STRUCTURAL VIBRATION ANALYSIS ON THE POLAR SUPPLY AND RESEARCH VESSEL THE S.A. AGULHAS II IN ANTARCTICA

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ABSTRACT

The Polar Supply and Research Vessel the S.A. Agulhas II plays a key role in the South African National Antarctic Program, and is relied upon for logistical and research support in Antarctica and the Southern Ocean. The vessel is exposed to various ice and open water conditions and encounters a number of different excitation mechanisms which are capable of causing structural fatigue. To this end full scale measurements were conducted during a 78 day voyage from Cape Town to Antarctica during 2013/2014 to investigate the effect of vibration on the vessel's structure. Nineteen vibration measurement channels were recorded on the hull structure and five on the superstructure in order to determine the global vibration response of the vessel. The structure is found to be most affected by vertical vibration during open water navigation, with a maximum peak velocity of 338 mm/s in 8 m swells. Comparatively, structural vibration levels in open water are greater than those measured during ice navigation. According to Germanischer Lloyd's (2001) ship vibration guidelines, structural fatigue as a result of vibration is found to reach levels where damage is possible in the stern and were damage is probable in the bow. The vibration levels with potential to cause fatigue damage were measured in 8 m swells during open water navigation. This calls for further investigations into the effects of the duration at these exposures, materials of construction, structural details in the affected areas, welding processes and environmental conditions. It is recommended that further investigations be conducted into the effects of hybrid ice-open water designs on vibration response.

INTRODUCTION

Antarctic research institutes and their scientists continue to rely on polar supply and research vessels (PSRVs) to supply bases and serve as floating laboratories. Vessels operating in Antarctica and the Southern Ocean are exposed to various ice and open water conditions and encounter a number of different excitation mechanisms, which are capable of causing structural fatigue.

Advances in the various fields of marine engineering have enabled modern ship designs which are lighter in weight and offer increased propulsion power. These advances are weighed against structural integrity and fatigue life (Orlowitz and Brandt, 2014). The importance of dynamic structural analysis in the design phase of vessels is therefore more relevant now than ever before. The reliability of these analyses is based on real engineering data and the extrapolation of such data on reasonable assumptions.

Full scale measurements have played an important role in understanding the dynamic responses of ice going vessels (Nyseth et al., 2013). These measurements are compared to relevant standards which provide guidelines for the measurement, evaluation and reporting of structural vibration. The current lack of high quality data has been cited as one of the most important factors limiting further understanding of the effects of various excitation mechanisms on ship dynamic responses (Dinham-Peren and Dand, 2010).

The S.A. Agulhas II is a state-of-the-art PSRV, and the work horse of the South African National Antarctic Program (SANAP). The vessel spends around 8 months a year at sea in some of the harshest operating conditions on the planet, and was designed with an operational lifetime of 30 years. After sea trials, delivery of the vessel from Finland to South Africa and the shakedown cruise, the vessel experienced cracking in the hull structure at the rear of the main cargo hold. While this could just be due to large bending moments in the midship and the need for some bending allowance in the hull structure, it does warrant a thorough investigation into the structural dynamic performance of the vessel, especially concerning structural fatigue caused by large bending and torsional moments.

This paper details the initial investigation into structural dynamic fatigue based on full scale measurements during a 78 day voyage from Cape Town to Antarctica in 2013/2014. The post processing and evaluation methods are presented and the results are compared to Germanischer Lloyd's (2001) ship vibration guidelines (Asmussen et al., 2001). This work is intended to be a precursor to further investigations as guided by the results of the structural vibration analysis.

THE S.A. AGULHAS II

Full scale measurements were conducted on-board the PSRV S.A. Agulhas II, see Figure 1, which was built by STX Finland at the Rauma Shipyard. The S.A. Agulhas II is designed to carry cargo, passengers, bunker oil, helicopter fuel and is also equipped with laboratories, a moon pool and drop keel to conduct scientific research in the Southern Ocean. The ship's main specifications are presented in Table 1.

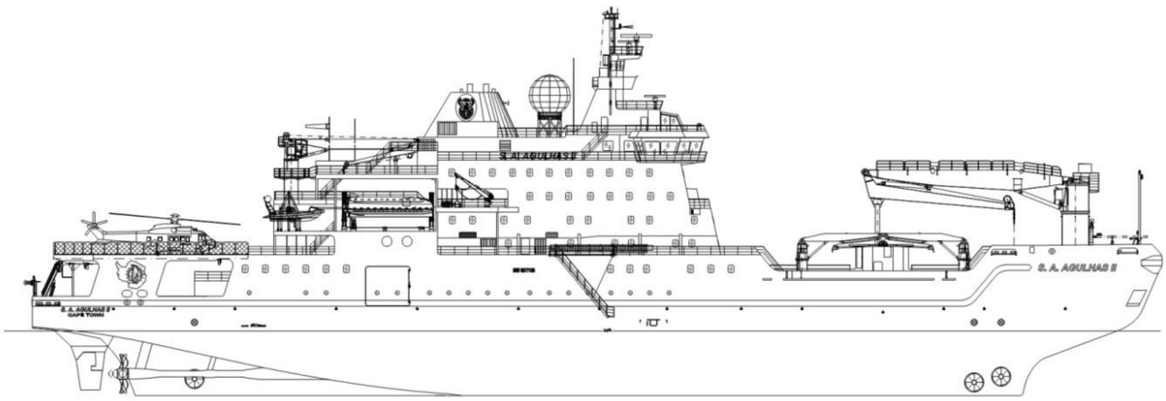


Figure 1- The S.A. Agulhas II.

Table 1- The main specifications of the S.A. Agulhas II.

Length, bpp	121,8 m
Beam	21,7 m
Draught, design	7,65 m
Deadweight at design displacement	5000 t

Installed power	4 x Wärtsilä 6L32 3000 kW
Propulsion	Diesel-electric 2 x 4500 kW
Speed, service	14 kn

MEASUREMENT EQUIPMENT

The data acquisition system (DAQ) and measurement equipment used is presented in Table 2. The LMS SCADAS were configured in a master-slave setup which allows simultaneous measurements controlled from one DAQ. The LMS SCADAS are equipped with a low-pass anti-aliasing filter. Accelerometers were calibrated according to the South African Bureau of Standards (SABS) by the National Metrology Institute of South Africa (NMISA).

Table 2- Measurement equipment.

Equipment
1 x 16 channel, LMS SCADAS
1 x 12 channel, LMS SCADAS
1 x 8 channel, LMS SCADAS
9 x DC PCB accelerometers, 20,4 mV/(m/s^2)
9 x ICP PCB accelerometers, 10,2 mV/(m/s^2)
3 x Seismic PCB accelerometers, 1019,4 mV/(m/s^2)
1 x Triaxial PCB accelerometers, 10,2 mV/(m/s^2)
LMS Test.Lab 11A Turbine Testing software

MEASUREMENT SETUP

Nineteen vibration measurement channels were recorded on the hull structure and five on the superstructure as seen in Figure 2. The measurement locations were chosen as follows:

- Measurements were conducted in the bow and stern to investigate the effect of hull slamming in open water as well as ice breaking and reversing during ice navigation.
- Measurements were conducted in the cargo hold and engine store room to determine the effect of global bending modes on the midship. Cracks had occurred prior to the current measurements in the cargo hold which is a further justification.
- Measurements were conducted in the bridge in order to investigate the effect of superstructure vibration on structural fatigue.
- Vertical vibration (+Z) was measured on the port and starboard sides of the hull and at as close to equal increments along its length, in order to investigate the vibration response caused by normal bending and torsional modes.
- Lateral vibration (+Y) was measured in the hull to determine the response of transverse bending.
- Longitudinal vibration (+X) was measured in the superstructure to investigate fore aft bending.
- Lateral vibration (+Y) was measured in the superstructure to investigate transverse bending and vertical vibration (+Z) was measured to investigate torsion.

The measurement system was controlled by a single laptop mounted in the central measurement unit (CMU) measurement rack. A fibre optic cable was routed through water tight cable trays from the CMU to the steering gear room to enable synchronous measurements using the master-slave setup. Accelerometers were mounted to girders, transverse beams or longitudinal beams using super-glue. Rigid structural members were chosen in order to measure the global ship vibration response.

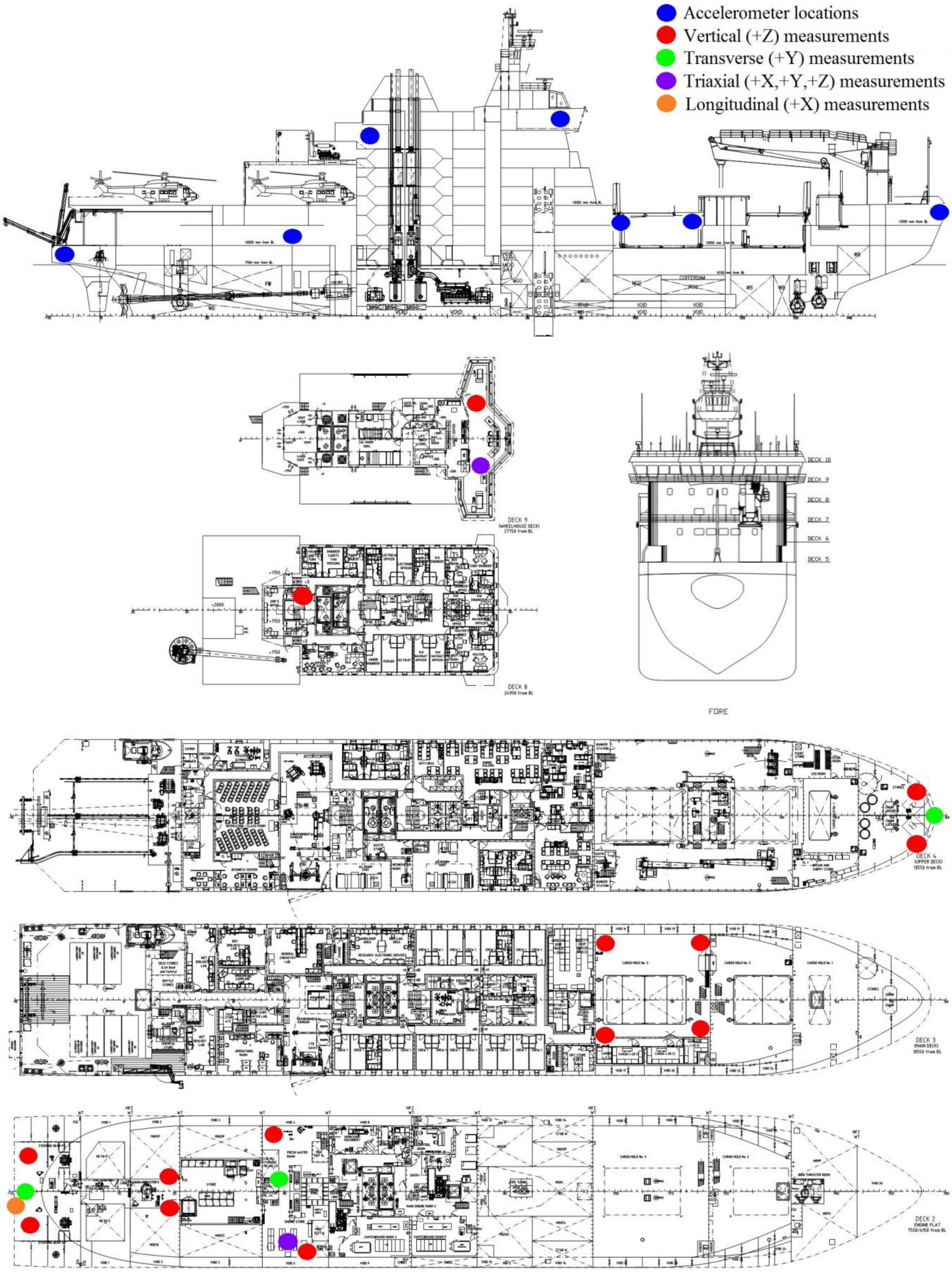


Figure 2 – Acceleration measurement locations on the S.A. Agulhas II.

DESCRIPTION OF THE VOYAGE

The voyage started from Cape Town harbour on the 28th of November 2013 and lasted 78 days. Figure 3 shows the track of the S.A. Agulhas II and is followed by a brief description of each leg. Please note that the numbers of the descriptions match those in Figure 3.

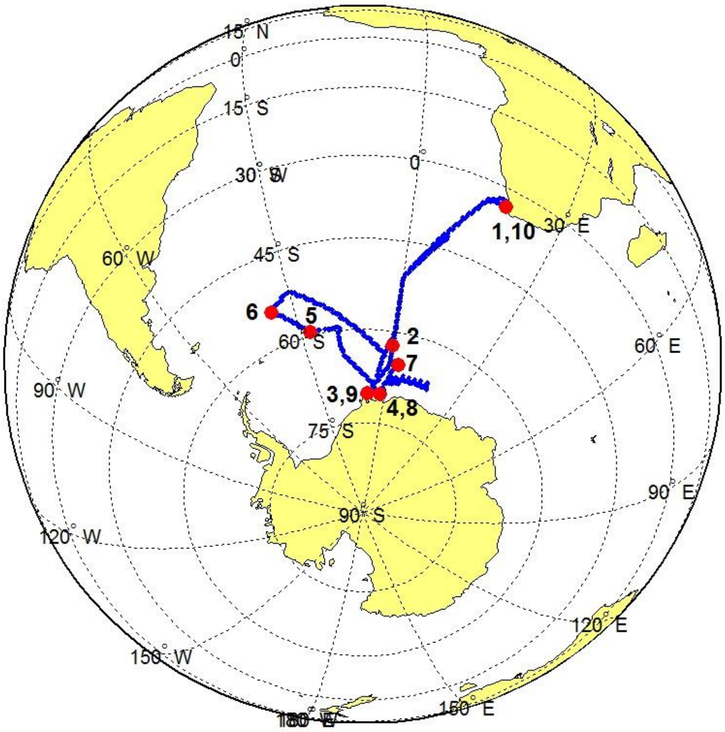


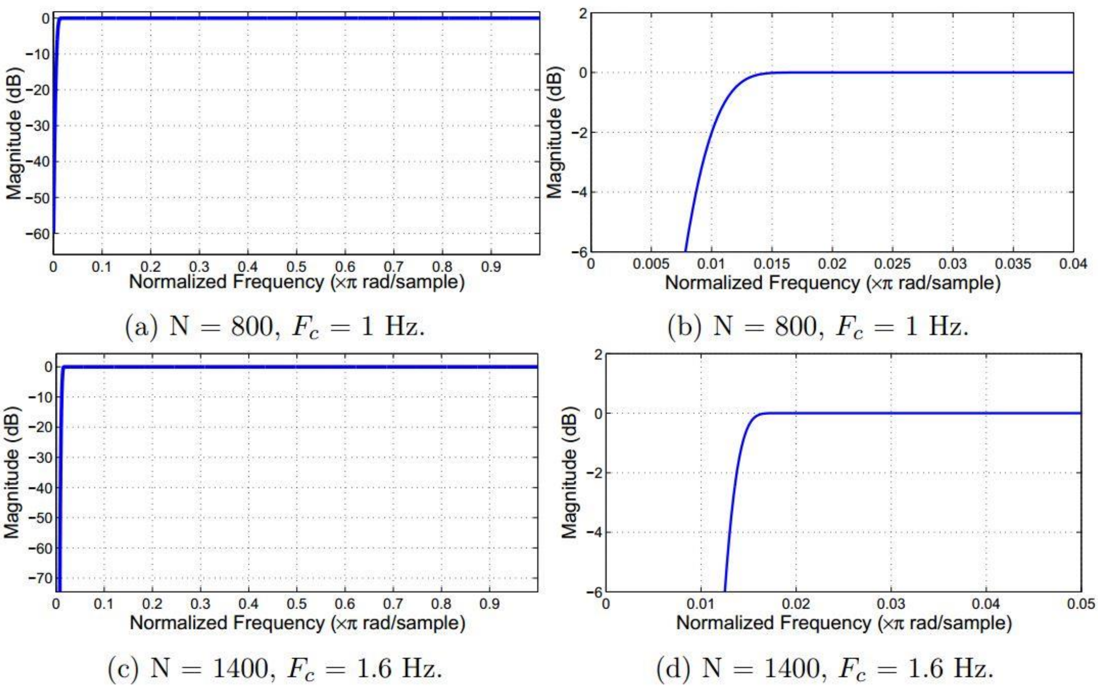
Figure 3 - GPS data of the 2013/2014 voyage to Antarctica.

1. The first leg saw the S.A. Agulhas II depart from Cape Town harbour in a South Westerly direction on the Good Hope line, turning due South on the Greenwich Meridian. Vibration measurements began on the 4th December 2013. Wave heights averaged 3,8 m with a maximum of 8 m. The navigating officers measure the wind speed and then estimate the wave height using the Beaufort scale.
2. The ship entered ice on the 7th December 2013. The ice began as pancake, brash and small ice floes. Floe ice became thicker and more concentrated as the ship moved deeper into the pack ice of the Weddell Sea. On the 9th December 2013 the ship encountered thick pack ice with large ice ridges, and became stuck (beset). Ramming techniques were used to break through thick ridges and ice floes. Large ridges and thick ice floes resulted in the ship being beset, often for several hours, and ramming numerous times over the next 13 days.
3. On the 22nd December 2013 the ship arrived at Atka Bay to begin offloading cargo for the German Neumayer Station III. In order to reach the ice shelf the ship first carved away the bay ice.
4. On the 24th December 2013 the ship departed for Penguin Bukta and arrived on 25th December 2013. The ship offloaded cargo and fuel at Penguin Bukta and remained pushed up against the ice shelf.
5. The ship departs on the 30th December 2013 for Southern Thule. Navigation progresses well through pack ice with occasional bergy bits. The ice pack begins to thin and open up, and the ship reaches Southern Thule on the 4th January 2014.

6. The ship departs on the 4th January 2014 for South Georgia. Shortly after departure the ship enters open water, with an average wave height of 4,3 m and a maximum of 7 m. The ship arrives at Grytviken Bay, South Georgia on the 6th January 2014.
7. The ship departs from South Georgia on the 6th January 2014 to conduct 13 days of whale research on the edge of the ice pack.
8. The ship enters the ice pack on the 23rd January 2014 and reaches Penguin Bukta on the 24th January 2014 to begin flying passengers back from SANAE IV base.
9. On the 26th January 2014 the ship departs for Atka Bukta and arrives on the 27th January 2014. The ship then carves bay ice until the 28th January 2014 to complete back loading.
10. On the 31st January 2014 the ship sets sail for Cape Town. Ice navigation progresses well and the ship enters open water on the 1st February 2014. Scientific stations see the ship stop several times along the Good Hope line. The average wave height during the 11 day return voyage is 4 m with a maximum of 7 m. The ship enters Cape Town harbour on the 13th February 2014.

DATA PROCESSING

Structural vibration data is post-processed according to BS ISO 20283-2 (2008) which provides guidelines for the measurement of vibration on ships. The raw acceleration data is first converted from g to mm/s^2, and then integrated using the Matlab *trapz.m* function to mm/s. It is then decimated from 2048 Hz to 256 Hz using *decimate.m* which first low-pass filters the data with a cut-off frequency of 102,4 Hz before re-sampling. The signal is then high-pass filtered to remove vibration amplitude in the rigid body bandwidth. BS ISO 20283-2 (2008) specifies that data should be high-pass filtered above 2 Hz.



(a) N = 800, F_c = 1 Hz. (b) N = 800, F_c = 1 Hz.

(c) N = 1400, F_c = 1.6 Hz. (d) N = 1400, F_c = 1.6 Hz.

Figure 4 - Chebyshev high-pass filters.

Two high-pass filters were designed in order to effectively attenuate low frequency vibration measured by the ICP and DC accelerometers respectively. The filters were designed using Matlab's Filter Design and Analysis Tool. A Chebyshev high-pass filter with an order

N = 800, and a cut-off frequency F_c = 1 Hz (Figure 4a and b) was used to filter the ICP data. A higher order filter was required for the DC accelerometers which are able to measure low frequency vibration. A Chebyshev high-pass filter with an order N = 1400, and a cut-off frequency F_c = 1.6 Hz (Figure 4c and d) was used to filter the DC data. The steepness and complexity of the frequency response curve is determined by N, the filter order (Smith, 2007).

The Chebyshev finite impulse response (FIR) filters were selected due to their sharp drop off and low ripple at 0 dB. The high filter order provides significant attenuation below the cut-off frequency. While higher filter orders are more computationally expensive, they do not effect the filter accuracy and it was decided that longer computational times was a necessary trade-off. Structural vibration metrics were subsequently calculated which include peak velocity values and frequency spectra.

RESULTS

Peak Vibration Velocity

The peak vibration velocity values are presented in Figure 5 and 6. The vertical dashed lines indicate the events listed in the Description of the Voyage. The crosses indicate the maximum peak vibration velocity values in the vertical, lateral and longitudinal directions. The following sensors are plotted in Figure 5: Steering Gear Stb X, Y and Z, Bow Centre Y and Stb Z, CMU Triaxial X, Y, Z, Cargo Hold Stb Z. Vibration in the Bridge Stb X, Y, Z is presented in Figure 6.

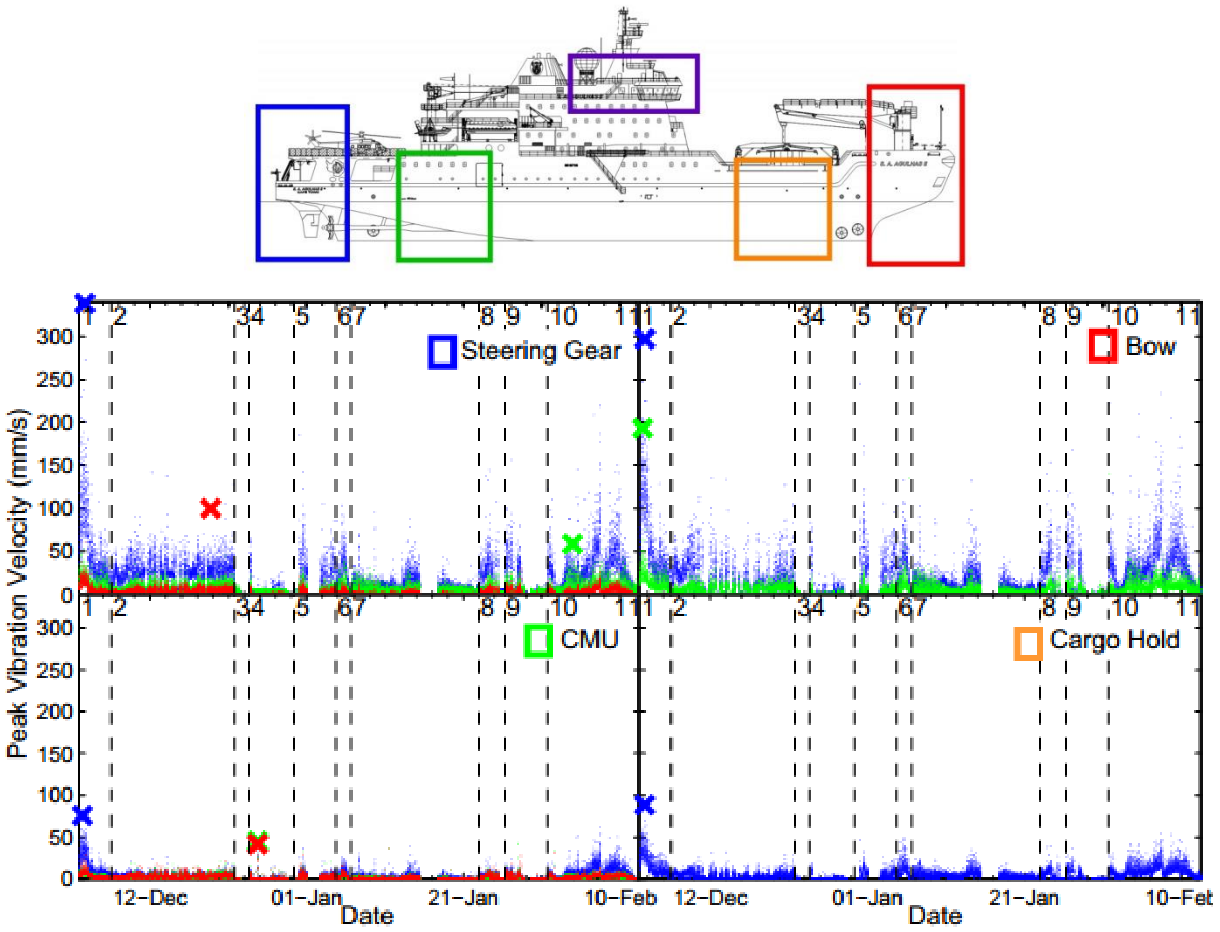


Figure 5 - Structural Vibration.● Longitudinal vibration (+X), ● Lateral vibration (+Y), ● Vertical vibration (+Z)

The following observations are made:

1. The largest peak vibration value is 338,35 mm/s in the vertical (+Z) direction in the steering gear room of the vessel in open water.
2. The largest maximum values occur in open water in the vertical (+Z) direction at all the measurement locations.
3. Vibration amplitude is largest in the bow and stern, and decreases towards the middle of the vessel, increasing vertically towards the bridge.
4. The peak structural vibration in the Bridge is roughly a third of that experienced in the steering gear room.

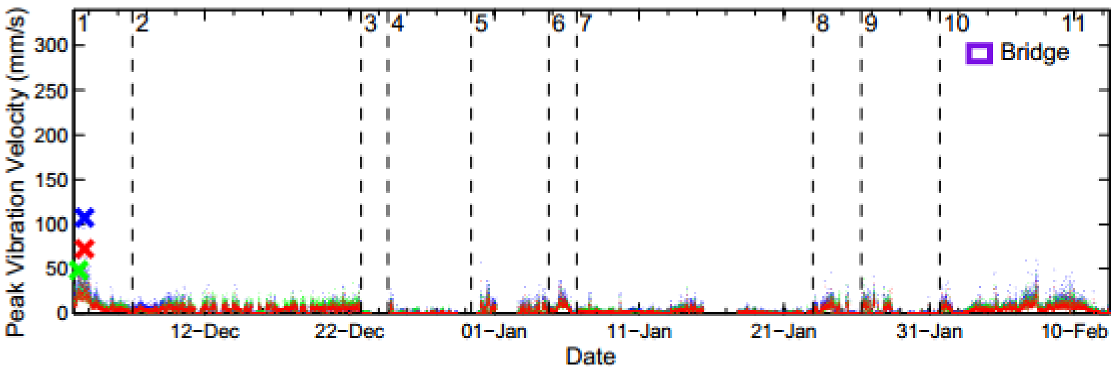


Figure 6 - Structural vibration.● Longitudinal vibration (+X), ●Lateral vibration (+Y), ●Vertical vibration (+Z)

The raw acceleration time history of the largest peak vibration value is shown in Figure 7. It can be seen that an impulse of -1,85 g was measured in the vertical (+Z) direction in the steering gear room on the starboard side. The resulting acceleration time signal after integrating to velocity, decimating and high pass filtering the signal is shown in Figure 8.

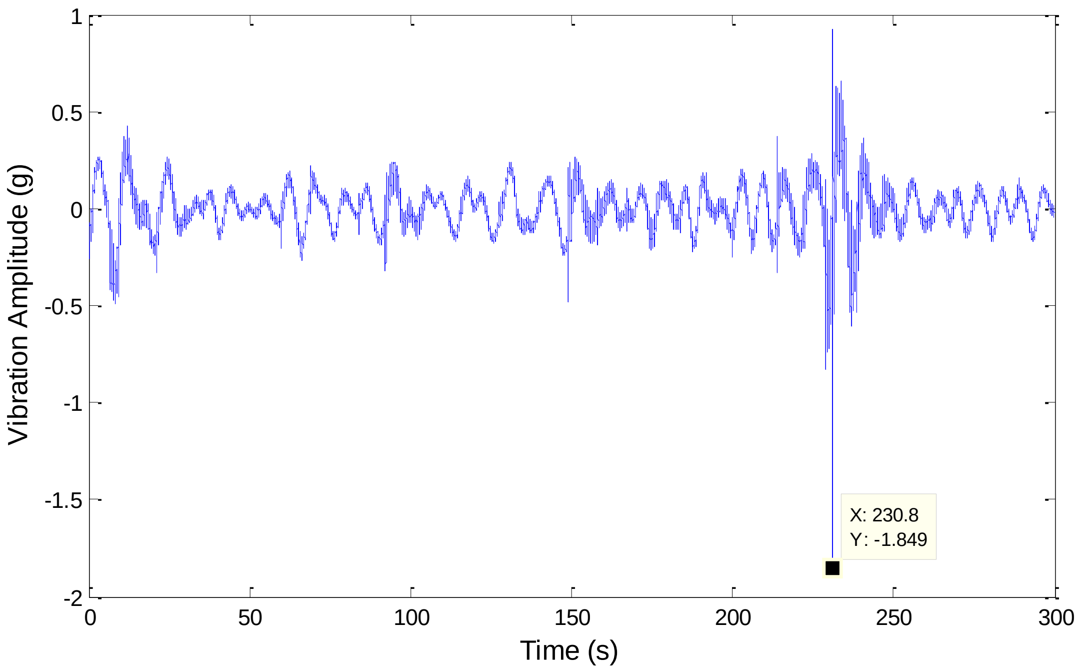


Figure 7 - Raw acceleration time history of the maximum peak velocity value.

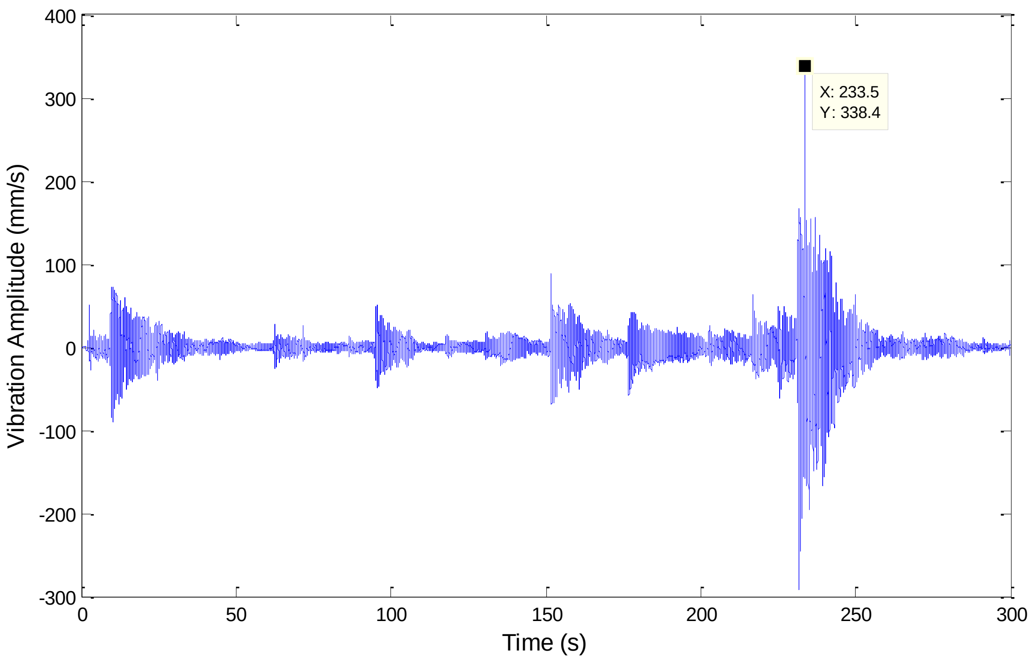


Figure 8 - Post-processed velocity time history of the maximum peak velocity value.

Frequency Spectra

The frequency spectra of the maximum peak values are presented in Figure 9. The PSDs are shown in the left hand column and the FFTs in the right hand column. The FFTs are compared to Germanischer Lloyd's (2001) guidelines for structural fatigue as a result of vibration. Two limit curves define the lower region in which vibration is unlikely to cause damage, the intermediate region where vibration may cause damage, and the upper region in which damage is probable.

The PSDs provide an accurate estimate of the frequency content of the random signals since they are based on the FFT of the autocorrelation function, which is a statistical indicator (Inman, 2014). The PSDs are calculated in Matlab using the following input parameters: Flattop window, 50 % overlap, block size of 4096 NFFT points, sample frequency of 256 Hz. This results in a frequency resolution of 0,0625 Hz. Two distinct peaks at 2,06 Hz and 3,88 Hz can be seen in the PSD plots at all the measurement locations.

The FFT plots are seen to contain peaks at the same frequencies. Results show that vibration in the stern of the vessel reaches amplitudes at which vibration may cause damage, see Figure 9, and that vibration in the bow of the vessel reaches amplitudes at which damage is probable. These vibration amplitudes occur at 2,06 Hz in both locations. This is identified as the 2-node first bending mode of the vessel (Soal and Bekker, 2014). These findings highlight the need for further investigation into the duration of possible fatigue exposure experienced by the vessel each year, and the effect this will have on its expected service life of 30 years. Other factors which also need to be investigated include the type of steel used in construction, the structural details in critical areas, the welding processes, the production methods and environmental conditions such as corrosion.

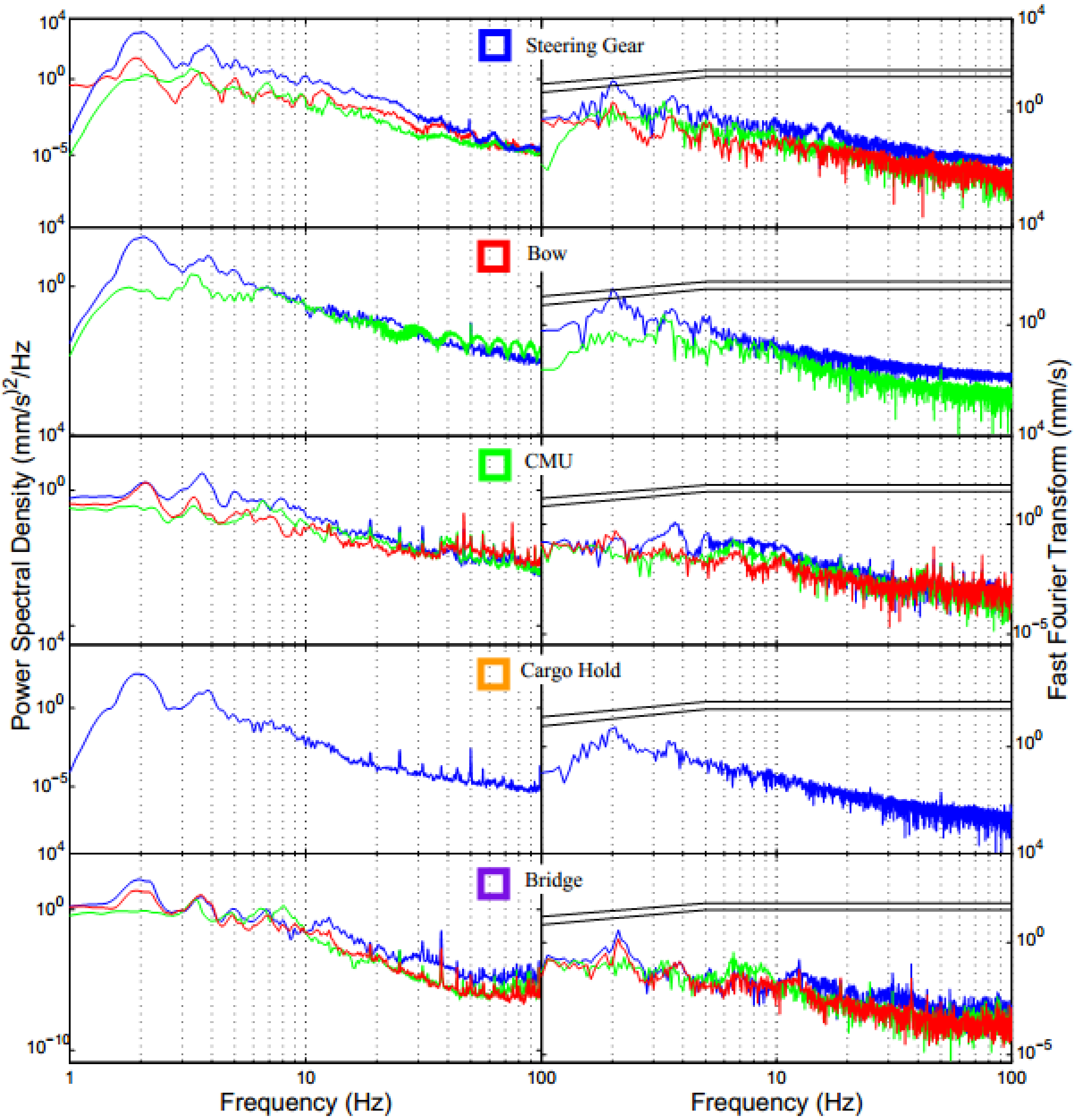


Figure 9 - Structural vibration. Longitudinal vibration (+X), Lateral vibration (+Y), Vertical vibration (+Z)

CONCLUSION

The structure of the vessel is found to be most affected by vertical vibration during open water navigation, with a maximum peak velocity of 338,35 mm/s in 8 m swells. Vibration levels are larger in the bow and stern, decreasing towards the centre of the vessel and increasing again as you move vertically to the bridge.

Structural fatigue as a result of vibration is found to reach the level where damage is possible in the stern and were damage is probable in the bow according to Germanischer Lloyd's ship vibration guidelines. The vibration levels with potential to cause fatigue damage were measured in 8 m swells during open water navigation. This calls for further research into the effects of the duration at these exposures, materials of construction, structural details in the affected areas, welding processes and environmental conditions. The occurrence of cracks on the ship hull in the cargo hold prior to these measurements provide justification for further research into structural health monitoring and damage detection.

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