Whipping/springing response in the time series of ship structural stresses

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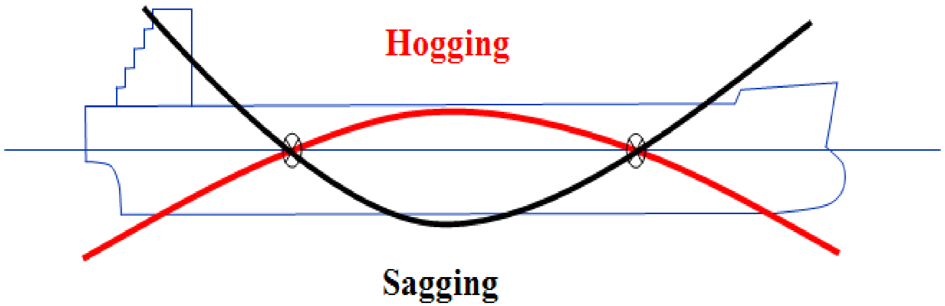
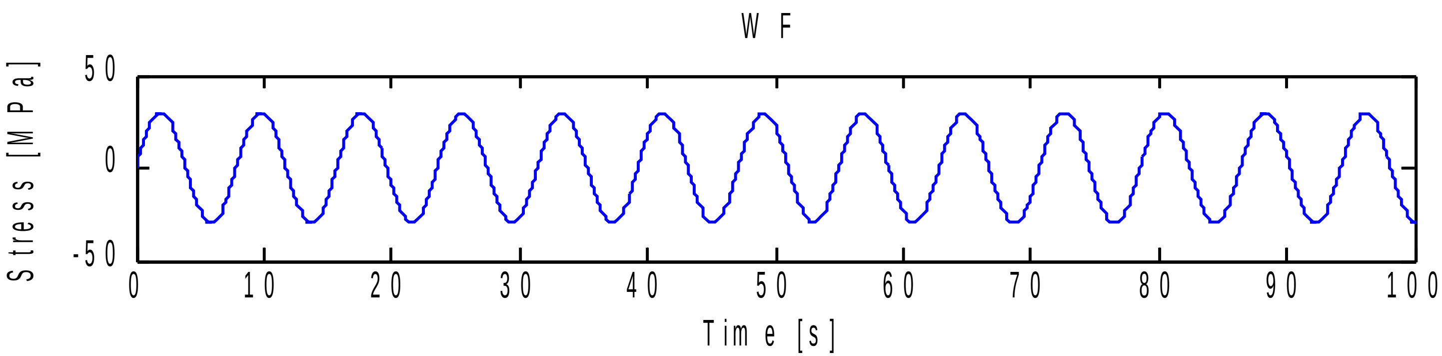
Outline

- Background
- Full-scale measurements from containerships
  - Time series of structural stresses (sample frequency 25 Hz)
  - Wave height, ship speed,heading... (each 30 minutes)
  - Wave (WF) and high frequency (HF) signals from the stresses
  - Fatigue and extreme response due to WF and HF signals
- Modeling of whipping/springing by LMA
  - Spectrum and kernel for whipping signals
  - Modeling of HF + WF response

Wave frequency (WF) ship response

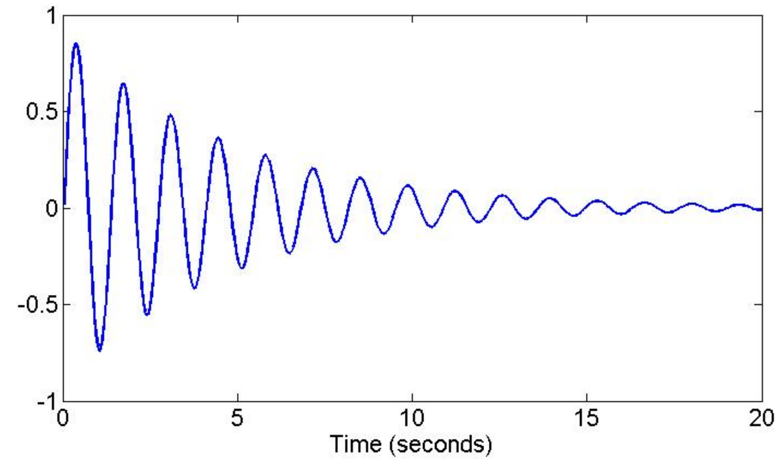
Vertical 2-node vibrations of ship as a beam



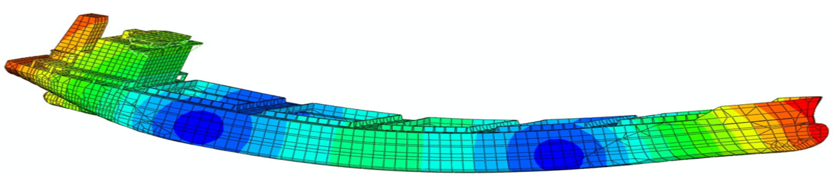


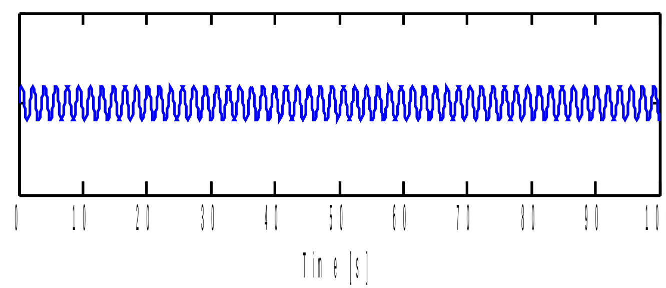
WF signals: the response frequency is close to the encountered wave frequency

HF signals– whipping/springing



Whipping signals: due to transient loads such as slamming, green water





Springing signals: resonance response

Fatigue problems and extreme loadings

Fatigue cracks observed in ship structures with only **about 2-5 years service** (Gaute Storhaug).

Slamming loads applied on ship's bow section and effect of extreme loadings (photos from internet)

Containerships in the future

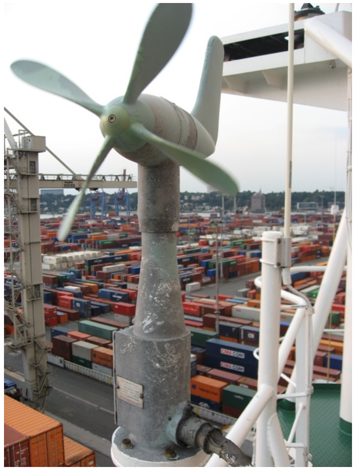
One of the biggest container vessel 350 m long (more than 12 000 TEU containers)

The full-scale measurements

- Measurements from 2 different container ships
- Based on the time series of data, we will study
  - If WF signals in a stationary sea condition are Gaussian
  - How much fatigue damage caused by WF signals
  - HF effect to ship's fatigue and extreme response
  - How to model HF signals by LMA

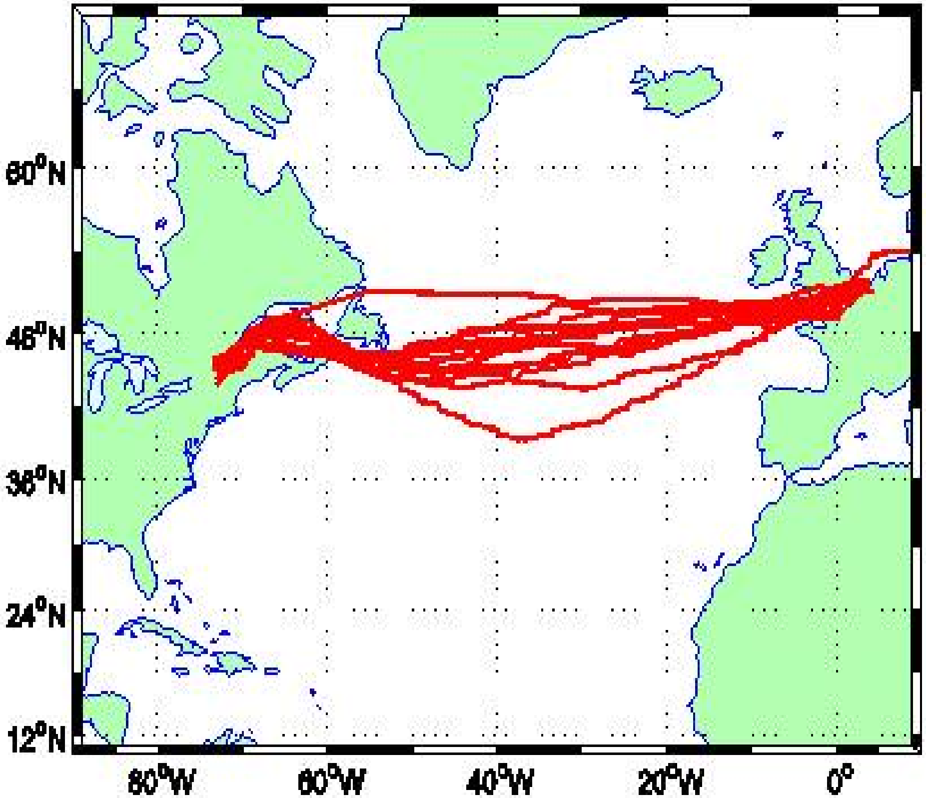
Measurement instruments

- **Strain sensors**
- **Wave radar**
- **Wave buoys**
- **Satellites/hindcast**
- **GPS**
- Wind sensor
- Accelerometer
- Rudder angle
- RPM
- ...



Gaute Storhaug

Ship sailing routes



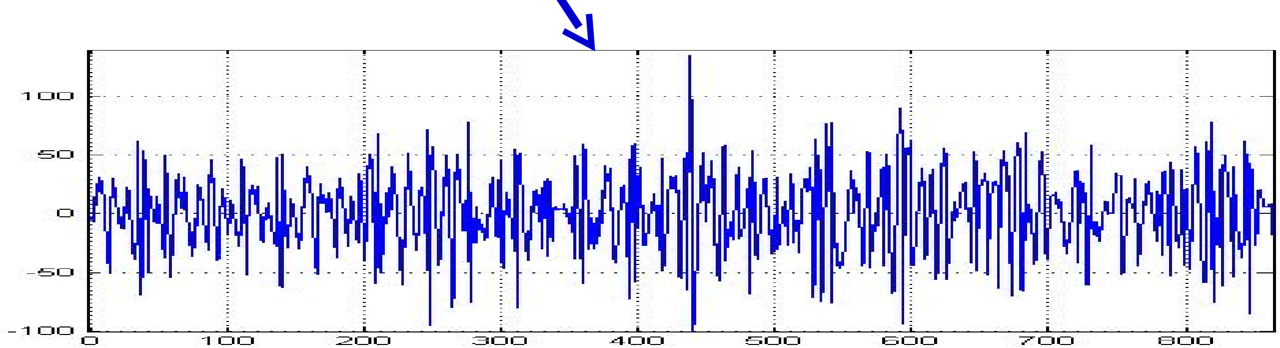
2800TEU containership

- 7 voyages from EU to NA
- 7 voyages from NA to EU
- Time in total 6 months

4400TEU containership

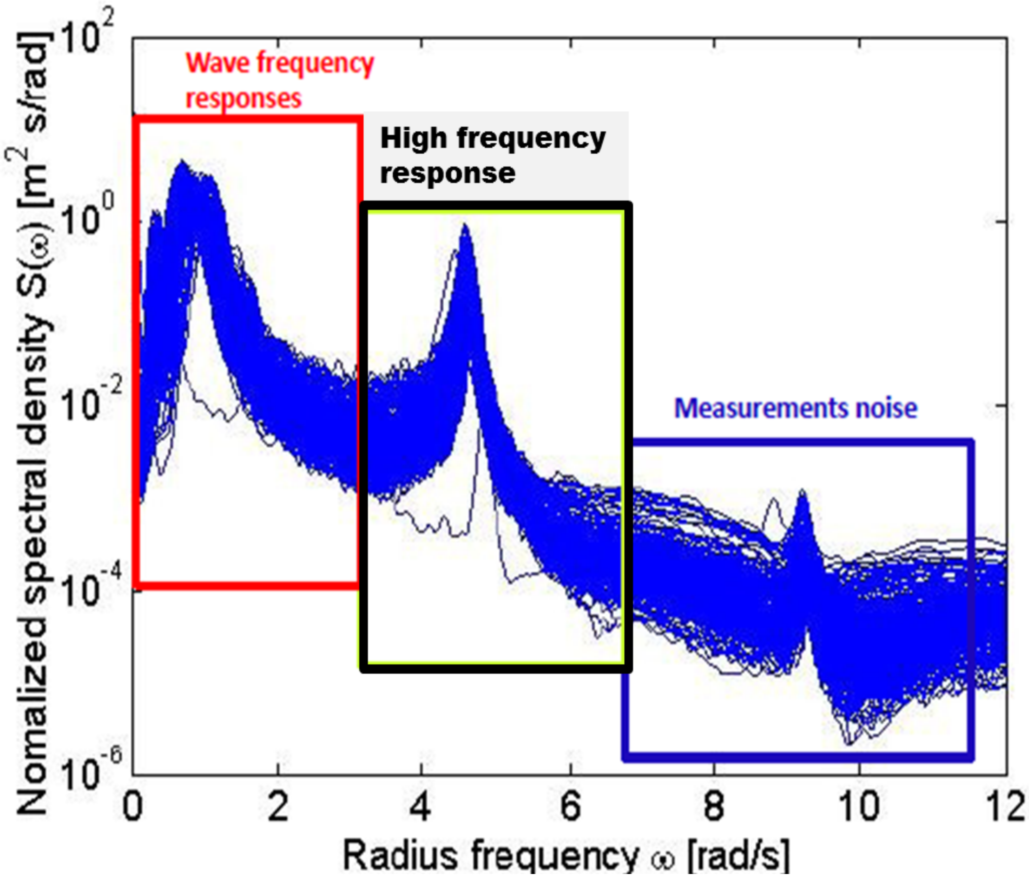
- 2 voyages from EU to NA
- 2 voyages from NA to EU
- Time in total 2 months

Measured time series of stresses



Measured times series of ship structural stresses in 30 minutes (a stationary sea state)

Spectra of measured ship responses



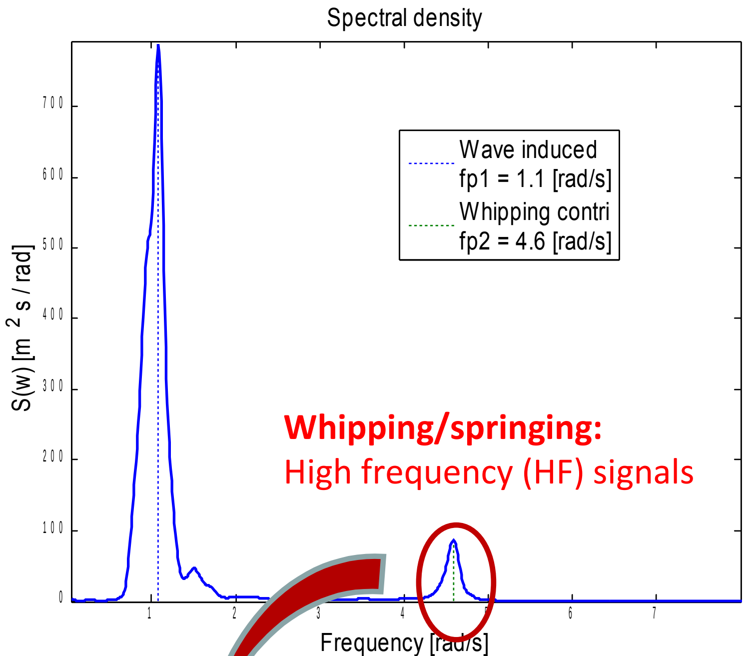
- The real signals of all sea states contain 3 peaks:
  i. Wave frequency signals (about 97% energy)
  ii. High frequency signals (3%)
  iii. Measurement noise

- High frequency signals Transient oscillation-- whipping, and resonance vibration -- springing.

  Hard to compute!

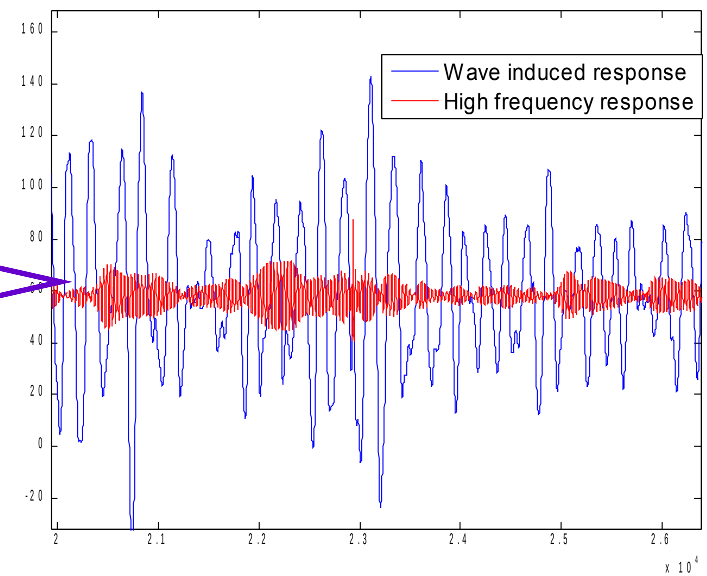
Response spectrums at different sea sates during one winter voyage

Definition and time series of HF response



Whipping/springing:
High frequency (HF) signals

Time series

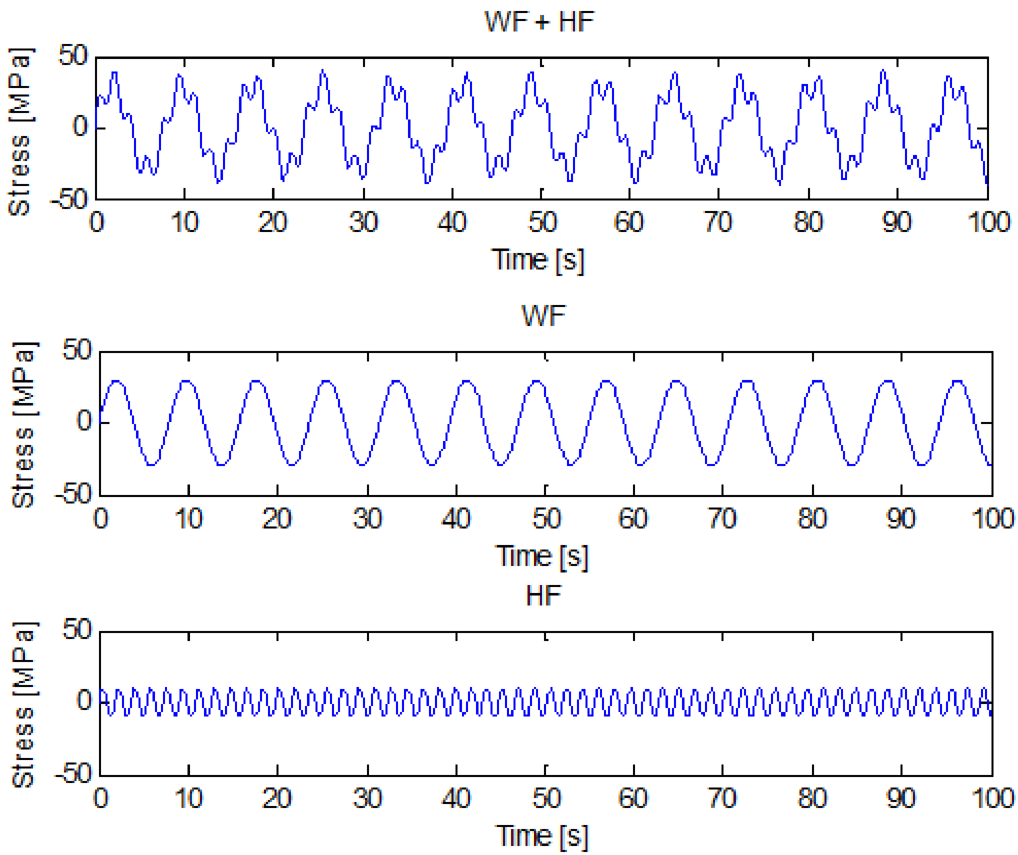


Separated signal with wave frequency & high frequency

Total response = WF + HF (whipping/springing)

1. WF signals: $\omega \in [0, 2]$ [rad/s]
2. HF signals: $\omega \in [2, 7]$ [rad/s]
3. Measurement noise: $\omega > 7$ rad/s

Fatigue damages due to HF response



Step 1: D_t
Total fatigue damage

Step 2: D_{wf}
Extract WF signals and get the damage

Step 3: $D_{hf} = D_t - D_{wf}$

WF response caused fatigue

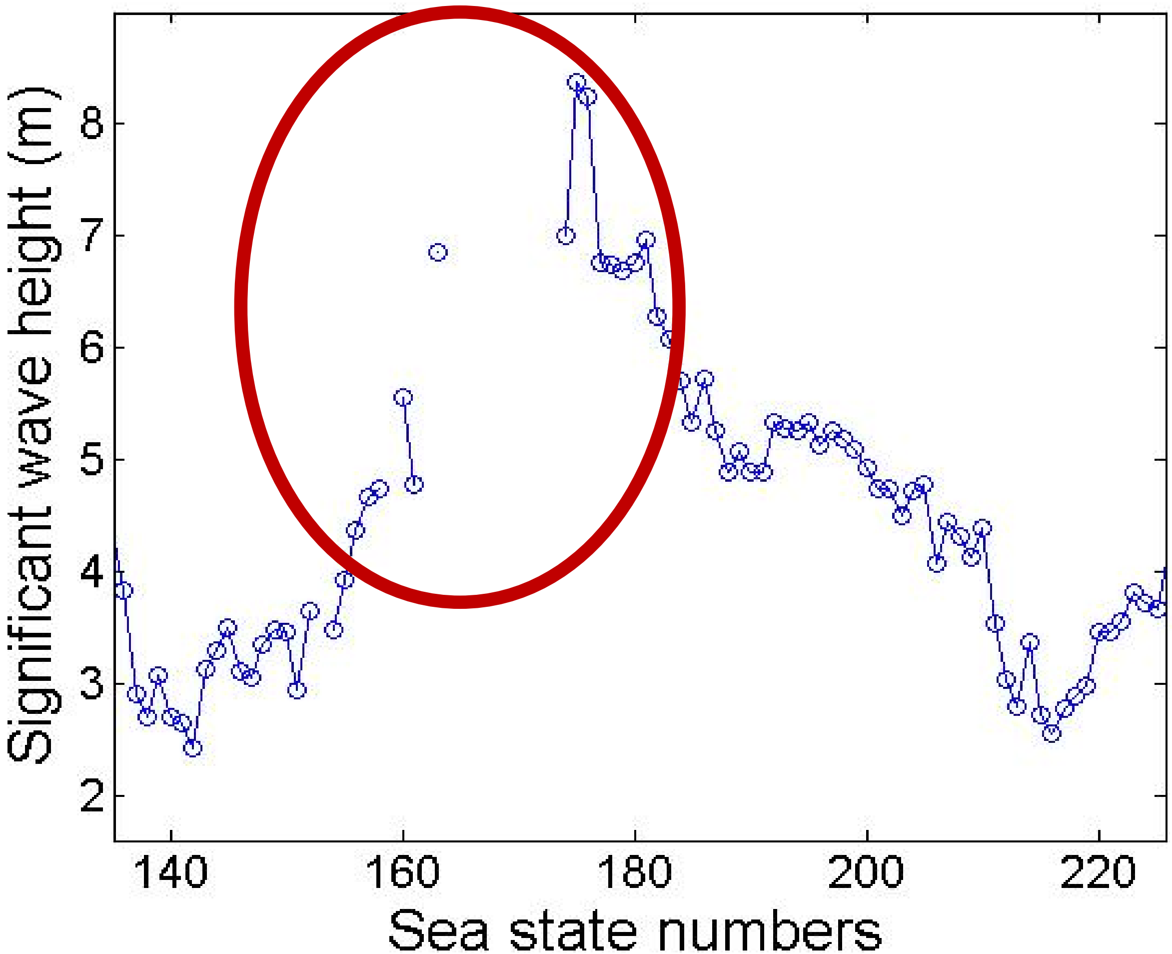
$$Fatigue\ \ Damage = f\left[V,\ \theta,\ T,\ S(H_s, T_p),\ C\right]$$

Operation profiles
- V - Ship speed
- θ - Heading angle
- T - Sailing time

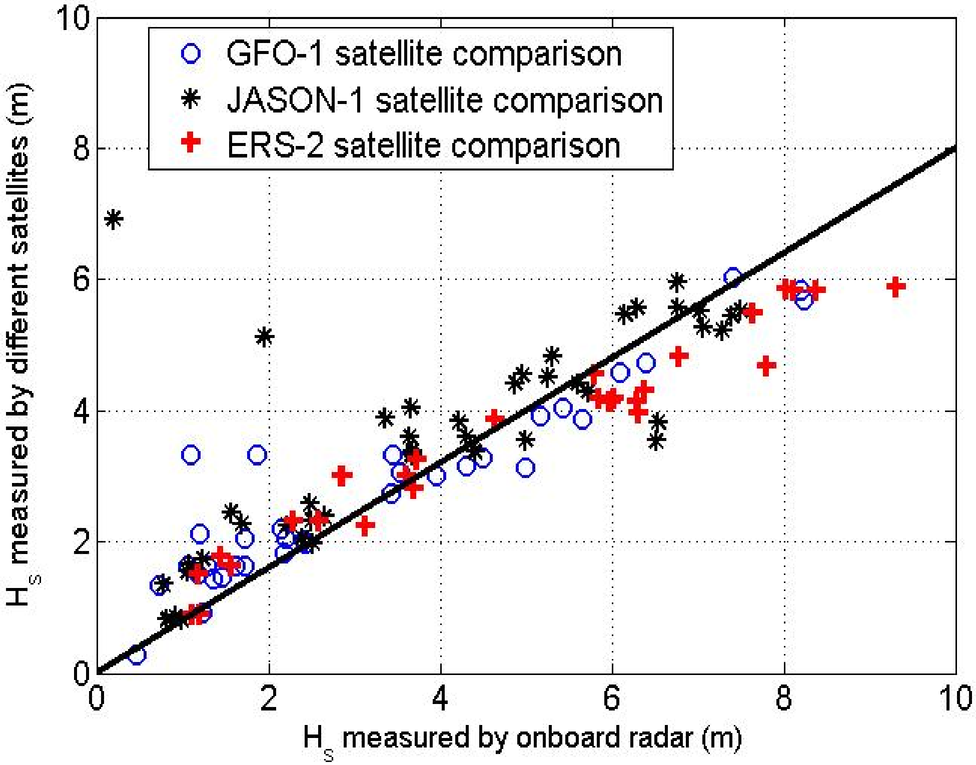
Wave environment
- H_s – Wave height
- T_p – Wave period

Structural response characteristics, got from engineering analysis

Measured Hs in one storm

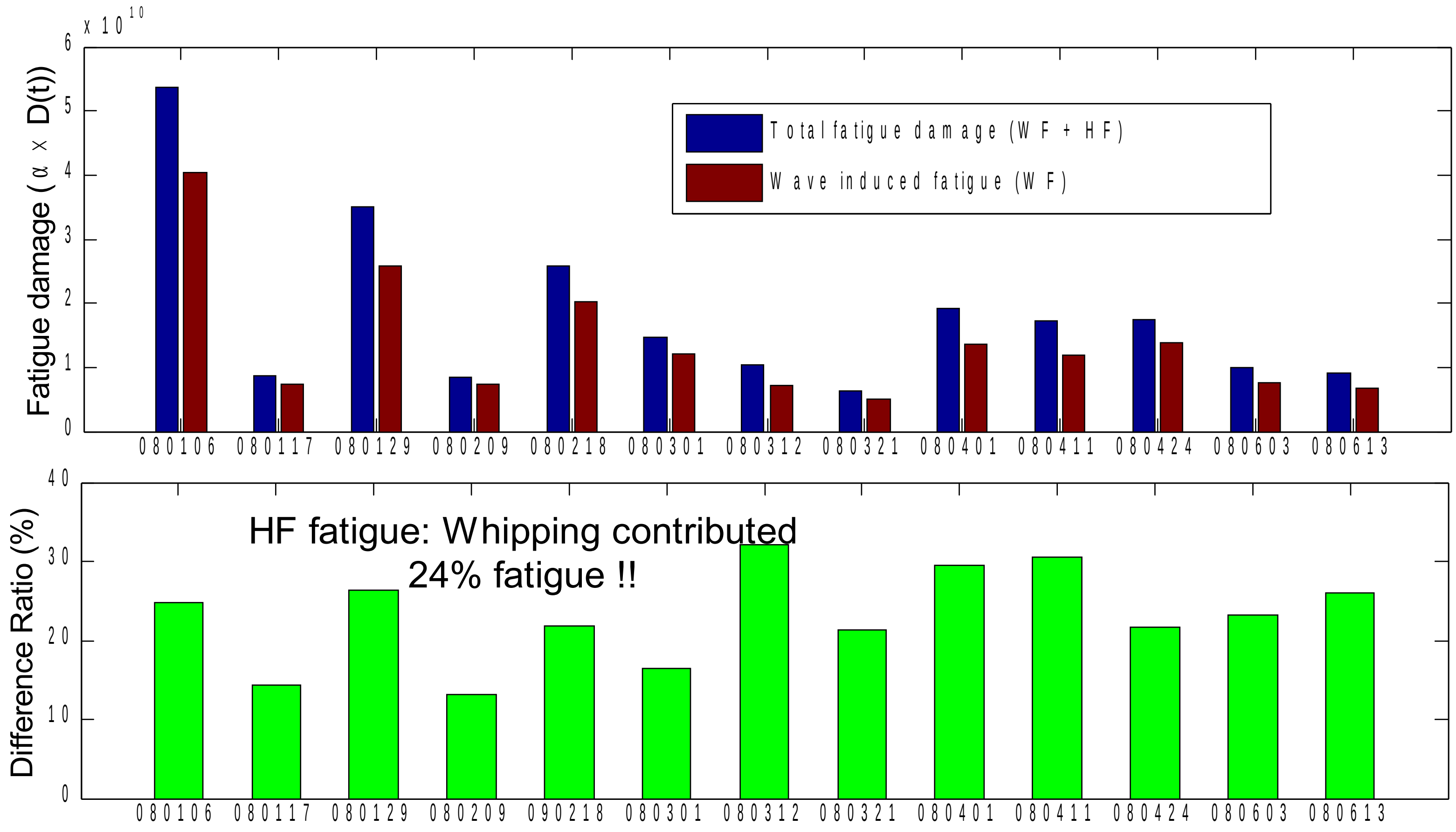


Calibration of wave measurements



1. Onboard wave measurements include some uncertainties;
2. Radar measurements should be calibrated before practical applications;
3. Some statistical model may be used to interpolate Hs for missing data.

Results: Fatigue due to HF signals (1)



Results: Fatigue due to HF signals (2)

- General container/cargo – 23%
- 2800 TEU – 28%
- 4000 TEU – 39-46%
- 4400 TEU – 37% (model test)
- 4600 TEU – 35% (Rathje et al. 2012)
- 4400 TEU – 26%
- 6700 TEU – 50%
- 8600 TEU – >60% (model test)
- 14000 TEU – 57% (Rathje et al. 2012)

The increase of extreme response follows similar trend!

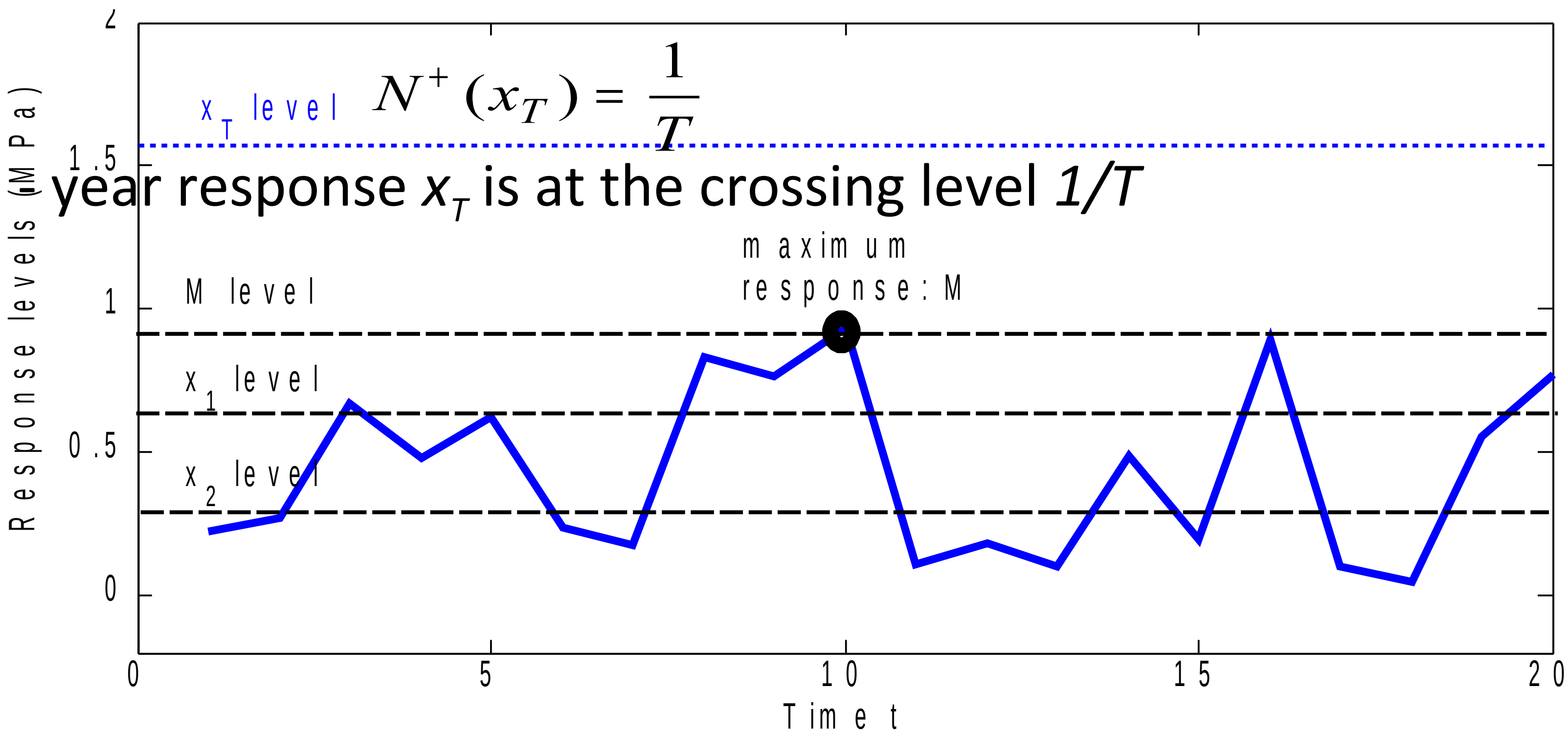
HF effect on extreme response

--from the full-scale measurements of 2 container ships

Predict extreme response by upcrossings

is the time series of stresses (signals) in 1 year

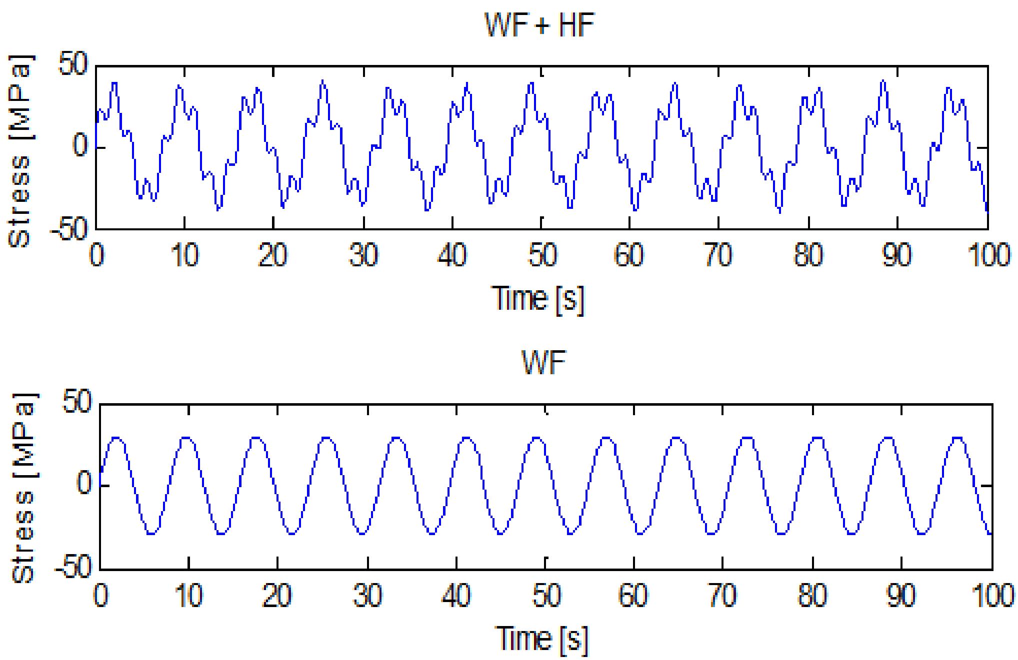
$^{+}$*(x)* is expected no. of upcrossings during one year;



$$N^{+}(x_T) = \frac{1}{T}$$

year response x_T is at the crossing level *1/T*

Extreme response due to HF effect



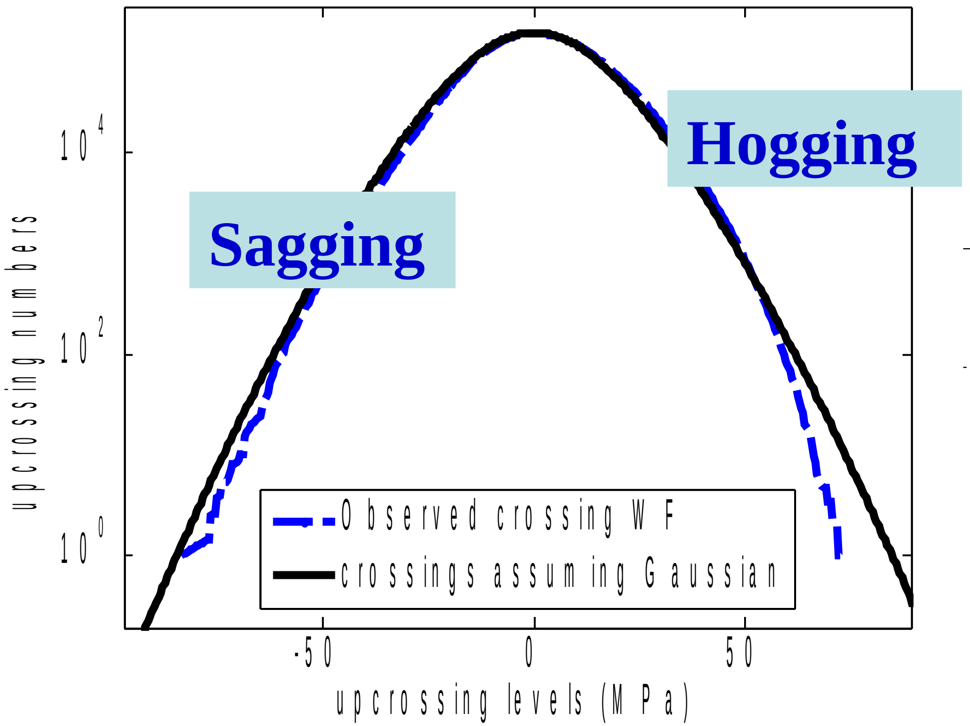
Step 1: *Extract WF* signals *from the measurement (WF+HF* signals*)*

Step 2: *Upcrossing from extracted* WF signals (observed and Rice's formula)

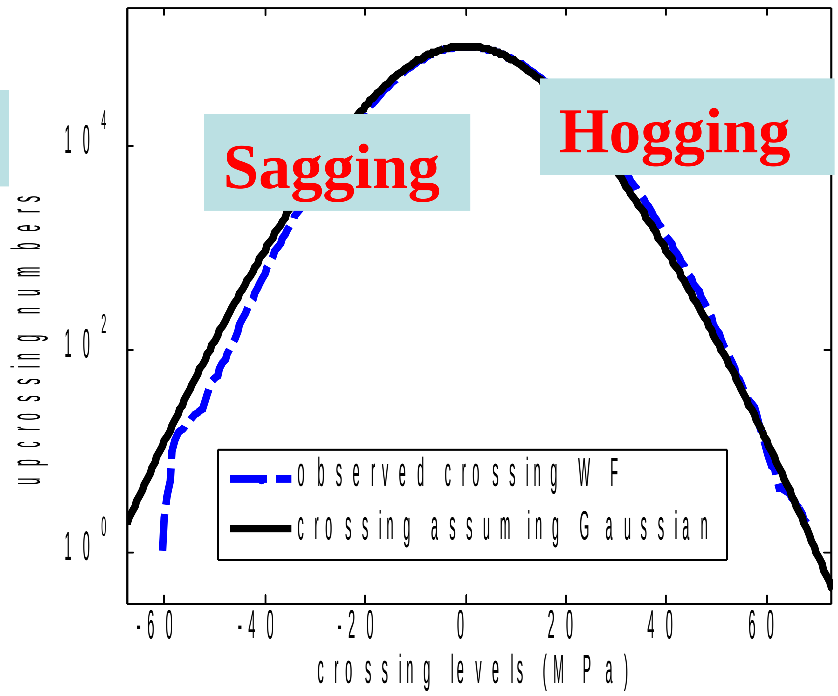
Step 3: *Upcrossings from HF+WF* signals

Step 4: *Extrapolate the upcrossings to some extreme levels to get* X_T.

WF signals → is it Gaussian?



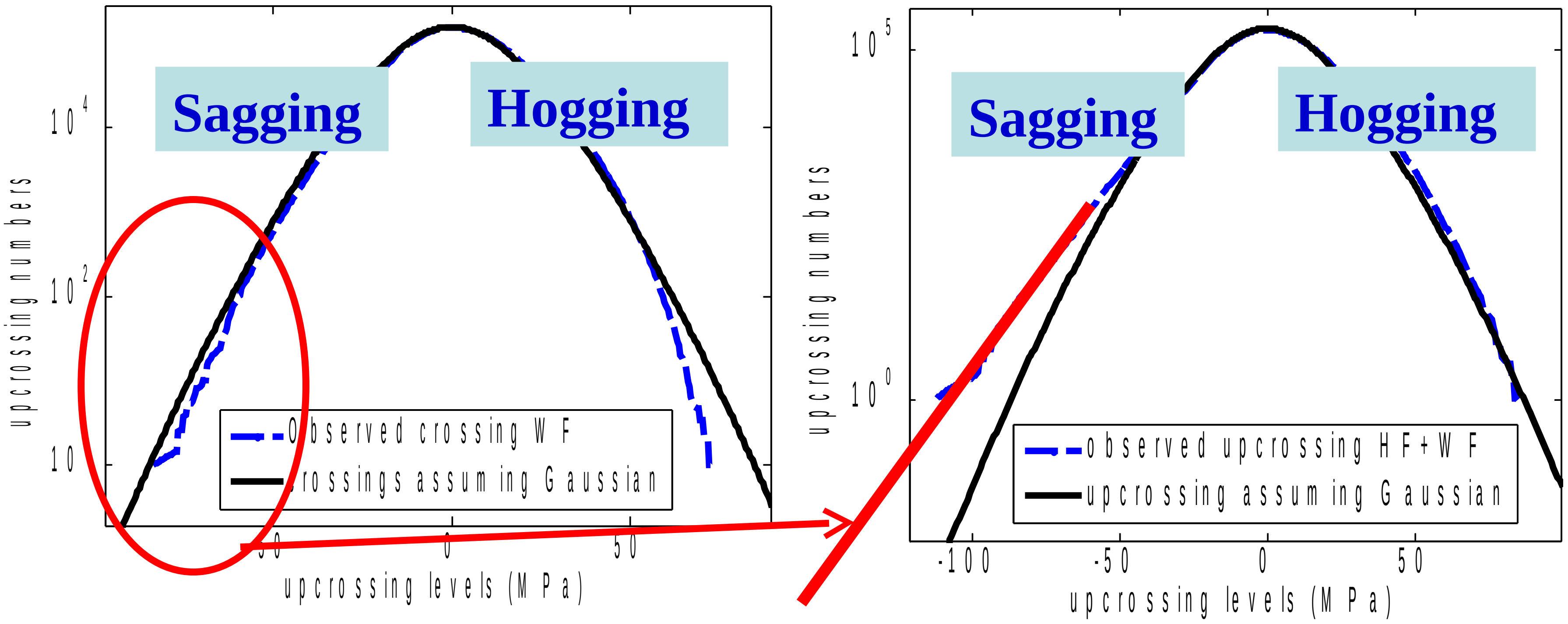
2800TEU in 6 months



4400TEU in 2 months

HF signals → extreme stress

Measurements of **2800 TEU**

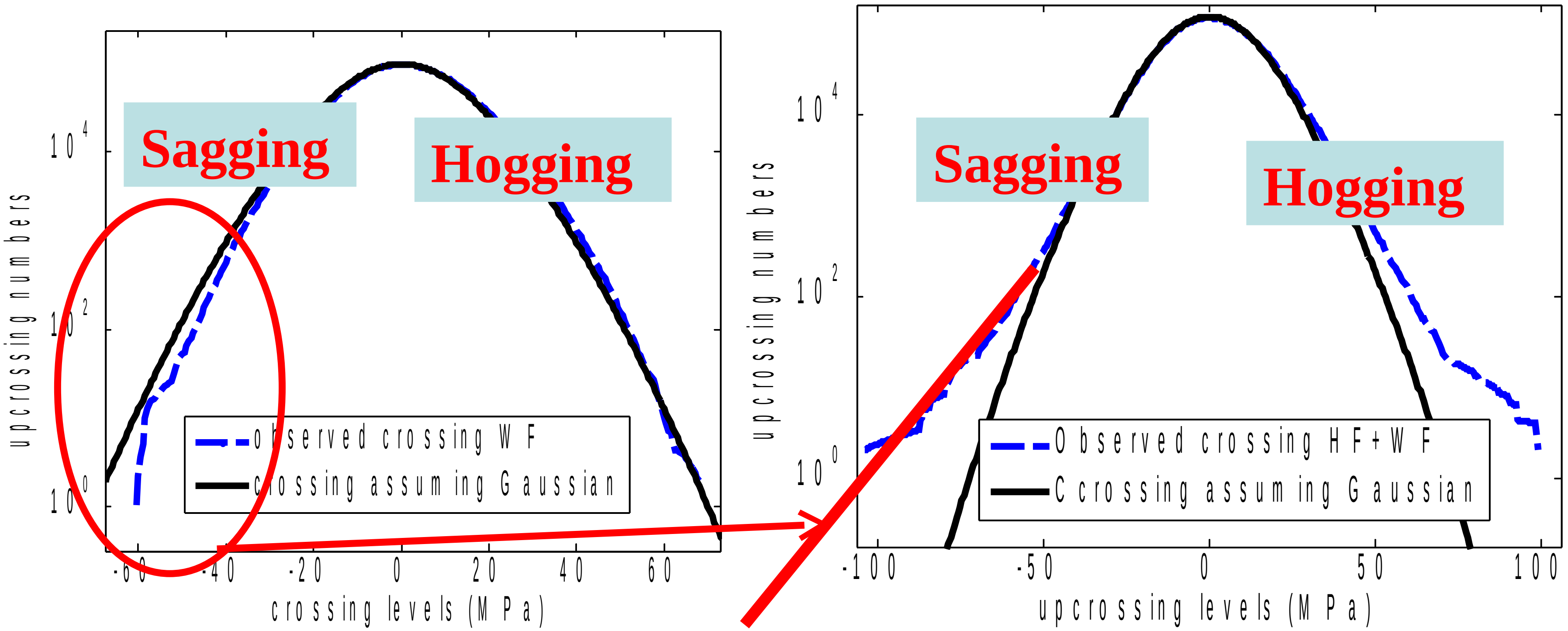


WF signals

HF + WF signals

HF response → extreme stress

Measurements of **4400 TEU**



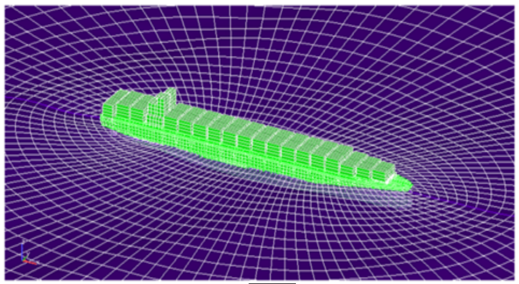
WF signals

HF + WF signals

Modelling of ship response

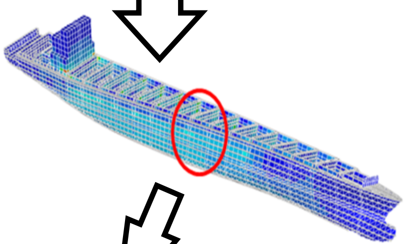
- WF signals by Gaussian processes
  - Response spectrum can be computed
  - Gaussian process is simulated from response spectrum
- HF signals by LMA processes
- Hybrid model to combine the two processes (correlated/independent)
  - WF signals – Gaussian process (low frequency)
  - HF signals -- Symmetric LMA (high frequency)

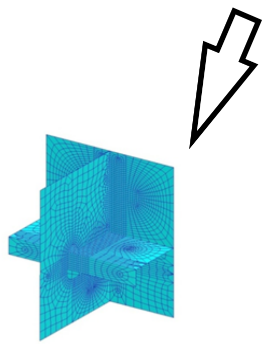
Wave frequency (WF) ship response



Hydrodynamic loads:

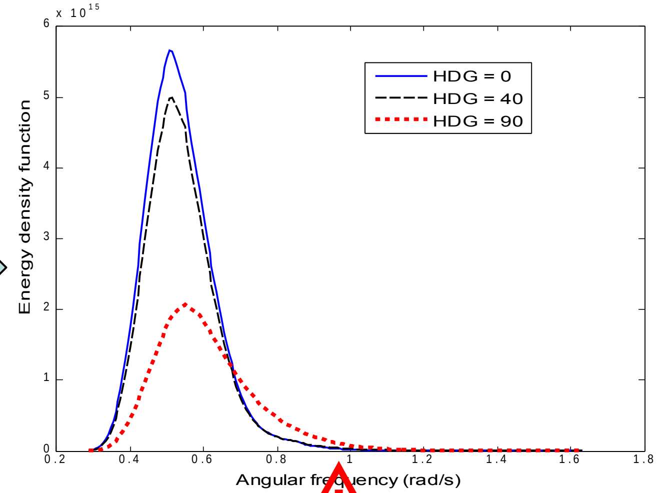
- Loading conditions
- Ship speed
- Heading angles
- Panel method for hydrodynamic analysis



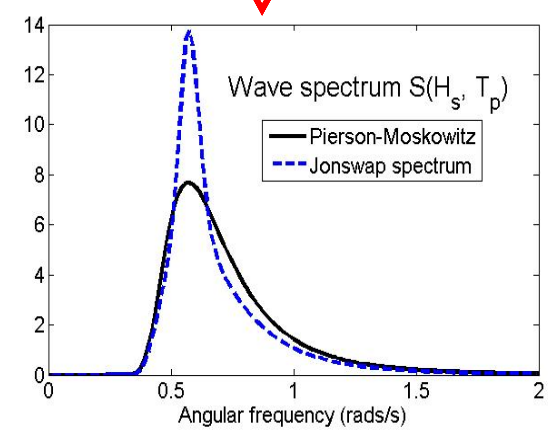


Structural analysis:

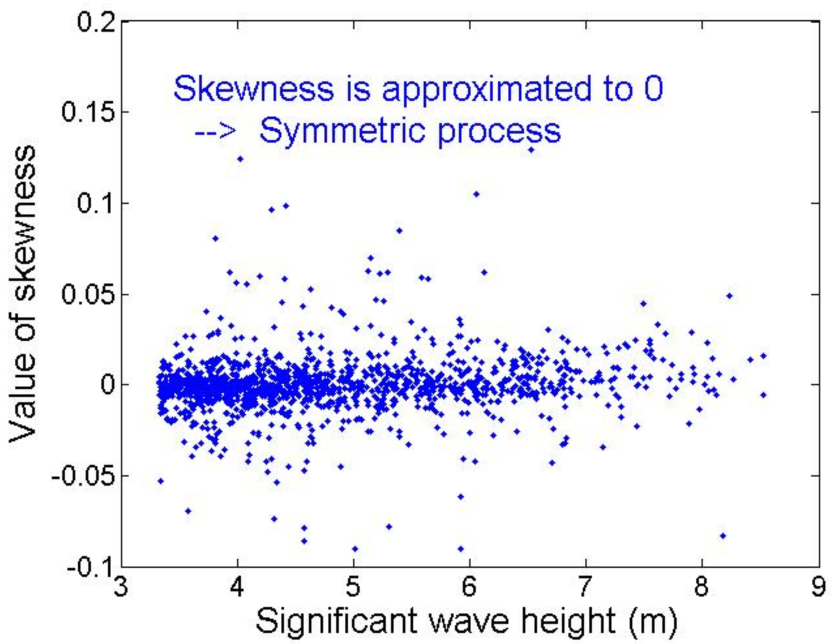
- Global response
  - Simple beam theory
  - Direct Finite Element analysis
- Local structural details



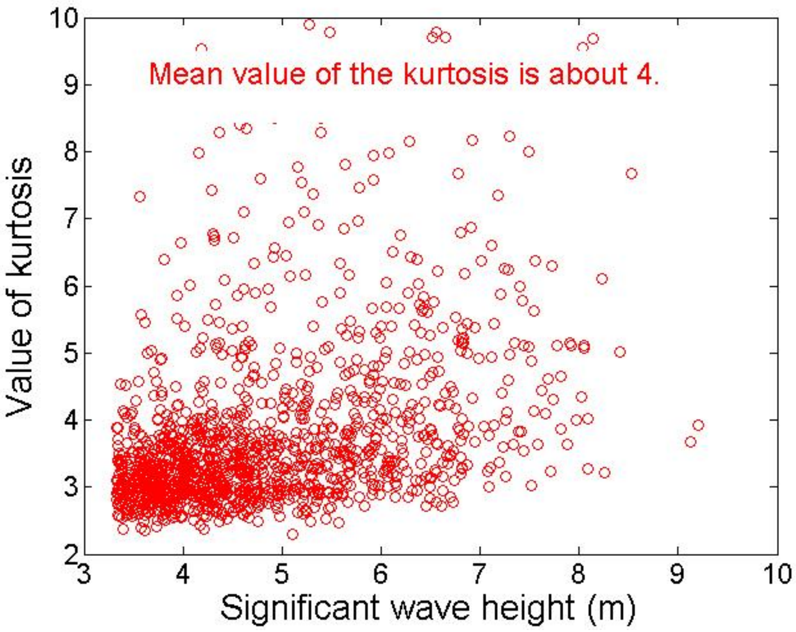
Transfer function (RAOs)



Skewness and kurtosis of HF signals



Skewness of HF signals



Kurtosis of HF signals

Symmetric Laplace Moving Average (LMA)

- Gaussian Moving Average (GMA) process

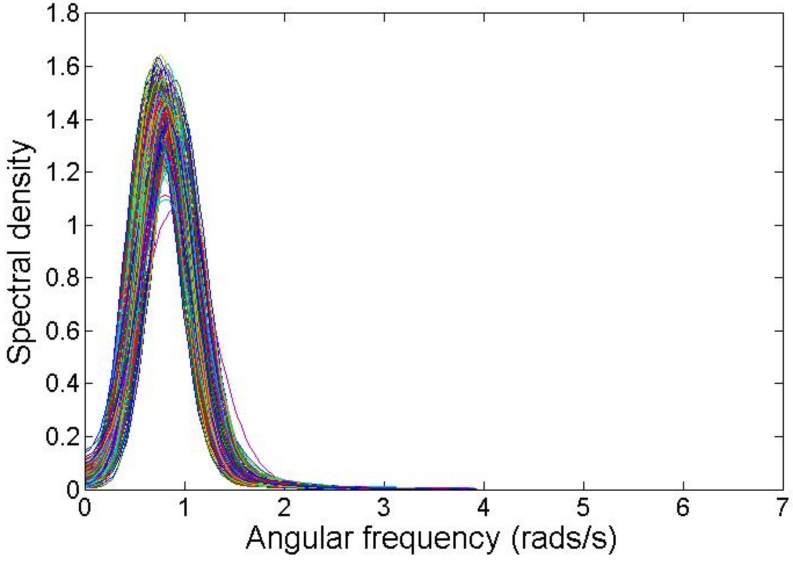
$$X(t) = \int_{-\infty}^{\infty} g(t-u)dB(u) \approx \sum_i g(t-t_i)Z_i\sqrt{dt}$$

- Laplace Moving Average (LMA) process

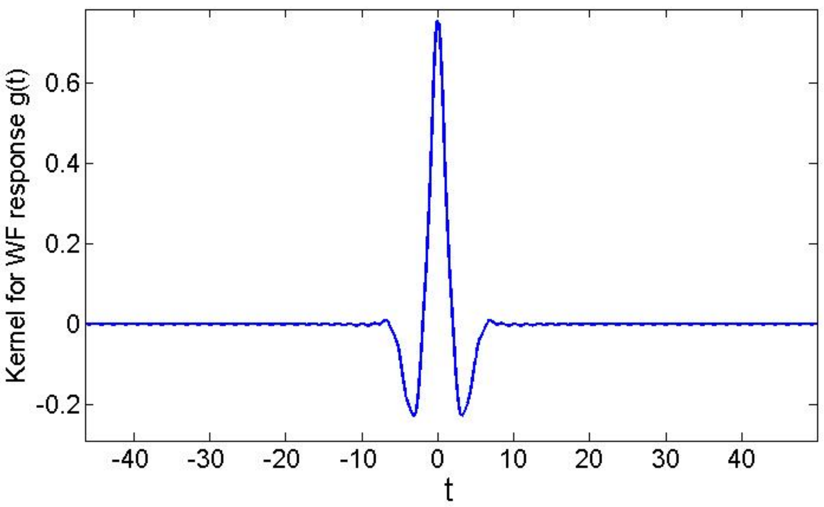
$$X(t) = \int_{-\infty}^{+\infty} g(t-u)d\Lambda(u) \approx \sum_i g(t-t_i)\,Z_i\sqrt{K_i}$$

In the GMA process, $B(u)$ is the Brownian motion, while in the LMA process, $\Lambda(u)$ is the Laplace jump process, and $g(t)$ is the kernel of the response signal.

Spectrum and kernels for WF response

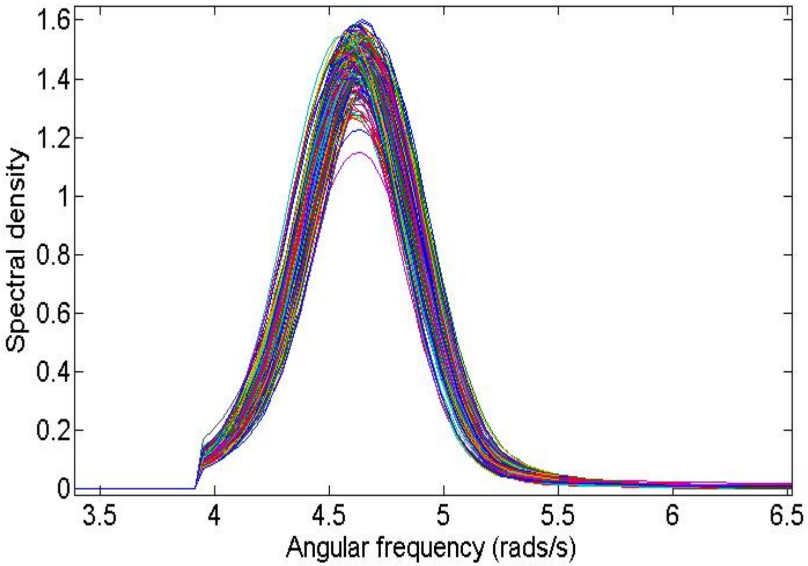


WF response spectrums

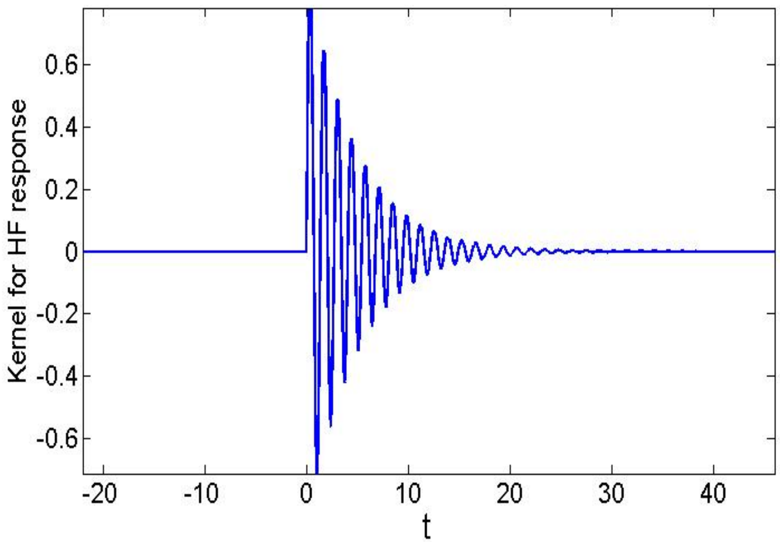


Kernel for WF signals simulation

Spectrum and kernels for HF response

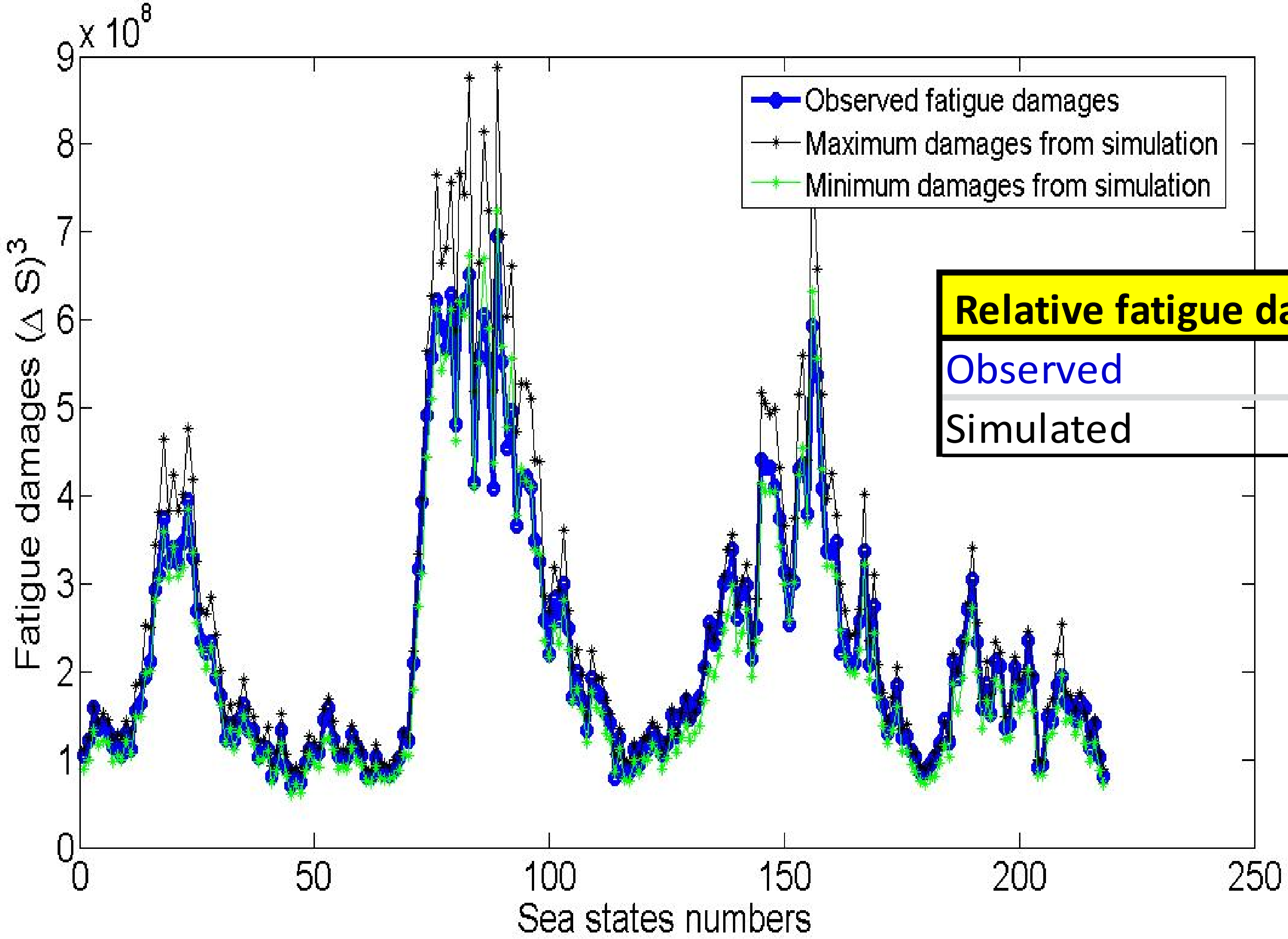


HF response spectrums



Kernel for HF signals simulation

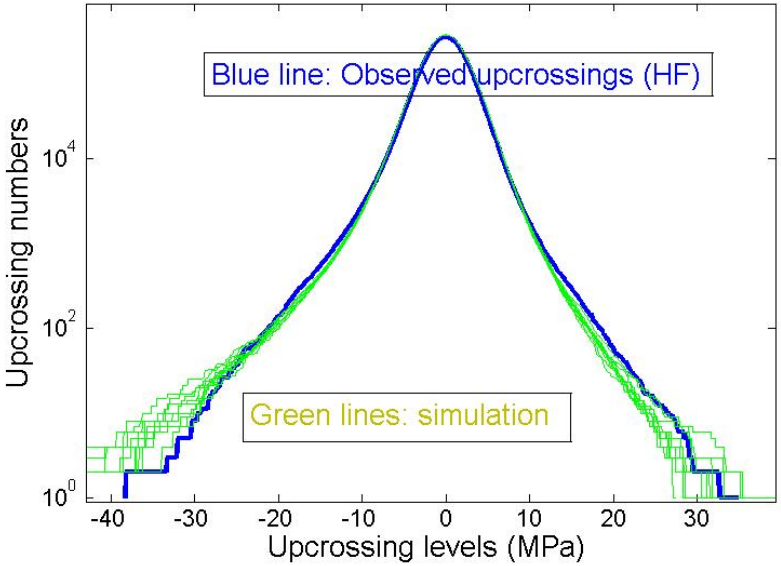
Comparison of fatigue damages



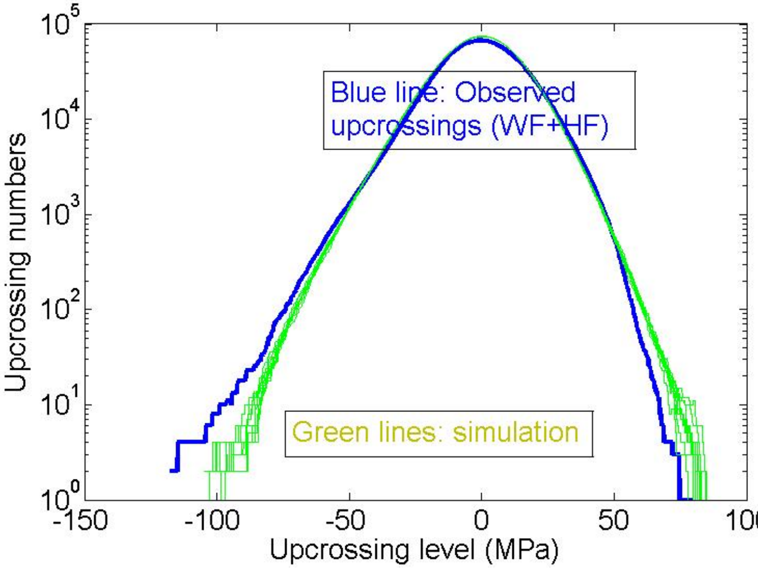
Relative fatigue damage D=sum($\Delta\sigma^3$)	
Observed	5.21e10
Simulated	5.34e10

Extreme prediction

- Upcrossings of simulated ship response using observed Kurtosis



Upcrossings of HF signals



Upcrossings of HF+WF signals

Conclusions

- HF response induces average energy 3%
- HF response contributes fatigue > 30%
- The wave frequency response is close to Gaussian
- The HF response is symmetric process
- The LMA modeling works well to simulate ship response for fatigue assessment
- For extreme prediction, it is very sensitive to decide how to put on the whipping transient on the wave frequency response. It will affect significantly of the prediction.

Thanks for your attention.