

U.S. Advances in Digital Twinning for Offshore Wind Assets

RAVE Workshop 2024

Eric Hines, Azin Mehrjoo, Nasim Partovi-Mehr

Acknowledgements: Babak Moaveni, Chris Baxter,
David Ciochetto, Aaron S. Bradshaw, Per Sparrevik,
Bridget Moynihan, Eleonora Tronci, John DeFrancisci,
Dan Kuchma

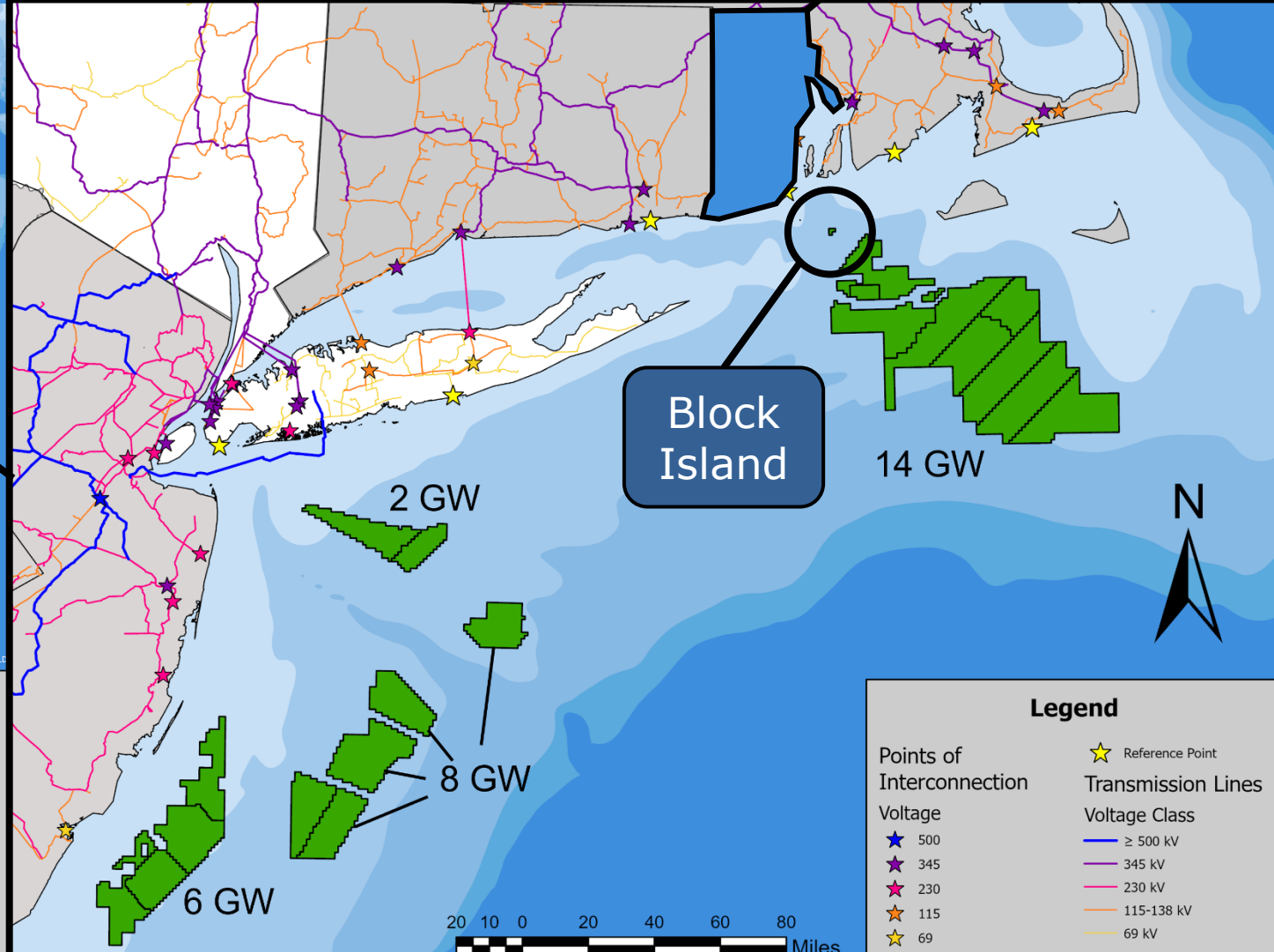
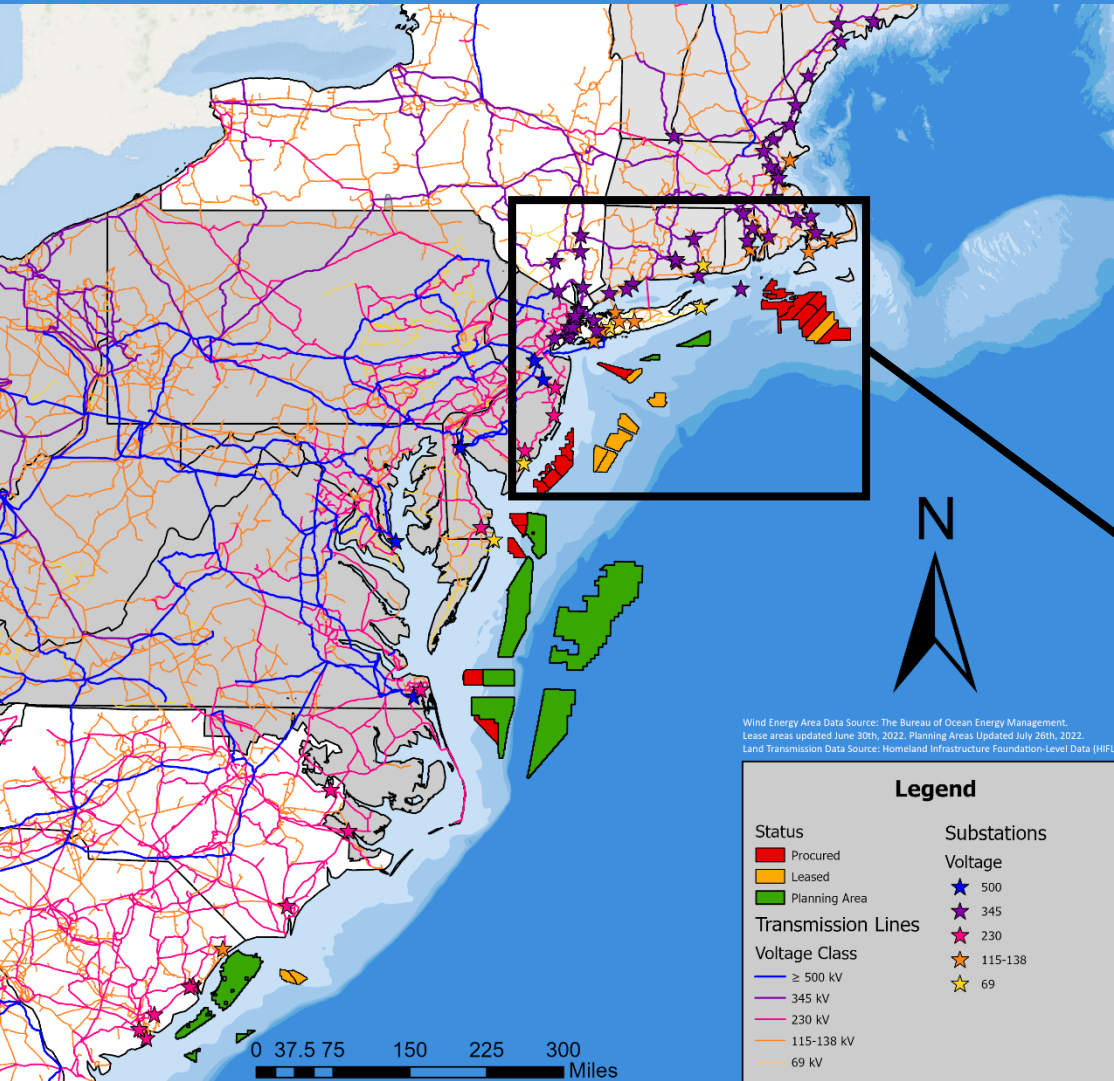
March 13, 2024

Fatigue Performance

Ph.D. work by Nasim Partovi-Mehr

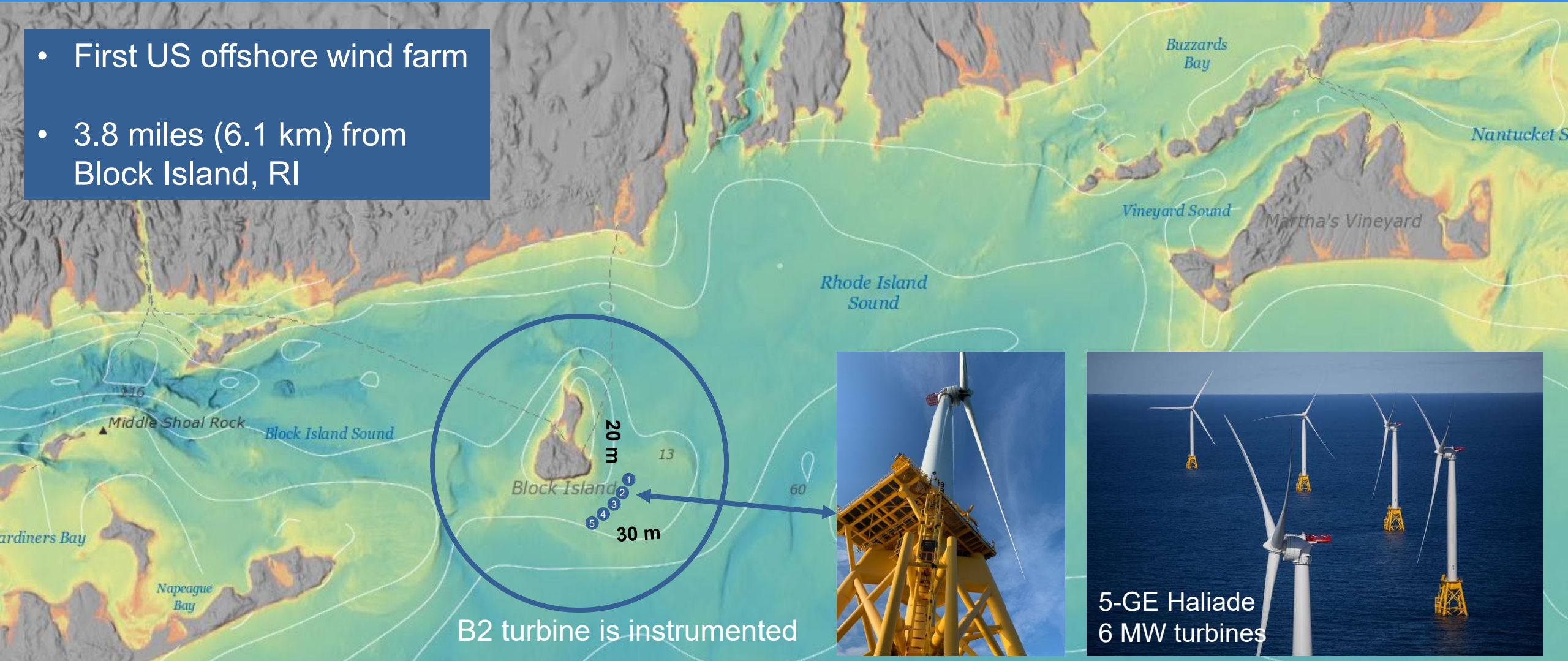
U.S. East Coast Offshore Wind

Rhode Island



Block Island Wind Farm

- First US offshore wind farm
- 3.8 miles (6.1 km) from Block Island, RI



B2 turbine is instrumented

5-GE Haliade
6 MW turbines

Structural Fatigue Analysis Framework

REFERENCES
 - IAHK Y8/23
 - B/WF ANALYSIS UPDATE

(SEE P. 33 FOR NUMERICAL SUMMARY)

GE HULLADE 6 MW
 ROTOR DIAMETER = 150.95 m
 SWEEP AREA = 17896 m²
 ASSUME C_r = 11.0 m/s

$$\frac{6,000,000 W}{(0.5)(1.225 \text{ kg/m}^3)(17896)(11 \text{ m/s})^3} = C_p = 0.411$$

$$0.411 = 0.593(0.893)$$

φ5000
 t = 24
 A = 0.375 m²
 I = 1.16 m⁴

ASSUME C_f = 0.754 (0.528)

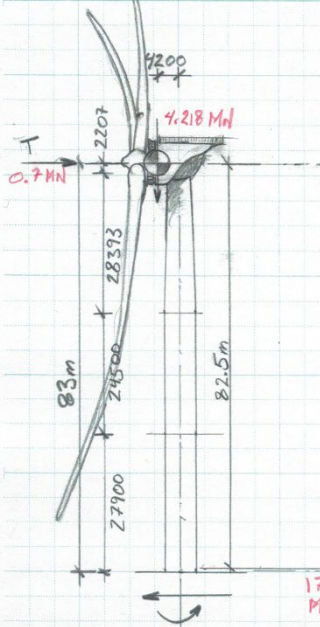
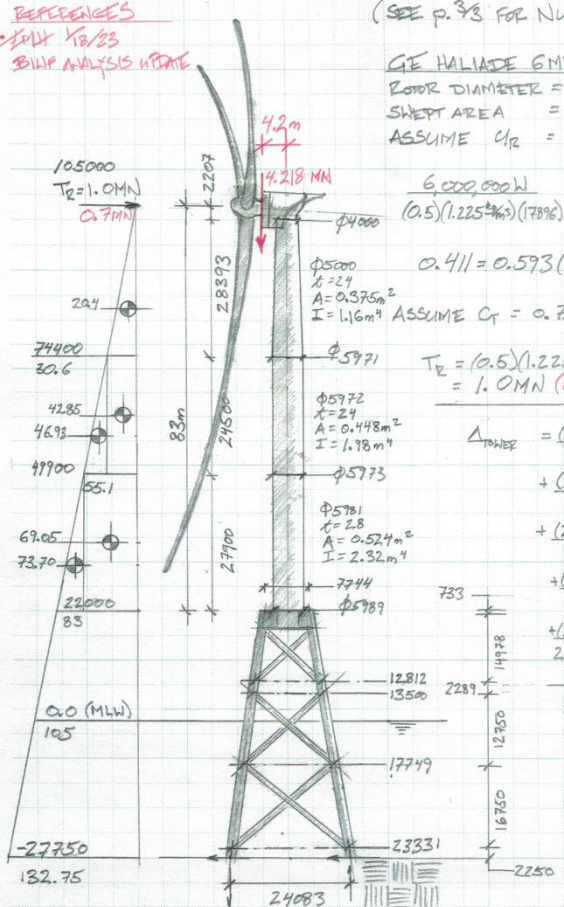
$$T_R = (0.5)(1.225)(11)^3(17896)(0.754) = 1.0 MN (0.7 MN \text{ MAX})$$

$$\Delta_{POWER} = \frac{(30.6)(30.6)(20.9)}{2(200,000)(1.16)} + \frac{(30.6)(24.5)(42.85)}{(200,000)(1.98)} + \frac{(24.5)(24.5)(46.93)}{2(200,000)(1.98)} + \frac{(55.1)(23.9)(69.05)}{(200,000)(2.32)} + \frac{(27.9)(27.9)(73.7)}{2(200,000)(2.32)} = 0.449 m$$

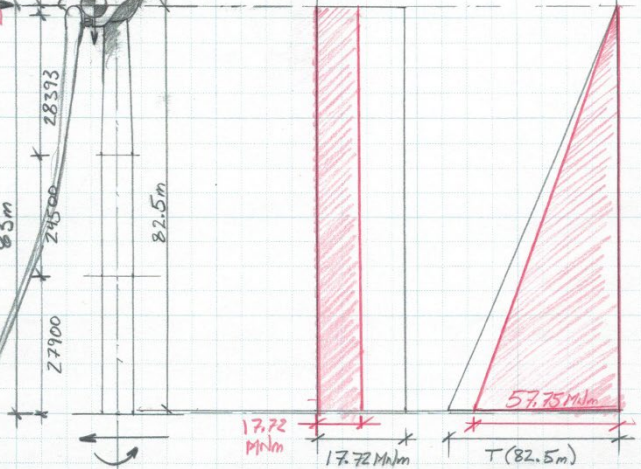
K = 2.23 MN/m
 m = 555 s⁻¹
 $w = \sqrt{\frac{2230}{555}} = 2.00 \text{ rad/s}$

f = 0.32 Hz

JACKET ASSUMED TO BE RIGID ON THIS PAGE.
 SEE P. 2 FOR JACKET FLEXIBILITY CALCS.



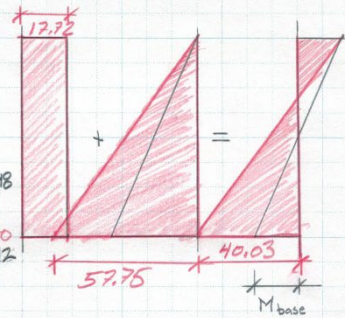
RNA = 430 t
 = 4.218 MN
 (4.218 MN)(4.2 m)
 = 17.72 MNm



$$T = \frac{M_{FA} + 17.72 \text{ MNm}}{82.5 m}$$

$$T_{avg} = \frac{20.63 + 17.72}{82.5} = 0.4648 \text{ MN}$$

$$T_{max} = \frac{35.43 + 17.72}{82.5} = 0.6442 \text{ MN}$$



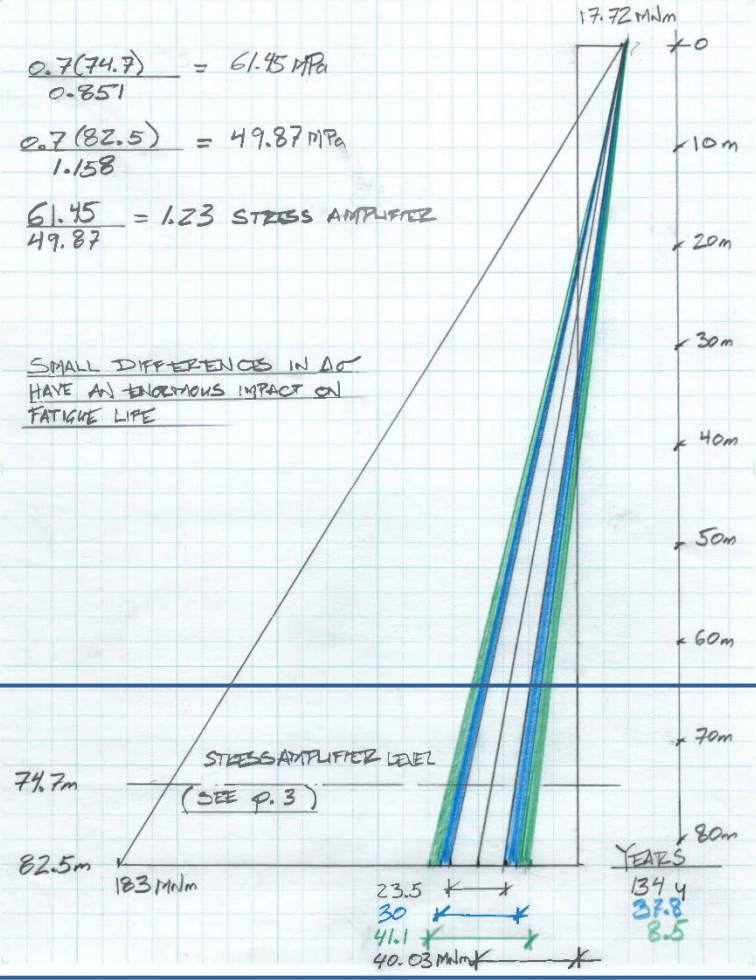
FATIGUE

$$\frac{0.7(74.7)}{0.851} = 61.45 \text{ MPa}$$

$$\frac{0.7(82.5)}{1.158} = 49.87 \text{ MPa}$$

$$\frac{61.45}{49.87} = 1.23 \text{ STRESS AMPLIFIER}$$

SMALL DIFFERENCES IN Δσ
 HAVE AN ENORMOUS IMPACT ON
 FATIGUE LIFE



Structural Fatigue Analysis Framework

FOR DNV FATIGUE CURVE C1

$$\log N = \log \bar{a} - m \log \Delta \sigma$$

$$\log \bar{a} = 16.081$$

$$m = 5$$

SOLVE FOR N ASSUMING $\Delta \sigma = 20 \text{ MPa}$

$$\text{NOTE: } \Delta M = (20 \text{ MPa}) (3.469 \text{ m}^3) \\ = 23.5 \text{ MNm}$$

$$\log N = 16.081 - 5(1.301)$$

$$= 9.576$$

$$N = 10^{9.576} = 3.767 \times 10^9 \text{ CYCLES}$$

f_n RANGES FROM 0.29 - 0.32 Hz

$$T_{n \min} = \frac{1}{0.32 \text{ Hz}} = 3.125 \text{ s/c}$$

$$(3.767 \times 10^9 \text{ c}) (3.125 \text{ s/c}) = 1.177 \times 10^{10} \text{ s}$$

$$\frac{(1.177 \times 10^{10} \text{ s})}{(3600 \text{ s/h}) (8760 \text{ h/y})} = 373 \text{ y}$$

W/STRESS
AMPLIFIED
= 1.23

20	24.6
25.53	31.4
35	43.0

9.131
8.581
7.931

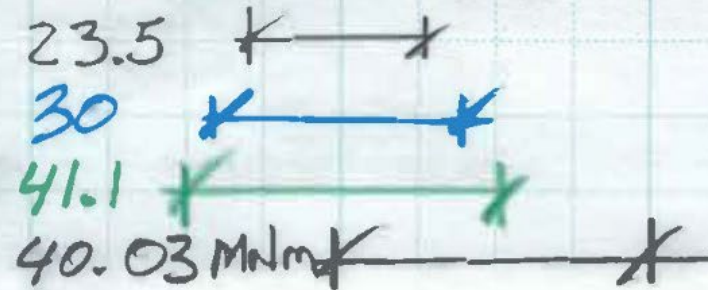
1.352×10^9
 0.381×10^9
 0.0853×10^9

$4.225 \times 10^9 \text{ s}$
 1.191×10^9
 0.267×10^9

134 y
37.8 y
8.5 y

SAMPLER LEVEL

0.3)

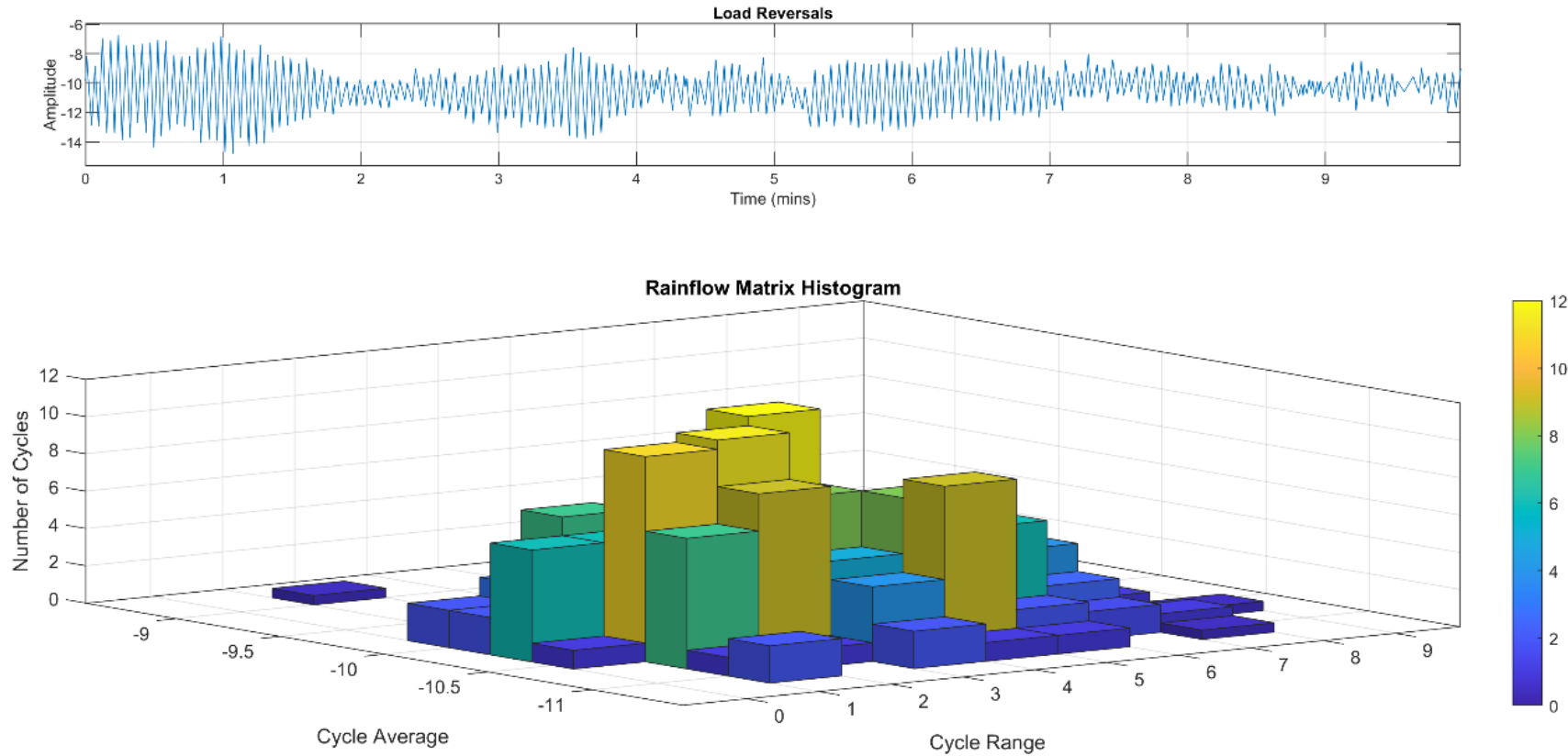


70m

YEARS
80m

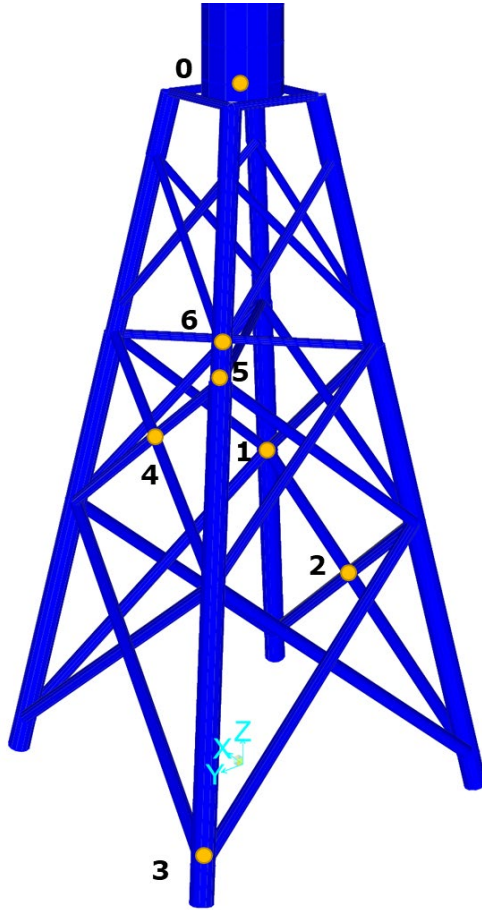
Rainflow counting of stress cycles

- Rainflow counting for a 10-minute interval on December 17, 2021 starting at 06:52 am



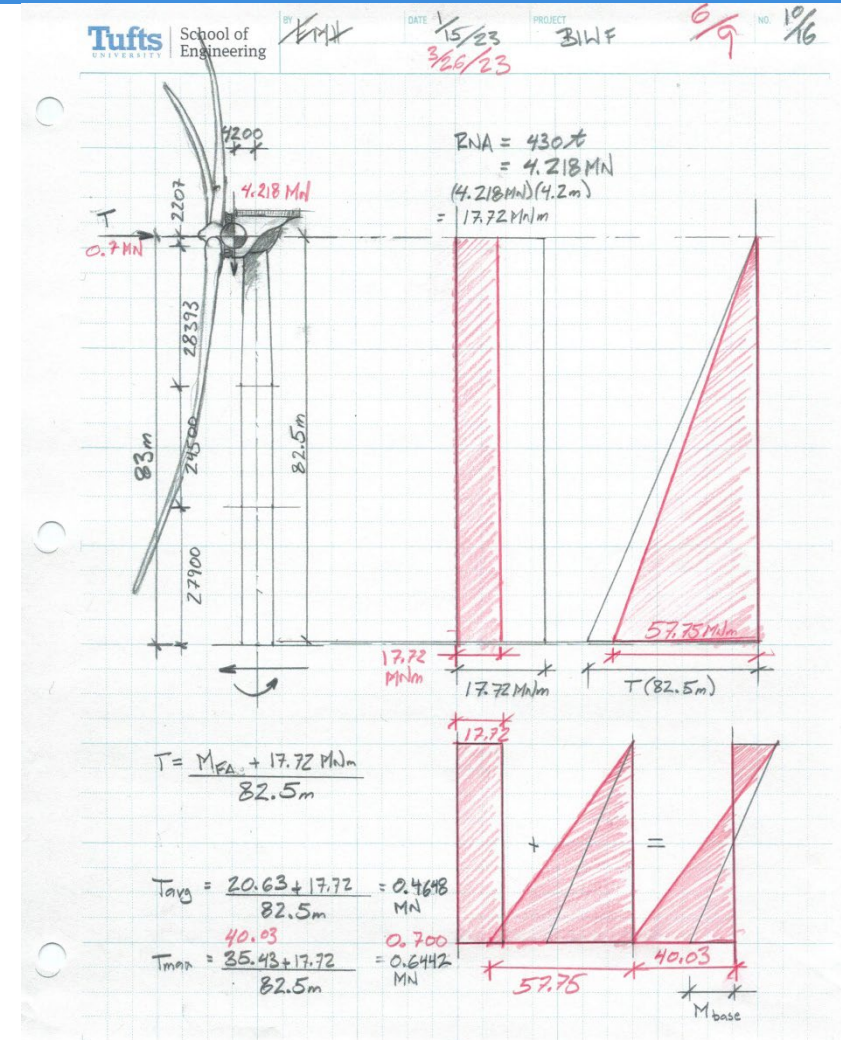
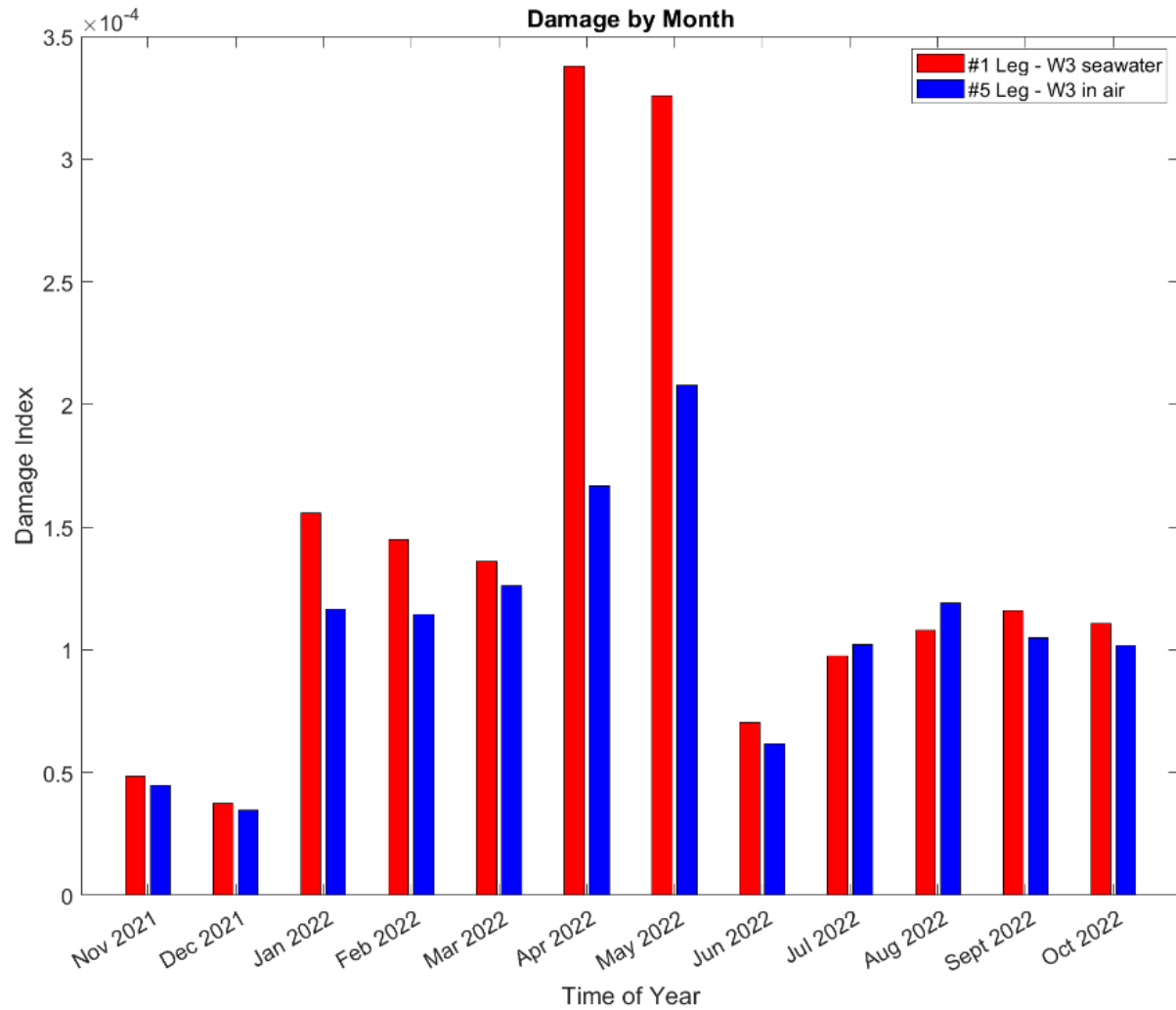
Virtual Sensors via Modal Expansion

- Damage vs. time ratio to the lifetime of 25 years using extrapolating 1-year monitoring:

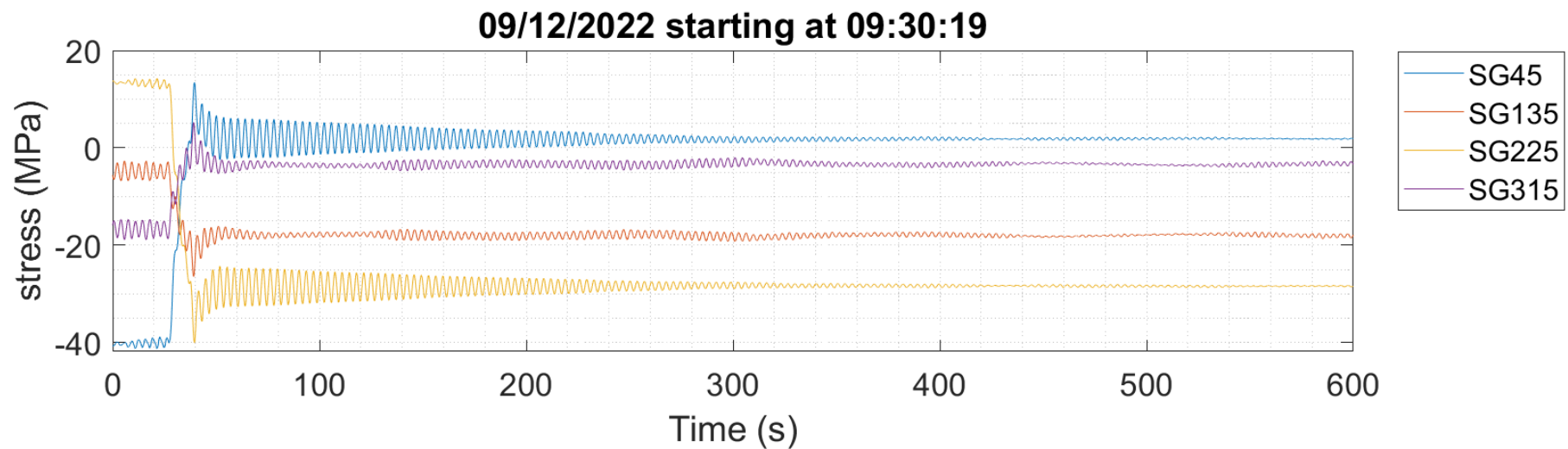
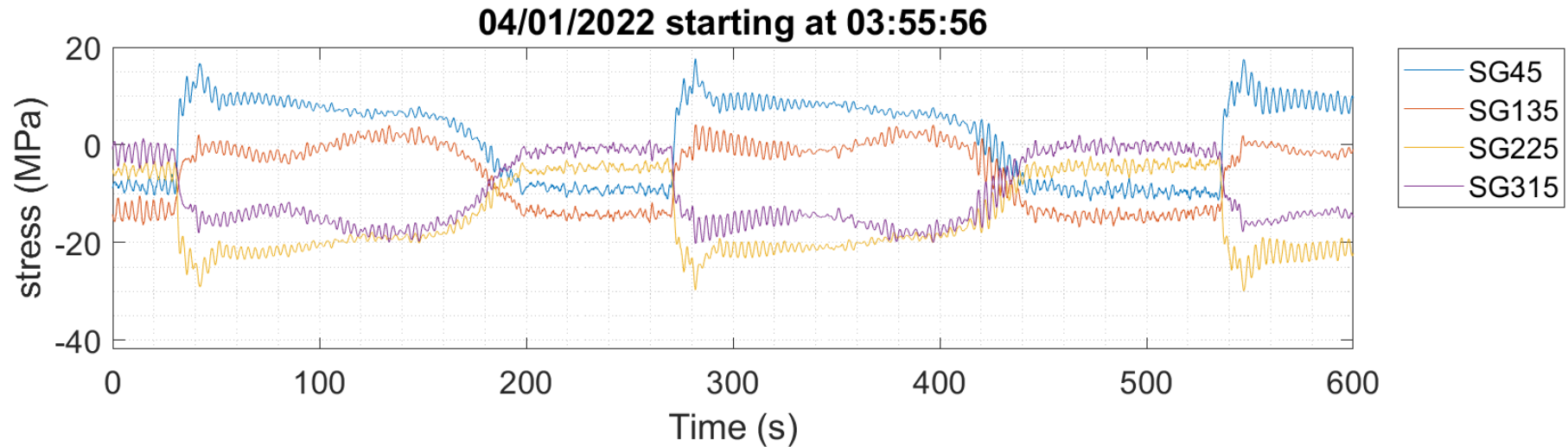


Joint	Environment	Measured	Designed
#1	W3 Cath.Prot. DFF = 3	196 y	26 y
#2	W3 Cath.Prot. DFF = 3	222,000 y	76 y
#5	W3 in air DFF = 2	386 y	50 y

What cycles cause the most damage?



Sample stress time histories with high damage



2021 Wangwen Review of Fatigue Curves

W. Zhao

International Journal of Fatigue 145 (2021) 106075

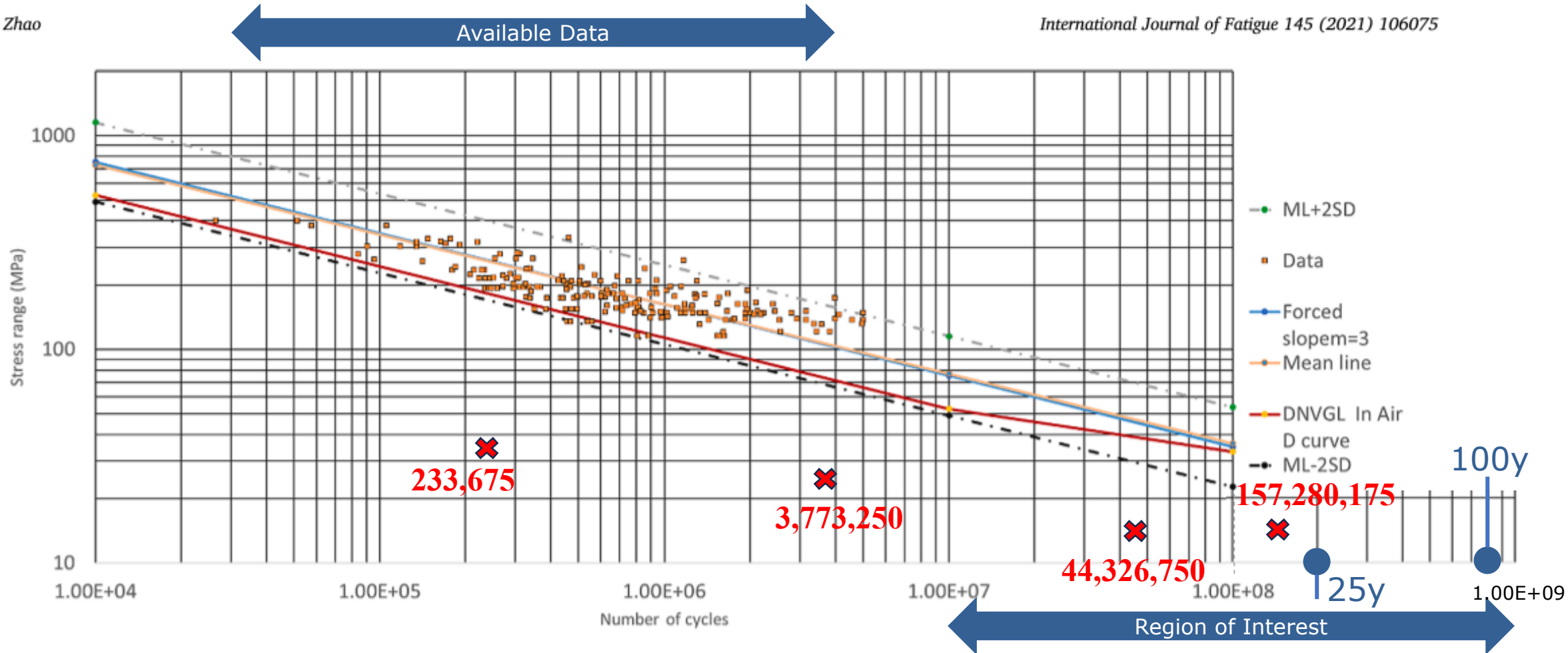


Fig. 9. Fatigue tests data points for Butt Welds and DNVGL D curve In Air.

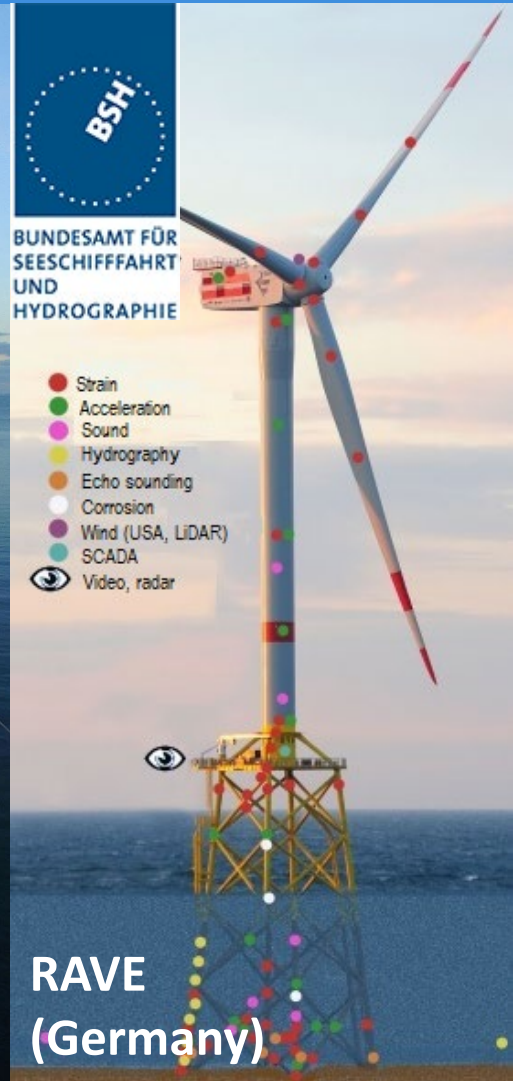
$$(3600 \text{ s/h})(8760 \text{ h/y})(25 \text{ y}) / (T = 4 \text{ s}) = 1.97 \text{ E}+08$$

Windows-Based Bayesian Assimilation Framework

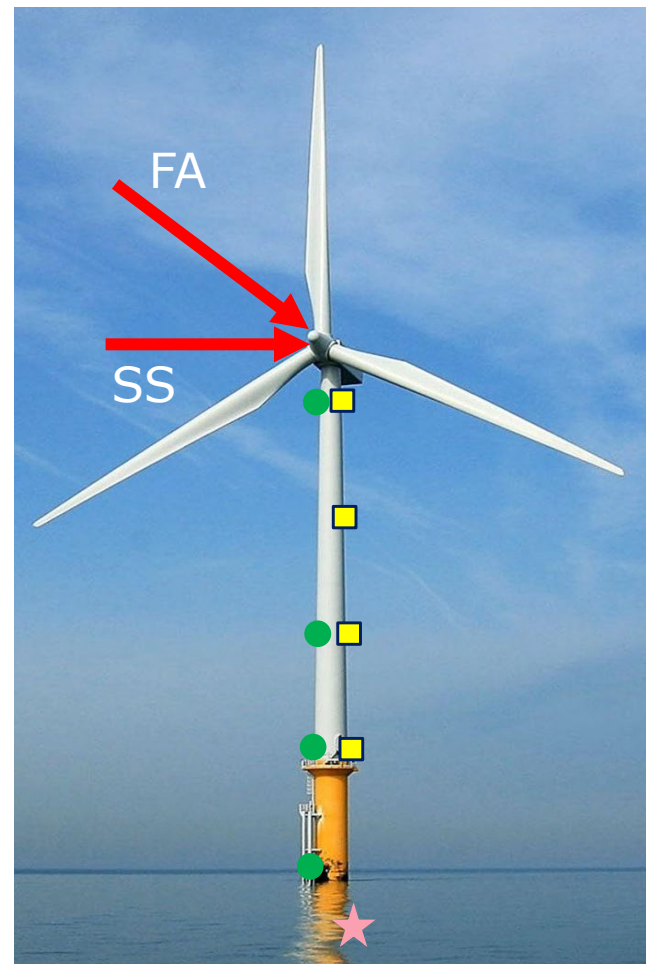
Physics-Informed Neural Networks

Ph.D. work by Azin Mehrjoo

U.S. + North Sea Experience



Find a dynamic input at hub height that reproduces measured results



- Input load
FA = fore-aft
SS = side-to-side
- Accelerometers
- Strain gauges
- ★ Virtual Sensor

- 1- Windowed Based Input Estimation(WBIE)
- 2- Physics Informed Neural Network(LSTM)

Given:

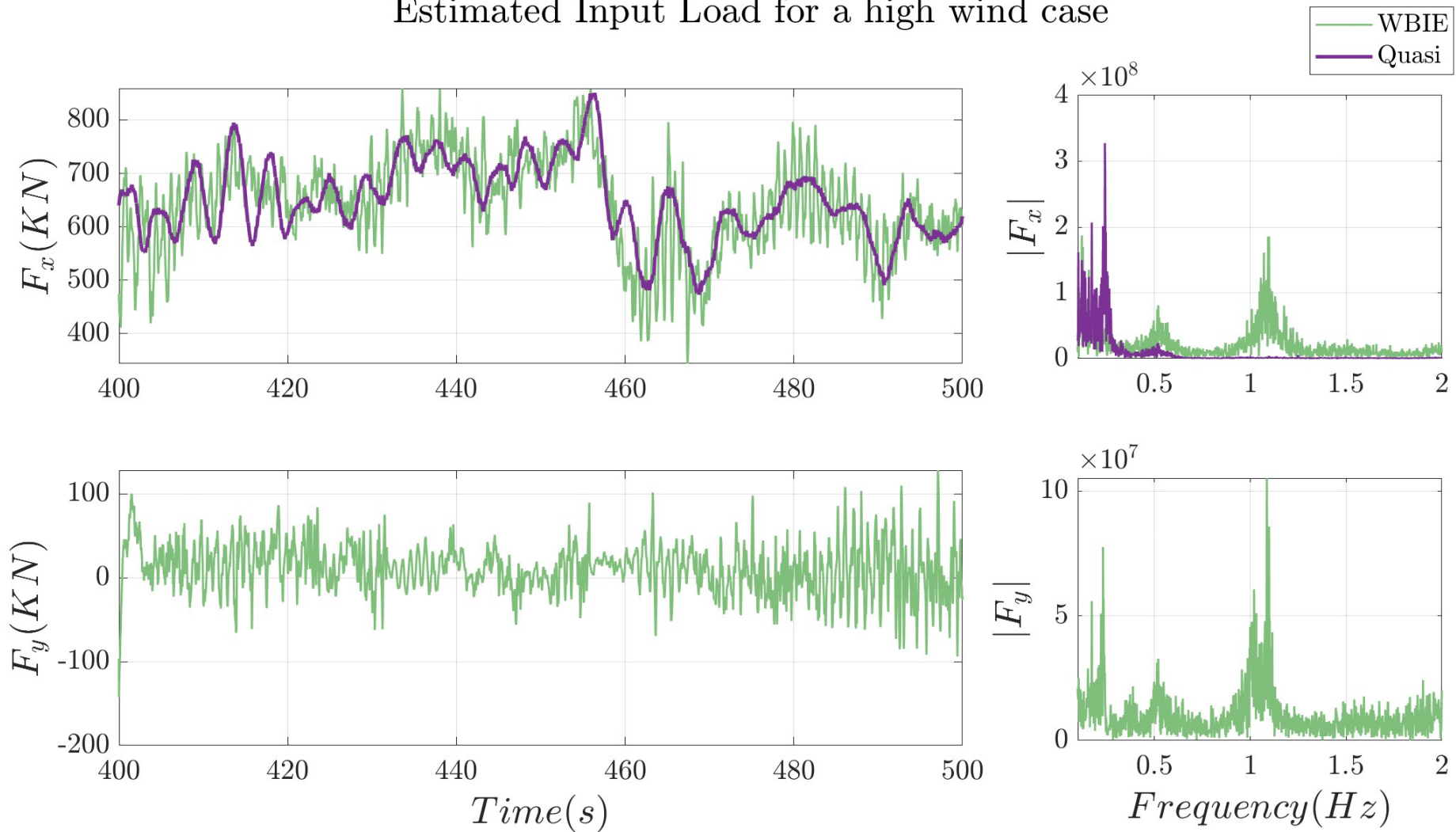
- A validated model
- Available Measurements
- Position and number of the unknown loads

Find:

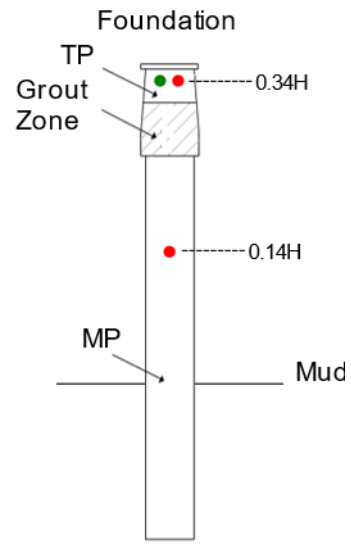
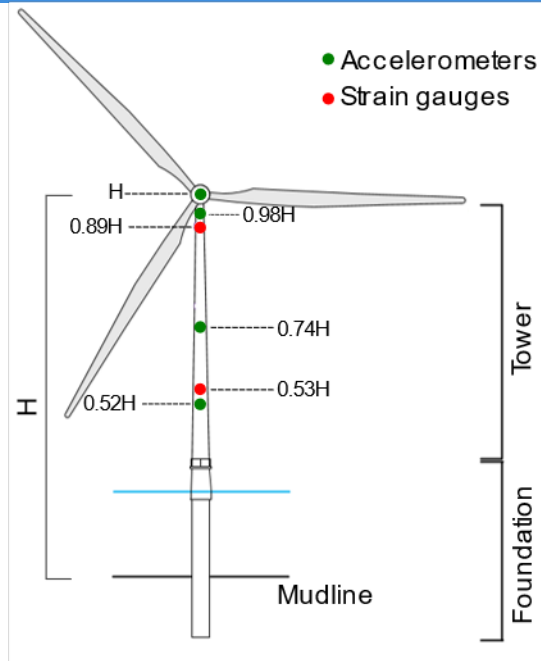
- Input load time history
- Estimation of vibration response at unmeasured locations (virtual sensing)

Estimated input load for a high wind case

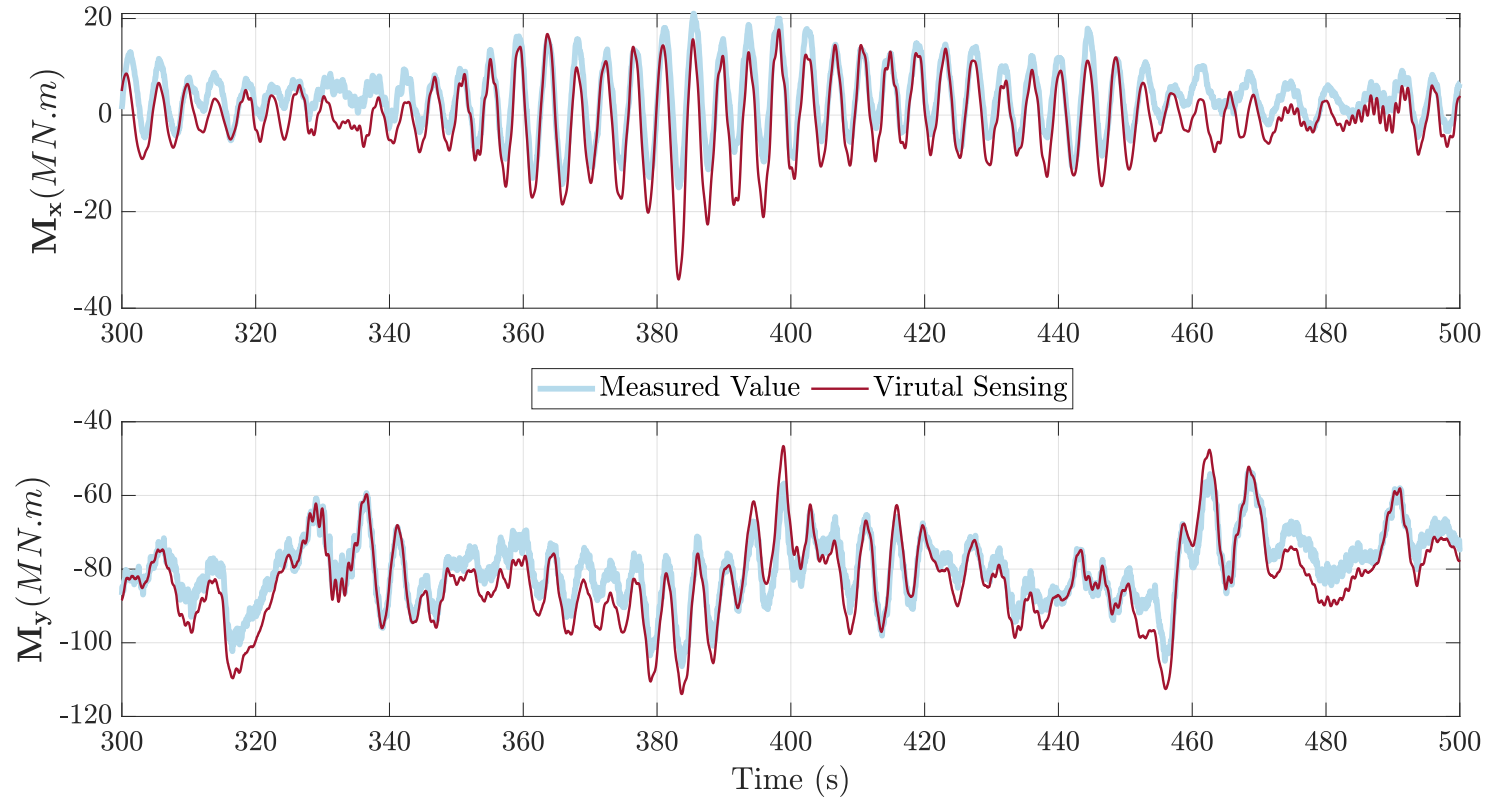
Estimated Input Load for a high wind case



Virtual Sensing at unmeasured locations



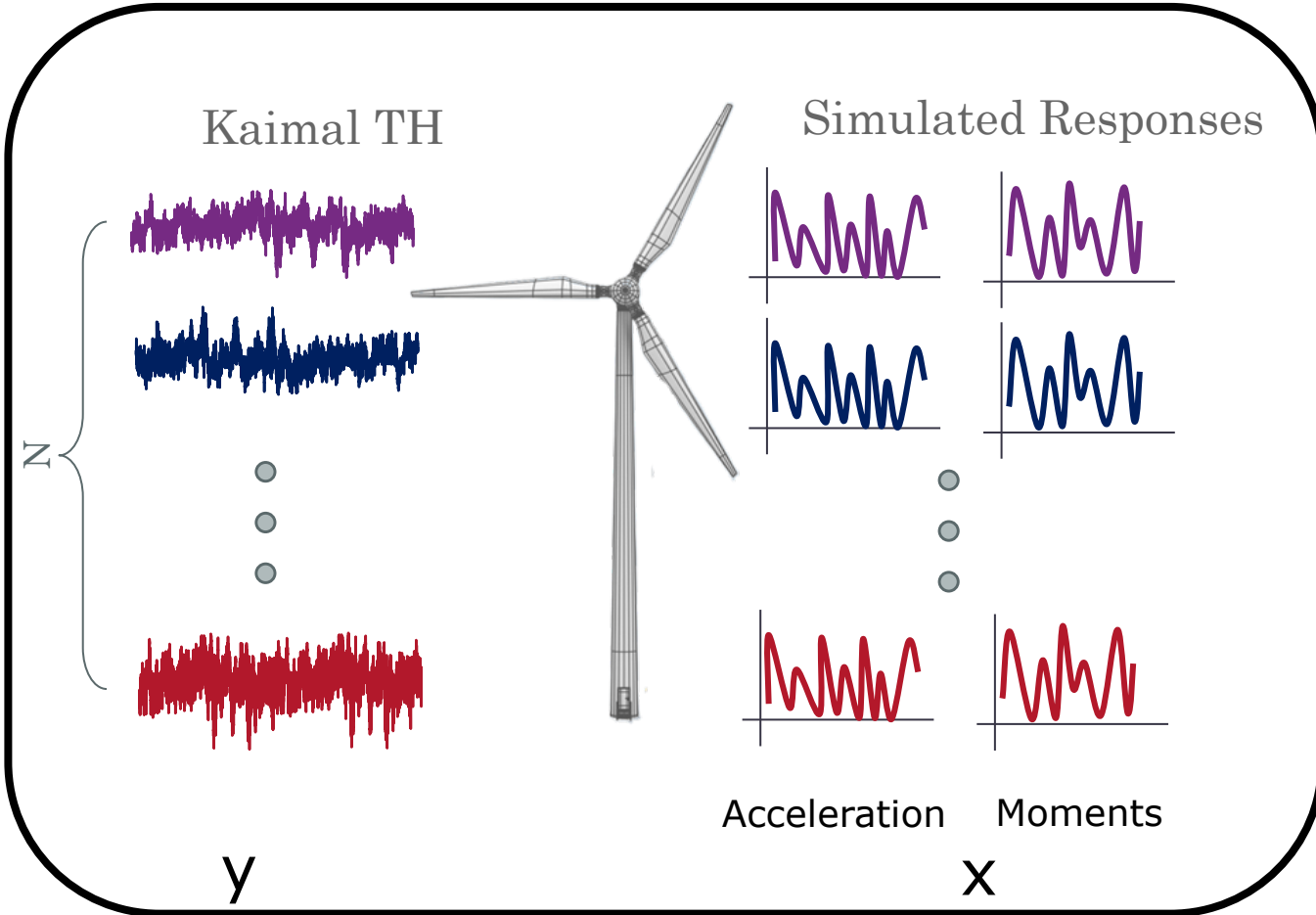
Moments' Virtual Sensing for underwater sensors



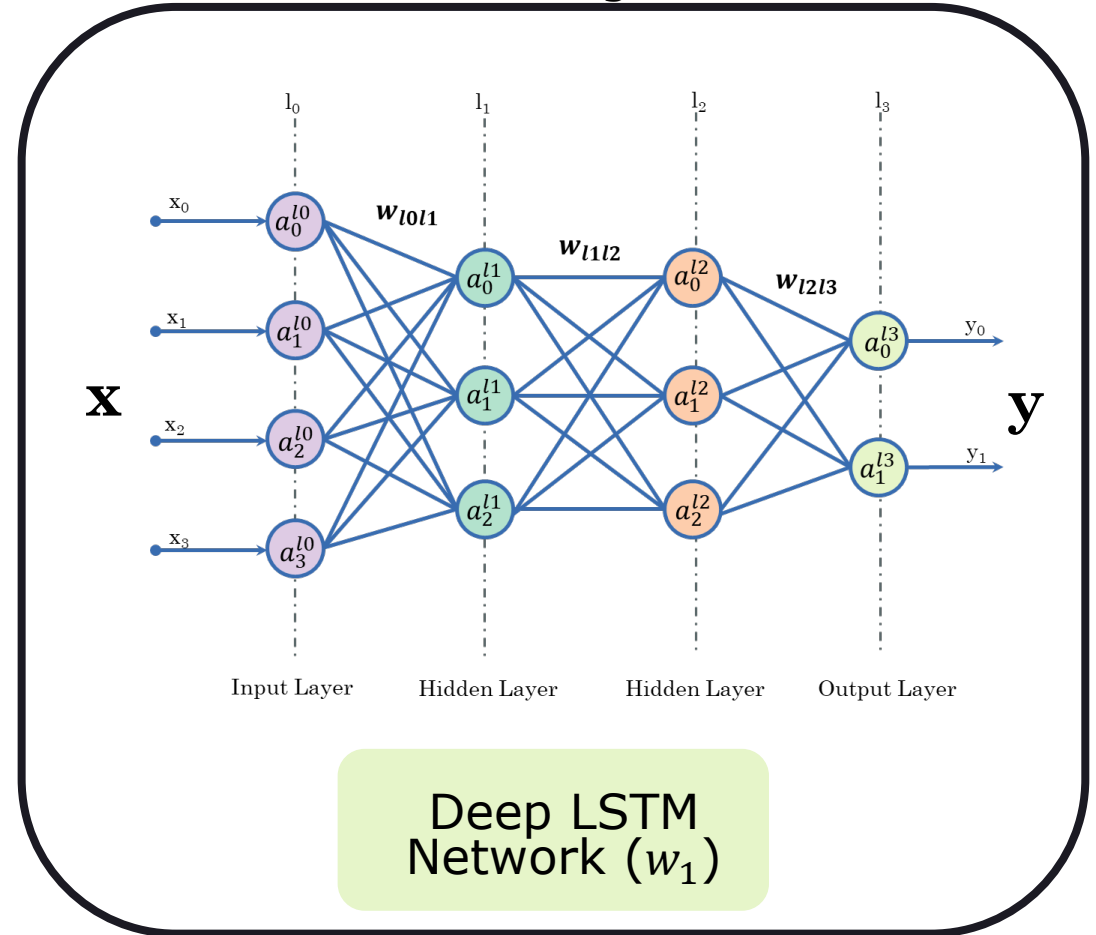
Physics Informed Neural Network

I Train Using Numerical simulated data

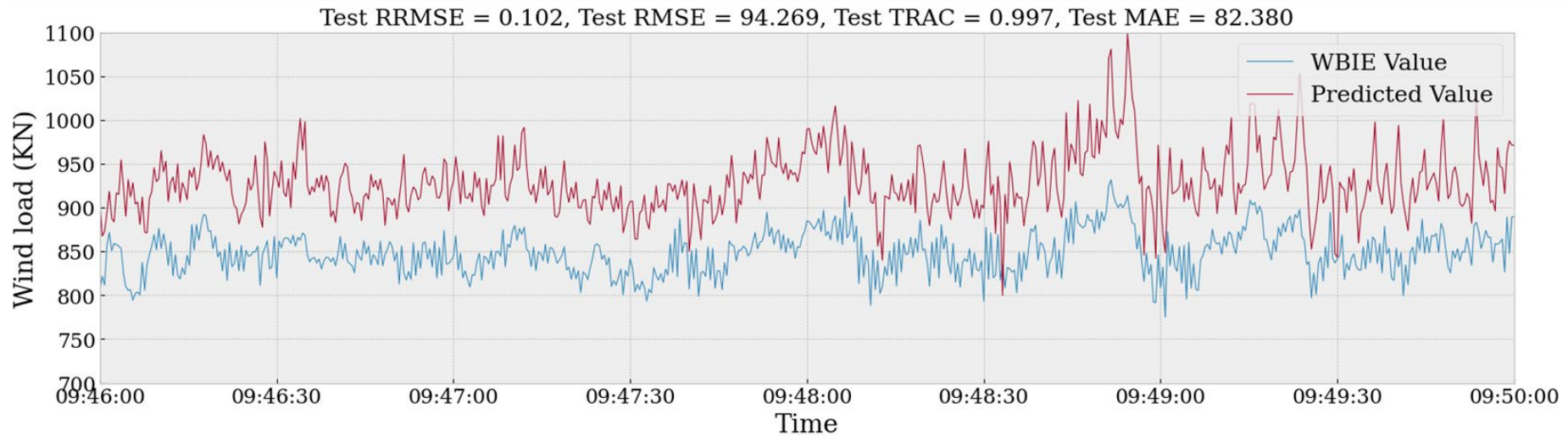
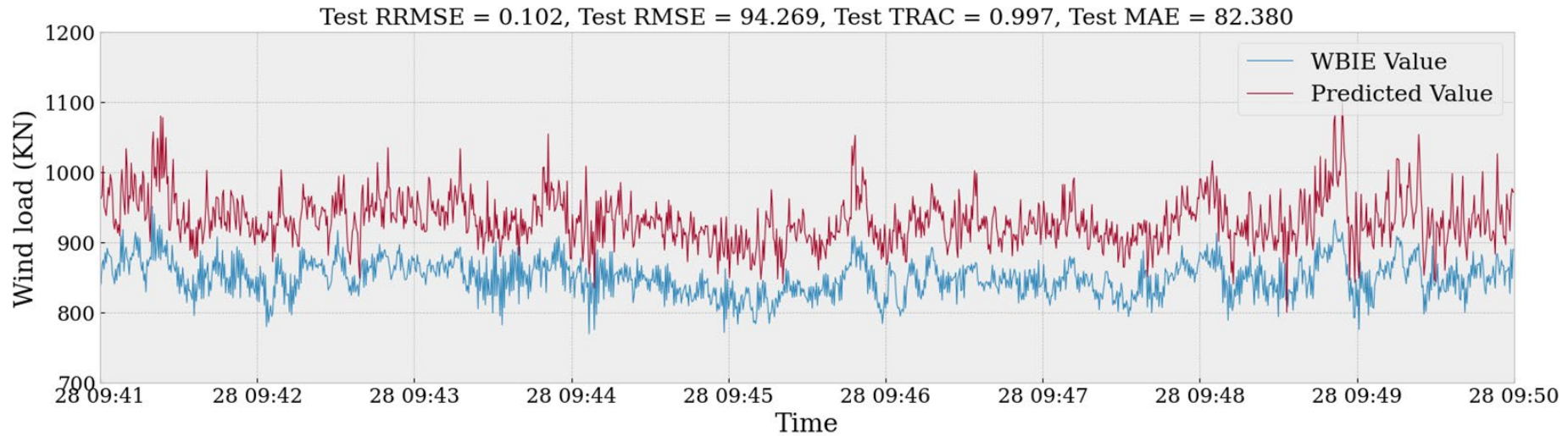
Simulation



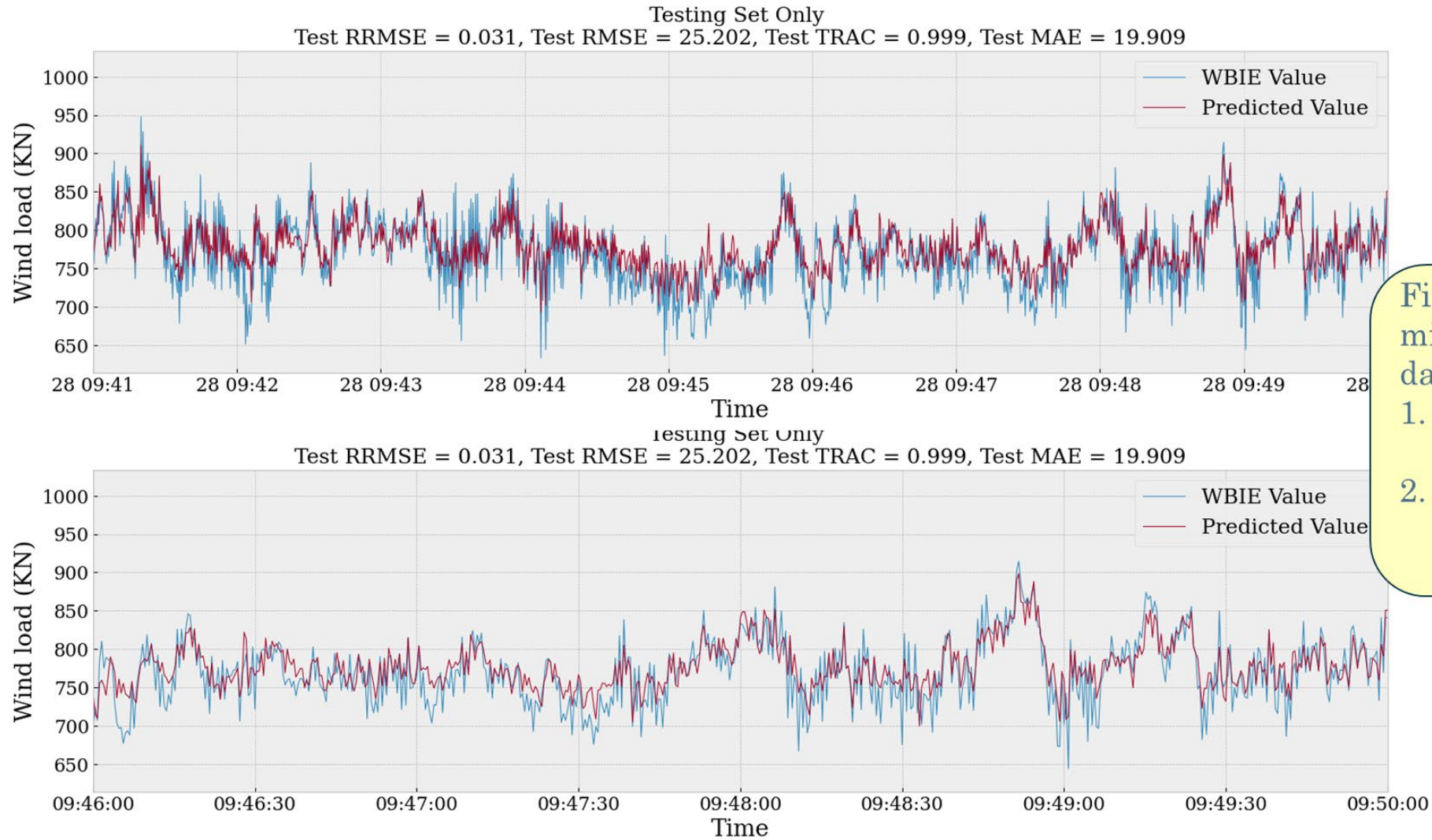
Training



Phase I model: Test on Real Data



Train Phase 2 by Fine-tuning

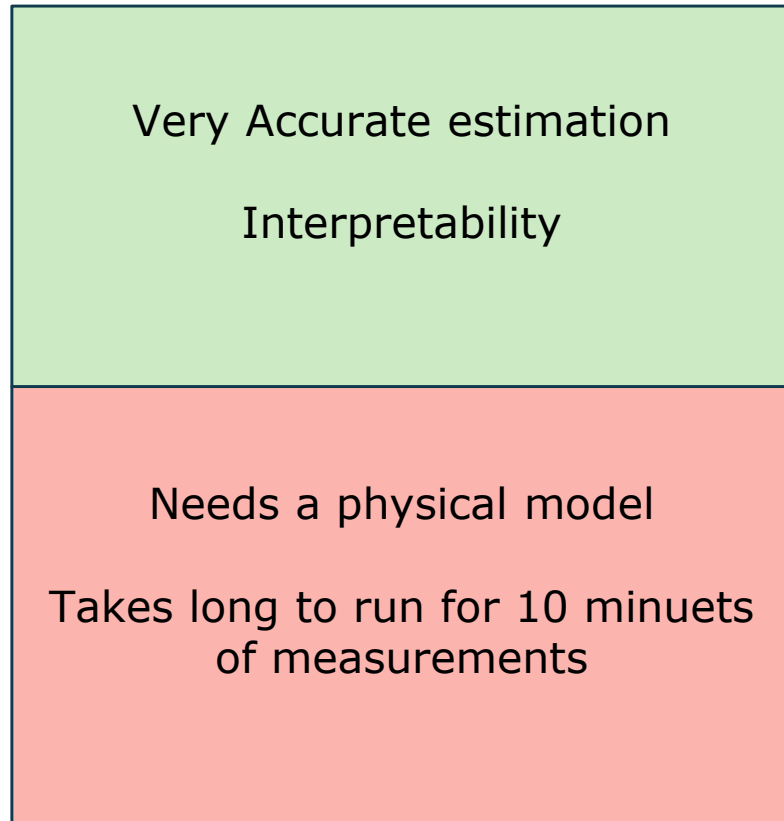


Fine tuning on 80 minutes of real data:

1. Measured acc and mom (x)
2. Estimated Inputs from WBIE (y)

Comparison

Physics-based estimator



Physics Informed NN estimator

