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Improving the performance of a stability monitoring system by adding wave encounter frequency estimation

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Abstract: Onboard guidance systems have emerged to improve the safety of fishing vessels providing the skipper with simplified stability information. In the last years, the authors have developed a stability monitoring system that automatically estimates the natural roll frequency of the vessel. Although the performance was acceptable, there were some specific situations where the influence of external excitations reduced the accuracy of the stability estimations. In this work, a methodology to automatically estimate the wave encounter frequency from ship motions is proposed. Then, this methodology is included in the stability monitoring system. Towing tank tests of a mid-sized stern trawler in different conditions have been used to analyse the improvements obtained with this approach.

Keywords: Estimation and filtering, Decision support systems in marine systems, Fishing vessels, Empirical Mode Decomposition, Generalized Likelihood Ratio Test, Experimental validation

1. INTRODUCTION

Fishing is considered one of the most dangerous occupations worldwide and its high fatal injury rate confirms it (Gudmundsson, 2013; Krata, 2008). In spite, the distribution of the accidents is not uniform. Looking at the size and the type of fishing gear, it can be concluded that the most affected are, on the one hand, small and medium-sized fishing vessels and, on the other hand, trawlers (European Maritime Safety Agency, 2018; MAIB, 2008).

Regarding the type of accidents, stability failures are not the most common. However, they are responsible for the largest number of fatalities (Transportation Safety Board of Canada, 2012).

Among all the possible causes of these accidents, the main ones seem to be: the lack of training, the human factor and the unavailability of useful, practical and objective stability information on board (Wolfson Unit, 2004).

In an attempt to reduce stability-related accidents, onboard guidance systems have been proposed. Initially, these systems were based on diagrams of the vessel representing different loading conditions, associated with a colour code that represents the inherent risk of each of them. In this group can be highlighted the well-known Womack matrix (Deakin, 2005; Míguez González et al., 2012).

Then, the guidance systems have evolved towards simplified computer software with a graphical interface, that from the hull forms and weight distribution performs all the stability calculations. A good example is the Safe Skipper from the Integrated Group for Engineering Research (Míguez González et al., 2012).

Since 2014, the authors have been trying to automate the stability evaluation on fishing vessels as one of the main requirements of guidance systems is the avoidance of interaction with the crew. Their proposal is based on the assumption that roll spectrum has a peak around its natural frequency (ω_0). So that, if this frequency is identified the metacentric height (GM) of the vessel can be obtained.

The first proposal consisted of monitoring the roll motion, computing its spectrum using the recursive application of the Fast Fourier Transform (FFT) and, then, obtaining the GM. This methodology has been tested with simulated roll motion time series, towing tank test and sea trials (Míguez González et al., 2016, 2017, 2018; Santiago Caamaño et al., 2018b,a).

In the last years, in order to refine the obtained results and to provide additional information to the skipper a second methodology has been proposed. This new methodology is based on signal processing techniques in time domain to extract the frequency information contained in the roll motion time series and the application of change detection techniques to automatically raise an alarm when safety could be compromised. The validation has been done using roll motion time series from a mathematical model and towing tank experiments. Furthermore, both

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methodologies have been compared (Santiago Caamaño et al., 2019b,a,c).

The obtained results from the validation were satisfactory. Nevertheless, it has been observed that, in situations where the wave encounter frequency (ω_e) is higher than the ω_0, the performance of the methodology degrades. In these cases, what usually happens is that the methodology is not able to extract the natural roll frequency of the vessel as it is masked by ω_e. In consequence, there is a wrong stability estimation.

In order to avoid or reduce this effect, it is necessary to complement the monitoring stability system with data about the wave frequency in the sailing area.

In this work, a methodology for estimating in real-time the wave encounter frequency from ship motions is presented and tested with time series from towing tank tests. Furthermore, this methodology is included in the already mentioned stability monitoring system adding some modifications.

2. WAVE ENCOUNTER FREQUENCY ESTIMATION

Knowledge of environmental conditions is essential to improve the safety and efficiency of offshore operations. Also, it can be considered a benefit for guidance systems, representing support in the decision-making process (Pascoal et al., 2007; Pennino et al., 2021).

There are many alternatives to estimate the wave spectrum, such as radar, satellite or buoy. Among all of them, wave rider buoys have been the most popular wave measurement instrument since 1966. Nevertheless, their use in real-time operations in open waters is not suitable as it would be necessary to develop a grid of buoys that covered the entire ocean surface. In addition, they are not always operative due to the maintenance periods and could suffer from damage or loss. (Ren et al., 2021; Kasinatha Pandian et al., 2010). For this reason, sea state estimation from ship responses has become very appealing.

Since the '70s, different approaches to obtain the directional wave spectrum from ship motions have been presented. Most of them can be categorised into two groups: parametric modelling and non-parametric modelling. Both methods are based on the wave buoy analogy. The main difference between them relies on the assumption or not of parameterised wave spectra (Nielsen, 2006; Ren et al., 2021).

Despite of all the already available methods for estimating the wave spectrum, in this work a simpler approach is presented. The primary reason is that the stability monitoring system has been designed vessel model independent and is desirable to maintain this characteristic.

In same way that roll spectrum has a peak around its natural frequency, it is well known that the peak of the spectrum of some ship motions correspond to the wave encounter frequency. The motions chosen in most of the applications are heave and pitch (Pascoal et al., 2007). In this case, as motions have been recorded using an Inertial Measurement Unit (IMU), heave acceleration and pitch have been analysed.

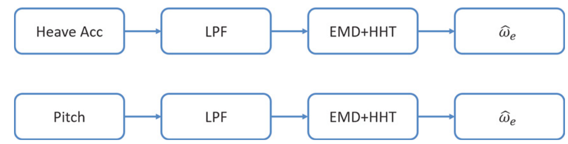

Fig. 1. Wave encounter frequency estimation methodology.

Figure 1 shows the proposed methodology for estimating the wave encounter frequency in real-time. As it can be seen, it is based on the same time domain techniques as the stability monitoring system. It consists of measuring heave acceleration and pitch. Then, these signals are pre-processed with a low-pass filter to remove frequency components related to sensor noise, rebounds of the waves in the tank and wall effects in the experiments. After that, the Empirical Mode Decomposition (EMD) and the Hilbert-Huang Transform (HHT) are applied to obtain the wave encounter frequency.

Finally, the obtained results from both motions are compared in order to decide which one will be implemented in the stability monitoring system.

2.1 Measuring motions

In order to fulfil the requirement of real-time, heave acceleration and pitch are recorded in a batch length of 3 minutes. Furthermore, an overlap of 50% between consecutive batches has been used. The reason is that each batch has to be long enough to obtain a good estimation but at the same time short enough to get information about the sea state every little time.

2.2 Low-pass filter

As it was mentioned, there are some unwanted frequencies contained in the signal that need to be removed or, at least, attenuated. These frequencies are a product of sensor noise or, in this case, as the validation has been performed with data from towing tank tests, rebounds of the waves in the tank, wall effects, etc.

The employed filter is a 10th order Chebychev Type II with a cut-off frequency of 1.2 rad/s.

2.3 Empirical Mode Decomposition

The EMD is a signal processing technique in the time domain. Its function is to decompose the signal into its main oscillatory modes, called Intrinsic Mode Functions (IMFs). The characteristics of an IMF are its equal number of extrema (maxima and minima) and zero-crossings and a time-varying frequency and amplitude (Dätig and Schlurmann, 2004; Huang et al., 1998).

The process for obtaining the IMFs is known as sifting and the result is:

$$\phi(t) = \sum_{i=1}^{N_{\mathrm{IMF}}} \mathrm{IMF}_i(t) + R(t), \quad t \in [\bar{t} - 3\,\mathrm{min}, \bar{t}] \tag{1}$$

Being $\phi(t)$ the time series to which the EMD is applied, $R(t)$ a monotonic function, N_{IMF} the total number of obtained IMFs and $\bar{t}$ the current time.

2.4 Hilbert-Huang Transform

The HHT is very useful in spectral analysis due to the fact that computes the instantaneous frequency ($\omega(t)$), amplitude ($a(t)$) and phase ($\theta(t)$) of a signal (Dätig and Schlurmann, 2004; Huang et al., 1998).

$$a(t) \triangleq \sqrt{x(t)^2 + y(t)^2} \quad (2)$$

$$\theta(t) \triangleq \arctan\left(\frac{y(t)}{x(t)}\right) \quad (3)$$

$$\omega(t) \triangleq \frac{\mathrm{d}\theta(t)}{\mathrm{d}t} \quad (4)$$

Where x(t) represents the i-th IMF and $y(t)$ is Hilbert transform.

Reaching this point, only remains the calculation of the mean instantaneous frequency of each IMF to obtain a constant estimate. The mean instantaneous frequency is computed following the proposal of Xie and Wang (2006):

$$\hat{\omega}_i = \frac{\sum_{k=1}^{L_\phi} \omega_i(k) a_i^2(k)}{\sum_{k=1}^{L_\phi} a_i^2(k)}, \quad i = 1, \ldots, N_{\mathrm{IMF}} \quad (5)$$

Being L_ϕ the number of samples contained in the IMF.

Finally, the wave encounter frequency should be selected from all obtained mean instantaneous frequencies. As frequencies are ranked from high to low due to their power content, the estimated wave encounter frequency ($\hat{\omega}_e$) is chosen as the first one. The reason is that it is supposed to be the most energetic component in the signal as it corresponds to the peak frequency of the spectrum.

3. STABILITY MONITORING SYSTEM

Once the methodology for estimating the wave encounter frequency has proven to be successful, it is time to incorporate it into the stability monitoring system. Subsection 4.4 shows the results of both motions, and it can be seen that heave acceleration provides a better estimate of the wave encounter frequency. Due to this fact, its monitoring is included in the stability monitoring system.

As a result, the new proposed stability monitoring system is summarised in Figure 2. It is composed of 3 main blocks:

Block 1 represents the wave encounter frequency estimation already described in Section 2.
Block 2 decides how roll motion should be pre-processed to avoid the influence of ω_e in the stability assessment.
Block 3 evaluates the stability of the vessel and triggers an alarm when a risky situation is met.

Block 2 and 3 are explained in detail in Subsections 3.1 and 3.2.

3.1 Block 2

Block 2 represents the filtering process of the roll motion time series.

If a vessel is subjected to any external excitation (for instance, waves, wind or current) and its roll motion is

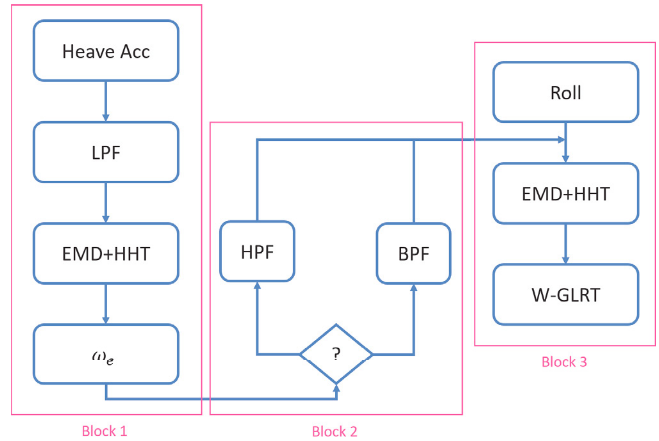

Fig. 2. Modified stability monitoring system.

measured, in the time series will be contained the natural roll frequency, as well as the frequency related to the excitation, sensor noise, etc. Usually, due to the dynamic characteristics of this movement, the most energetic component is the natural roll frequency.

However, this situation may change when the wave encounter frequency is not close to ω_0. In particular, when ω_e is higher than ω_0, it becomes the most energetic component in the signal and tends to mask the other frequencies. Thus, it is necessary to remove this component from the roll motion before being analysed.

Considering that the natural roll frequency varies with the loading condition, it is necessary to define the interval where the natural roll frequency could be contained in order to set the area in which the filter cannot be used. The limits of the interval are the maximum expected value ($\omega_{0,max}$) and the minimum ($\omega_{0,min}$). $\omega_{0,\max}$ is the largest GM condition contained in the vessel's stability booklet and $\omega_{0,\min}$ is associated with the minimum stability level necessary to keep heel beyond 15 degrees under a 30-knot lateral wind (International Maritime Organization, 2012).

Moreover, as the validation has been performed with time series from towing tank tests, there are some low-frequency components present in the signal. These components correspond to sensor noise and other effects that should be removed in order to avoid possible masking.

Hence, when $\hat{\omega}_e \geq \omega_{0,max}$ a bandpass filter is applied to roll motion signal. The filter is a 10th order Chevychev Type II with a lower cut-off frequency equal to $\omega_{0,\min}$ and an upper cut-off frequency equivalent to $\omega_{0,\max}$ with an attenuation in the stopband of 40 dB.

Finally, if $\hat{\omega}_e < \omega_{0,max}$ a 8th order Chevychev Type II highpass filter is employed. The cutoff frequency is $\omega_{0,\min}$ and the attenuation in the stopband is 30 dB.

3.2 Block 3

Block 3 represents the stability assessment that can be summarised in the following steps.

First, the roll motion is recorded in batches of 3 minutes with a 50% overlap as the heave acceleration.

Then, the EMD+HHT are applied to estimate the natural roll frequency of the vessel.

After that, the Weibull generalized likelihood ratio test (W-GLRT) evaluates if the estimates of the natural roll frequency belong to a safe or dangerous situation. When the safety threshold is crossed an alarm is raised.

The W-GLRT is a statistical test that compares to competing hypothesis and is based on the Neyman–Pearson theorem, that maximizes the probability of detection for a desired probability of false alarms (Kay, 1998).

For the monitoring system, the null hypothesis ($\mathcal{H}_0$) is a safe loading condition and the alternative hypothesis ($\mathcal{H}_1$) is an unsafe situation. As in previous works (Santiago Caamaño et al., 2019b,c) has been demonstrated that the natural roll frequency estimates ($\hat{\omega}_0$) fit a Weibull distribution and its probabilistic median is a robust estimator of this parameter, both hypothesis can be described as:

$$\begin{aligned} \mathcal{H}_0 &: \lambda_0(\ln 2)^{\frac{1}{\kappa_0}} > \omega_{0_c} \\ \mathcal{H}_1 &: \hat{\lambda}_1(\ln 2)^{\frac{1}{\hat{\kappa}_1}} \leq \omega_{0_c} \end{aligned} \quad (6)$$

where κ and λ are respectively the shape and scale parameters of the Weibull distribution and vary with the loading condition. $\omega_{0,c}$ represents the critical natural roll frequency of the vessel and is related to the minimum required GM to consider a loading condition as safe. For a fishing vessel the minimum GM is 0.350 m (International Maritime Organization, 2012).

Considering that Ω_0 is the vector containing the N latest natural roll frequency estimates, the detector decides that the current situation belongs to $\mathcal{H}_1$ if:

$$L_G(\boldsymbol{\Omega}_0) = \frac{\mathcal{W}(\boldsymbol{\Omega}_0; \hat{\boldsymbol{\theta}}_1, \mathcal{H}_1)}{\mathcal{W}(\boldsymbol{\Omega}_0; \boldsymbol{\theta}_0, \mathcal{H}_0)} > \gamma \quad (7)$$

where $\boldsymbol{\theta} = [\lambda, \kappa]^T$ is the vector containing the characteristic parameters of the Weibull distribution; θ_0 is its realization for the null hypotheses; $\hat{\theta}_1$ is the maximum likelihood estimate of the parameter vector for the hypotheses, which is calculated by maximizing the Weibull probability density function $\mathcal{W}(\boldsymbol{\Omega}_0; \theta)$ under $\mathcal{H}_1$. Finally, γ is the detection threshold for a chosen probability of false alarms and it is calculated according to (Kay, 1998):

$$P_{FA} = \int_{\Omega_0 : L_G(\Omega_0) > \gamma} \mathcal{W}(\Omega_0; \theta_0, \mathcal{H}_0) d\Omega_0 \quad (8)$$

In order to ensure that possible punctual wrong stability predictions do not mask true alarms, a second threshold has been defined. It has been set to 1/3 of γ. Thus, if an alarm is raised by the detector, then it will not be deactivated until the detector's output is lower than this second threshold.

4. TEST AND VALIDATION

In this section, the analysis of the performance of the proposed methodology for estimating the wave encounter frequency, and also, the modified stability monitoring system is carried out by using heave acceleration, roll and pitch time series from towing tank tests.

The experiments were performed at the University of A Coruña towing tank by the authors and the details about the vessel and wave conditions can be found in the following subsections.

4.1 Test vessel

The test vessel is a stern trawler, whose hull forms are representative of the Spanish fishing fleet. The model of the vessel was made in fibreglass and the scale is 1/30 (see Figure 3). Furthermore, it was equipped with an IMU to measure the motions and the acceleration. The sampling frequency was 50 Hz.

The main characteristics of the fishing vessel can be found in Table 1.

Table 1. Test vessel: main characteristics

Overall Length	34.50 m
Beam	8.00 m
Depth	3.65
Minimum Roll Natural Frequency ($\omega_{0,\min}$)	0.300 rad/s
Maximum Roll Natural Frequency ($\omega_{0,\max}$)	0.912 rad/s

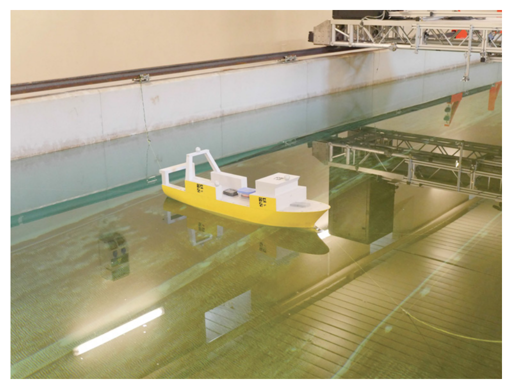

Fig. 3. Scale model of the fishing vessel.

In order to test the ability of the monitoring system to distinguish between safe and potential unsafe loading situations, two loading conditions were tested during the experiments. The details of each loading condition can be seen in Table 2. As it can be appreciated, LC 1 is the one corresponding to the minimum mandatory GM and LC 2 is a safer one.

Table 2. Test vessel: loading conditions

LC	Δ (t)	T (m)	GM (m)	ω_0 (rad/s)
1	448	3.340	0.350	0.563
2	489	3.484	0.501	0.701

4.2 Test wave conditions

As the wave encounter frequency has shown in previous works an influence on the performance of the monitoring system (Santiago Caamaño et al., 2019a,b), two different sea states were tested. In the first one, the wave frequency is higher than the maximum expected roll natural frequency of the vessel. This is the most harmful situation for the monitoring system, as it was not able to accurately identify the current roll natural frequency of the ship nor sometimes trigger the alarm if a risky loading condition was met.

In the second sea state, the wave frequency is between the minimum and the maximum expected roll natural frequencies of the vessel.

In both cases, the tests were performed at zero forward speed and in regular beam waves (90 deg) with the same wave height.

The tested wave conditions are shown in Table 3.

Table 3. Sea state parameters.

Sea state	H_w (m)	ω_w (rad/s)
1	3.000	0.956
2	3.000	0.574

4.3 Tuning of the monitoring system

The detector has been designed assuming that the parameters of the null hypothesis were known. For the stability monitoring system this fact is not true, as the loading condition of the vessel may have changed since it was used the last time.

Due to this fact, two operational stages have been considered. The first one is the estimation phase. It takes place when the vessel leaves the port and the system is started. During this period the system is only collecting $\hat{\omega}_0$ and, at the end, computes the parameters of $\mathcal{H}_0$. The estimation period has been set to 13.5 minutes. In the second stage, called detection, the system is fully working. The parameters of $\mathcal{H}_1$ are calculated and compared against $\mathcal{H}_0$ according to Equation 7. The time window of this phase has been set to 3 minutes to fulfil the requirement of real-time

Finally, P_{FA} has been calculated considering one every three months.

4.4 Results of wave encounter frequency estimation

Because of the size of the towing tank where the experiments were run, each sea state and loading condition has been tested 4 times in order to obtain a sufficiently long time series. Then, they have been stitched together.

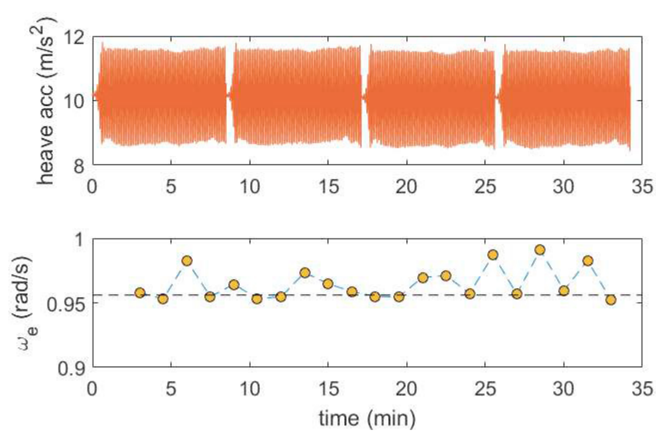

Fig. 4. Results of applying the wave encounter frequency estimation methodology to heave acceleration time series for LC 1 and Sea State 1.

Figure 4 shows, on the top, the heave acceleration time series for loading condition 1 in sea state 1 and, on the bottom, the wave encounter frequency estimates. As it can be seen, the estimates are very close to the target value, represented by the black dashed line, and the dispersion is small. furthermore, a slight overestimation can be perceived.

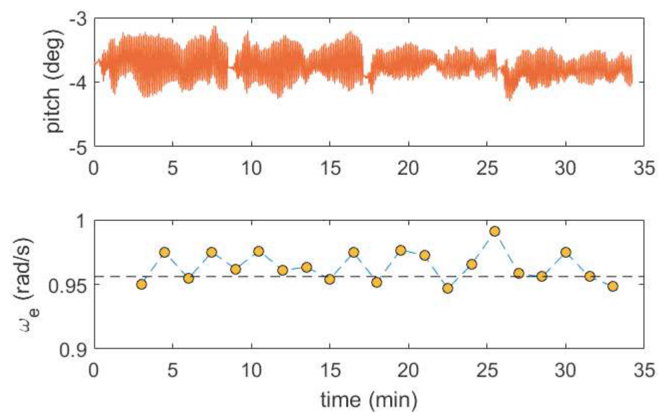

Fig. 5. Results of applying the wave encounter frequency estimation methodology to pitch time series for LC 1 and Sea State 1.

Figure 5 illustrates the result of applying the methodology for estimating ω_e to the pitch time series for the same loading condition and sea state. Again, the estimates are close to the target value showing a good approximation. However, the dispersion has increased a little bit.

In order to compare the results of heave acceleration and pitch for both sea states and loading conditions, the median (Med), the percentiles 5th and 95th (P5 and P95, respectively) and the deviation from the target value (Dev) have been calculated. The obtained values are summarise in Tables 4 and 5.

On the one hand, it can be observed that the deviation from the target value in both motions is quite small, being as much 3.136%. Results for heave acceleration are slightly better. On the other hand, if the percentiles are considered, it can be perceived that the results of pitch motion provide greater dispersion. Thus, heave acceleration seems to be the best alternative to estimate the wave encounter frequency.

4.5 Results of stability monitoring system

In this subsection, the results of the modified stability monitoring system are presented.

Figure 6 shows from top to bottom, the heave acceleration time series, the wave encounter frequency estimates, the roll motion time series, the natural roll frequency estimates and the output of the detector for sea state 1. As it can be seen, the output of the EMD and HHT provides a good estimation of ω_e in both loading conditions. Regarding the natural roll frequency, the estimates are very close to the target value in LC 2 but there is a small overestimation in LC 1. Despite this fact, the detector is able to correctly classify both situations. There are no false alarms or miss detections.

Figure 7 illustrates the time series and the output of each methodology for sea state 2. In this case, the dispersion

Table 4. Results of applying the wave encounter frequency estimation methodology to heave acceleration time series.

Sea State	Target ω_e (rad/s)	Loading condition 1 Med (rad/s)	P5 (rad/s)	P95 (rad/s)	Dev (%)	Loading condition 2 Med (rad/s)	P5 (rad/s)	P95 (rad/s)	Dev (%)
1	0.956	0.959	0.953	0.989	0.314	0.960	0.951	0.987	0.418
2	0.574	0.586	0.553	0.607	2.091	0.582	0.550	0.601	1.394

Table 5. Results of applying the wave encounter frequency estimation methodology to pitch time series.

Sea State	Target ω_e (rad/s)	Loading condition 1 Med (rad/s)	P5 (rad/s)	P95 (rad/s)	Dev (%)	Loading condition 2 Med (rad/s)	P5 (rad/s)	P95 (rad/s)	Dev (%)
1	0.956	0.962	0.948	0.983	0.628	0.959	0.942	0.986	0.314
2	0.574	0.592	0.571	0.675	3.136	0.588	0.550	0.649	2.439

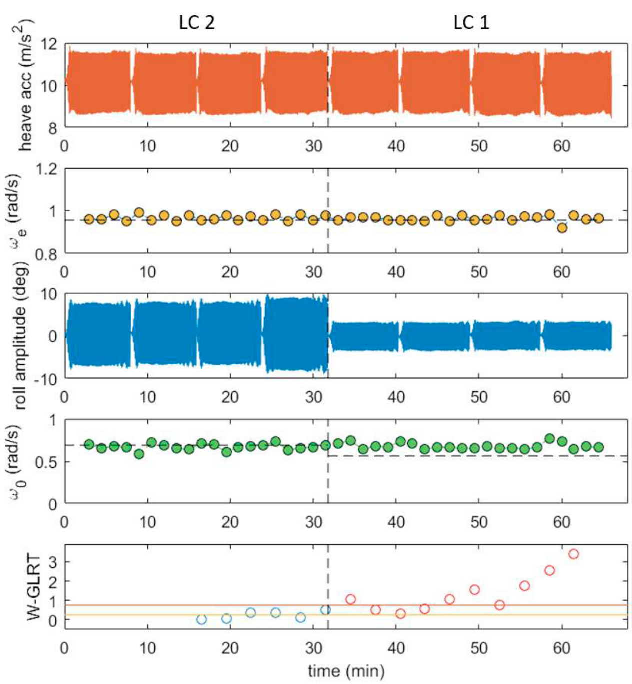

Fig. 6. Results of the proposed monitoring stability assessment system in Sea State 1.

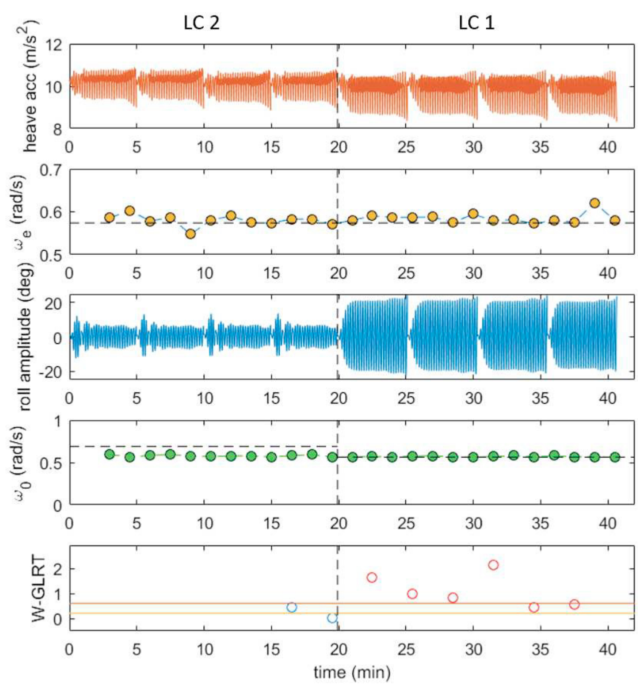

Fig. 7. Results of the proposed monitoring stability assessment system in Sea State 2.

in $\hat{\omega}_e$ is slightly greater. Nevertheless, the estimates are very close to the target value. As ω_e is close to ω_0 in loading condition 1, the roll amplitude is large. Due to this fact, $\hat{\omega}_0$ almost match the target value. In this case, in LC 2 there is an underestimation of the natural roll frequency. Regarding the performance of the detector, it can be considered really good as no miss detections or false alarms.

5. CONCLUSION

Onboard guidance systems have manifested to be a feasible alternative to increase the safety of the crew of fishing vessels. This paper represents a step forward in the design of this kind of systems.

Firstly, a methodology to automatically estimate the wave encounter frequency from heave acceleration and pitch has been presented. This methodology has been tested with time series from towing tank experiments. The results obtained from both motions have been compared and heave acceleration has demonstrated to provide a better estimation of ω_e.

Furthermore, the estimation of ω_e using heave motion has been included in a stability monitoring system. The objective was to increase its performance attenuating this component from the roll motion time series. The results were satisfactory. The obtained natural roll frequency estimates were close to the target value with little dispersion, even though in some loading conditions there is a small over or underestimation. Regarding the detector, its performance is adequate as it correctly classified the loading conditions with no false alarms or miss detections.

To sum up, the modified stability monitoring system showed promising results. Although validation in more wave conditions and directions, different operational scenarios and longer time series is needed to test its capability.

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