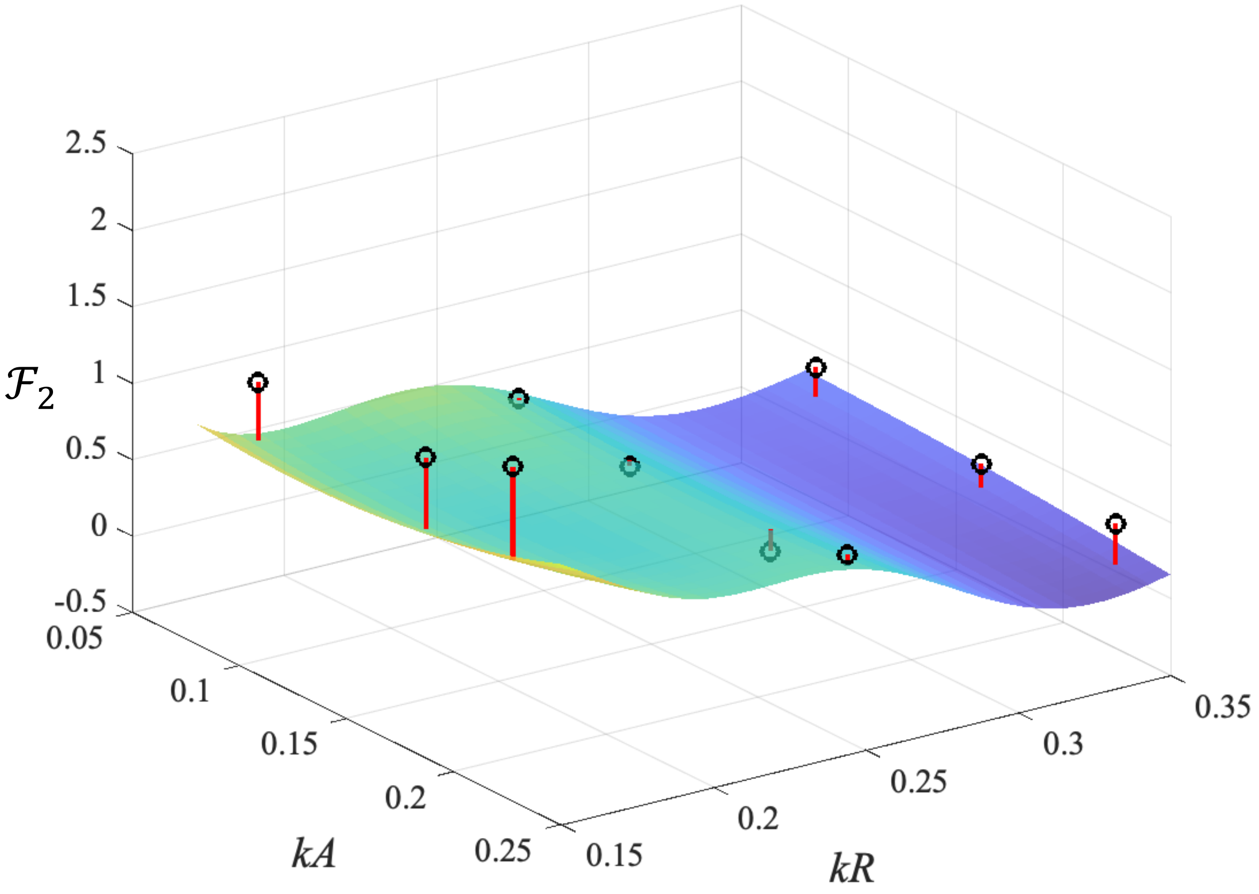
Numerical tests:
Extended database by CFD.

d/R = 2.56, 7.2 and 12

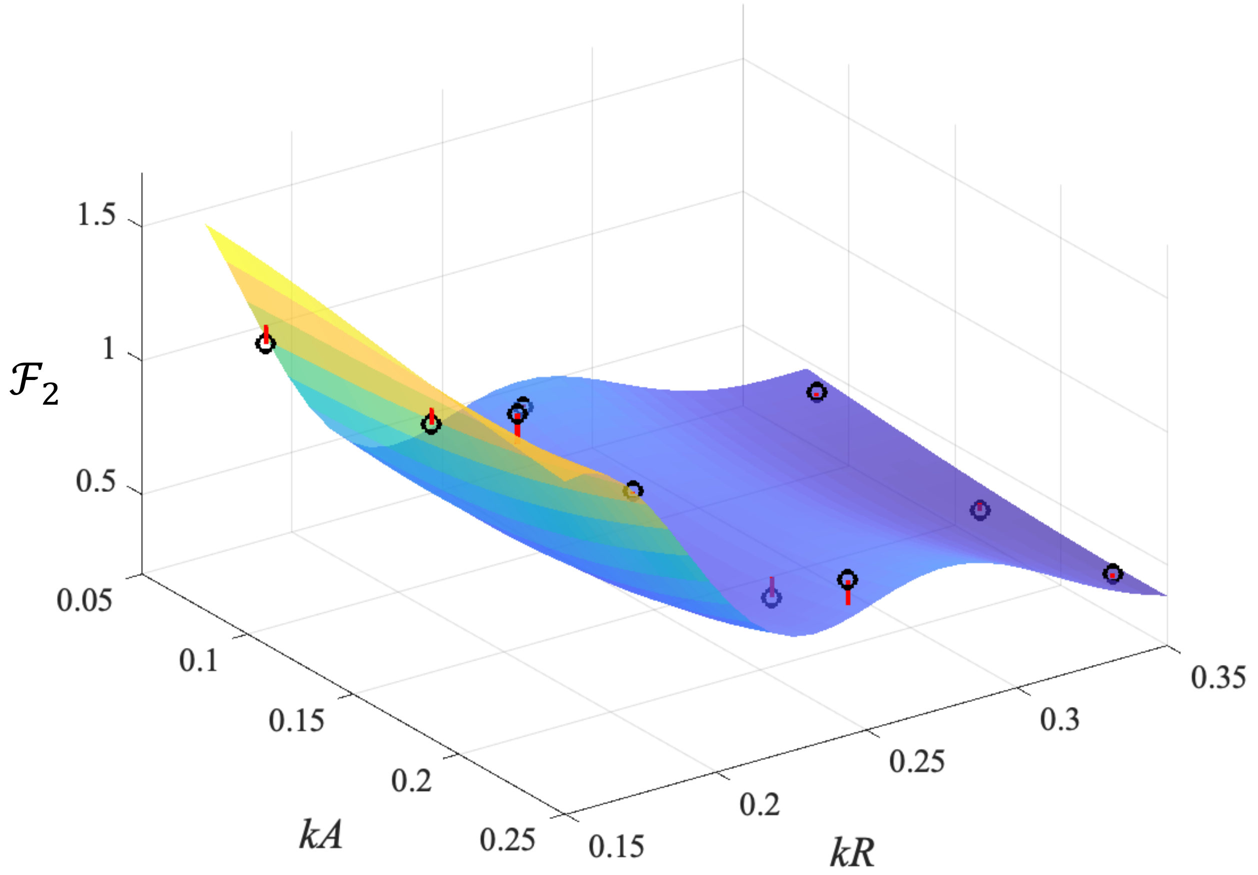


- **CFD data (in black dots)**: *d* = 0.9 m, *R* = 0.125, *d/R* = 7.2.

Amplitude coefficients for the 2nd-harmonic force compared for the **GP model** without and with **CFD data**.



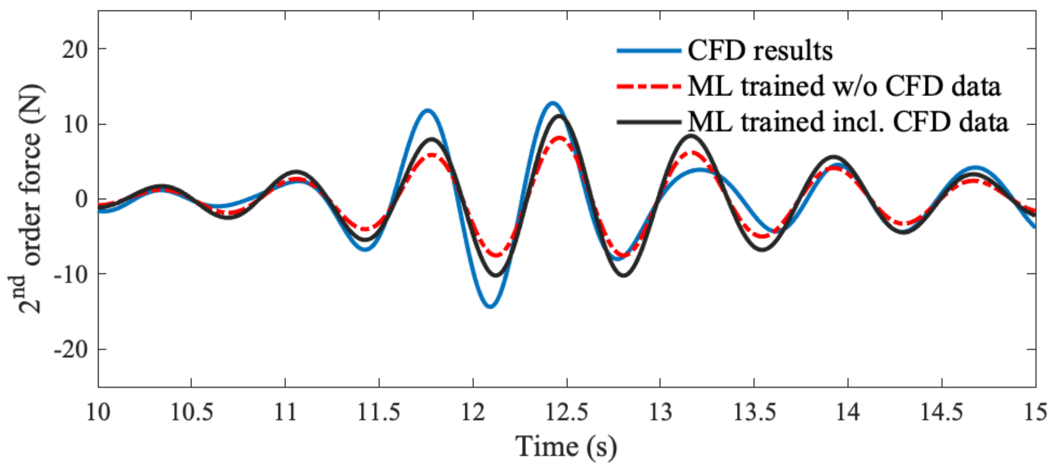
GP model prediction
(predicted w/o CFD data)

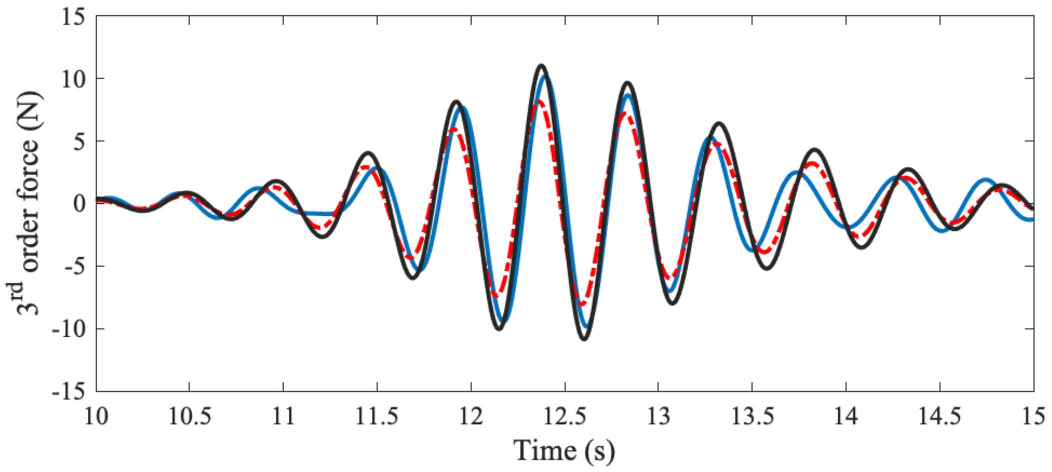


GP model prediction
(predicted, incl. CFD data)

- **GP fitting model with extended database**

Example case: kA_I = 0.242, kR = 0.29, and kd = 1.796, with d/R = 7.2
A condition not covered by previous physical experiments.



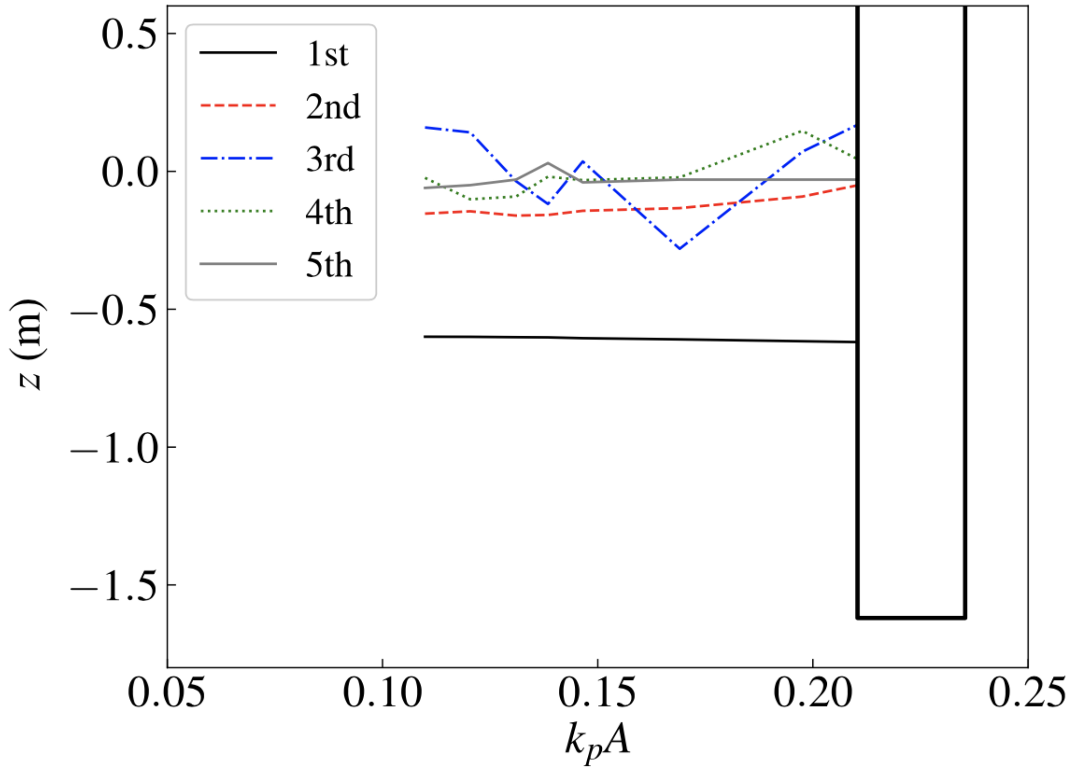


Moment

The moment arms to the seabed of each harmonic are estimated based on (Feng et al., 2020):

Feng, X., Taylor, P. H., Dai, S., Day, A. H., Willden, R. H. J., Adcock, T. A. A., 2020, Experimental investigation of higher harmonic wave loads and moments on a vertical cylinder by a phase-manipulation method, *Coastal Engineering*, 160, 103747.

Acting points of each force harmonic (Feng et al., 2020)



Arm for F_1 (Arm1) $= d - \frac{1}{k}\tanh(k\frac{d}{2})$

Arms for F_2 to F_5 $= d$

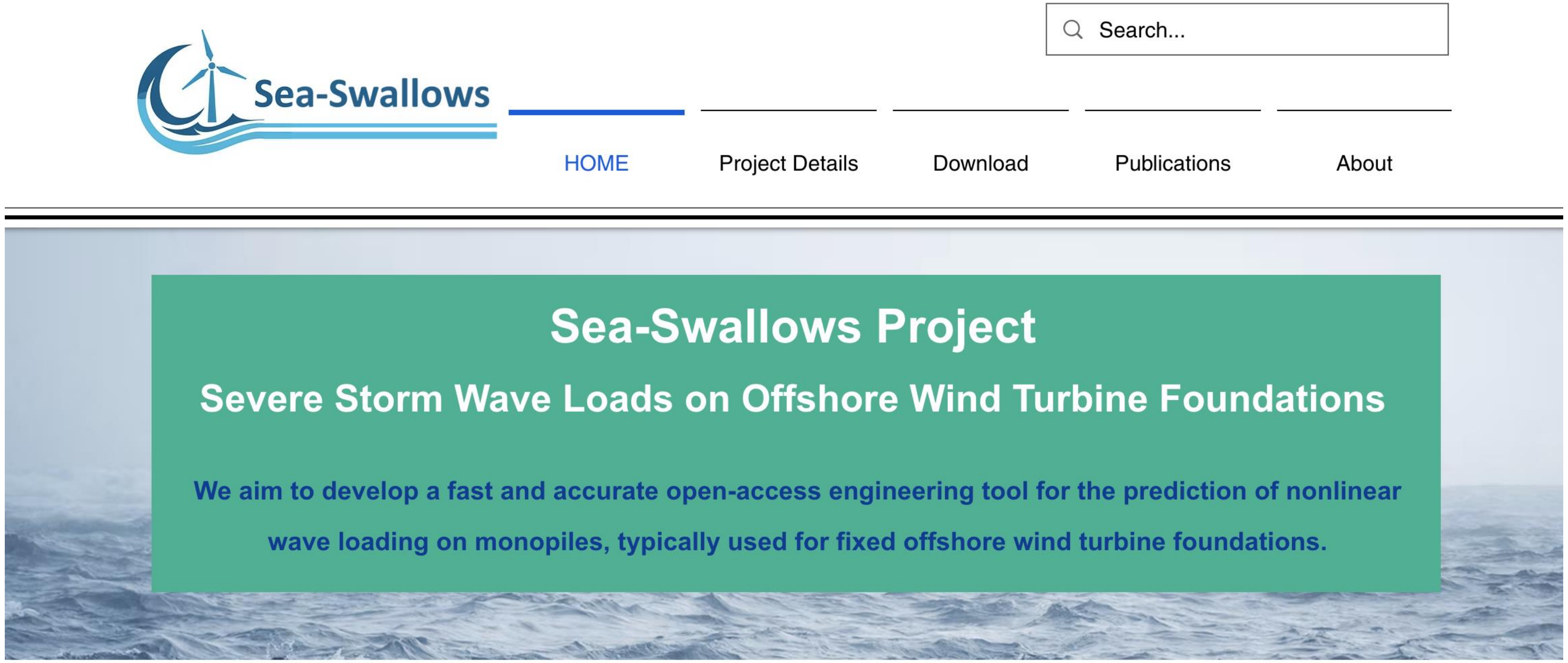
$M_1 = F_1 * \text{Arm1}, \ldots, M_5 = F_5 * \text{Arm5};$

$M = M_1 + \ldots + M_5$

Sea-Swallows Engineering Tool (SeaSwallowsTool)

Project website: https://www.sea-swallows.org

Download information: https://www.sea-swallows.org/download



- **License agreement**

The Sea-Swallows Engineering Tool version 1.0 operates on a request-on-access mechanism.

It is currently only open for academic use and testing.

Before downloading it by clicking the “Request Access” button, you will request access via email and receive this license agreement.

Please read and sign the licence agreement to gain access.

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Signature of Authorized Representative: __________
Name/Title of Authorized Representative: __________
Date: _______________________________________

- **Input**

Input	Example Case	Notes
1. Incoming wave (Choose by up and down arrow keys)	Crest-focused	1. Crest-focused: Crests of wave components are focused at t = 0 s and the focal point (cylinder centre). 2. Trough-focused: Same as crest-focused, but the deepest trough is at t = 0 s. 3. 90° Shift (crest): 90° phase shift of the crest-focused waves (Max force at t = 0 s). 4. 90° Shift (trough): Same as 90° Shift (crest), but built from the trough-focused wave.
2. Peak wave period T_p (s)		Peak wave period.
3. Water depth d (m)		Constant water depth where the cylinder is installed.
4. Cylinder diameter D (m)		Diameter of the wind turbine foundation.
5. Peak wave amplitude A (m)		Linearised amplitude of the synthesised crest (≈ peak wave elevation of crest-focused waves for small-steepness waves).
6. Folder to save result files		Any writable directory. Hit ↲ to accept the default.

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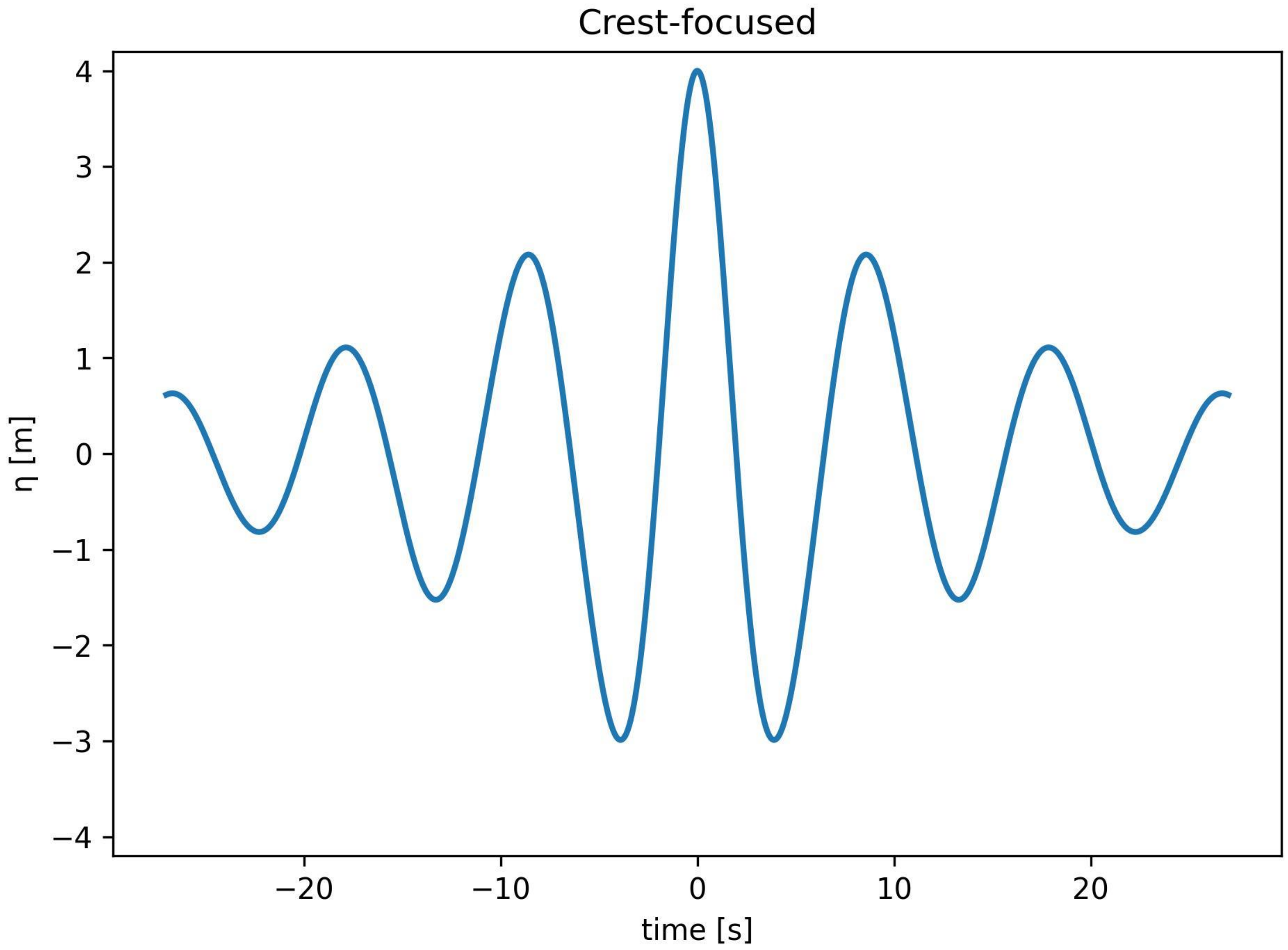
2. Peak wave period T_p (s)	9	Peak wave period.
3. Water depth d (m)	25	Constant water depth where the cylinder is installed.
4. Cylinder diameter D (m)	9	Diameter of the wind turbine foundation.
5. Peak wave amplitude A (m)	4	Linearised amplitude of the synthesised crest (≈ peak wave elevation of crest-focused waves for small-steepness waves).
6. Folder to save result files	↲	Any writable directory. Hit ↲ to accept the default.

- **Incoming wave condition**

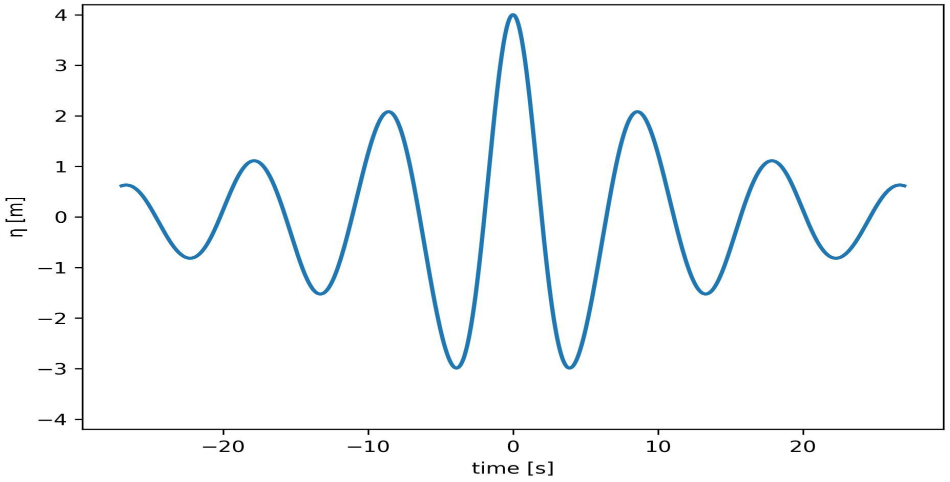
A **focused wave** type, generated by the **NewWave theory** and based on the **JONSWAP** spectrum, is used to represent a short-term extreme wave.



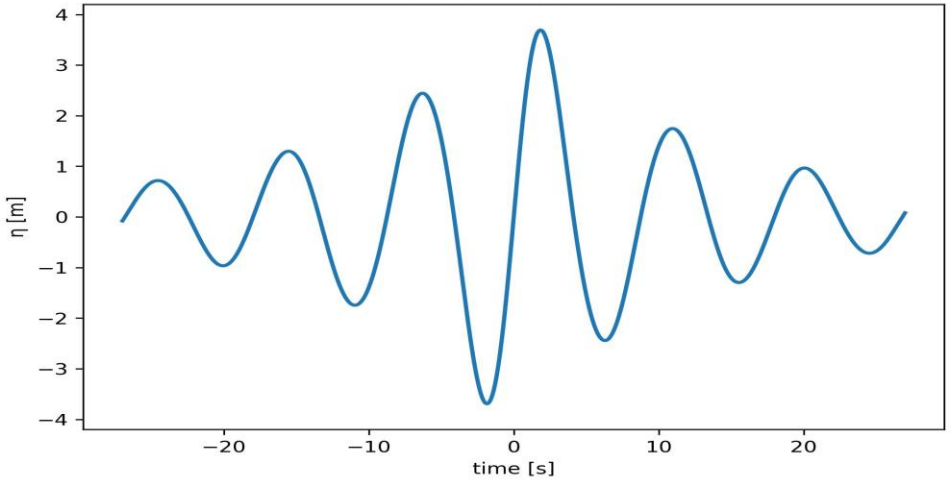
- **Incoming wave condition – surface elevation time history**

Phase shift options:

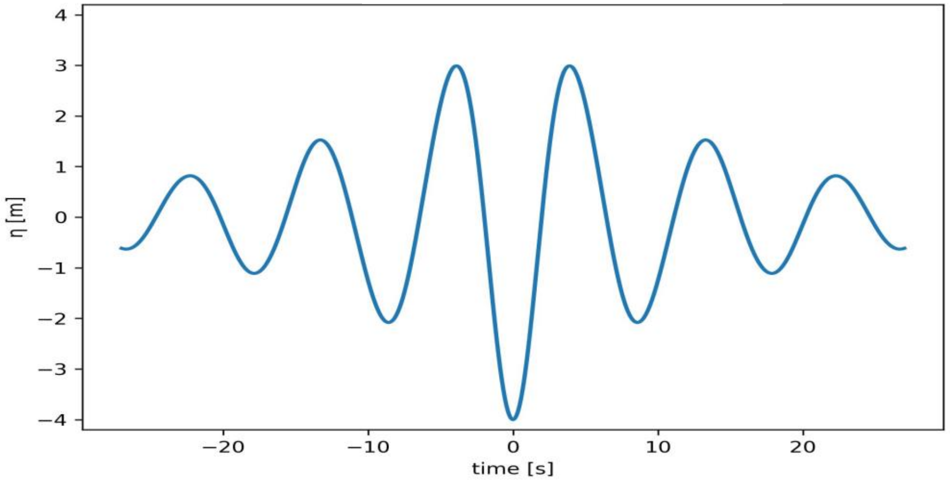
Crest-focused



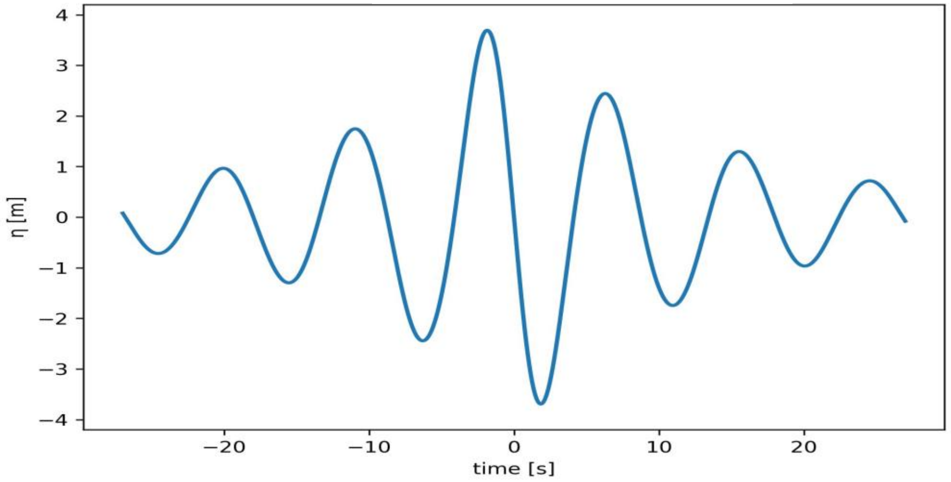
90° shift (crest)



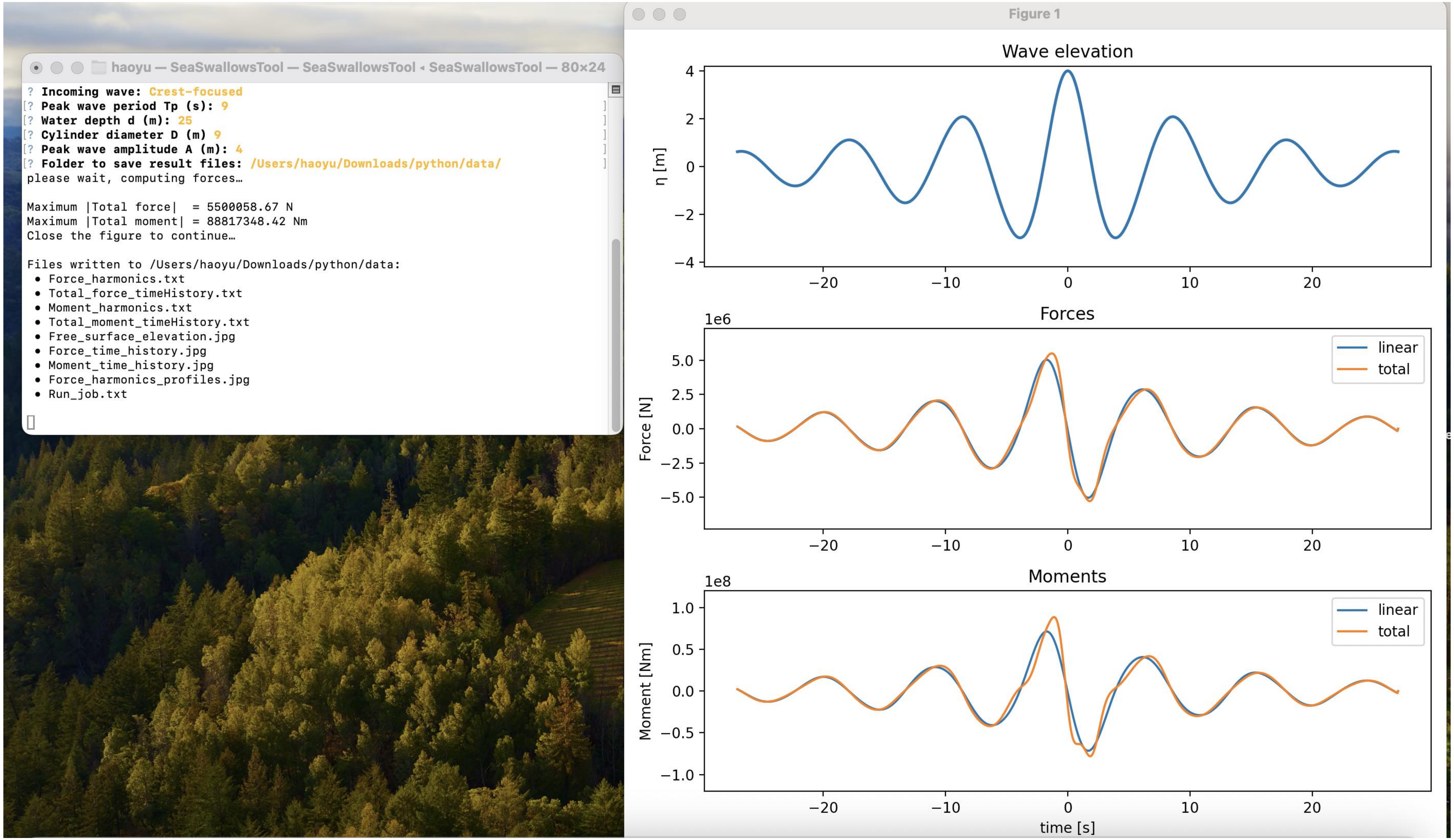
Trough-focused



90° shift (trough)



- **Output**

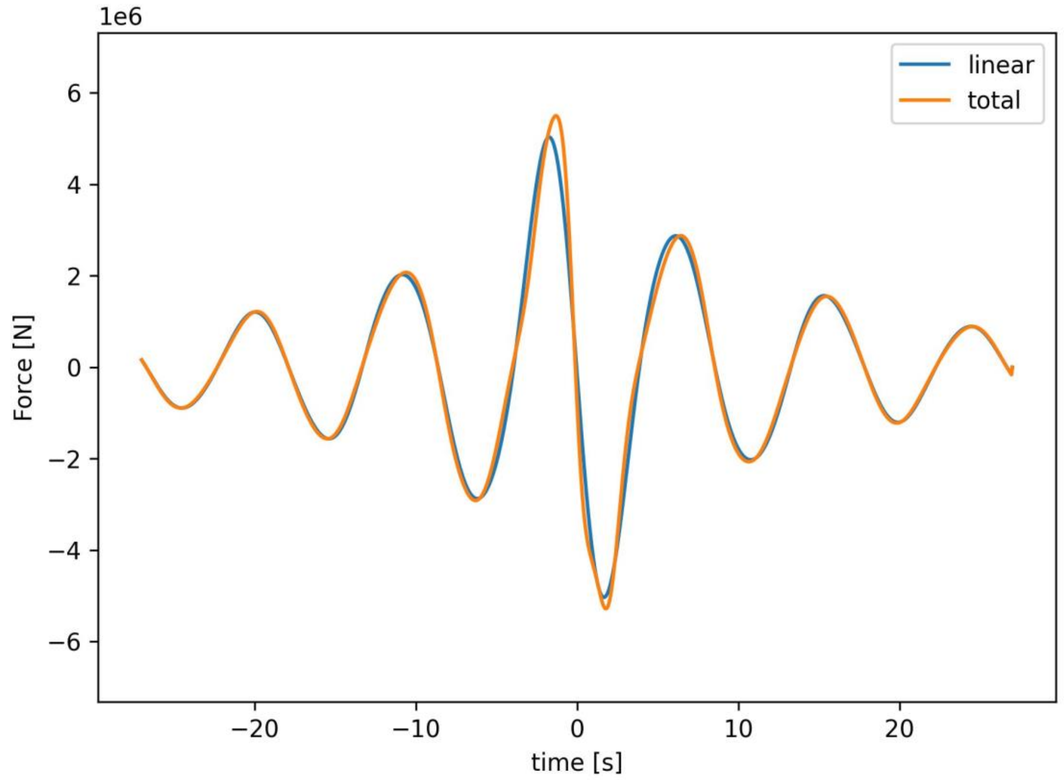

haoyu — SeaSwallowsTool — SeaSwallowsTool ‹ SeaSwallowsTool — 80×24
? Incoming wave: Crest-focused
? Peak wave period Tp (s): 9
? Water depth d (m): 25
? Cylinder diameter D (m) 9
? Peak wave amplitude A (m): 4
? Folder to save result files: /Users/haoyu/Downloads/python/data/
please wait, computing forces…
Maximum |Total force| = 5500058.67 N
Maximum |Total moment| = 88817348.42 Nm
Close the figure to continue…
Files written to /Users/haoyu/Downloads/python/data:
• Force_harmonics.txt
• Total_force_timeHistory.txt
• Moment_harmonics.txt
• Total_moment_timeHistory.txt
• Free_surface_elevation.jpg
• Force_time_history.jpg
• Moment_time_history.jpg
• Force_harmonics_profiles.jpg
• Run_job.txt
Figure 1
Wave elevation
η [m]
Forces
1e6
Force [N]
linear
total
Moments
1e8
Moment [Nm]
linear
total
time [s]

- **Output files**

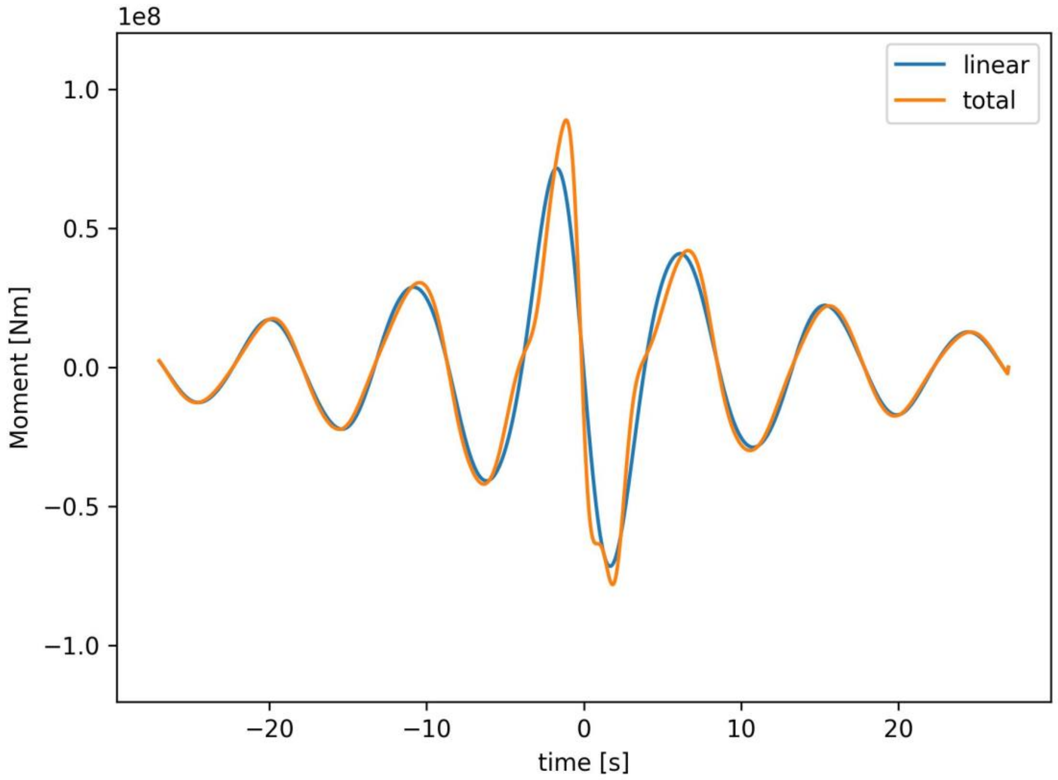
File	Content
Force_harmonics.txt	Time series of linear force harmonics to 5th harmonics, $F_1 \ldots F_5$
Total_force_timeHistory.txt	Time series of linear and nonlinear total force
Moment_harmonics.txt	Time series of linear moment harmonics to 5th moment harmonics, $M_1 \ldots M_5$
Total_moment_timeHistory.txt	Time series of linear and nonlinear total moment
Free_surface_elevation.jpg	Free surface elevation of incident waves
Force_time_history.jpg	Linear vs Nonlinear total force in time histories
Moment_time_history.jpg	Linear vs Nonlinear total moment in time histories
Force_harmonics_profiles.jpg	5-panel plot: $F_1 \ldots F_5$
Run_job.txt	Full input record, peak nonlinear force and moment values

- **Output files**

Force_time_history.jpg

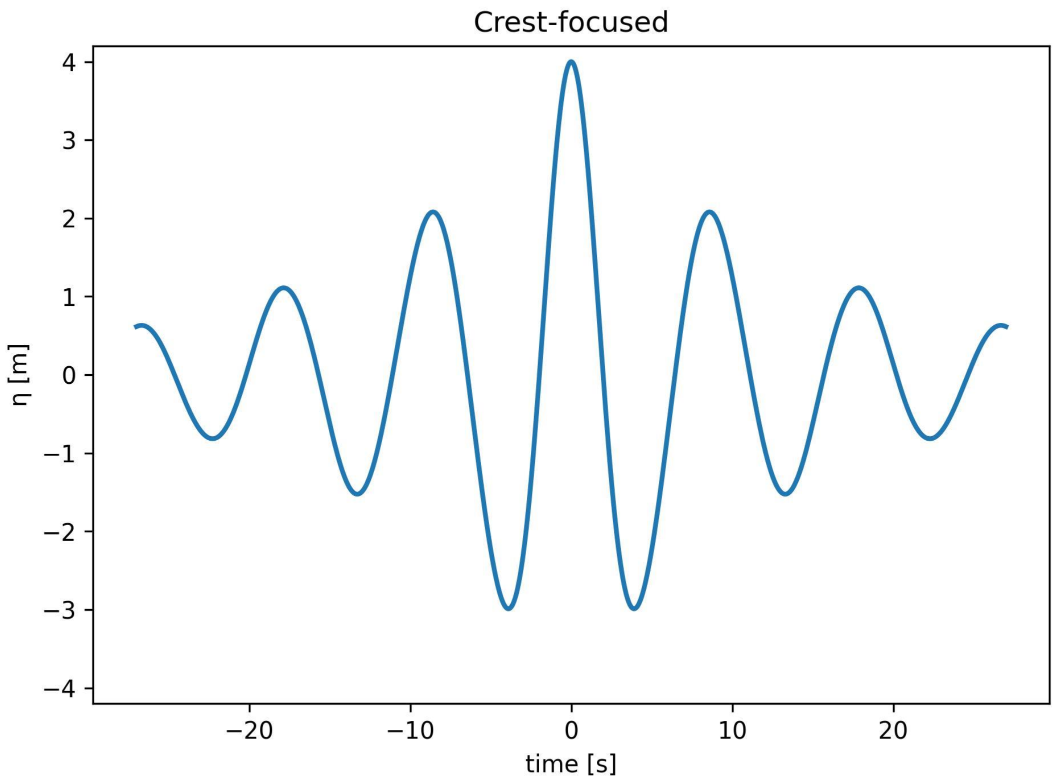


Moment_time_history.jpg

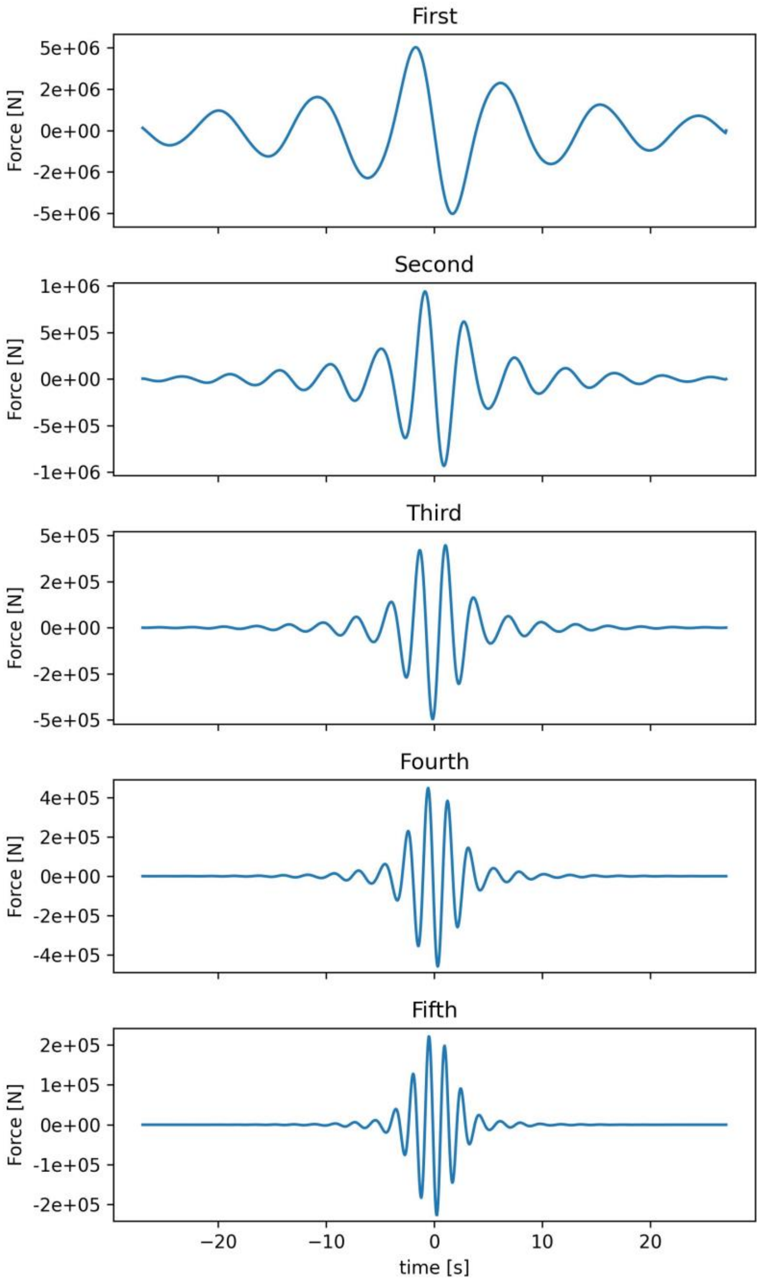


- **Output files**

Free_surface_elevation.jpg

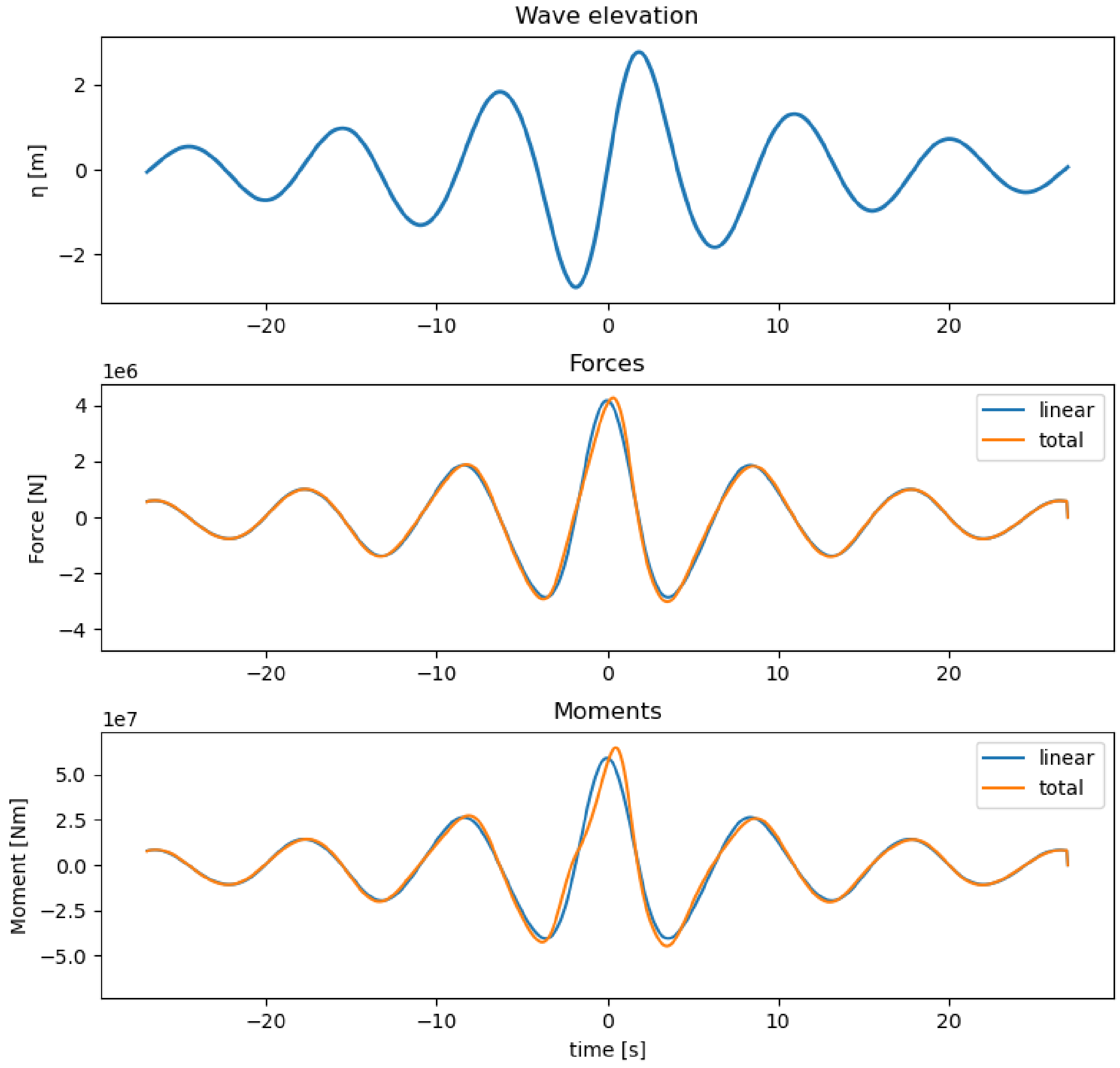


Force_harmonics_profiles.jpg

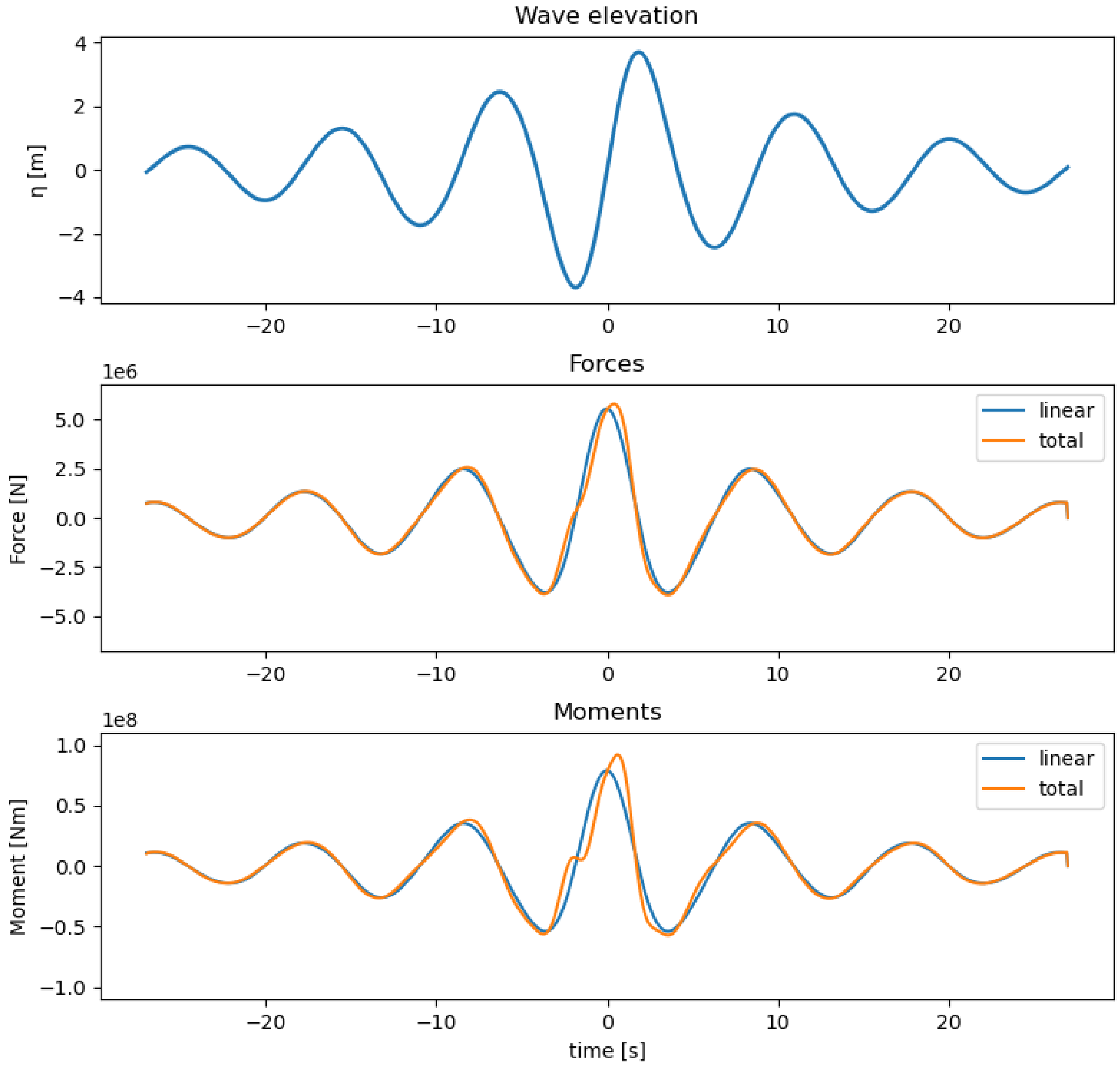


- **Different tests (varying amplitude)** $T_p = 9$ s, $d = 25$ m, $D = 9$ m, $kR = 0.25$, $kd = 1.40$

$A = 3$ m, $kA = 0.17$



$A = 4$ m, $kA = 0.22$



- **Different tests (varying amplitude)**

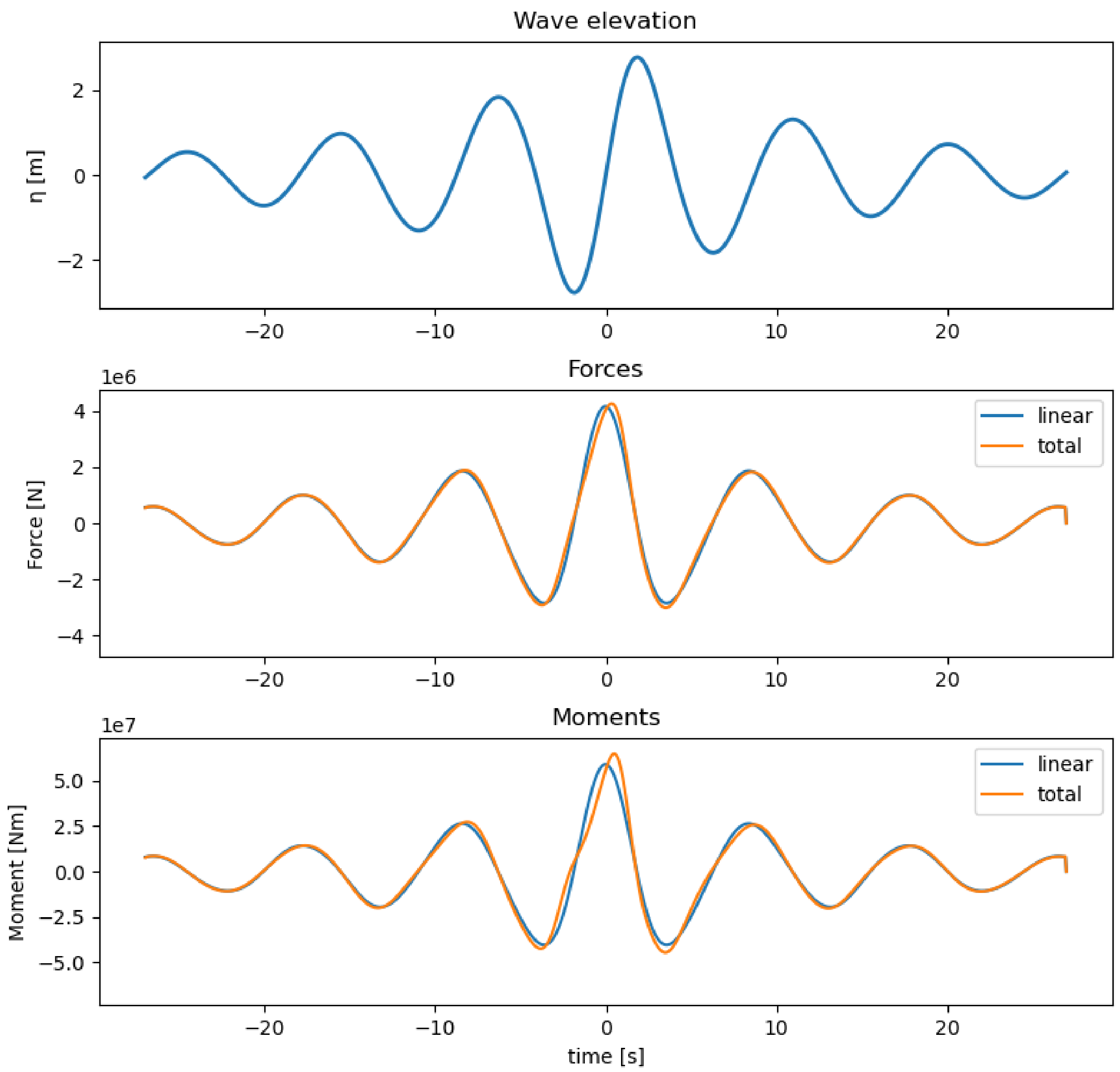
Up crossing wave

$T_p = 9$ s, $d = 25$ m, $D = 9$ m,

$kR = 0.25$,

$kd = 1.40$

$A = 3$ m, $kA = 0.17$



- **Different tests (varying amplitude)**

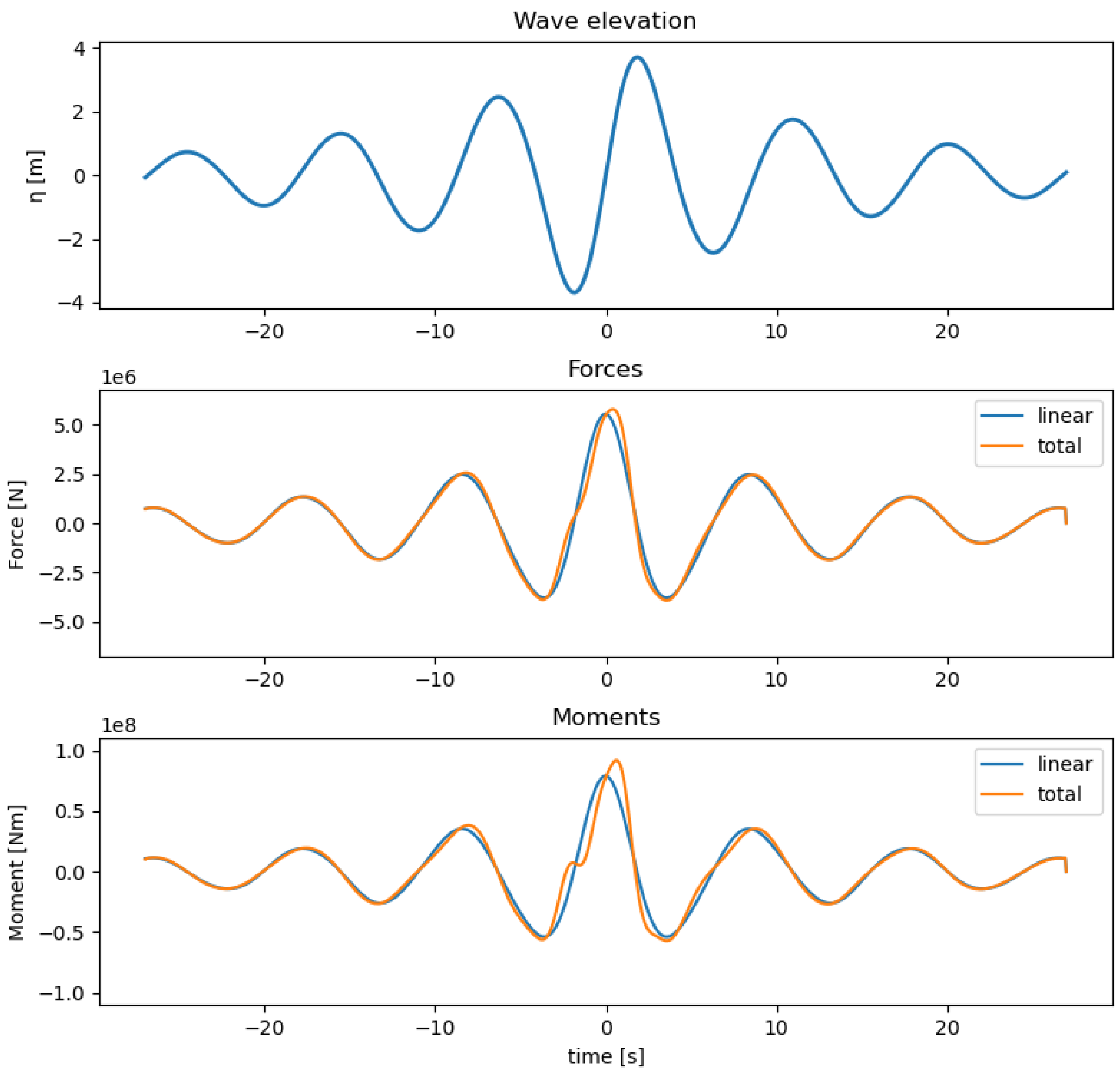
Up crossing wave

T_p = 9 s, d = 25 m, D = 9 m,

kR = 0.25,

kd = 1.40

A = 4 m, kA = 0.17



- **Different tests (varying amplitude)**

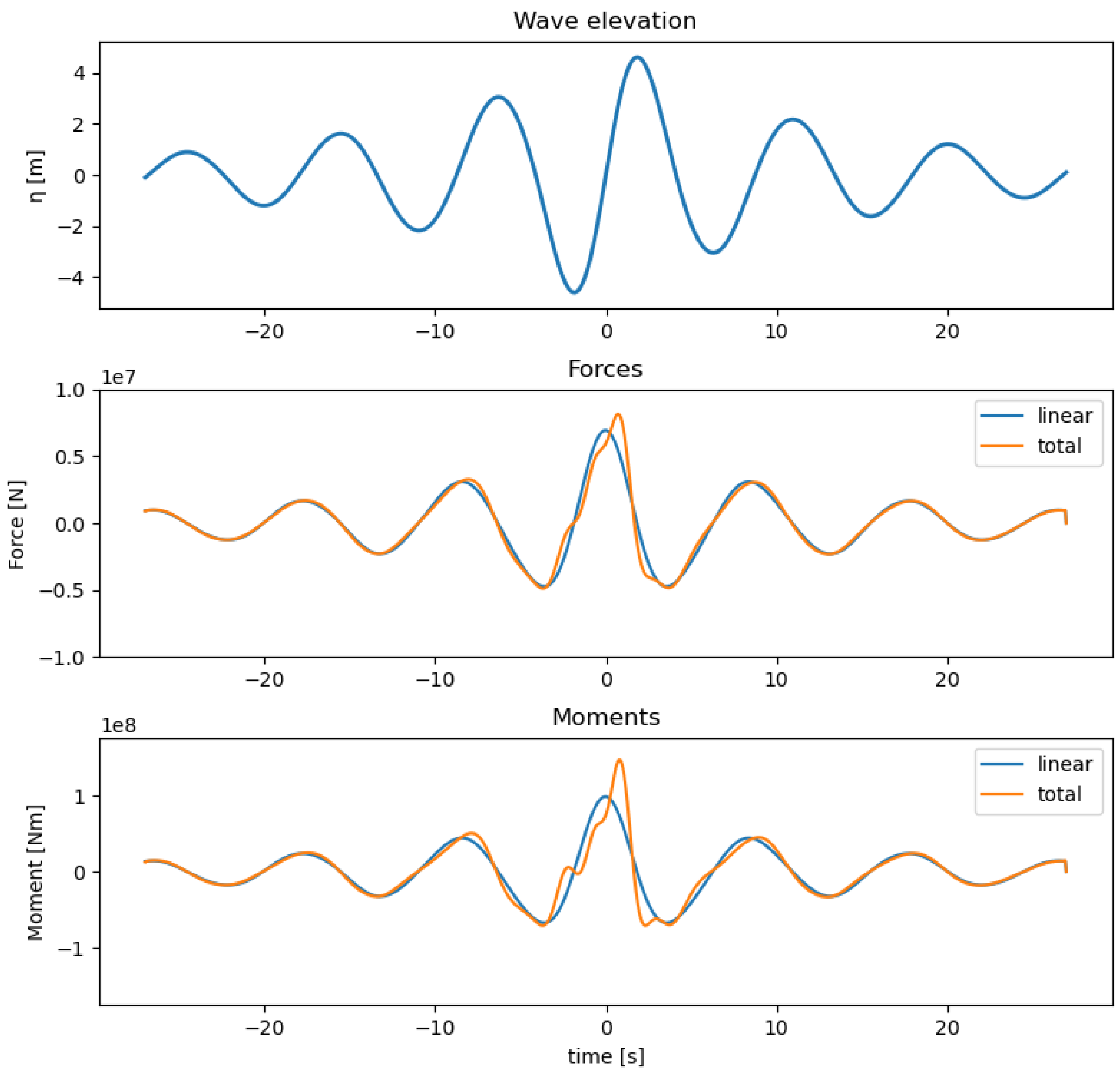
Up crossing wave

T_p = 9 s, d = 25 m, D = 9 m,

kR = 0.25,

kd = 1.40

A = 5 m, kA = 0.17



- ## Training data range

For most wave regime:

$d/R \leq 12$, (Scale between water depth to cylinder radius)
$0.05 \leq kA \leq 0.30$, (wave steepness)
$0.10 \leq kR \leq 0.49$, (cylinder slenderness)
$0.76 \leq kd \leq 4.4$. (Relative depth)
where, k – wavelength, A – linearised wave amplitude, R – cylinder radius, d – water depth

Some exceptional regimes, e.g., when $d/R > 9$, $kA \leq 0.19$

Calculations outside the range will be detected and the current calculation will be stopped, then skipped to the next run:

```
? Incoming wave: Crest-focused
? Peak wave period Tp (s): 9
? Water depth d (m): 25
? Cylinder diameter D (m) 9
? Peak wave amplitude A (m): 6
? Folder to save result files: /Users/haoyu/Downloads/python/data/
⚠️ WARNING — Requested wave regime is outside the model's training range. Results may be unreliable.
Skipping to the next run.
? Run another case? (Y/n)
```

Thank you!

Project website: https://www.sea-swallows.org