Application of real-time estimation techniques for stability monitoring of fishing vessels

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Abstract This work presents a comparative study of two signal processing methods for the estimation of the roll natural frequency towards the real-time transverse stability monitoring of fishing vessels. The first method is based on sequential application of the Fast Fourier Transform (FFT); the second method combines the Empirical Mode Decomposition (EMD) and the Hilbert-Huang Transform (HHT). The performance of the two methods is analysed using roll motion data of a stern trawler. Simulated time series from a one degree-of-freedom nonlinear model, and experimental time series obtained from towing tank tests are utilized for the evaluation. In both cases, beam waves are considered but, while irregular waves are adopted in the simulated data, the towing tank tests are made in regular waves. Based on the available data the performance of both estimation methods is comparable, but the EMD-HHT method turns out slightly better than the sequential FFT. Finally, the use of a statistical change detector, together with the EMD-HHT methodology, is proposed as a possible approach for the practical implementation of an onboard stability monitoring system.

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1 Introduction

Small and medium fishing vessels have historically suffered a large amount of stability-related accidents, which led to one of the highest fatality rates among all industrial sectors. It has been acknowledged by administrations and the research community, that this very high accident rate could be related not only to the lack of a (common) regulatory framework, but also to the lack of crew training programs or formation in vessel stability. In the last two decades, the use of simplified stability guidance systems has been proposed as a possible solution to try reducing the number of accidents by providing the crew with simple, easy to understand information regarding the stability situation of their vessel. These approaches include the use of simplified stability posters [19, 20], the analysis of residual freeboard [15], or the real-time estimation of stability parameters [4, 16, 17, 18].

The main objective of this work is to evaluate and compare the performance of two frequency estimation methods. The first method was introduced in [10], and it is based on sequential application of the Fast Fourier Transform (FFT) for estimation of the vessel's roll natural frequency, which in turn can be used to estimate the metacentric height and initial stability. The second method [12, 13] also estimates the natural roll frequency, achieved through the combined use of Empirical Mode Decomposition (EMD) and the Hilbert-Huang Transform (HHT).

The investigation utilizes two sets of roll motion data from a stern trawler. The first data set consists of simulated roll time series generated in irregular beam waves applying a one degree of freedom nonlinear model [2]. The second data set consists of experimental roll time series obtained from towing tank tests in regular beam waves.

It is noteworthy that, although two techniques are introduced for the estimation of the roll natural frequency of the vessel, the current chapter presents the theory of just the method based on EMD-HHT. The FFT-based approach is presented and analyzed in detail in [10] and in another chapter of this book.

Potentially, both methods can be part of a computer based stability guidance system for small and medium sized fishing vessels. This is demonstrated by briefly presenting the condition monitoring system built atop the EMD-HHT estimator. Here a statistical change detector based on the Generalized Log-likelihood Ratio Test (GLRT) for Weibull stochastic processes is shown to trail changes in the vessel transverse stability and differentiate between safe and non-safe navigation situations.

This work updates and complements the findings previously described in [14].

2 Estimation of roll natural frequency through EMD-HHT

Vessel rolling in waves is nonlinear thanks to the nonlinearities in the restoring moment and damping. Therefore the extraction of frequency information from roll time series, such as the estimation of the roll natural frequency, should be performed by relying on signal processing methods developed for nonlinear (and non-stationary) signals.

Míguez González et al [10] proposed to estimate the roll natural frequency by applying a sliding window FFT to bypass the lack of signal stationarity and attempt a quasi real-time estimation. Due to the time-frequency constraint, the window length played an important role in the trade-off between estimation accuracy and real-time processing.

To overcome the drawbacks of the sliding-window FFT, Santiago Caamaño et al [13] proposed to use the Empirical Mode Decomposition and the Hilbert-Huang Transform to develop a roll natural frequency estimator that processes the roll motion signal directly in the time domain. The EMD-HHT method does not require stationarity and linearity of the signal to be processed.

The EMD is applied to decompose the measured roll motion signal into its main oscillatory components, the IMFs (Intrinsic Mode Functions) [3, 5, 6]. For a vessel sailing in waves, the IMFs will include components oscillating at frequencies included in the wave encounter spectrum, which are not naturally filtered out by the ship's roll dynamics; a component oscillating at or nearby the roll natural frequency; and additional components oscillating at very low frequencies corresponding to e.g. wind, swell. Once the IMFs have been obtained from the original signal, the Hilbert-Huang Transform (HHT) [3, 6] is applied to them for computing an estimate of the instantaneous frequency of each IMF. From these values the mean instantaneous frequency is computed according to [21] for each IMF, and stored in the vector Ω_{IMF}

$$\mathbf{\Omega}_{\text{IMF}} = [\hat{\omega}_1, \hat{\omega}_2, \ldots, \hat{\omega}_{N_{\text{IMF}}}] \tag{1}$$

where $\hat{\omega}_1 > \hat{\omega}_2 > \ldots > \hat{\omega}_{N_{\text{IMF}}}$. The vector Ω_{IMF} is naturally ordered since the EMD decomposes the signal from high to low frequencies.

Values of Ω_{IMF} being above and below a maximum and minimum expected value for the vessel's roll natural frequency (related with the maximum and minimum expected level of stability) are discarded.

The lower limit corresponds to the minimum metacentric height, calculated as the minimum GM needed to keep heel angles under 15 degrees under the action of a lateral wind of approximately 30 knots (computed following the IMO Weather Criterion guidelines).

The upper limit corresponds to the maximum possible GM of the vessel in all loading conditions contained in the stability booklet.Further explanation about how the maximum and minimum expected level of stability has been selected can be found in [13].

Finally, the vessel estimated natural roll frequency is selected as the maximum value from the remaining mean instantaneous frequencies (which is usually that one associated with the highest energy content).

The whole process is iterated to consecutive and partly overlapping batches of measured roll motion, in order to obtain a real-time estimate of the actual roll natural frequency and quickly capture changes due to variation in metacentric height.

To reduce the sensitivity of the estimation process to the wave conditions, in specific sailing conditions the measured roll motion is filtered prior to being processed by the EMD-HHT. The description of the filter and the conditions for its application, as well as the detailed description of this methodology can be found in [12, 13].

3 Test cases

In order to evaluate the performance of the proposed methodologies, roll motion time series have been obtained both from a nonlinear mathematical model of roll motion and from towing tank tests.

The mathematical model used in this work is a nonlinear one degree of freedom model of roll motion (ϕ), which is described in detail in [2] and has been already applied to the same vessel used in this work [9, 10]. Equation 2 represents this model:

$$\ddot{\phi} + 2 \cdot \nu \cdot \omega_0 \cdot \dot{\phi} + \beta \cdot \dot{\phi} \cdot \dot{\phi} + {\omega_0}^2 \cdot \frac{\overline{GZ}(\phi)}{\overline{GM}} = {\omega_0}^2 \cdot m_{wave}(t) \tag{2}$$

where ν and β are the linear quadratic damping coefficients, ${\omega_0}^2$ is the vessel natural roll frequency, $\overline{GM}$ is the metacentric height in calm water and $\overline{GZ}(\phi)$ is the righting lever. Finally, $m_{wave}(t)$ represents the wave excitation nondimensional moment in irregular beam seas, modelled using the "Absolute Angle Approach" [1]. On this respect, the effective wave slope coefficient $r(\omega)$ was obtained using linear hydrodynamics [9], while a Bretschneider spectrum was selected for the generation of the different sea states.

Regarding the scale model experiments, they have been carried out at the University of A Coruña towing tank. In this case, tests have been carried out under regular beam waves and zero speed. Further description of the experiments can be found in [12].

3.1 Test vessel

The vessel under consideration is a mid-sized stern trawler, which has been studied by the authors in previous works [9, 10, 12, 13].

In order to evaluate the performance of both methodologies, even when changes in the loading of the vessel take place during operation (which is very common in fishing vessels), two conditions have been analysed. The first one represents a realistic sailing situation with a GM over the minimum required value [7]. This one could be considered, for the sake of demonstration, as a safe loading condition. The second loading condition corresponds to the critical situation, ie., the one with the minimum mandatory GM value and which has been defined as the limit between a safe (acceptable) and a non-safe (non-acceptable) situation.

The main characteristic of the vessel and the parameters of these two loading conditions are included in Table 1.

3.2 Test conditions

Regarding the wave conditions under analysis, they have been selected in order to consider the possible impact of the wave encounter frequency on the performance of the methodolo-

Table 1 Test vessel: main characteristics and loading conditions.

Vessel main characteristics		Loading condition parameters	LC 1	LC 2
Overall Length (m)	34.50	Displacement (t)	489	448
Beam (m)	8.00	Metacentric height (m)	0.501	0.350
Depth (m)	3.65	Natural roll frequency (rad/s)	0.701	0.563
Linear Roll Damping Coefficient (ν)	0.0187	Natural roll period (s)	8.963	11.160
Quadratic Roll Damping Coefficient (β) (rad^{-1})	0.393	Draft (m)	3.484	3.294

gies [13]. In this work, and considering that ship speed is zero, wave encounter frequency will coincide with wave frequency. However, if the ship is moving, wave frequency will obviously differ from wave encounter frequency, which is the value which is expected to be found within roll spectral analysis.

Two different wave conditions have been tested, using both the mathematical model (irregular beam waves) and the towing tank experiments (regular beam waves). The first wave condition under consideration corresponds to a wave of which the frequency (or peak frequency in the irregular wave case) matches the natural roll frequency of the vessel in the loading condition LC 2. The second wave condition represents a situation where the wave encounter frequency is far from the roll natural frequency of the vessel in any of the considered loading conditions.

The wave parameters of both the mathematical model tests and the towing tank experiments, are included in Table 2.

Table 2 Wave condition parameters.

Mathematical model. Irregular waves			Towing tank tests. Regular waves			
Wave condition	H_s (m)	ω_{wp} (rad/s)	Wave condition	H (m)	ω_w (rad/s)	S_w
1	1.95	0.563	1	1.95	0.563	0.01
2	3.03	1.008	2	3.03	1.008	0.05

4 Comparative analysis

In order to analyse the performance of the EMD-HHT method and to compare it with results obtained by using the FFT-based one, both have been applied to the roll motion time series described in the previous section.

4.1 Mathematical model tests

Regarding the results obtained from the time series computed with the mathematical model, Figure 1 shows from top to bottom the roll motion time series, the results of the EMD-HHT and the results of FFT-based method for Wave condition 1. It has to be mentioned that the EMD-HHT provides an estimate every 45 seconds while the FFT every 10 seconds. This is due to the fact that overlapping in each analysed roll motion batch has been considered in both methodologies: a 75% in the first method and a 94% in the second one. In this case, the peak wave encounter frequency matches the roll natural frequency of LC 2. As it can be seen, the roll natural frequency estimates are very close to the target value in both loading conditions and both methodologies. It has to be mentioned that the output of the FFT shows a slightly larger dispersion of the frequency estimates than the one from the EMD-HHT.

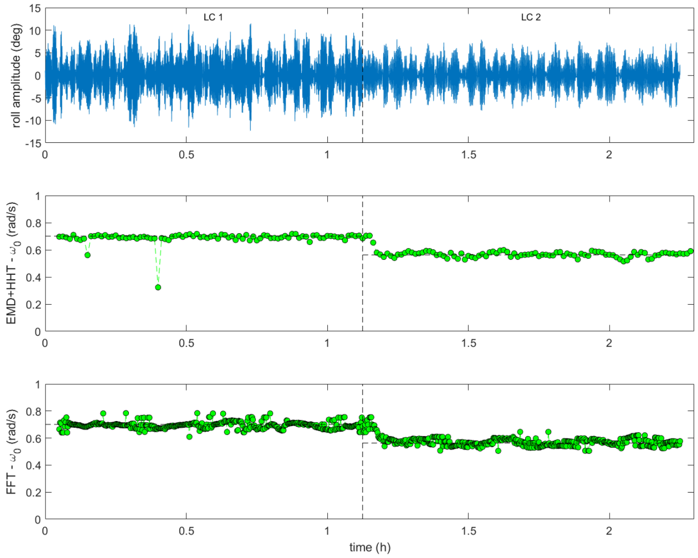

Fig. 1 Results of EMD-HHT and FFT-based methods for simulated roll motion and Wave condition 1.

For Wave condition 2, in which the wave encounter frequency is far from the roll natural frequency of the vessel, the performance of the EMD-HHT remains satisfactory (Figure 2). However, a slight overprediction of the frequency in LC 1 and an underprediction in LC 2 can be appreciated. Furthermore, the dispersion of the results is larger if compared to that observed in Wave condition 1. Regarding the FFT, in LC 1 the estimates are quite close to the target value, although there is a perceptible overestimation. In LC 2 the estimated roll natural frequency is wrong, and it oscillates around the peak wave encounter frequency. This fact suggests, as expected, that this methodology could be more affected by the wave encounter frequency than the EMD-HHT.

Figure 3 summarises the results of the two wave conditions for the simulated roll motion time series. As it can be seen for Wave condition 1 (Figure 3 (a)) both methods behave well, although the results from the EMD-HHT present less dispersion than those from the

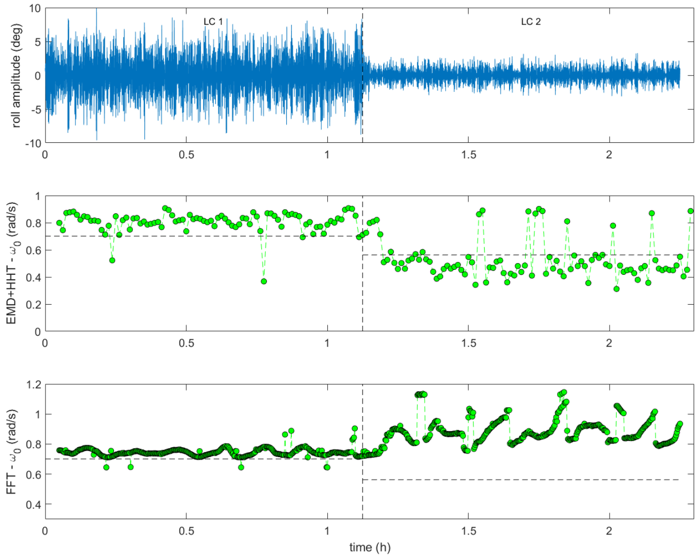

Fig. 2 Results of EMD-HHT and FFT-based methods for simulated roll motion and Wave condition 2.

FFT. In Wave condition 2 (Figure 3 (b)), the performance of the two methods decreases in comparison to the previous case. Although the EMD-HHT still performs relatively well in estimating the roll natural frequency of both loading conditions, the FFT is only able to obtain the roll natural frequency in one of them. This fact suggests, as it has been already mentioned, that the FFT is more vulnerable than the EMD-HHT to the effect of the wave encounter frequency.

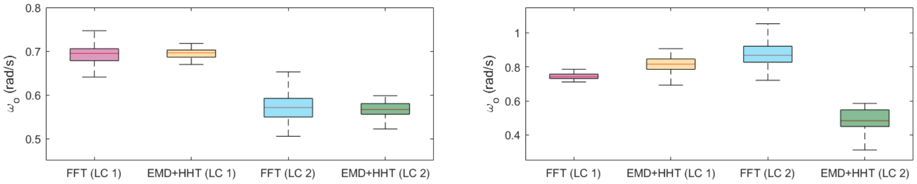

Fig. 3 Summary of results for simulated roll for Wave condition 1 (a) and 2 (b).

4.2 Towing tank tests

In this section, the results of applying the estimation methods to roll motion time series from towing tank test are presented. In this case, a low-pass filter with a cut-off frequency of 1.75 rad/s has been applied to the time series to mitigate signal content related to possible wave reflection in the tank, wall effects, etc.

Figure 4 shows the roll motion time series corresponding to Wave condition 1, the output of the EMD-HHT and the output of the FFT. In this case, again, the EMD-HHT seems to work much better. The roll natural frequency estimates are quite accurate for LC 2, showing little dispersion. Nevertheless, there is a considerable underestimation in LC 1. Regarding the output of the FFT, some dispersion could be appreciated in the estimates obtained in both loading conditions. In addition, the method is not able to distinguish between the wave encounter frequency and the roll natural frequency of the vessel in LC 1, as the obtained values are very close to the former one.

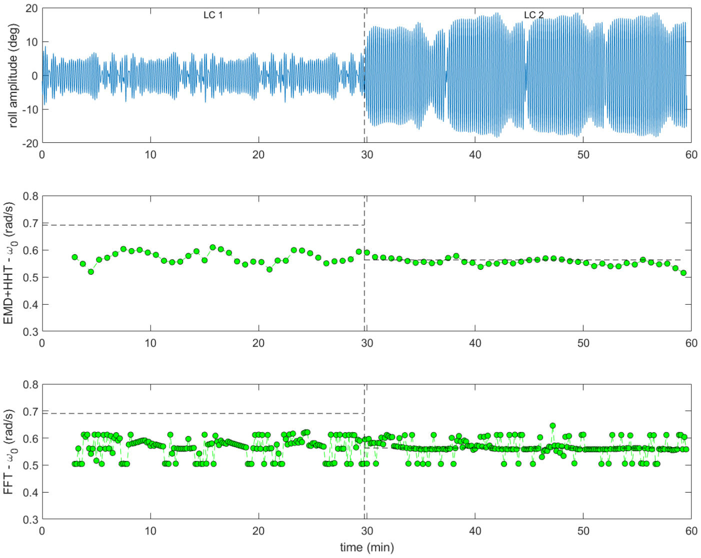

Fig. 4 Results of EMD-HHT and FFT-based methodologies for experimental roll motion and Wave condition 1.

Regarding Wave condition 2 (Figure5), on the one hand, the EMD-HHT presents again some underestimation in LC 1, and some dispersion of the results could be observed in both loading conditions. On the other hand, the performance of the FFT-based methodology is not satisfactory. As it can be seen, the obtained estimates of the roll natural frequency of the vessel are again very close to the wave encounter frequency in both loading conditions.

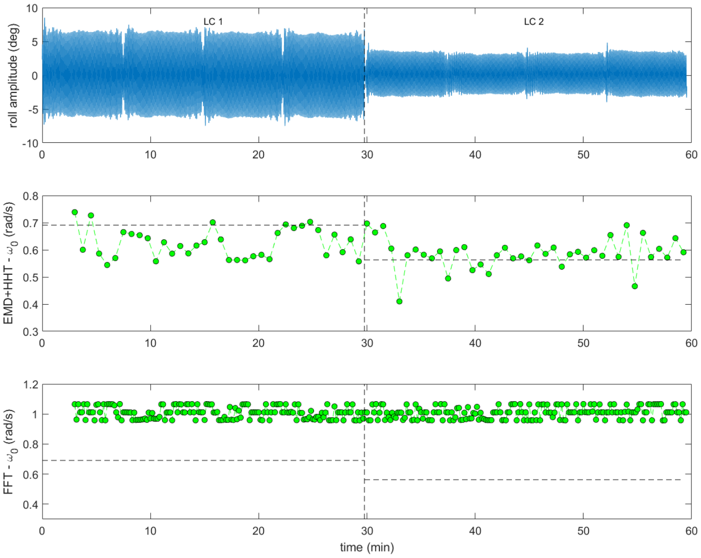

Fig. 5 Results of EMD-HHT and FFT-based methodologies for experimental roll motion and Wave condition 2.

Figure 6 summarises the results of both methodologies in both wave conditions. As it can be appreciated, in the case of the towing tank experiments, the FFT is highly influenced by the wave encounter frequency and it is not able to accurately identify the roll natural frequency of the vessel in some of time series. On the other hand, the EMD-HHT results seem to be better, and although especially some underpredictions take place, the general performance of the method is acceptable.

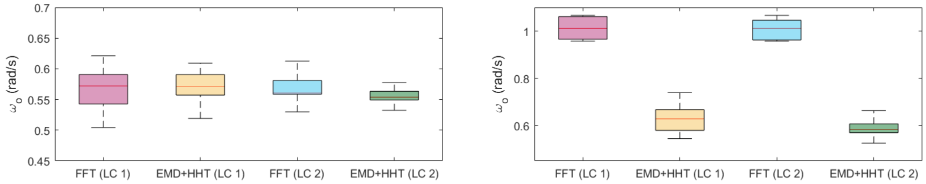

Fig. 6 Summary of results for experimental roll for Wave condition 1 (a) and 2 (b).

5 Change detection-based stability monitoring system

With a view in the practical implementation of an onboard stability guidance system, and in order to reduce its dependency on the accuracy of the roll frequency estimates, a monitoring system, based on the use of change-detection tools, has been implemented.

The objective of this statistical change detector is to determine, from the analysis of the roll natural frequency estimates obtained by the best performing method from the two previously analyzed (EMD-HHT), if a change between an acceptable and a non-acceptable sailing situation is taking place.

In Figure 7, a block diagram describing the structure of the proposed stability monitoring system has been included, where W-GLRT represents the proposed statistical change detector.

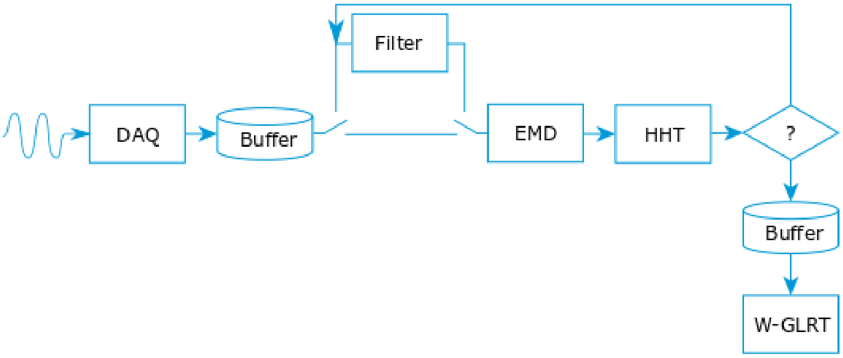

Fig. 7 Structure of the stability monitoring system.

In order to take into consideration that there is some level of uncertainty in the estimation of the natural roll frequency done by the EMD-HHT, these values have to be statistically characterized. After some testing comparing the fitting of four different statistical distributions (logistic, t-location scale, Weibull and double Weibull), the Weibull was selected as the most accurate [13]. The probabilistic median of this distribution is taken as the estimator of the natural roll frequency ($\hat{\omega}_0$):

$$\hat{\omega}_0 = \lambda(\ln 2)^{\frac{1}{\kappa}} \tag{3}$$

Being (κ) the shape parameter and (λ) the scale parameter.

Considering that both scale and shape parameters change with the vessel loading condition, the proposed detector has been designed to track their variations and subsequently, the variations in the vessel roll natural frequency. The detection problem under consideration is then to decide between two hypotheses; the null one ($\mathcal{H}_0$), which corresponds to a safe condition, and the alternative one ($\mathcal{H}_1$), which is related to a non-safe condition,

$$\mathcal{H}_0 : \lambda_0 (\ln 2)^{\frac{1}{\kappa_0}} \geq \omega_{0_c}$$
$$\mathcal{H}_1 : \hat{\lambda}_1 (\ln 2)^{\frac{1}{\hat{\kappa}_1}} < \omega_{0_c} \tag{4}$$

where ω_0 is defined as the critical natural roll frequency, and is the one corresponding to a GM equal to the minimum required by IMO for this type of ships (GM=0.350 m).

Taking into consideration that it depends on the Weibull parameters, the detection problem above could be reduced to a standard parameter test, where the decision between the two different hypotheses is done using the Generalized Likelihood Ratio Test (GLRT) [8]. This statistical test, based on the Neyman-Pearson theorem, maximizes the probability of detection for a desired probability of false alarms (γ). The GLRT would decide that the hypotheses is fulfilled if:

$$L_G(\mathbf{\Omega}_0) = \frac{\mathcal{W}(\mathbf{\Omega}_0; \hat{\boldsymbol{\theta}}_1, \mathcal{H}_1)}{\mathcal{W}(\mathbf{\Omega}_0; \boldsymbol{\theta}_0, \mathcal{H}_0)} > \gamma \tag{5}$$

where $\mathbf{\Omega}_0$ is the vector containing the estimations of natural roll frequency under analysis, $\boldsymbol{\theta} = [\lambda, \kappa]^T$ is the vector containing the characteristic parameters of the Weibull distribution, θ_0 is its realization for the null hypotheses and $\hat{\theta}_1$ is the maximum likelihood estimate of the parameter vector for the hypotheses, which is obtained by maximizing the Weibull probability density function $\mathcal{W}(\mathbf{\Omega}_0; \theta)$ under $\mathcal{H}_1$.

In addition to the above, a situation awareness system has been also included, with the objective of informing the crew about the stability level of their vessel following a colour coded pattern, in a similar way as it has been done in previous works by the authors [11]. This information is obtained by comparing $\hat{\omega}_0$ with ω_{0_c}.

Finally, the performance of the monitoring system for two of the previous test cases is analysed. Figure 8 shows, from top to bottom, the simulated roll motion time series for Wave condition 1, the results of the EMD-HHT, the results of the detector and the results of the awareness indicator. As it can be seen, the performance of the detector is very good. In the detector output graph, the upper continuous line represents the limit between safe and non-safe situation, which triggers the alarm, and the lower one represents the level in which this alarm is deactivated [12].

It adequately classifies the loading conditions and no false alarms or miss detections took place. Also the awareness indicator appropriately distinguish both loading conditions, providing the crew with a perception of the risk.

Figure 9 illustrates, from top to bottom, the roll motion time series, the output of the EMD-HHT, the output of the detector and the output of the awareness indicator for Wave Condition 2 of the towing tank tests. Despite of the fact that the roll natural frequency is underestimated in LC 1, the performance of the detector remains satisfactory. It correctly identifies the loading conditions, triggering the alarm in the risky situation. Only one false alarm appeared and two miss detections took place. Regarding the awareness indicator, its behaviour seems to be also acceptable.

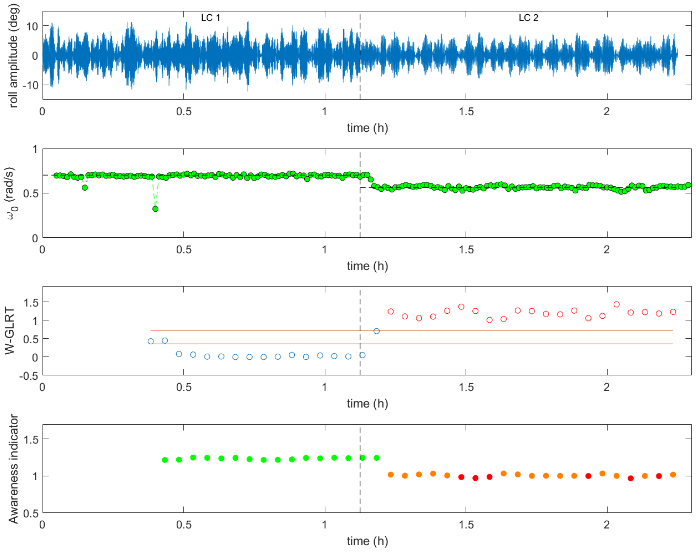

Fig. 8 Results of EMD-HHT and change detection methodology for simulated roll motion and Wave condition 1.

6 Conclusions

In this work, a comparison between two methods for real-time evaluation of the stability of the ship has been presented. The first method is based on the application of the EMD-HHT to estimate the natural roll frequency of the vessel. The second one is based on the recursive application of the FFT to obtain the same parameter.

In order to evaluate and compare the performance of both methods, a nonlinear mathematical roll model of a stern trawler in irregular beam waves has been used to simulate the vessel roll motion sailing in two different loading conditions, a safe one and another which is supposed to be non-safe from an initial stability point of view. Also, roll motion time series for the same loading conditions from towing tank tests in regular waves have been used.

The estimations of the natural roll frequency of the vessel obtained by the EMD-HHT method have shown to be quite accurate, performing better than the FFT-based estimator previously proposed in [10], at least in the wave conditions under analysis. In particular, in the case of the experiments, this method is strongly affected by the wave encounter frequency.

With the intention of implementing the EMD-HHT estimation method in an on board stability guidance system, and also to mitigate its dependency on the accuracy of the roll frequency estimates, a monitoring system that integrates change-detection tools has been

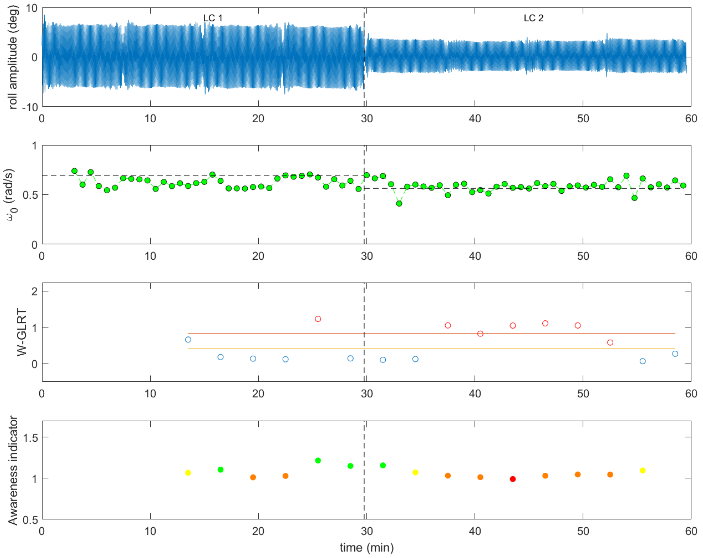

Fig. 9 Results of EMD-HHT and change detection methodology for experimental roll motion and Wave condition 2.

presented. It is based on a probabilistic detector which analyzes if the current loading condition is safe or not from a stability point of view (W-GLRT).

The performance of this monitoring system has been very satisfactory in the tested wave conditions, accurately differentiating between safe and non-safe conditions, and timely detecting the changes in the vessel loading condition. Even in situations where the roll natural frequency estimates are not too accurate, robustifying the methodology.

Although the results are very promising, and could represent a step forward compared to the previous developments of some of the authors of this work, additional testing is needed to verify this behaviour in more wave conditions and vessel speeds and headings.

This is a starting point to carry out a more detailed stability analysis. For example, if hydrostatics are available, GM could be used to calculate KG. Then, if both KG and hydrostatics are known, and if wave parameters could be somehow estimated, a detailed evaluation of large angle stability and vulnerability to dynamic failures (paremetric roll, pure loss of stability, dead ship condition, etc.) could be also carried out.

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