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

Wengang Mao*, Igor Rychlik
Chalmers University of Technology, Göteborg, Sweden
wengang@chalmers.se
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)
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 states during one winter voyage
Definition and time series of HF response

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**

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

- **Operation profiles**
  - \( V \) - Ship speed
  - \( \theta \) - 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 $H_s$ for missing data.
Results: Fatigue due to HF signals (1)

HF fatigue: Whipping contributed 24% fatigue!!

Total fatigue damage (WF + HF)
Wave induced fatigue (WF)
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

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

\( n \) is expected no. of upcrossings during one year;

\( x_T \) 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 \( \rightarrow \) is it Gaussian?

2800TEU in 6 months

4400TEU in 2 months
HF signals $\rightarrow$ extreme stress

Measurements of 2800 TEU

WF signals

HF + WF signals
HF response $\rightarrow$ 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)

Wave spectrum $S(H_s, T_p)$
- Pierson-Moskowitz
- Jonswap spectrum
Skewness and kurtosis of HF signals

Skewness of HF signals

Kurtosis of HF signals

Skewness is approximated to 0
--> Symmetric process

Mean value of the kurtosis is about 4.
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

![Diagram showing comparison of observed and simulated fatigue damages.](image)

Relative fatigue damage $D = \sum (\Delta \sigma^3)$

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
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<tbody>
<tr>
<td>Observed</td>
<td>5.21e10</td>
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<tr>
<td>Simulated</td>
<td>5.34e10</td>
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Extreme prediction

- Upcrossings of simulated ship response using observed Kurtosis

![Graphs showing upcrossings of HF signals and HF+WF signals](image-url)
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.