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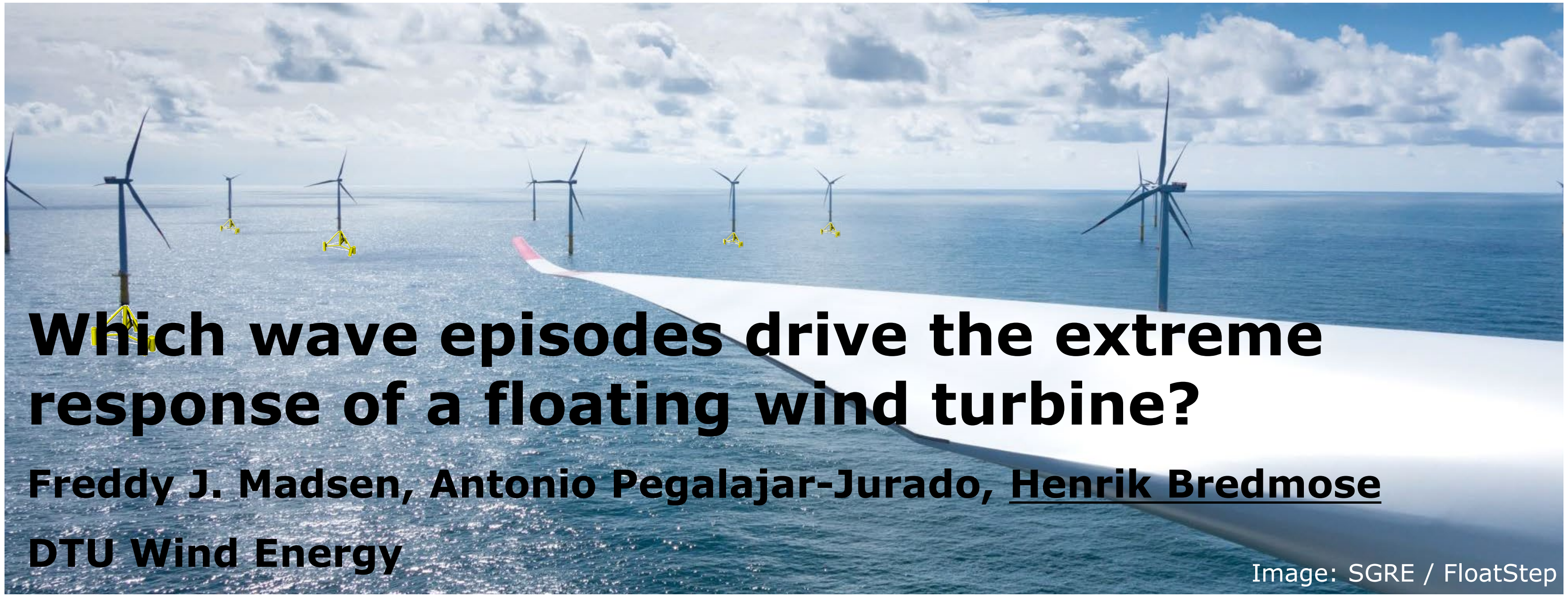
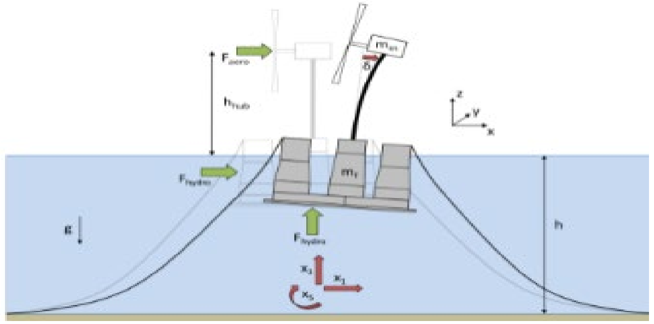


Which wave episodes drive the extreme response of a floating wind turbine?

Freddy J. Madsen, Antonio Pegalajar-Jurado, Henrik Bredmose

DTU Wind Energy

Image: SGRE / FloatStep



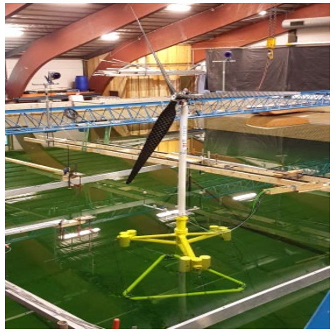


Image: Bourbon Offshore

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SIEMENS Gamesa RENEWABLE ENERGY

DHI

Stiesdal Offshore Technologies

STROMNING

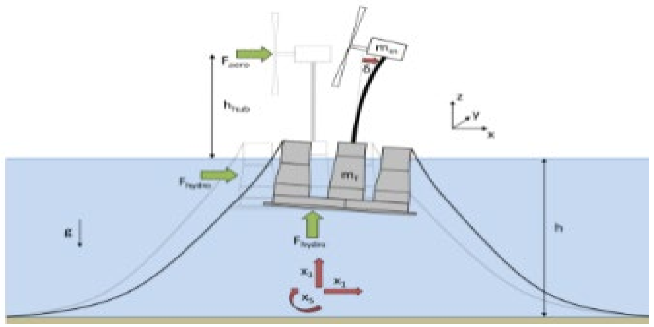
THE UNIVERSITY OF WESTERN AUSTRALIA

Present research is part of

The FloatStep Project

Innovation Fund Denmark (2018-2022)

Work done in interaction with Paul H. Taylor, Jana Orszaghova and Hugh Wolgamot, University of Western Australia



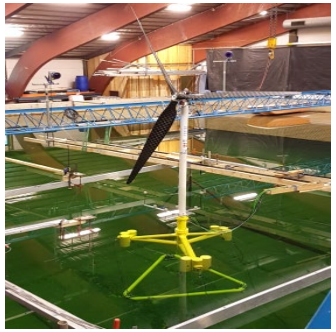


Image: Bourbon Offshore

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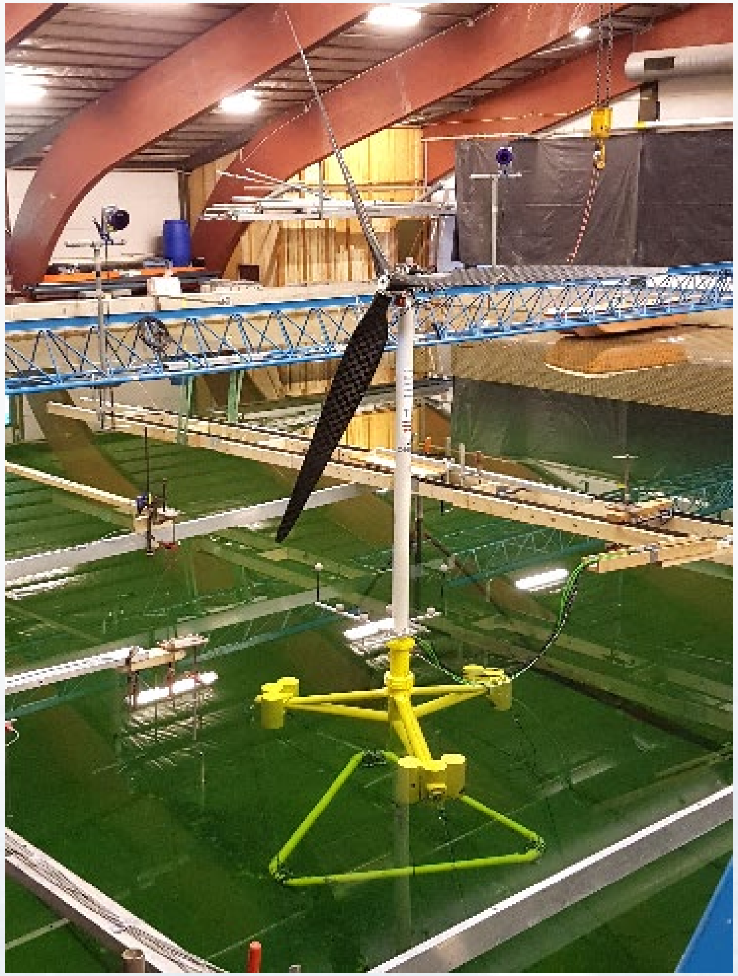
TetraSpar proof of concept tests 2017

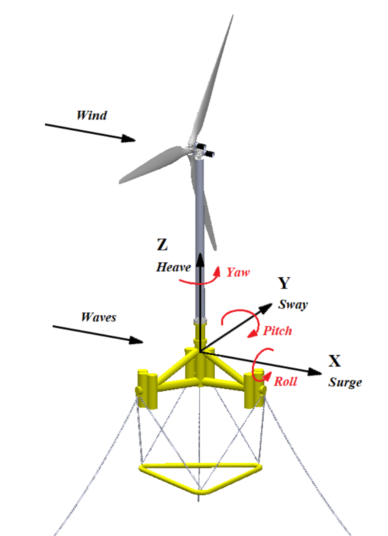
Stiesdal Offshore Technologies

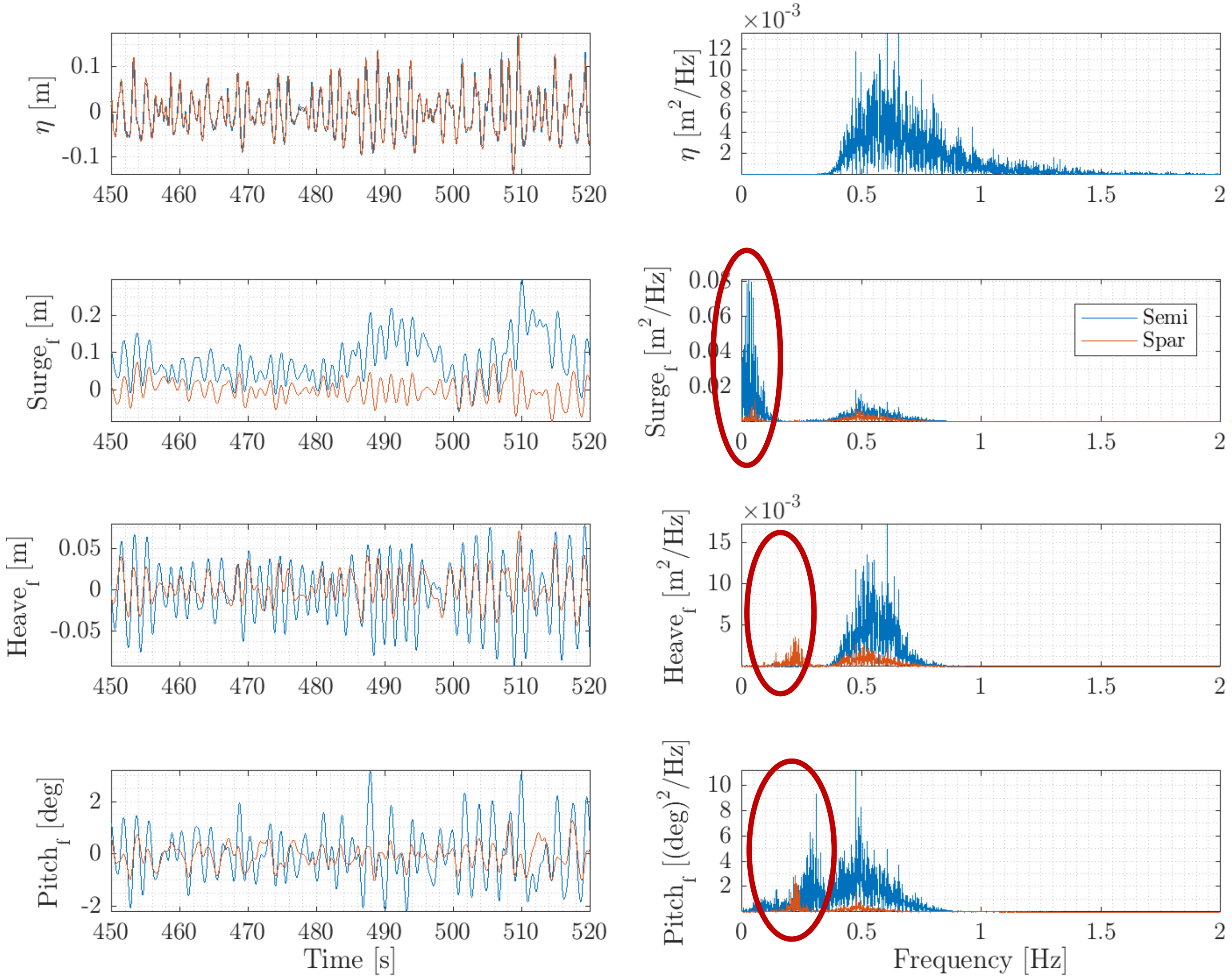
DHI

Borg et al (2018), EERA DeepWind



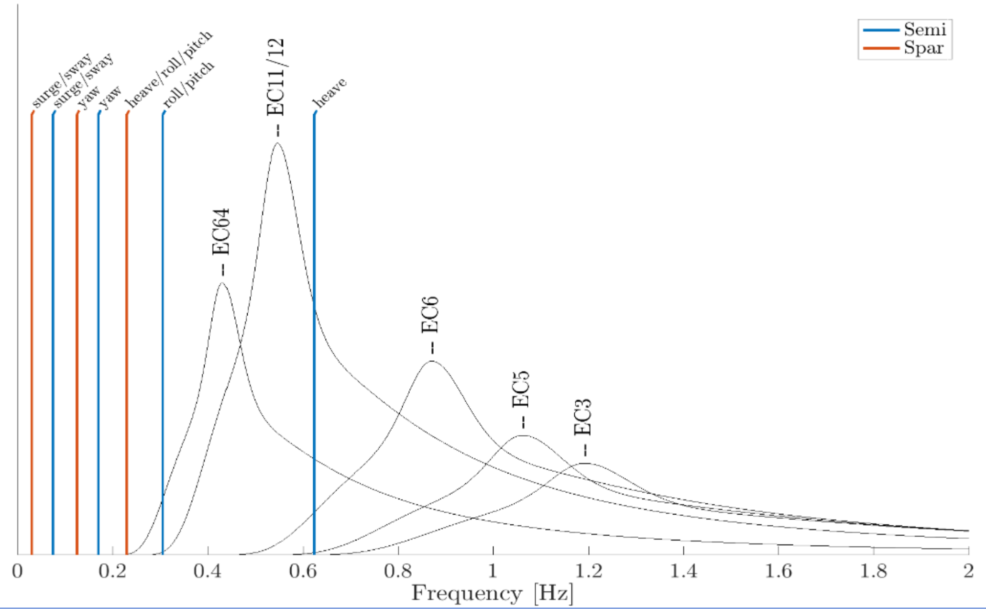
Extreme responses and subharmonic forcing

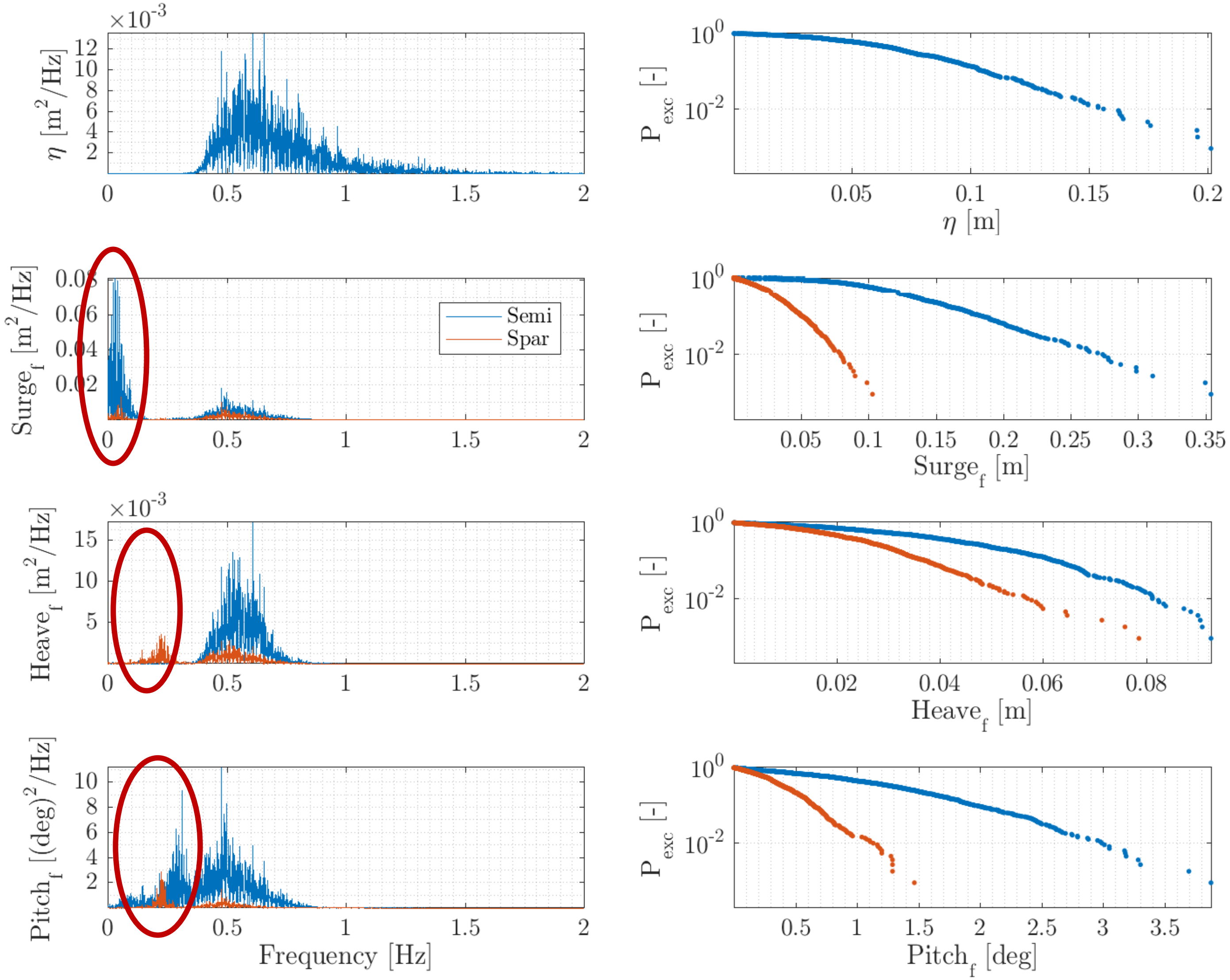


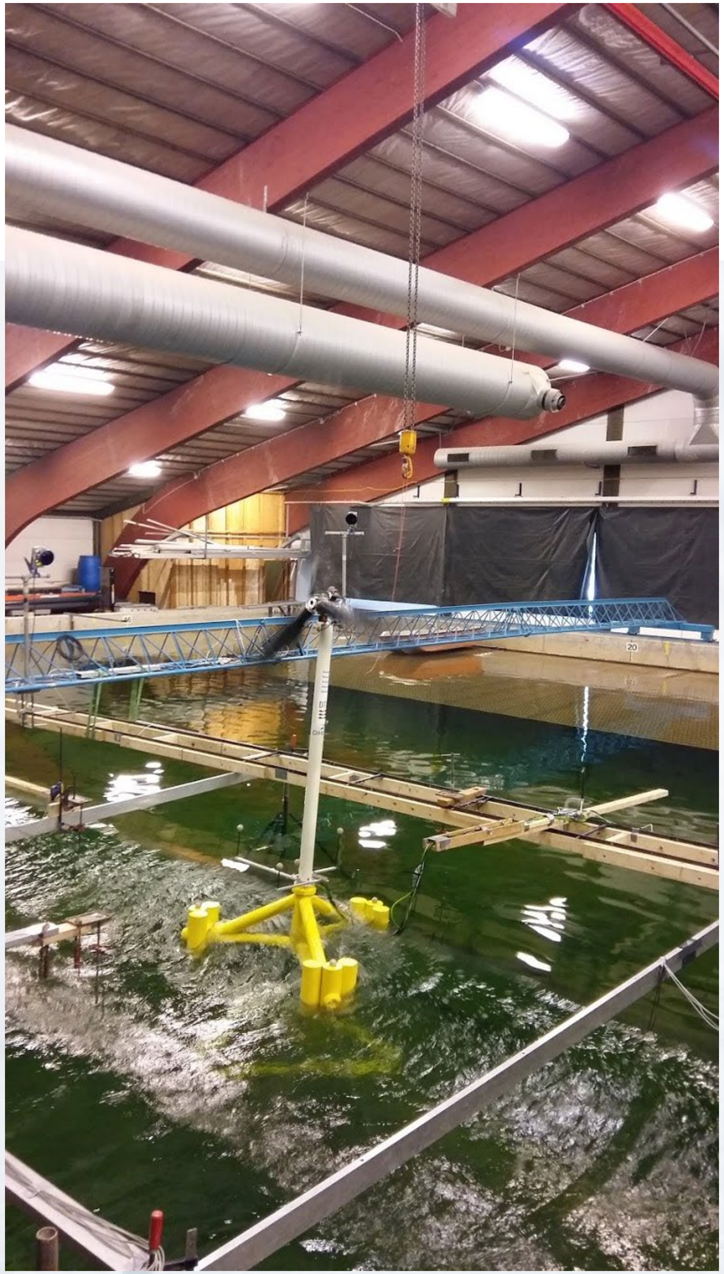


Extreme responses and subharmonic forcing

- Low-frequency response from nonlinear subharmonic wave forcing
- Excitations of the floater natural frequencies





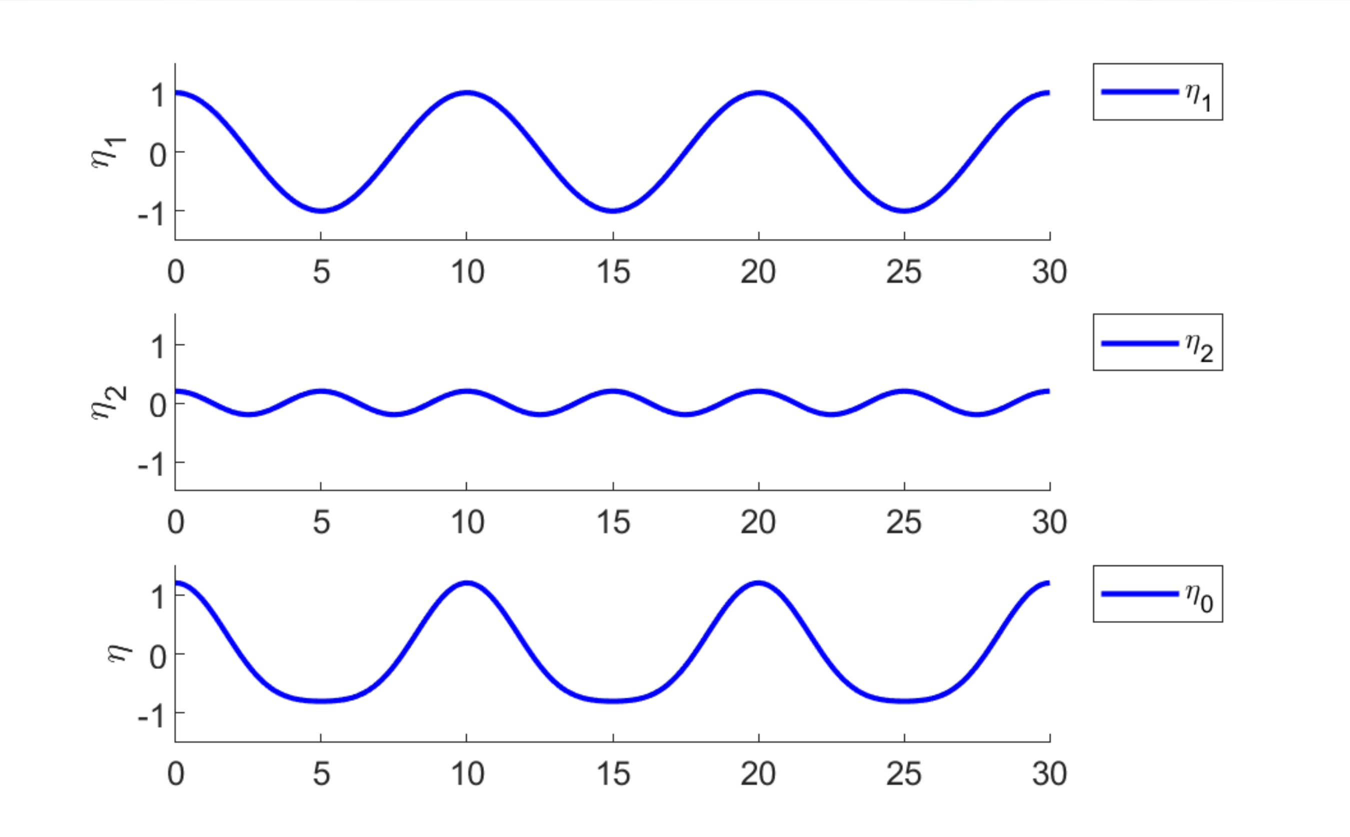


Which wave episodes drive the extreme response events?

- Experimental analysis with harmonic separation
- Second-order response model with modal calibration
- Accelerated QTF method
- NewResponse
- First-order reliability method (FORM)

Methodology – Harmonic separation

Walker, Taylor & Taylor (2004)



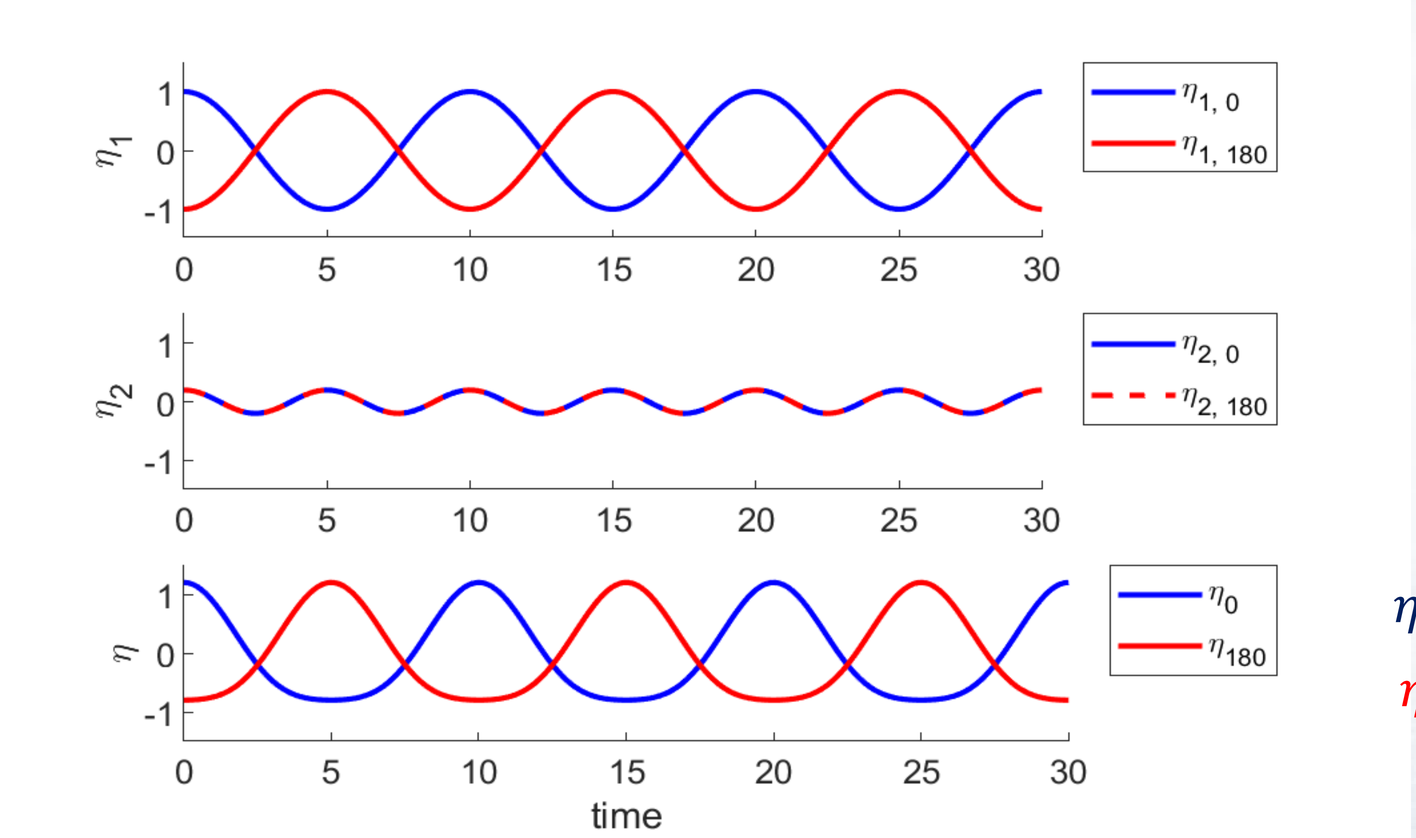
$$\eta_1 = a \cos \omega t$$

$$\eta_2 = c_{11} a^2 \cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

Methodology – Harmonic decomposition

Walker, Taylor & Taylor (2004)



$$\eta_1 = a\cos\omega t$$

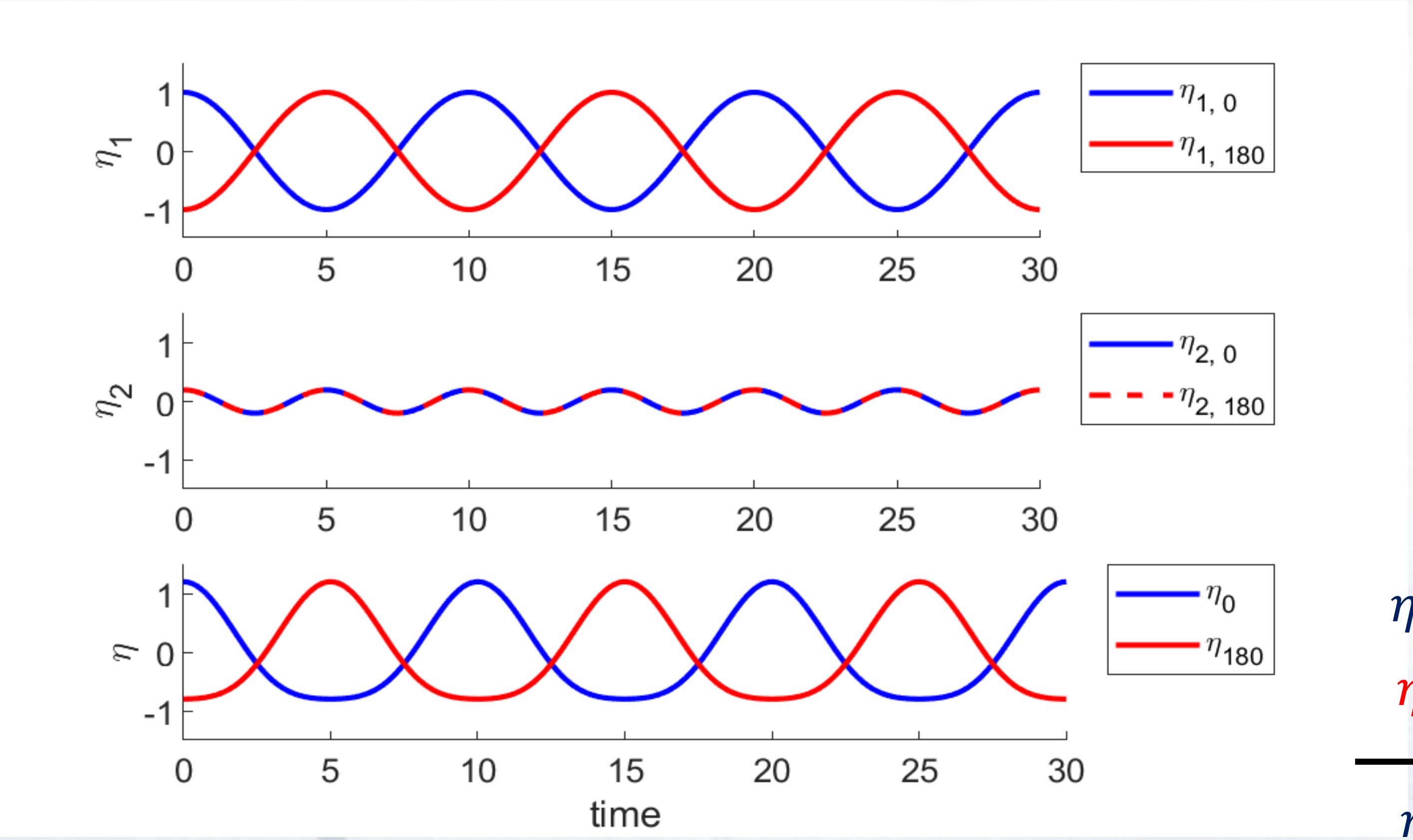
$$\eta_2 = c_{11}a^2\cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

$$\eta_{180} = -\eta_1 + \eta_2$$

Methodology – Harmonic decomposition

Walker, Taylor & Taylor (2004)



$$\eta_1 = a \cos \omega t$$

$$\eta_2 = c_{11} a^2 \cos 2\omega t$$

$$\eta_0 = \eta_1 + \eta_2$$

$$\eta_{180} = -\eta_1 + \eta_2$$

$$\eta_1 = (\eta_0 - \eta_{180})/2$$

$$\eta_2 = (\eta_0 + \eta_{180})/2$$

Methodology – Harmonic decomposition

- Non-linear Stokes perturbation expansion (Fitzgerald et al., 2014):

$$F = f_{11}a\cos\phi + f_{22}a^2\cos 2\phi + f_{33}a^3\cos 3\phi + f_{44}a^4\cos 4\phi$$

$$+f_{20}a^2 + f_{31}a^3\cos\phi + f_{42}a^4\cos 2\phi + O(a^5)$$

- Contributions to the odd and even harmonics:

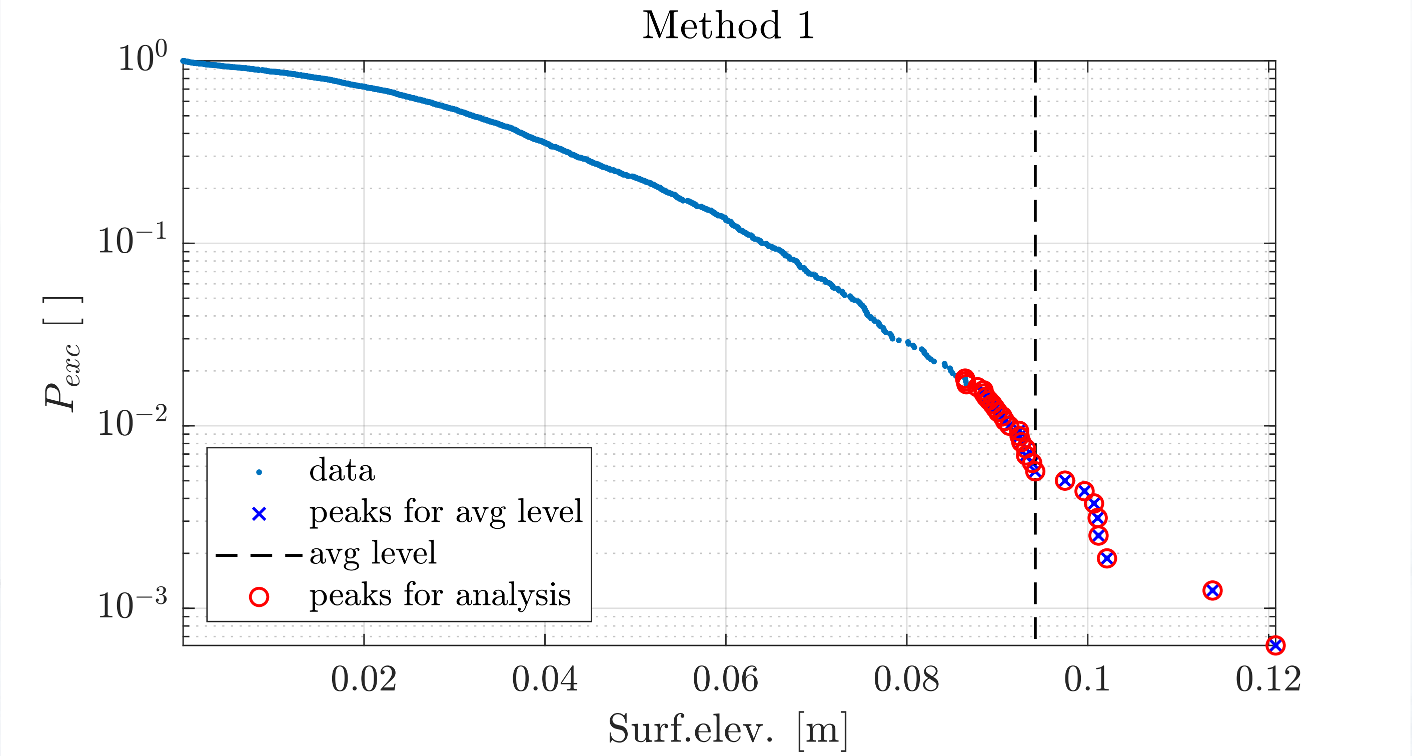
  Odd harmonic: $\frac{F_0 - F_{180}}{2} = f_{11}a\cos\phi + f_{33}a^3\cos 3\phi + f_{31}a^3\cos\phi + O(a^5)$

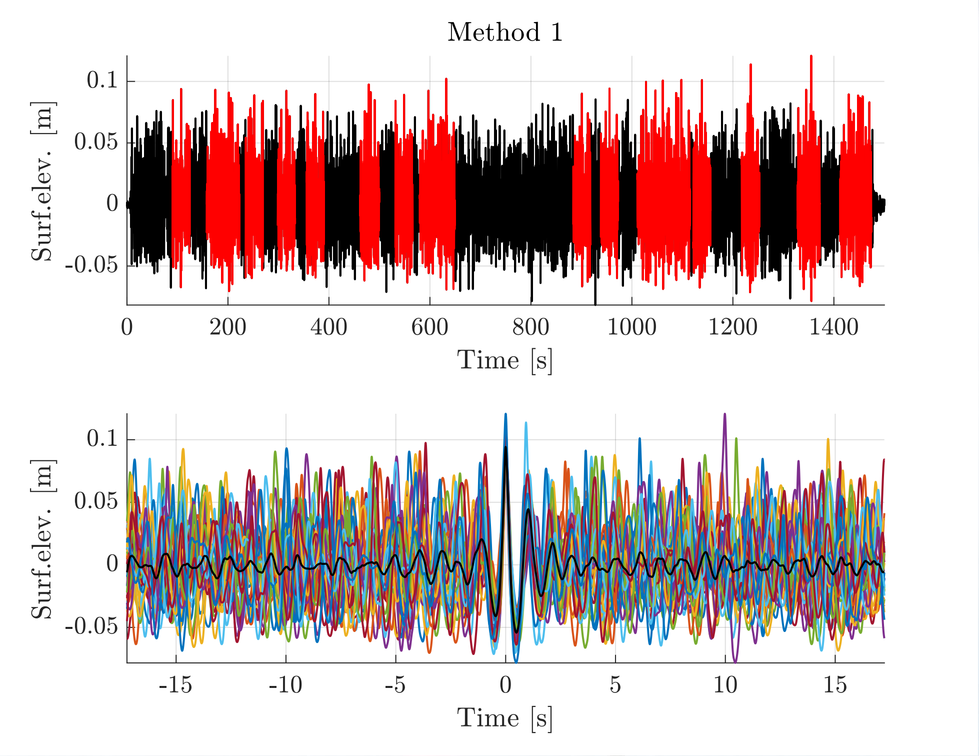
  Even harmonic: $\frac{F_0 + F_{180}}{2} = f_{22}a^2\cos 2\phi + f_{44}a^4\cos 4\phi + f_{20}a^2 + f_{42}a^4\cos 2\phi + O(a^6)$

- Can be extended even further if 90 degree and 270 degree phase shifted data is available – four-phase separation

- Can be adapted to responses as well (Orszaghova et al., 2020)

Methodology – Extreme events extraction



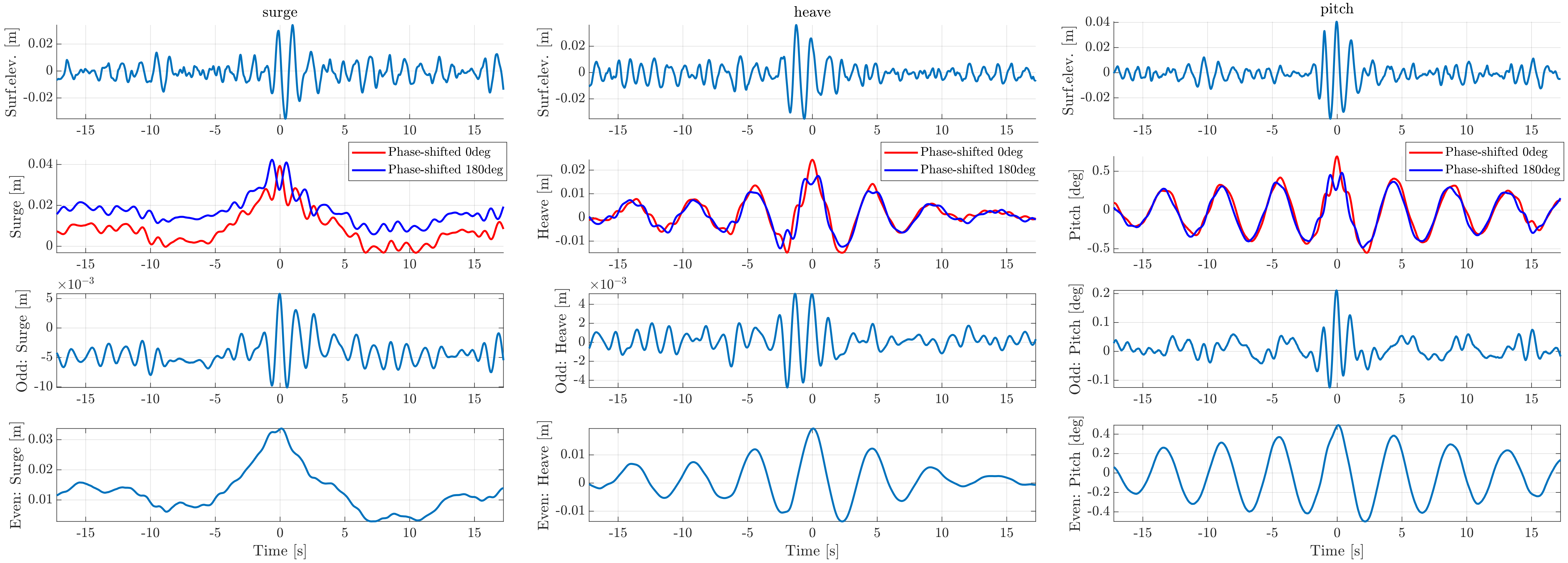


Environmental Conditions

- We focus on waves-only
- Sea state above rated conditions

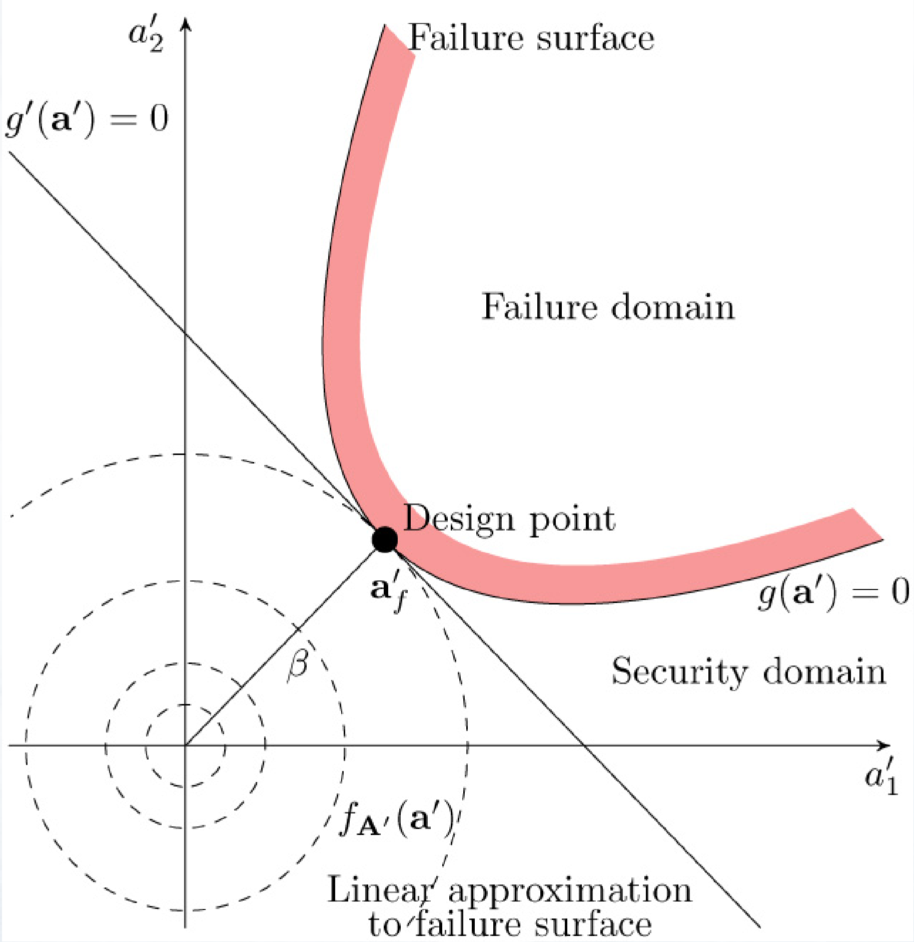
EC	Type	Full scale			Model scale			Turbine operation
		U_{hub} [m/s]	H, H_s [m]	T, T_p [s]	U_{hub} [m/s]	H, H_s [m]	T, T_p [s]	
03	below rated	8.5	3.3	6.5	1.10	0.055	0.839	yes
05	rated	11.4	4.16	7.3	1.47	0.069	0.942	yes
06	above rated	18.0	6.18	8.9	2.32	0.103	1.149	yes
064	above rated	18.0	6.18	18.0	2.32	0.175	2.324	yes
11	ULS	18.0	10.5	14.2	2.32	0.175	1.833	idling
12	ULS	18.0	10.5	14.2	2.32	0.175	1.833	yes

Results - method 1
Extreme events are conditioned on total response



Can we predict these wave episodes with a response model?

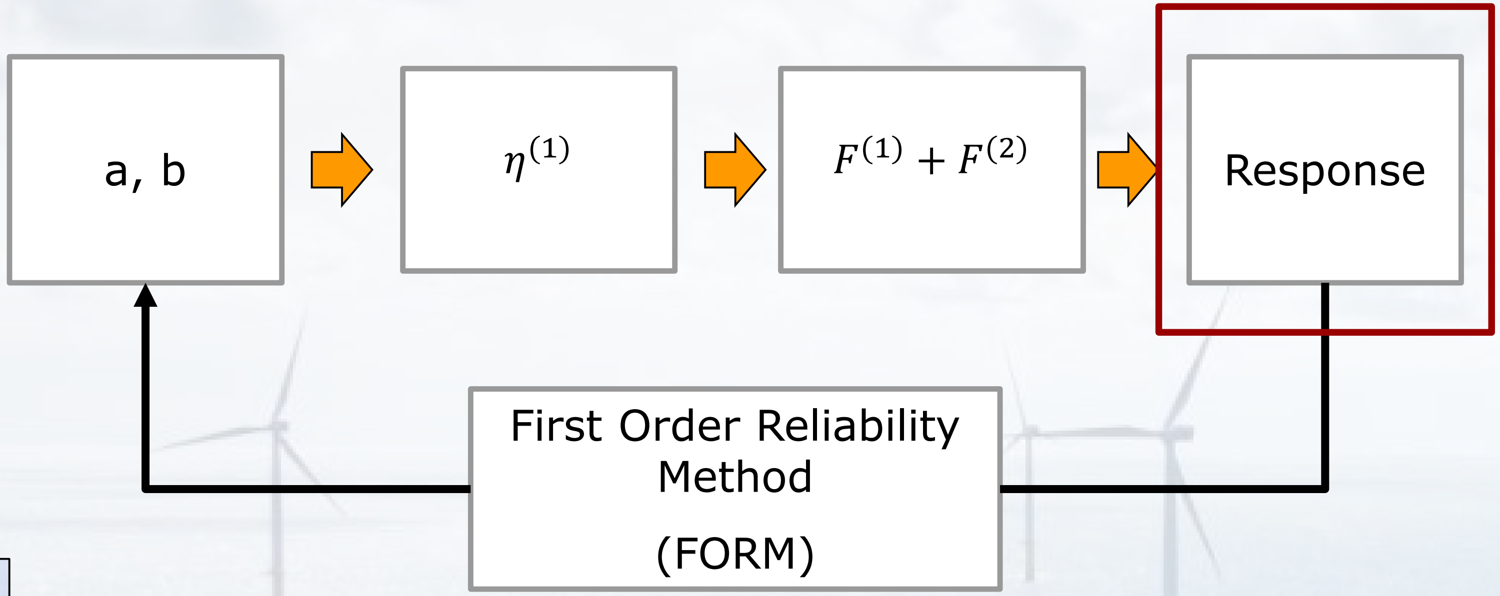
- Second-order forward model
- Run FORM to estimate the most likely extreme wave shapes (Ghadirian et al., 2017)
- Compare to tests



Source: Hernandez, Santiago & Diaz, Jacobo & Cid Montoya, Miguel & Baldomir, Aitor & Romera, Luis. (2012). Uncertainty and reliability in aircraft design and optimization. WIT Transactions on the Built Environment. 125. 219-230. 10.2495/OP120191.

Model setup

- Response modelling
  - HAWC2 (Morison based)
  - QuLAF
  - Linear model (RAO)
- Linear hydrodynamics
  - WAMIT
  - Slender-body model (TBI)
- Second-order forcing
  - Newman's approximation from WAMIT
  - Full response QTF from WAMIT
  - Accelerated second-order slender-body model (TBI)



The accelerated approach

- The traditional quadratic frequency interactions are costly in terms of CPU time
- Thus an accelerated approach is introduced (Bredmose and Pegalajar-Jurado, 2020a,b)
- Eigenvalues/eigenvectors of the combined QTF matrix
- ~1000 times faster than the traditional method for a 3 hour time series

$$F_{+}^{(2)} = \sum_{j=-N}^{N} \sum_{l=-N}^{N} QTF_{jl}^{+}\, \hat{\eta}_j\, \hat{\eta}_l\, e^{i(\omega_j+\omega_l)t} + CC$$

$$F_{-}^{(2)} = \sum_{j=-N}^{N} \sum_{l=-N}^{N} QTF_{jl}^{-}\, \hat{\eta}_j\, \hat{\eta}_l\, e^{i(\omega_j-\omega_l)t} + CC$$

$$\mathbf{Q} = \begin{bmatrix} \boldsymbol{QTF^{-}} & \boldsymbol{QTF^{+}} \\ \boldsymbol{QTF^{+}} & \boldsymbol{QTF^{-}} \end{bmatrix} \Rightarrow \lambda_s, \vec{v}_s \Rightarrow F^{(2)} = \sum_{s=1}^{n_{modes}} \lambda_s \left[\sum_{j=-N}^{N} \hat{\eta}_j\, e^{i\theta_j} v_{sj} \right]^2$$

Damping calibration of the forward model

- A constant linear global damping matrix $\mathbf{B}$ is built in the modal space
- The modal damping coefficients bn for each mode are calibrated
- The six modal damping ratios ζn are calibrated until the deviation of the standard deviation of the response is less than 5%

$$\mathbf{B} = (\mathbf{\Psi}_{num}^{T})^{-1}[b_n]\mathbf{\Psi}_{num}^{-1}.$$

$$b_n = 2\zeta_n\sqrt{m_n k_n}.$$

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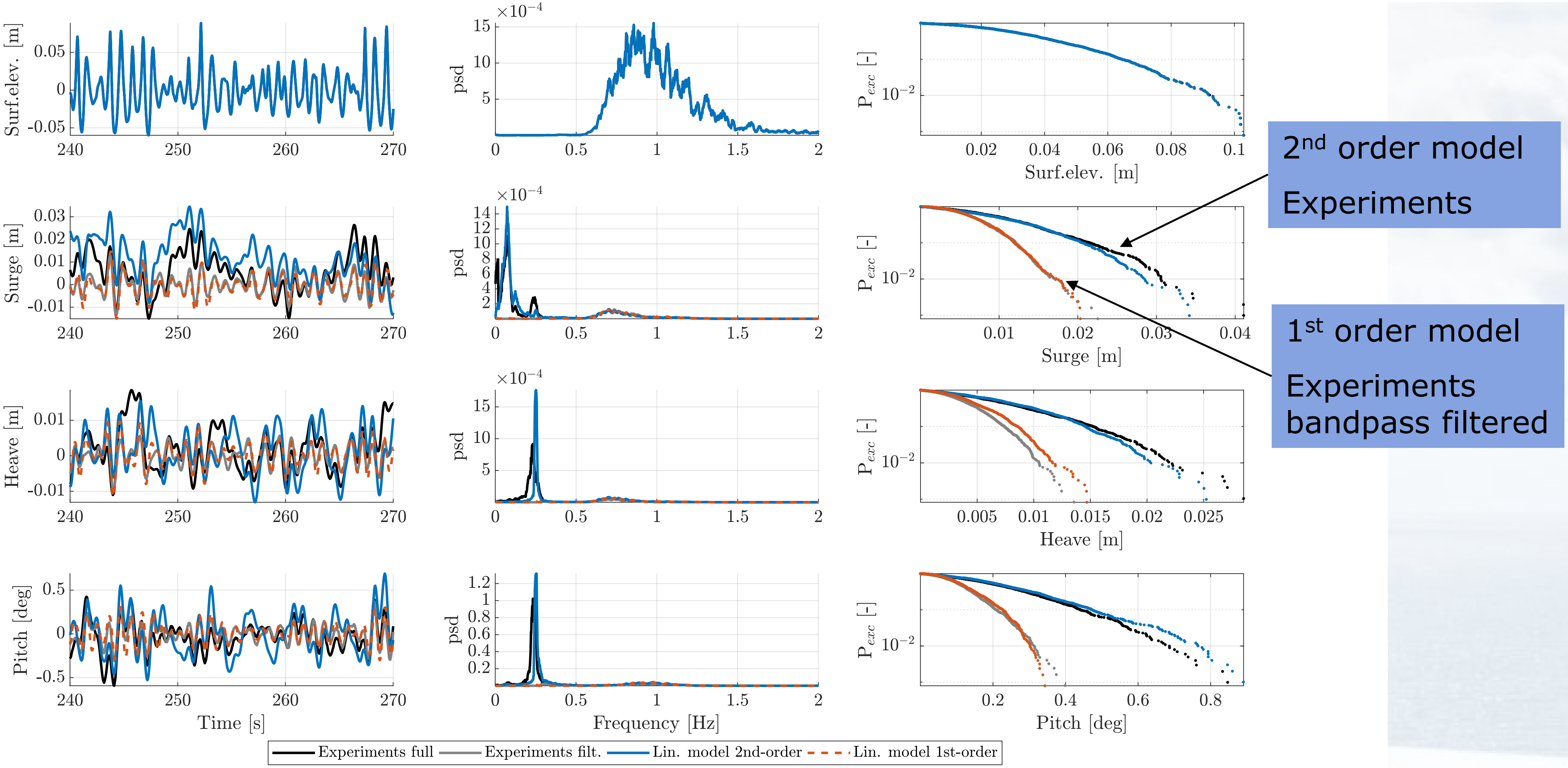
Statistics of the forward model: EC06



Flo

1st-order verification of FORM setup: NewResponse

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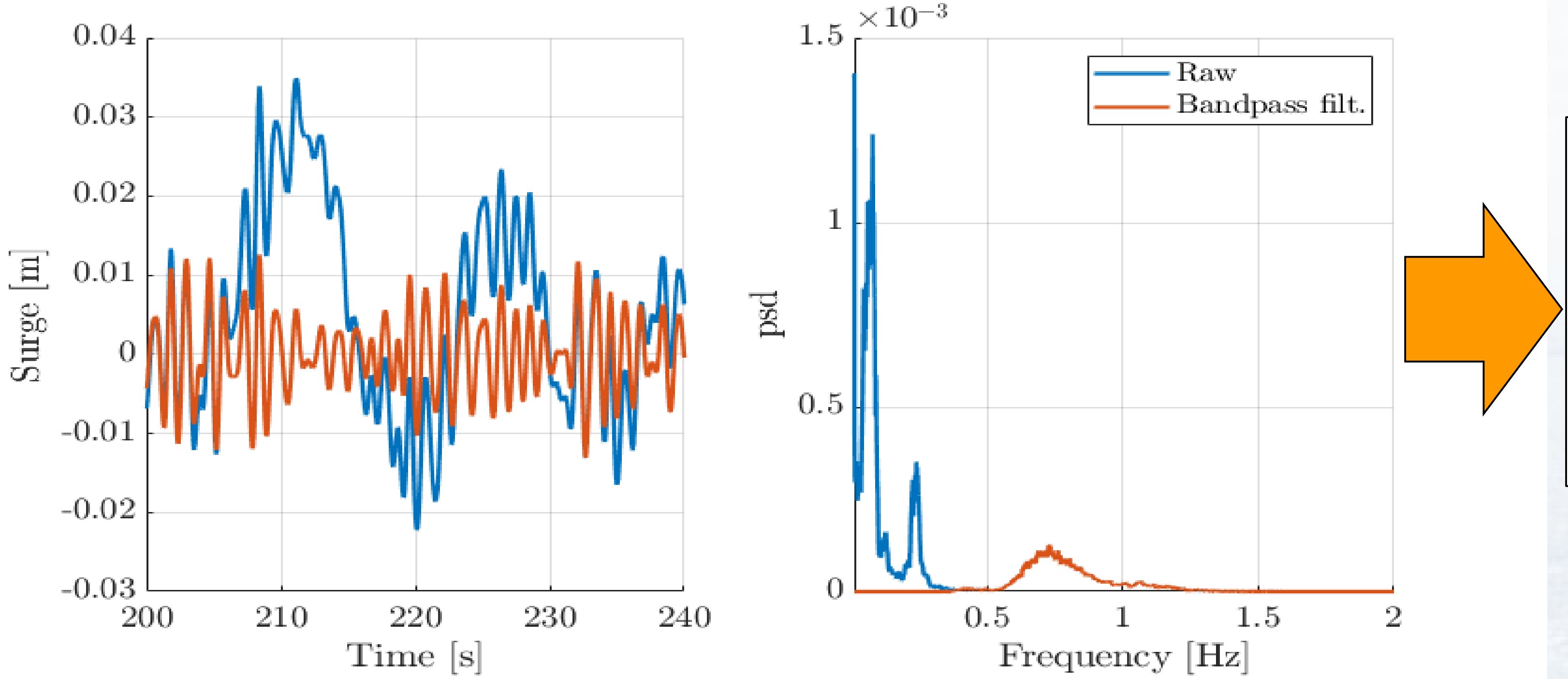
- Based on the NewWave theory (Tromans et al., 1991): The expected shape of an extreme event
- Is easily applied to linear force and response (Schløer et al 2017)

$$\eta_{NewResponse} = \frac{\alpha_X}{\sigma_X^2} \sum_j \mathrm{Re}\{S_\eta \Gamma(\omega_j) \Delta\omega e^{-i\omega_j t}\}$$

$$X_{NewResponse} = \frac{\alpha_X}{\sigma_X^2} \sum_j \mathrm{Re}\{S_\eta \Gamma(\omega_j) \Gamma^*(\omega_j) \Delta\omega e^{-i\omega_j t}\}$$

- Compared to filtered exp. data - 'linear' response

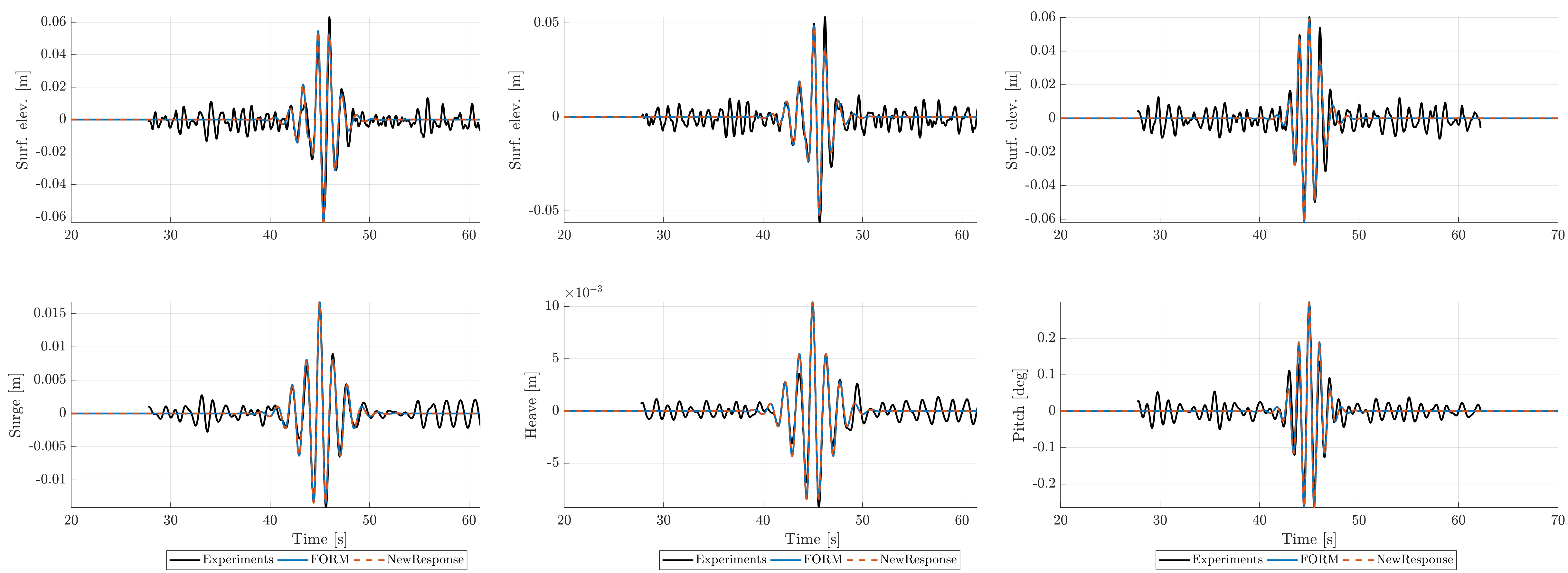


Extremes

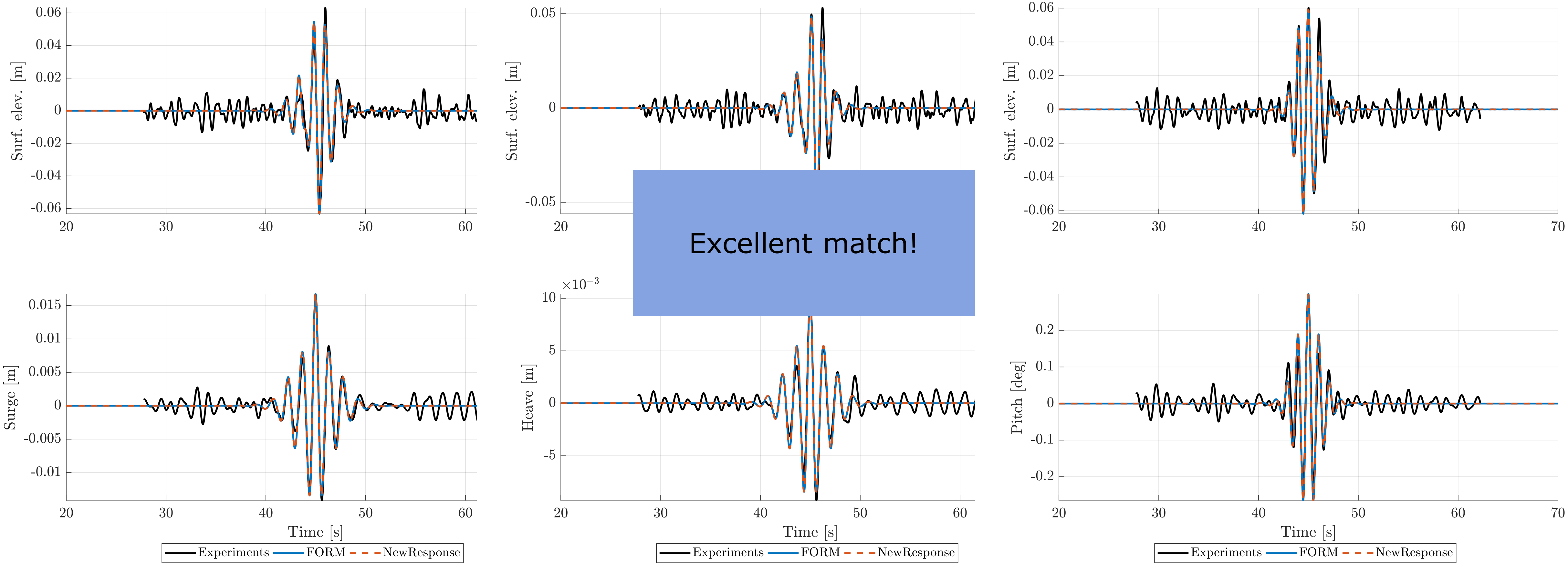
Averaging

Harmonic decomposition

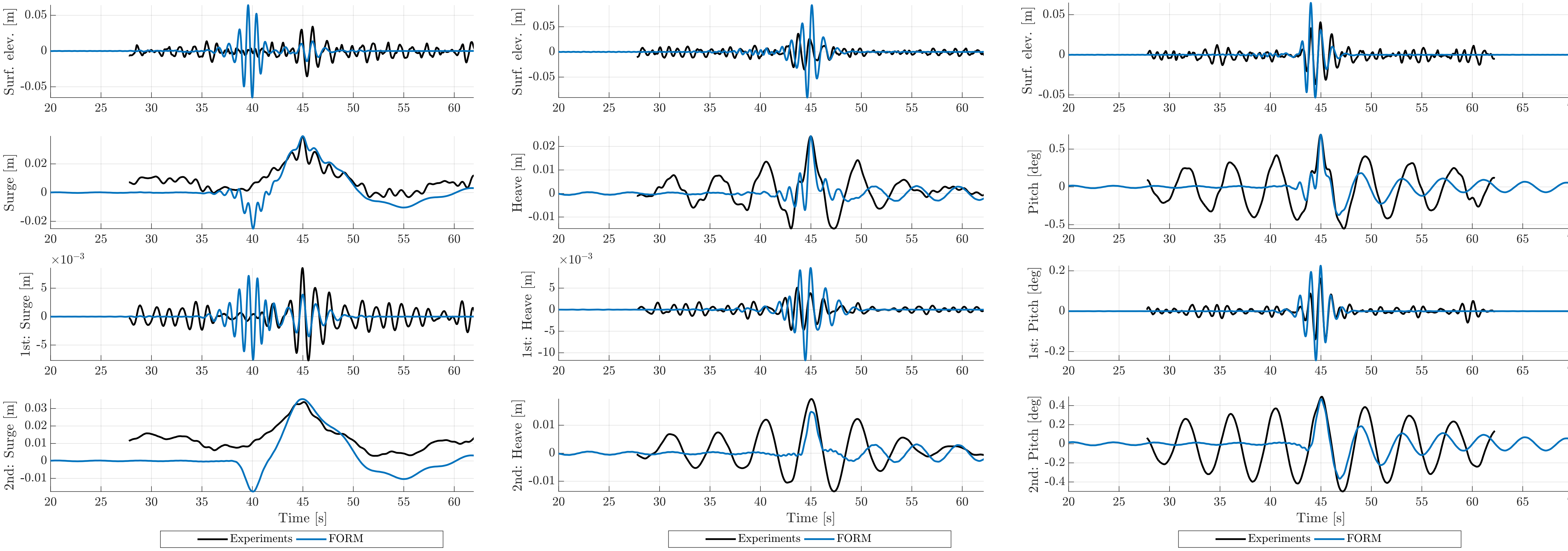
1st-order verification of FORM model: NewResponse



1st-order verification of FORM model: NewResponse



2nd-order FORM model – our present results



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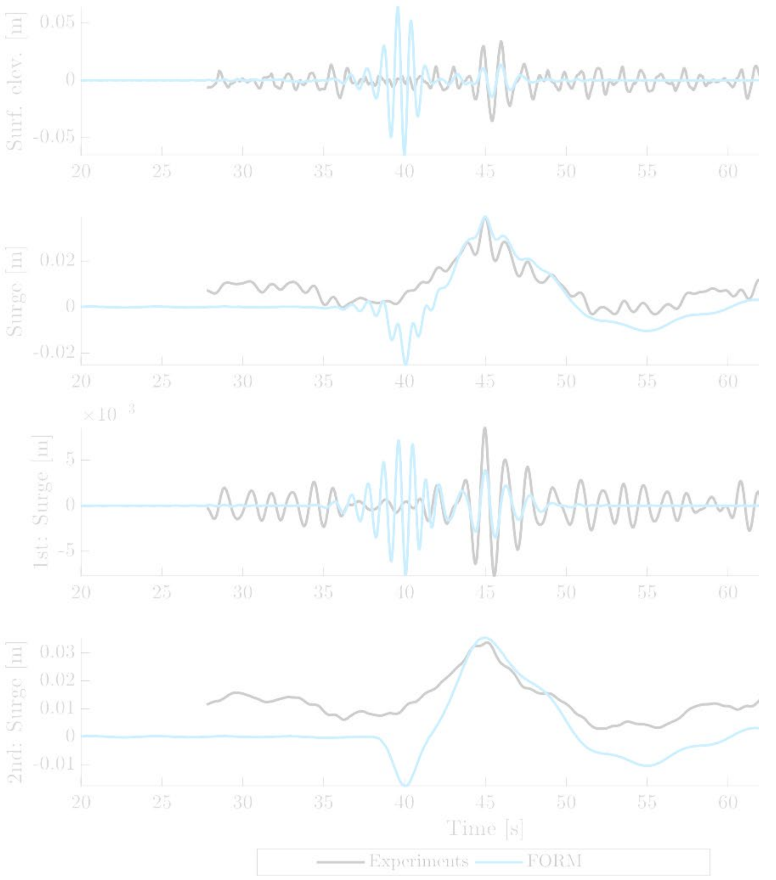
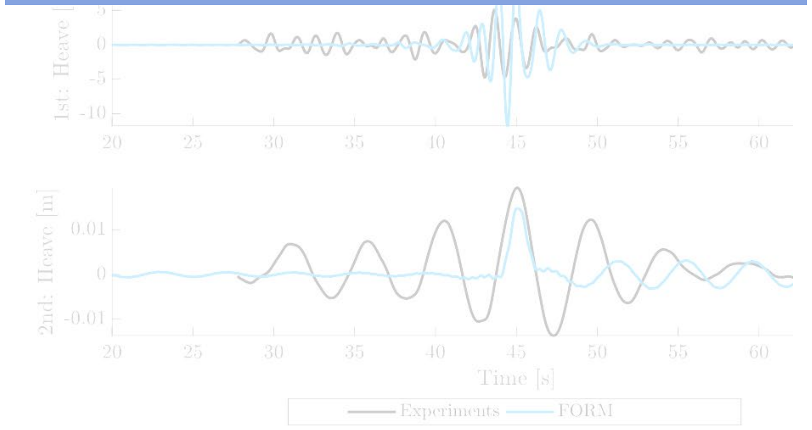
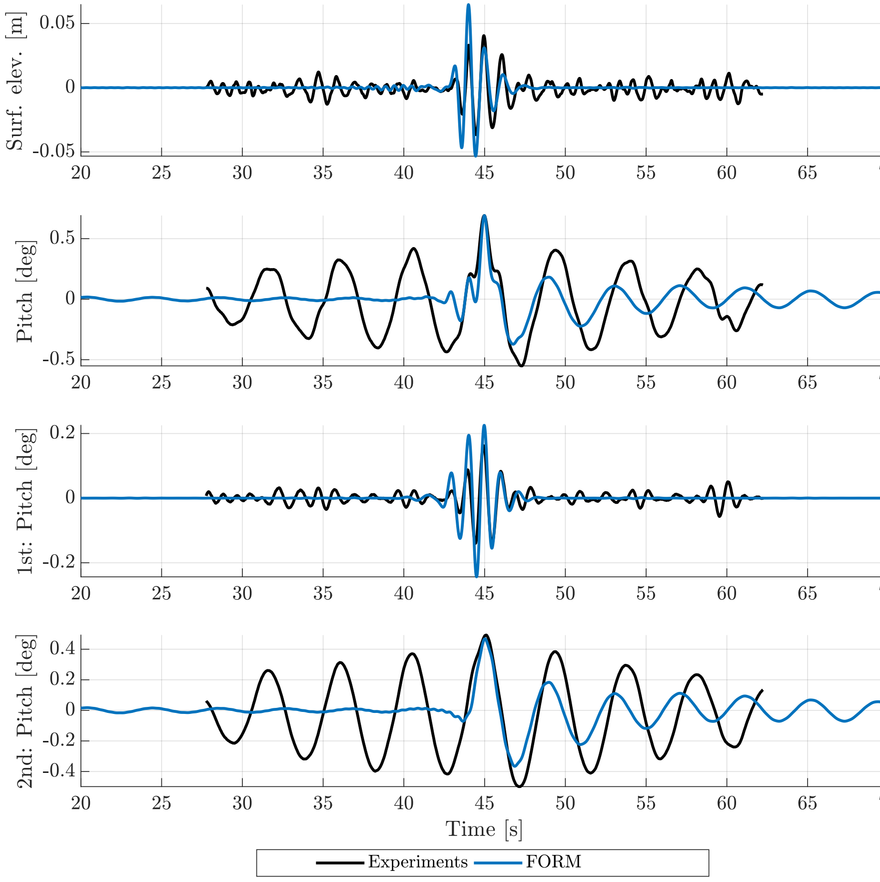
2nd-order FORM model – our present results





Pitch:

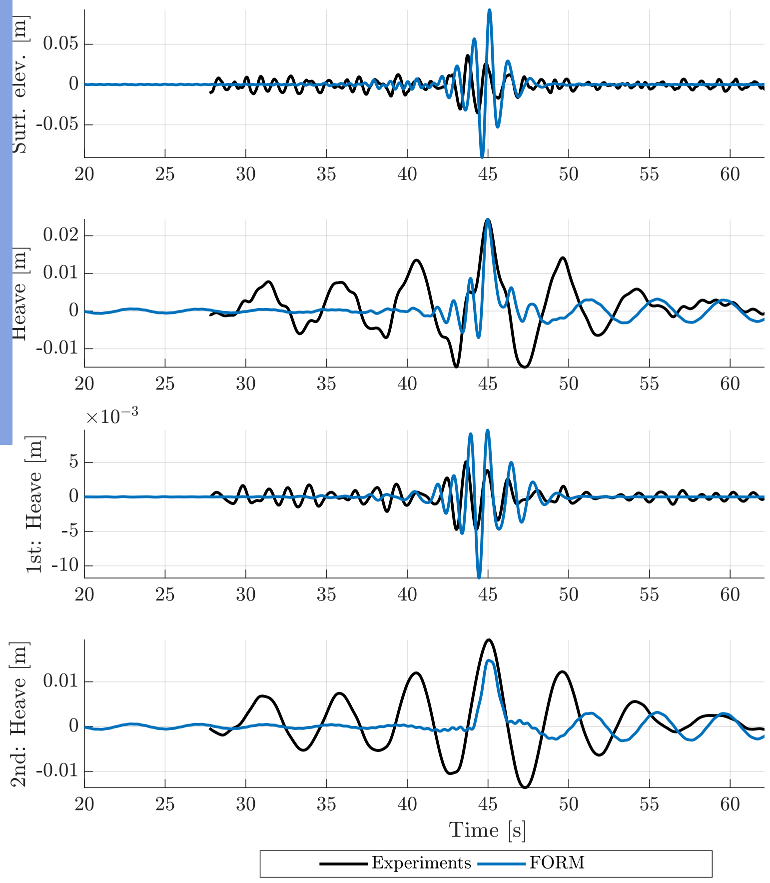
- Wave group and odd harmonic response shows fair match
- Total response is dominated by even harmonics
- Artefact of short-event approach: asymmetry in the even harmonic of the model



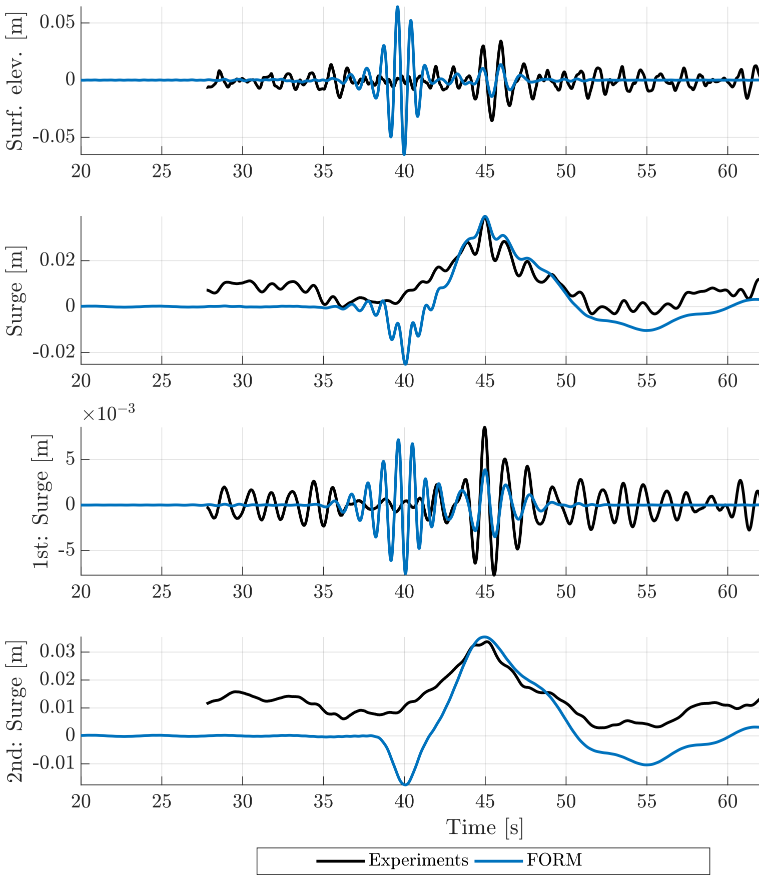
2nd-order FORM model – our present results

Heave:

- Wave group and odd harmonic response is over-predicted in the model
- Even harmonic peak is matched, but model damping too strong
- Total model response is dominated by the odd harmonics

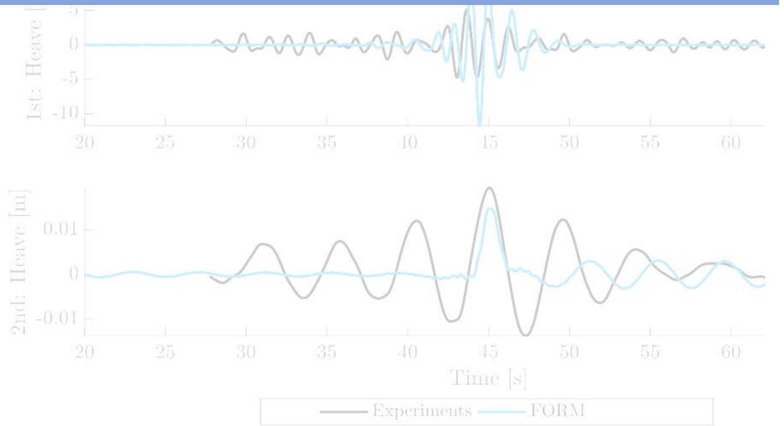


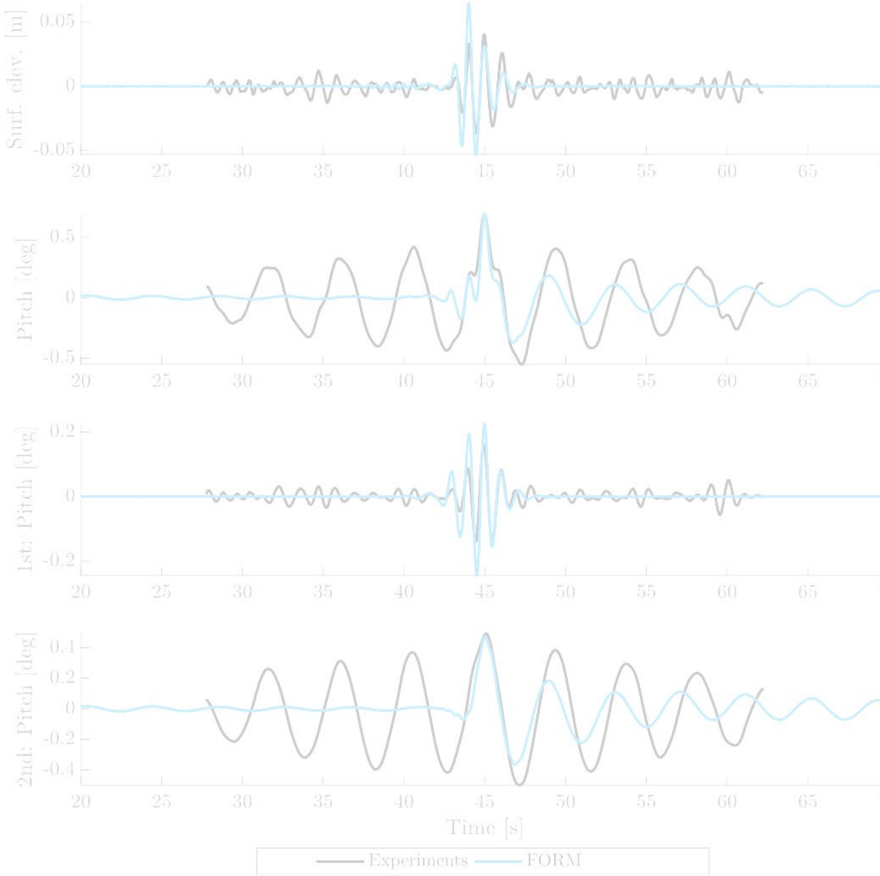
2nd-order FORM model – our present results



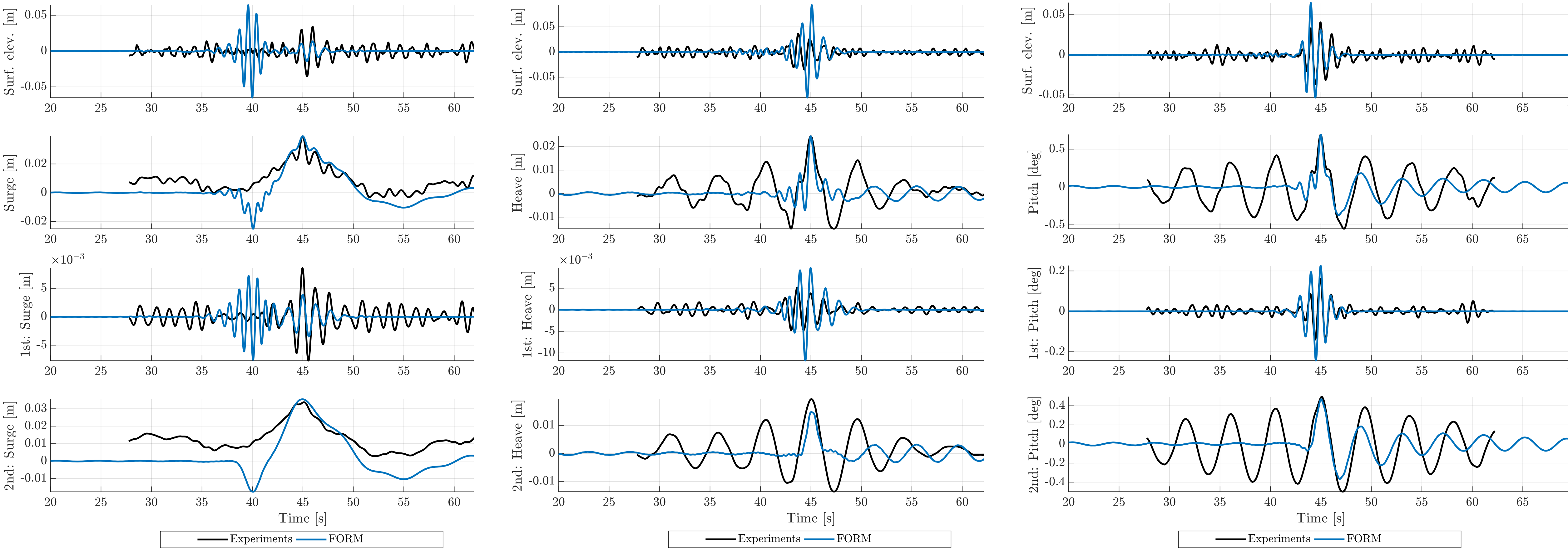
Surge:

- Total response is matched fairly well
- Funny feature: push-up by multiple wave groups
- Short-event artefacts may be avoided by direct averaging of numerical results





2nd-order FORM model – our present results



Which wave episodes drive the extreme response events?

Harmonic separation:

- Even and odd harmonic responses for surge, heave and pitch separated
- Show clear group structure at wave and natural freq, respectively

Second-order response model:

- Response level matched well in linear and full frequency range
- Calculation of QTF forcing speeded up to O(N logN) process

NewResponse:

- NewResponse matches linear experimental results well

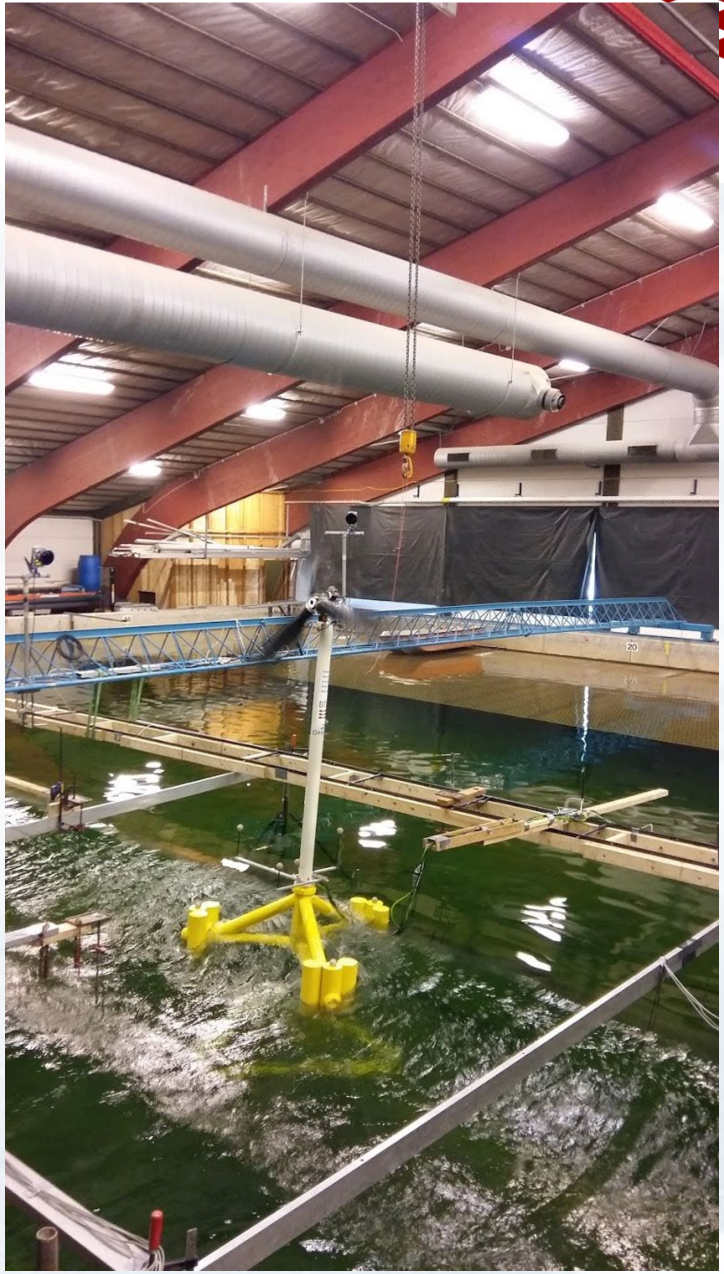
FORM for prediction of design waves

- Linear signal shapes are slightly over-predicted
- Second-order signal shapes are generally asymmetric
- Push-up by multiple groups seen in numerical surge
- Short-episode artefacts may be eliminated by direct averaging.

Method can be extended to e.g. tower top acceleration and mooring loads

Acknowledgements

- This work was carried out as part of the FloatStep project. The research leading to these results has received funding from Innovation Fund Denmark (IFD) under grant no. 8055-00075B.



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Thank you for your attention