Conditioning analysis of tower bending moment measurements from the TetraSpar Demonstrator

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TetraSpar Demonstrator Project

- Collaboration between Stiesdal (designer), Shell, RWE and TEPCO (investors)
- Towed to site off Karmøy, Norway in July 2021
- Began operating November 2021
- 3.6 MW turbine, 65 m blades, 88 m hub height
- Novel design allows construction in shallow harbour

UWA role

TetraSpar is a Demonstrator project → large investment in measurement campaign

- Process data from all sensors
- Quality checks
- Distribute checked data to investors
- Troubleshoot sensor issues
- Exploratory analysis of data
- Validating measurements
- Analysis of motion response

This study: Tower Bending Moments

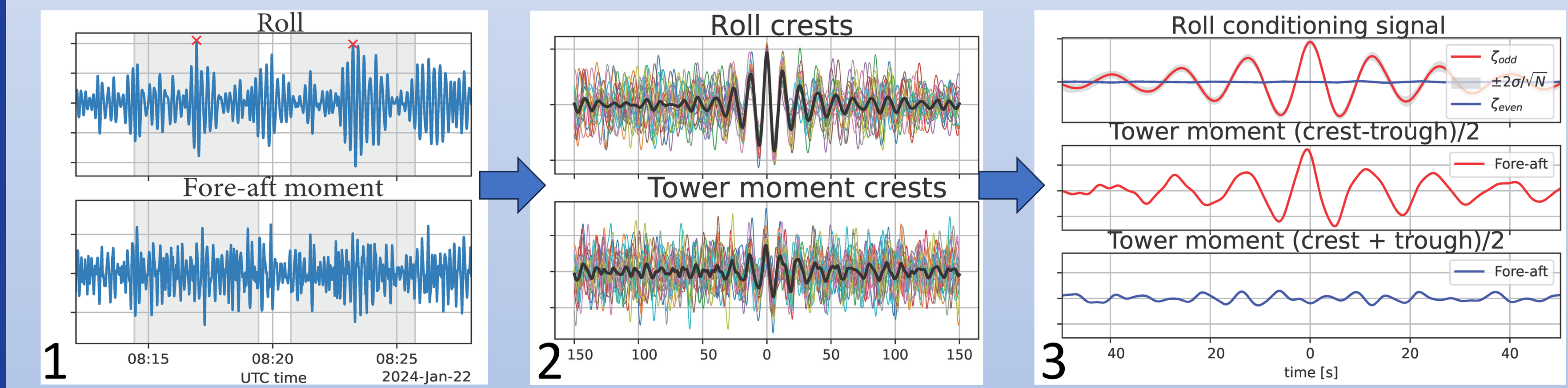
Motivation:
- Extract the relationship between floater motions and tower bending moments
- Can we predict bending moments & fatigue from motions?

Measurements used:
- Tower bending moment measured 15 m above the tower bottom flange
- 6 DoF motions are measured at the tower base (MRU & DGPS)
- Conditioning analysis and reciprocity plots use data from Storm Jocelyn (22/01/2024): H_{m0} = 8.5 m, T_p = 13 s

Methodology

Conditioning Analysis

- Extracts the relationship between forcing and response signals
- Take the 20 largest crests and troughs from the **'conditioning'** signal (e.g. roll motion), see Figure 1
- Extract the corresponding 20 timeseries of response (same time ranges) – this is the **'conditioned'** signal
- Calculate mean crest signal & mean trough signal (Figure 2)
- Calculate **(crest-trough)/2** – contains linear content (+ 3rd order) and **(crest+trough)/2** – contains 2nd order (+4th order), see Figure 3



- Roll/pitch are highly correlated with bending moment

Reciprocity Analysis

- If linear, conditioned signals should satisfy a **reciprocity** relationship
- Tests the extreme events (top 20 here) – more sensitive than taking the cross-correlation
- Successfully applied to several offshore engineering problems [1,2]

Define the response (ϕ) spectrum due to motion (ζ) as:

$$S_\phi(\omega_i) = S_\zeta(\omega_i)|H(\omega_i)|^2$$

where $H(\omega_i)$ is the linear transfer function from motion to response.
The response conditioned on motion is:

$$\phi|\zeta = \sqrt{2\ln(N)}\, Re\{\sum S_\zeta(\omega_i)H(\omega_i)e^{i\omega_i t}\Delta\omega\} / \sqrt{\sum S_\zeta(\omega_i)\Delta\omega}$$

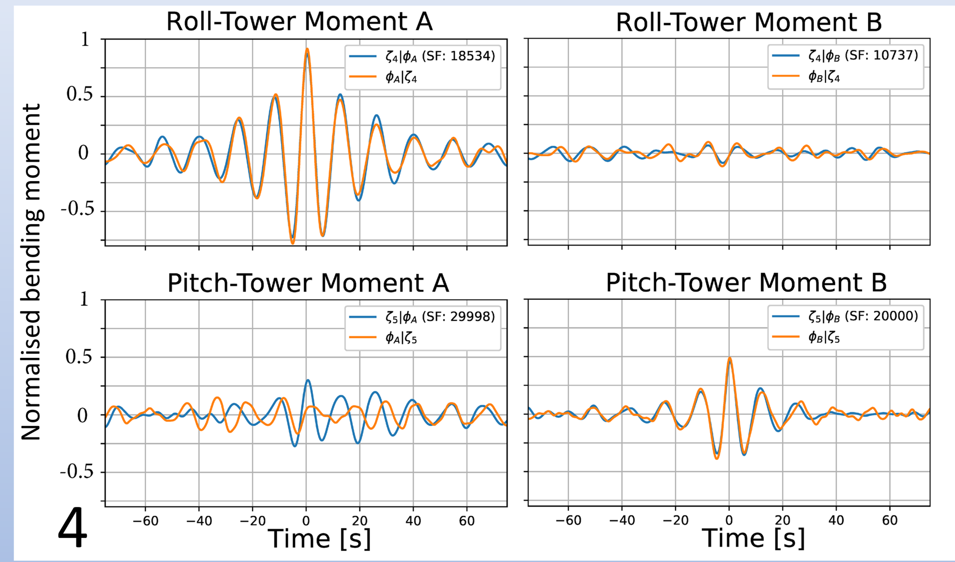
we can then write the motion conditioned on response as (noting $S_\phi\mu^{-1} = S_\zeta\mu^*$):

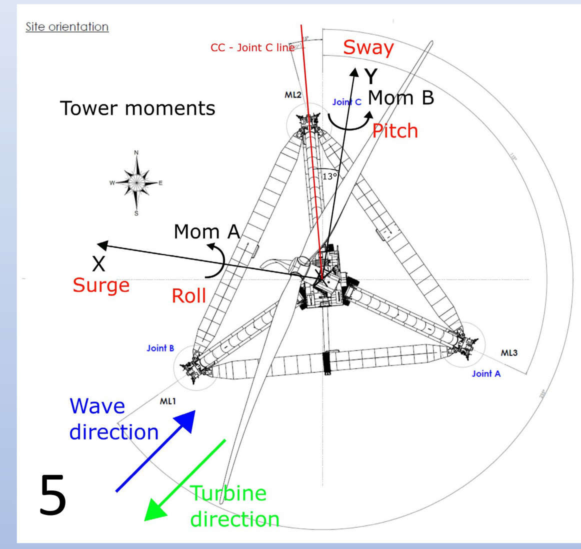
$$\zeta|\phi = \sqrt{2\ln(N)}\, Re\{\sum S_\zeta(\omega_i)H^*(\omega_i)e^{i\omega_i t}\Delta\omega\} / \sqrt{\sum S_\phi(\omega_i)\Delta\omega}$$

where H^* is the complex conjugate of H -> phase shift in opposite direction (or reversal in time)

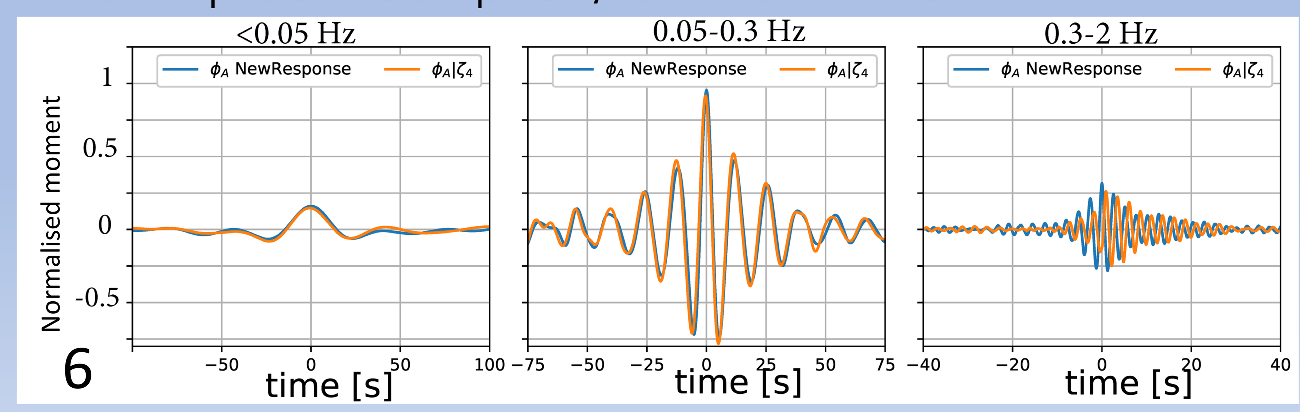
Results

- Roll/Tower Moment A and Pitch/Tower Moment B show excellent reciprocity agreement (see Figure 4 – band pass filtered 0.05-0.3 Hz)



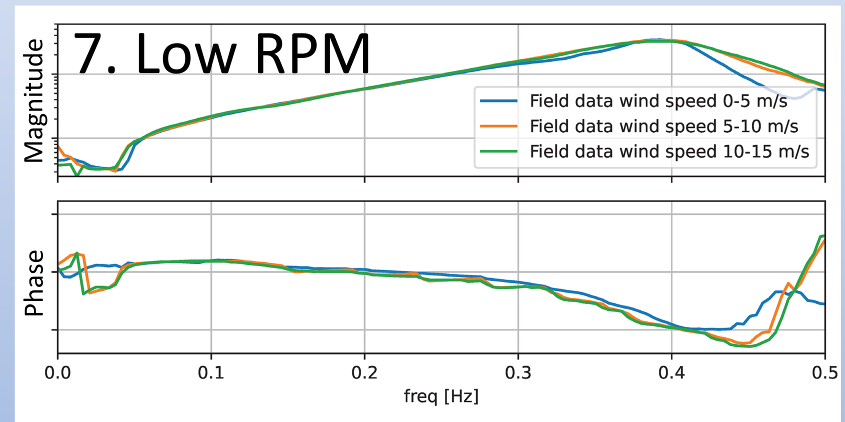


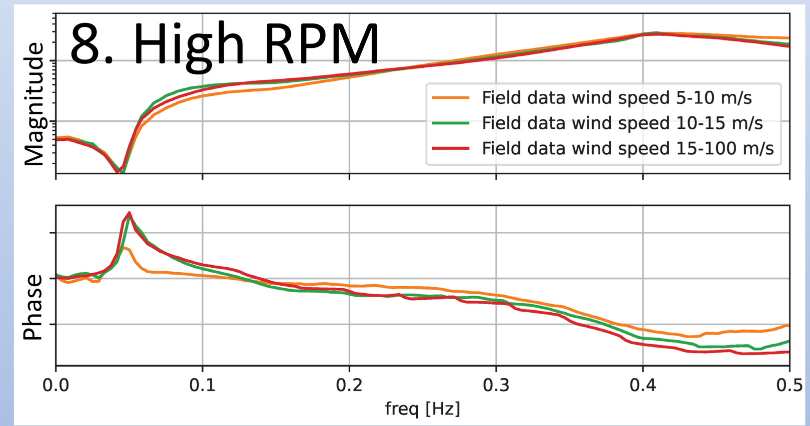
- Now compare motion conditioned bending (linear part) to total extreme response (NewResponse) – see Figure 6 (three freq. bands)
- NewResponse is the response conditioned bending moment (average crest – average trough)/2
- Can recreate the NewResponse by conditioning on roll motion alone – strong relationship between pitch/roll and moments



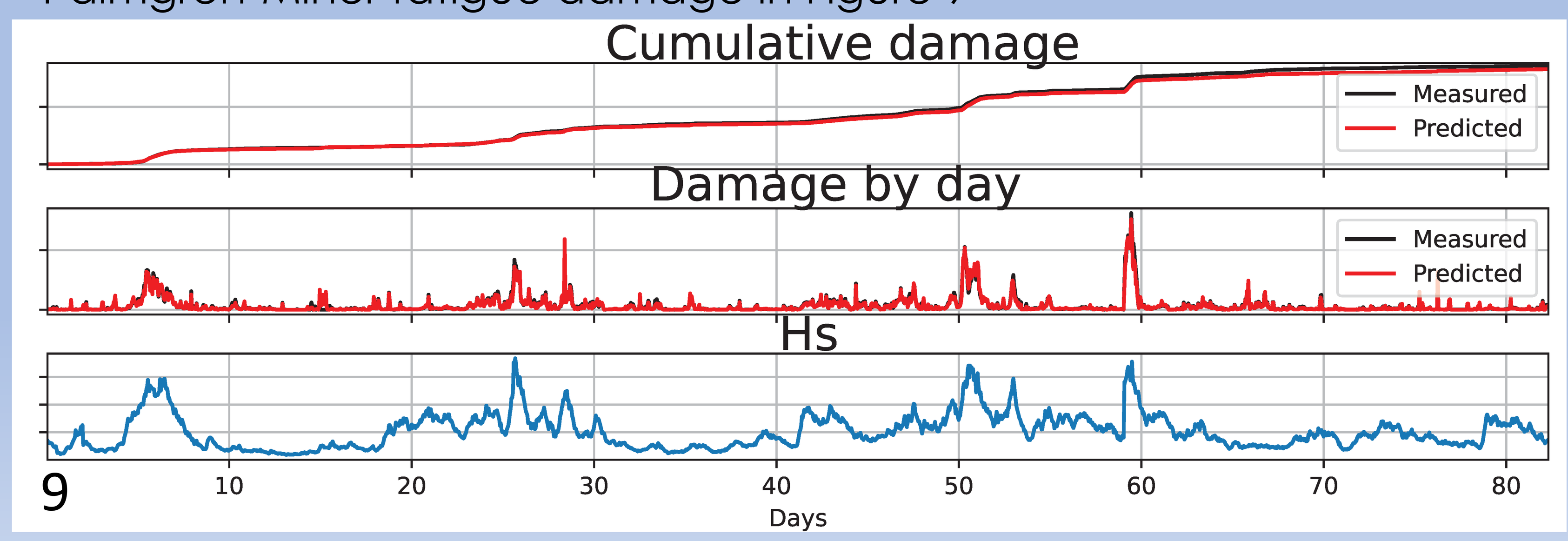
Tower fatigue prediction

- Tower bending transfer function from pitch and roll motions is linear, even in extreme conditions
- Can we use measured pitch and roll to predict fatigue?
- Generate a look-up table of transfer functions from field data (Figures 7 and 8), depending on mean wind speed and turbine speed





- Calculate fatigue damage using measured and predicted bending moments (Python package Py-Fatigue for fatigue analysis [3]) – see Palmgren-Miner fatigue damage in Figure 9



Conclusions

- Conditioning analysis of tower bending moments and pitch/roll motions indicates reciprocity: transfer function is linear (even in extremes)
- Linear transfer function method for predicting tower bending from motions gives same fatigue damage as measured bending
- Method can be applied for fatigue monitoring or design calculations: use transfer functions from numerical model or put strain gauges on one turbine in array

Acknowledgements and References

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[3] D'Antuono, P. D., Weijtjens, W. W., & Devriendt, C. D. (2022). Py-Fatigue [Software]. In Github (1.0.3). https://www.owi-lab.be/. https://owi-lab.github.io/py_fatigue