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OPERATIONAL MODAL ANALYSIS ON THE POLAR SUPPLY AND RESEARCH VESSEL THE S.A. AGULHAS II

Keith Soal[1], *Jörg Bienert*[2], *Anriëtte Bekker*[3]

[1] Mr, Stellenbosch University, keithsoal@gmail.com.
[2] Prof, Technische Hochschule Ingolstadt, Joerg.Bienert@thi.de.
[3] Dr, Stellenbosch University, annieb@sun.ac.za.

ABSTRACT

Operational Modal Analysis (OMA) was conducted on the S.A. Agulhas II while moored in Cape Town harbour to investigate the global structural dynamic characteristics of the vessel. Measurements were conducted while the vessel was exposed to small wave (ripple) and wind excitation at the quayside without harmonic excitation from the main engines or harbour generator. Twenty three vibration measurement channels were recorded in total with eighteen sensors on the hull structure and five on the superstructure. The sensor locations and directions were selected to investigate the normal and transverse bending modes as well as torsional modes of the structure. The LMS Operational PolyMAX frequency domain and ARTeMIS CCSSI time domain OMA techniques are used to estimate the modal parameters. Both techniques identified three stable modes which include the two-node (first), three-node (second) and four-node (third) normal bending modes. In terms of frequency the Operational PolyMAX and CC-SSI agree to within 1,2 %. However the damping estimates show less agreement especially for mode 3 which differs by 59 %. The Modal Assurance Criterion confirms three unique modes, and the complexity plots reveal real valued mode shapes which confirm the proportional damping model approximation. The results of the OMA were then compared to those of the Finite Element (FE) model developed by STX Finland. The natural frequencies predicted by the FE model are found to be bigger than those measured using OMA. The FE calculations are based on a vessel draught of 7,7 m which is deeper than the 6,8 m draught during OMA testing. The effect of the vessel draft on the modal parameters will form part of future research. This work is a precursor to investigations into the effect of various ice and open water boundary conditions as well as ship loading and operating conditions on the dynamic characteristics of the vessel structure.

Keywords: Full Scale Measurements, Operational Modal Analysis, Polar Supply and Research Vessels

1. INTRODUCTION

Vessels operating in Antarctica and the Southern Ocean are exposed extreme and unpredictable conditions, and encounter a number of excitation mechanisms. These excitation mechanisms include waves, ice and wind as well as the engines, propellers and machinery on board. This results in a variety of forces being applied to the structure which can cause structural fatigue, excessive vibration and slamming.

Polar Supply and Research Vessels (PSRVs) play a key role in scientific and logistical support in Antarctica and the Southern Ocean. The PSRV S.A Agulhas II is the work horse of the South African National Antarctic Program (SANAP). The S.A Agulhas II entered service in 2012, and was designed with an operational lifetime of 30 years. The vessel spends around 8 months a year at sea in some of the harshest operating conditions on the planet. Investigations into the structural dynamic response of the vessel are therefore important to assess its dynamic performance, its ability to operate safely for 30 years as well as to compare the measured dynamic response to the predicted response used during the design phase.

In order to investigate the vessel's structural dynamic response to these excitation mechanisms, it is important to first determine the structural dynamic characteristics of the vessel. Operational Modal Analysis (OMA) is used to investigate the global structural dynamic characteristics of the ship. The aim of OMA is to obtain the structure's modal parameters, namely the natural frequencies, damping ratios and unscaled mode shapes from response only measurements. These modal parameters will provide insight into the operational dynamic response of the structure and can then be used to investigate phenomena such as structural fatigue, excessive vibration and slamming.

2. 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 main specifications of the ship are presented in Table 1.

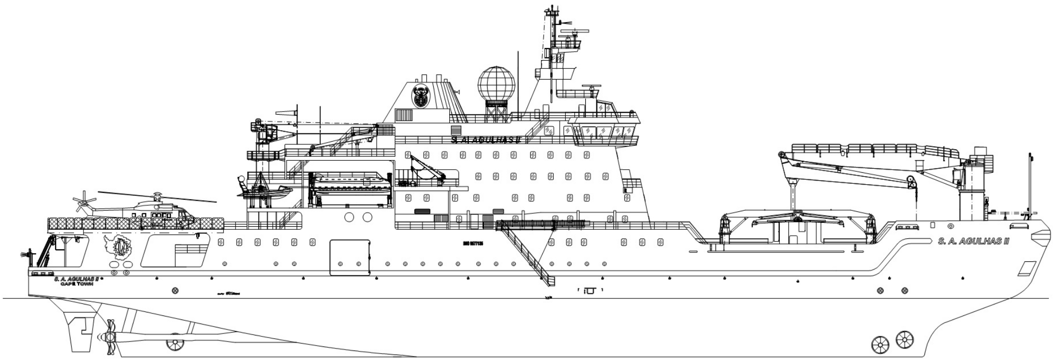


Figure 1: The S.A. Agulhas II.

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 × Wärtsilä 6L32 3000 kW
Propulsion	Diesel-electric 2 × 4500 kW
Speed, service	14 kn

3. FULL SCALE MEASUREMENTS

3.1. Measurement Equipment

The data acquisition system (DAQ) and measurement equipment used are presented in Table 2. The LMS SCADAS were configured in a master-slave setup which allowed simultaneous measurements controlled from one DAQ. The LMS SCADAS are equipped with a hardware 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). Accelerometers were mounted to rigid structural members in order to measure the global ship vibration response.

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 accelerometer, 10,2 mV/(m/s^2)
LMS Test.Lab 11A Turbine Testing software

3.2. Measurement Setup

Twenty three vibration measurement channels were recorded in total with eighteen on the hull structure and five on the superstructure as shown in Figure 2.

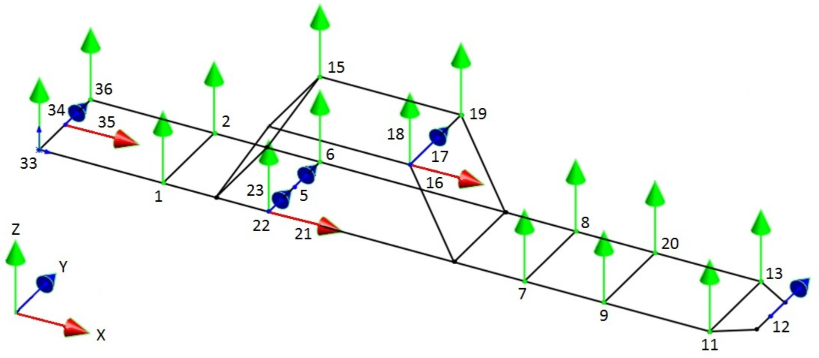


Figure 2: Measurement model indicating sensor location and measurement direction.

Vertical vibration (+Z) was measured on the port and starboard side of the ship hull at as close to equal increments as was physically possible. This was done in order to investigate the horizontal (x-y) plane for vertical bending and torsional modes. Lateral vibration was measured at three points along the hull to investigate the longitudinal vertical (x-z) plane for transverse bending modes. Longitudinal vibration (+X) in the hull is not considered in the present work.

Vibration measurements in the superstructure include longitudinal (+X) measurements to investigate fore-aft bending, lateral (+Y) measurements to investigate transverse bending and vertical (+Z) measurements to investigate torsion. A measurement duration of an hour was selected based on the results from Rosenow [1]. This study concluded that measurement durations of one hour or more were necessary to obtain stochastic excitation. The global modes of the vessel are expected to lie below 10 Hz, but in order to improve the resolution of the data, a sample frequency of 128 Hz was chosen.

3.3. Measurement Conditions

OMA was conducted on the S.A. Agulhas II while moored at East Pier in Cape Town harbour. Mooring lines were used to secure the vessel against large rubber tyres hanging from the quayside. The 1 hour run selected for the present analysis was between 00h00 and 01h00 on 28 February 2014. The offloading of heavy cargo had been completed, and the ship had not been refuelled with polar diesel. The draft was 6,7 m fore, 6,8 m midship and 6,9 m aft. The ship was on shore power and the wind had picked up during the night to 43 km/h. This measurement run was chosen due the lack of harmonic contamination from the engines and harbour generator as well as good wind and wave excitation.

4. RESULTS

4.1. Power Spectral Density

The power spectral density (PSD) in Figure 3 indicates the distribution of the signal power in the frequency domain. The PSDs of the acceleration measurements were calculated using the peak amplitude mode, Hanning window, 50 % overlap and 2048 NFFT points resulting in a frequency resolution of 0,0625 Hz. The following observations are made:

1. There are distinct low frequency peaks at 1,9 Hz, 3,37 Hz and 4,66 Hz.
2. The amplitude of the frequency content under 5 Hz is the largest in the bow, closely followed by that in the stern.
3. The amplitude in the frequency range between 5 Hz and 30 Hz is the largest in the stern.
4. The frequency content in the vertical (+Z) direction in the bridge is dominant in the frequency range from 30 Hz to 36 Hz.

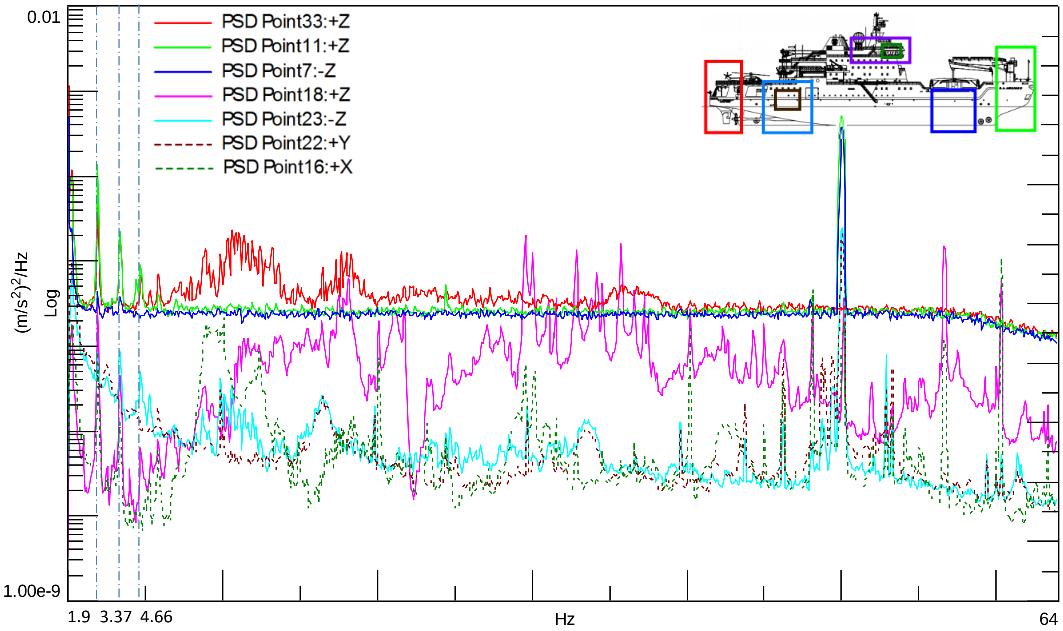


Figure 3: Power Spectral Density (PSD) of the time signals.

4.2. Stabilization Diagrams

The structural dynamic characteristics of the vessel are identified using LMS Operational PolyMAX and ARTeMIS CCSSI algorithms. An Eigenvalue analysis is used to plot the stabilization diagram from which the modal parameters can be estimated. Figure 4 shows the stabilization diagram produced by the LMS Operational PolyMAX frequency domain algorithm. Stable poles with high confidence are seen to align at 1,94 Hz and 3,37 Hz indicating stable physical modes. A third less stable pole at 4,72 Hz is also selected. Poles at higher frequencies were investigated but did not provide clear results.

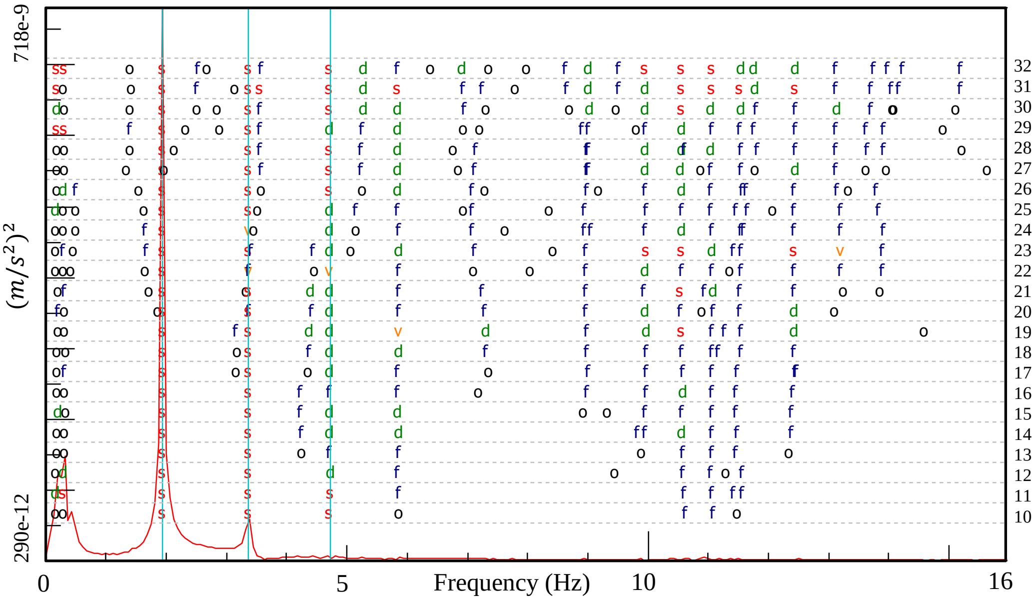


Figure 4: Operational PolyMAX stabilization diagram. (s) Stable pole with high confidence, (v) Some confidence in the Eigenvector, (d) Some confidence in damping, (f) Some confidence in the Eigenvalue, (o) Unstable pole.

The stabilization diagram from the ARTeMIS CCSSI time domain algorithm is presented in Figure 5. Three stable poles are identified at 1,93 Hz, 3,36 Hz and 4,67 Hz. The CCSSI stabilization diagram is clearer than that produced by Operational PolyMAX, as the third mode is also identified with high confidence in CCSSI.

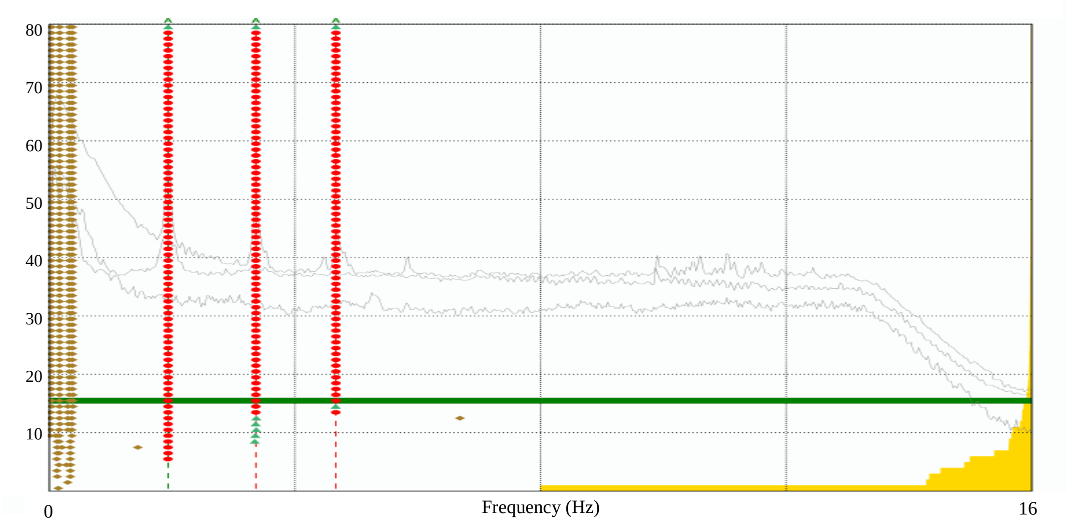


Figure 5: CCSSI stabilization diagram of estimated state space models. ● Stable mode, ▲ Unstable mode, ♦ Noise mode.

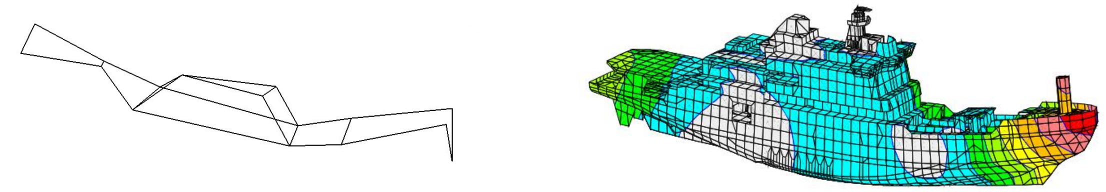
The natural frequencies and damping ratios of the three selected modes using Operational PolyMAX and CCSSI as well as the percentage difference between the two estimates are presented in Table 3. CCSSI and Operational PolyMAX agree to within 1,2 % on the natural frequencies. The damping estimates however show less agreement, especially for mode 3 which differ by 59 %. The damping percentage for all three selected modes is small due to the high stiffness of the structure which is reinforced for ice navigation.

Table 3: A Comparison of natural frequencies and damping ratio estimates using Operational PolyMAX and ARTeMIS CCSSI as well as their percentage difference.

	Frequency (Hz)			Damping (%)		
Mode	PolyMAX	CCSSI	Diff (%)	PolyMAX	CCSSI	Diff (%)
1	1.935	1.934	0.052	0.651	0.571	-12.289
2	3.367	3.363	0.119	0.969	1.075	10.939
3	4.721	4.667	1.157	1.512	2.406	59.127

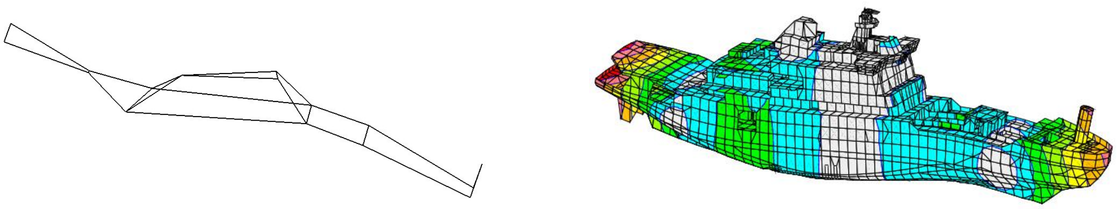
4.3. Mode Shapes

The operational mode shapes of the three selected poles are presented alongside the FE model prediction of STX Finland in Figure 6. Vertical vibration in the bow is selected as the reference as this resulted in a clear stabilization diagram. The modes are identified as the 2-node (first), 3-node (second) and 4-node (third) normal bending modes of the vessel. Due to the fairly symmetrical geometry of the structure, the three modes show little complex mixing of modes, i.e. modes comprised of a combination of bending and torsion.



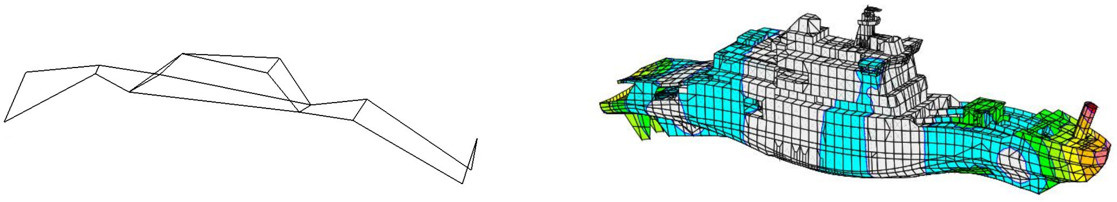
(a) f = 1,94 Hz, 2-node vertical bending.

(b) f = 2,60 Hz, 2-node vertical bending.



(c) f = 3,37 Hz, 3-node vertical bending

(d) f = 4,28 Hz, 3-node vertical bending



(e) f = 4,72 Hz, 4-node vertical bending

(f) f = 5,63 Hz, 4-node vertical bending

Figure 6: Mode shapes for the first three vertical bending modes. OMA models generated using LMS are on the left, and FE models developed by STX Finland are on the right.

The FE model shows the nominal vectors, which do not have physical dimensions. The surrounding water has been taken into account by the addition of mass to the mass matrix connected to the wet surface of the shell. The method is based on green functions of pressure distribution, and describes the case when the vessel is located in deep water with a draught of 7,7m [2].

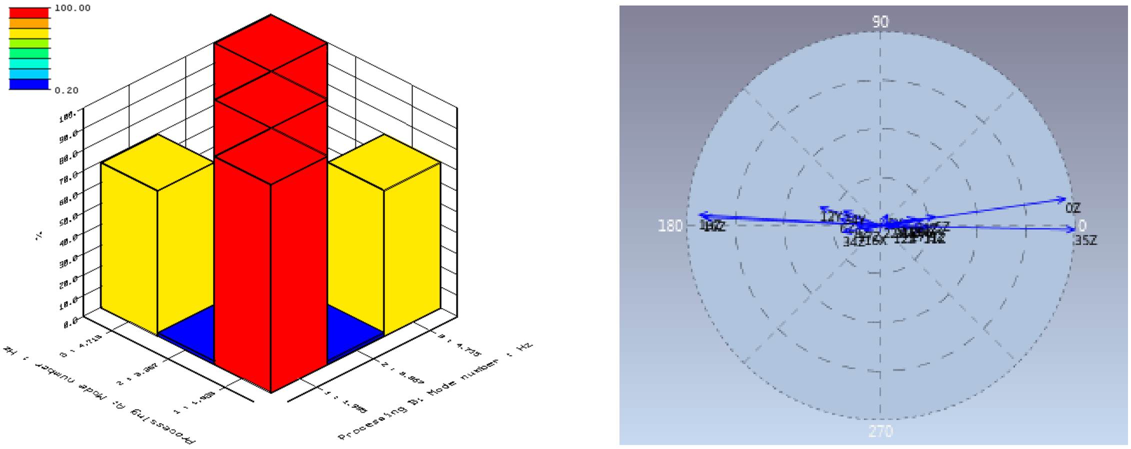
The analytical FE natural frequencies are larger than the measured OMA natural frequencies by 34 %, 27 % and 19 % respectively. The FE model draught is 0,9 m deeper than the draught during OMA measurements. The effect of adding mass in the form of cargo and fuel is however expected to further decrease the measured OMA natural frequencies, due to the relationship between the natural frequency (ω_n), mass (m) and stiffness (k) matrices:

$$\omega_{n_i} = \sqrt{\frac{k_i}{m_i}} \tag{1}$$

This implies that the stiffness of the elements used in the FE model may be inaccurate. The effects of greater hull surface area exposed to water and the mooring boundary conditions on the natural frequencies and damping however need to be further investigated. The absence of torsional modes from the OMA is thought to be due to the structure not being physically excited to measurable amplitudes in a torsional manner by waves and wind in the harbour mooring.

4.4. Modal Assurance Criterion (MAC) Matrix

The MAC matrix provides a quantitative comparison between mode shapes, were mode shapes are expected to be independent of one another and comprised of orthogonal vectors. The MAC matrix for the three modes identified using Operational PolyMAX is presented in Figure 7a, were it can be seen that mode pair 1-2 as well as 2-3 have low MAC values and are therefore decoupled, while mode pair 1-3 show a 69 % correlation. This is due to the physical similarity between the 1st and 3rd bending mode shapes and similar results were found by Orlowitz [3]. A cross MAC matrix can be computed to determine the statistical similarity between the different algorithms as well as between OMA and FE results, and is proposed for future research.



(a) MAC - Isometric view.

(b) Complexity Plot - Mode 2.

Figure 7: MAC matrix and Complexity Plot.

4.5. Complexity Plots

The modes are validated by plotting the components of the Eigenvectors in the complex plane. The resulting complexity plots for the second mode are presented in Figure 7b, with the real values on the x-axis and imaginary values on the y-axis. The complexity plots show that all the DOF are nearly in phase within each mode. This means that the Eigenvectors reach their respective maximums and minimums at the same time, and that there is little complex mixing of modes. This confirms the proportional damping model approximation for lightly damped structures which expects real valued mode shapes [4].

5. CONCLUSIONS

Operational Modal Analysis (OMA) is used to investigate the structural dynamic characteristics of the vessel. The LMS Operational PolyMAX frequency domain and ARTeMIS CCSSI time domain OMA techniques are used to estimate the modal parameters. Three stable modes are identified at 1,94 Hz, 3,37 Hz and 4,72 Hz and show agreement to within 1,2 % by both Operational PolyMAX and CCSSI. The damping estimates show less agreement, especially for mode 3 which differs by 59 %. The three modes are identified as the 2-node (first), 3-node (second) and 4-node (third) normal bending modes. The MAC confirms three unique modes, with cross coupling between mode pair 1-3 due to the geometrical similarities. The complexity plots reveal real valued mode shapes which confirm the proportional damping model approximation for lightly damped structures and thus validate the results.

The natural frequencies predicted by the FE model are greater than those measured using OMA by 34 %, 27 % and 19 % respectively. The FE calculations are based on a vessel draught of 7,7 m which is deeper than the 6,8 m draught during OMA testing. The effect of adding mass to the structure is however expected to further reduce the OMA natural frequencies. Investigations into the effect of boundary and operation conditions is recommended for further insight into the modal parameters.

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