On the application of change detection techniques for the stability monitoring of fishing vessels

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ABSTRACT

This work includes the description of a novel way to tackle the problem of real time stability monitoring. Instead of taking natural roll frequency as the only variable to estimate the stability level of the vessel, a methodology based on the use of signal-based methods with statistical change detection tools is used for detecting changes in the vessel stability and differentiating between safe and non-safe situations. This methodology also includes a colour coded risk alarm that informs the crew about the current state of the vessel. Moreover, in the proposed work, the behaviour and performance of this method is analysed using roll motion data of a stern trawler generated by a one degree of freedom nonlinear model in irregular beam waves. In addition, the obtained results are compared to those from the application of a Fast Fourier Transform (*fft*)-based methodology previously developed by the authors. The performance of this new proposal has been good, both regarding the estimation of the vessel natural roll frequency and the change detection schemes, showing a better performance than the *fft*-based method. However, further analysis is needed to validate these results under more wave conditions and sailing situations.

Keywords: *Fishing vessels, intact stability, stability monitoring, guidance systems.*

1. INTRODUCTION

Medium and especially small 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 (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 to reduce 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 (Wolfson Unit, 2004; Womack, 2003), the analysis of residual freeboard (Scarponi, 2017), or the real time estimation of stability parameters (Wawrzynski and Krata, 2016; Terada et al. 2018 and 2019; Galeazzi et al., 2011).

On this matter, some of the authors of this work have been working on the development of a computer based stability guidance system for small and medium sized fishing vessels, which operates in real time and provides information regarding the stability of the ship with no need of crew interaction, thus reducing the uncertainty of the stability estimations. The state of development of this system has been previously presented, in its different stages, in Santiago Caamaño et al. (2018), Míguez González et al. (2017) and Míguez González et al. (2018). In these works, the performance of a methodology based on the sequential application of the Fast Fourier Transform (*fft*) for the real time estimation of the natural roll frequency of the vessel (and so of its metacentric height and initial stability), was tested using both a nonlinear mathematical model of roll motion and data from a real scale test campaign onboard a stern trawler, obtaining satisfactory results. If this methodology is applied, the stability level of the vessel could be evaluated based on the last available metacentric height estimation, or on the median value of a set of metacentric height estimations obtained during a given time period (which should be as small as possible to avoid missing possible sudden changes in stability). Due to this fact, the performance of this method, including the appearance of false alarms or stability over predictions, only depends on the precision of the obtained metacentric height estimations and their stability in time.

In this work, a novel way to tackle the problem of stability monitoring is presented. Instead of taking natural roll frequency as the only variable to estimate the stability level of the vessel, a methodology based on the combined use of signal-based methods (Empirical Mode Decomposition and Hilbert-Huang Transform) with statistical change detection tools (Weibull - Generalized Likelihood Ratio Test) are used for detecting changes in the vessel stability and differentiating between safe and non-safe situations.

The use of change detection tools has been already applied in the maritime sector, even including some applications within ship stability, such as the approach included in Galeazzi et al. (2015), where these type of tools are used for predicting the appearance of parametric rolling. Other uses include the detection of faults in mooring systems (Fang et al., 2015) or the detection of incoming vessels within marine traffic (Pradhan and Gupta, 2017).

The main objective of the proposal presented herein is to include in the stability evaluation a tool which provides an indication of whether a loading condition is safe or not, and which is less dependent on metacentric height estimations than the one previously described. In this new methodology, the *fft* is substituted by the EMD+HHT, providing better resolution and performance for estimating the vessel natural roll frequency in short time records. Moreover, the direct stability evaluation obtained from this frequency estimations, done in the previous proposal, is substituted by a probabilistic detector, which should provide a more robust stability level indication.

2. CONDITION MONITORING SYSTEM ARCHITECTURE

The proposed methodology consists of an estimator which, applying the Empirical Mode Decomposition method and the Hilbert Huang Transform (EMD + HHT), obtains from a given time record of the vessel roll motion, information about its natural roll frequency and possible variations of this parameter over time. These estimates are then modelled following a Weibull distribution and used as input of a statistical change detector, based on the Generalized Likelihood Ratio Test (W – GLRT), which determines if a change between a safe and a non-safe situation is taking place.

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 (Míguez González et al., 2012).

In Figure 1, a block diagram describing the structure of the proposed stability monitoring system has been included.

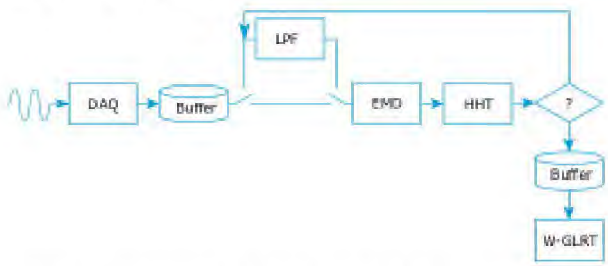

Figure 1. Structure of the stability monitoring system.

EMD + HHT estimator

The EMD technique is applied to decompose the roll motion signal of the time record under analysis into its main oscillatory components, the *IMF*s (Intrinsic Mode Functions) ((Dätig and Schlurmann, 2004; Gupta et al., 2014; Huang et al., 1998)). After its application, the vessel roll motion $\phi(t)$ could be represented as:

$$\phi(t) = \sum_{i=1}^{N_{IMF}} IMF_i(t) + R(t) \quad (1)$$

where $R(t)$ is a monotonic function, $IMF_i(t)$ is each of the Intrinsic Mode Functions obtained from the time series after the application of the EMD and N_{IMF} is the number of obtained *IMF*s. In the typical situation of a vessel sailing under the effect of wind, waves and other external excitations, the IMFs usually include those corresponding to these excitations, plus the one related with the ship natural oscillation and some others. Once the *IMF*s have been obtained from the original signal, the Hilbert-Huang Transform (HHT) is applied to them (Dätig and Schlurmann, 2004; Huang et al., 1998). This transform, designed for representing a signal in a time-frequency-energy basis, is used in this work for providing an estimate of the instantaneous frequency of each *IMF*. From these values, and for a given time record, the mean instantaneous frequency ($\hat{\omega}_j$) for each *IMF* is computed according to Xie and Wang (2006) and stored in a vector Ω_{IMF}

$$\Omega_{IMF} = [\hat{\omega}_1, \hat{\omega}_2, ..., \hat{\omega}_{N_{IMF}}] \tag{2}$$

where $\hat{\omega}_1 > \hat{\omega}_2 > ... > \hat{\omega}_{N_{IMF}}$.

In the case of a vessel rolling under external excitations, the extracted *IMF*s from the roll motion time series, and so its corresponding mean instantaneous frequencies, usually include the oscillatory modes due to these excitations, as well as the mode corresponding to the vessel natural frequency, sensor noise and other possible components. The chosen estimate of the natural roll frequency of the vessel for that given time record will be one of these values. In order to carry out this selection firstly, from the whole set of obtained values, all of those which are over and under a given value are disregarded. This range is determined by the maximum expected roll natural frequency of the vessel (previously determined, for example, by considering a maximum stability condition), and a minimum value (which in this case is associated with the minimum stability level necessary to keep heel beyond 15 degrees under a 30 knot lateral wind). After this process, the estimated natural roll frequency is selected as the maximum value from the remaining ones, based on observations and some experience, which showed that the first and second largest values usually concentrate most of the energy. However, this assumption is arguable, and more testing is needed to confirm such an hypothesis.

W-GLRT detector

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 been statistically characterized. After some previous testing in different load cases and sea states, it has been concluded that the distribution which best fits the natural roll frequency estimates is the Weibull, which main parameters are the shape (κ) and the scale parameter (λ). If the probabilistic median of this distribution is taken as the estimator of the natural roll frequency ($\hat{\omega}_0$)

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

and 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, those in the vessel roll natural frequency. The detection problem under consideration is then to decide between two hypotheses; the null one (H_0), which corresponds to a safe condition, and the alternative one (H_1), which is related to a non-safe condition,

$$\begin{aligned} &\mathrm{H}_0 : \lambda_0 \cdot (\ln 2)^{1/\kappa_0} \geq \omega_{0_c} \\ &\mathrm{H}_1 : \hat{\lambda}_1 \cdot (\ln 2)^{1/\hat{\kappa}_1} < \omega_{0_c} \end{aligned} \tag{4}$$

where ω_{0_c} is defined as the critical natural roll frequency, and is the one corresponding to a $\overline{GM}$ equal to the minimum required by IMO for this type of ships ($\overline{GM} = 0.350$ m).

Taking into consideration that $\hat{\omega}_0$ 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) (Kay, 1998). 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 H_1 hypotheses is fulfilled if:

$$L_G(\Omega_0) = \frac{Weibull\left(\Omega_0; \hat{\theta}_1, H_1\right)}{Weibull\left(\Omega_0; \theta_0, H_0\right)} > \gamma \tag{5}$$

where Ω_0 is the vector containing the estimations of natural roll frequency under analysis, $\theta = [\lambda, \kappa]^T$ 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 (MLE) of the parameter vector θ for the H_1 hypotheses, which is obtained by maximizing $Weibull(\Omega_0;\theta)$ under H_1.

In addition to deciding between the two previous hypotheses, and so to deciding if the sailing situation under analysis is safe or not from a stability point of view, the value of $\hat{\omega}_0$ is used for generating stability – related information to the crew. This information is obtained by comparing $\hat{\omega}_0$ with ω_{0_c}, in a similar way as it has been proposed in Míguez González et al. (2017) or Caamaño Santiago et al. (2018). However, there is a remarkable difference between both proposals. While in the previous ones the stability estimation relied on the instantaneous estimations of the natural roll frequency, in this case it is done based on a probabilistic approach which, in principle, should represent a more robust approach.

3. TEST CASE

Fishing vessel model

In order to evaluate the performance of the proposed methodology, a nonlinear mathematical model of roll motion of a stern trawler in irregular beam seas has been applied for generating the roll motion time series.

The model, shown in equation (6), is described in detail in Bulian and Francescutto (2004), and has been already applied to the same vessel in Míguez González et al. (2017).

$$\ddot{\phi}+2\cdot\upsilon\cdot\omega_0\cdot\dot{\phi}+\beta\cdot\dot{\phi}\cdot\left|\dot{\phi}\right|+\omega_0^2\cdot\frac{\overline{GZ}(\phi)}{\overline{GM}}= \\ =\omega_0^2\cdot\left(m_{wave}(t)\right) \tag{6}$$

In this model, υ and β are the linear and nonlinear quadratic damping coefficients, ω_0 is the natural roll frequency of the vessel, $\overline{GM}$ is the still water metacentric height and $\overline{GZ}(\phi)$ is the nonlinear righting lever in calm water. The irregular beam wave excitation ($m_{wave}(t)$) has been modelled applying the Absolute Roll Angle Model (Bulian and Francescutto, 2006), as shown in Equation (7).

$$m_{wave}(t)=\sum_{i=1}^{n}\pi\cdot r(\omega_i)\cdot s(\omega_i)\cdot\cos(\omega_i t+\xi_i) \tag{7}$$

In this equation, $r(\omega_i)$ is the effective wave slope coefficient (computed for the tested vessel using linear hydrodynamics), $s(\omega_i)$ is the wave slope and ω_i and ξ_i are the wave frequency and phase of each wave component (i). Wave excitation has been modelled using a Bretschneider spectrum and the vessel has been considered to be sailing at zero speed which, due to the typical operational profile of these type of stern trawlers, is a quite frequent condition.

The vessel under consideration is a mid-sized stern trawler, which has been already used by some of the authors in previous works (Míguez González et al., 2017; Míguez Gonzálezand Bulian, 2018), and which main characteristics, hull forms, arrangement and $\overline{GZ}(\phi)$ and $r(\omega)$ curves for the critical condition with $\overline{GM}=0.350$ m are shown in Table 1 and in Figures 2, 3 and 4.

Table 1. Test vessel: main characteristics.

Overall Length	34.50 m
Beam	8.00 m
Depth	3.65 m
Linear Roll Damping Coefficient (υ)	0.0187
Quadratic Roll Damping Coefficient (β)	0.393 1/rad

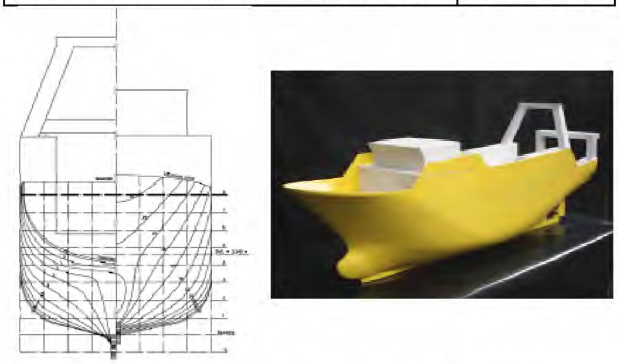

Figure 2. Test vessel: hull sections and scale model.

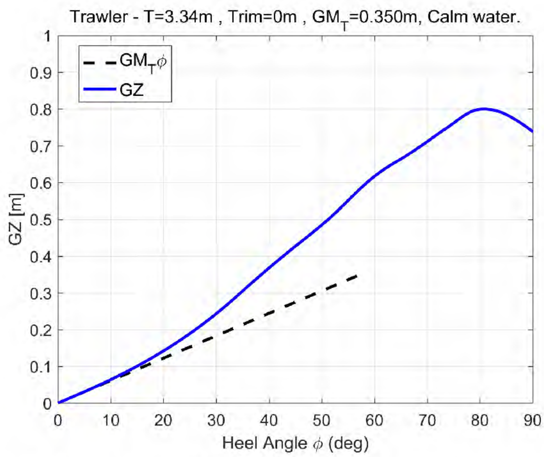

Figure 3. Test vessel: *GZ* curve in calm water.

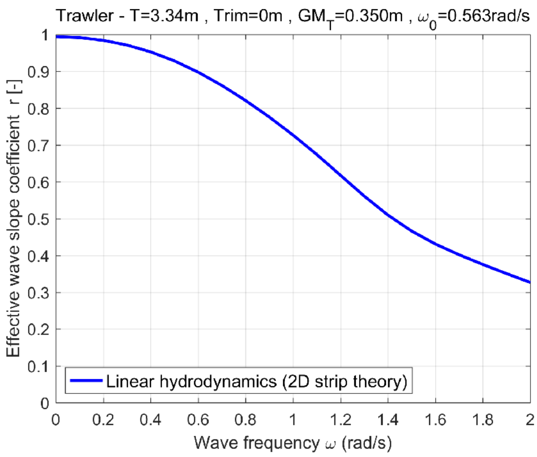

Figure 4. Test vessel: effective wave slope coefficient.

Test condition

In order to test the performance of both the EMD+HHT and the W-GLRT schemes, two time series of 4200 seconds of roll motion have been generated, for the same wave parameters but for different loading conditions, and have been stitched together. The resulting time series is a 8400 seconds long roll motion time series, where a change in loading condition (but also in waves, as both cases have been randomly generated) takes place approximately after 4200 seconds, going from an initial loading condition which fulfils all stability requirements (LC1), to another one with a low $\overline{GM}$, which is supposed to represent a non-safe situation (LC2). The parameters characterizing these two loading conditions are included in Table 2. The safe condition, LC1, has been obtained directly from the stability booklet of a very similar vessel, so that it represents a realistic sailing condition. The non-safe condition, LC2, has been defined by the authors to represent a sailing situation with a slightly lower $\overline{GM}$ than the IMO minimum required value.

Regarding the wave situation under analysis, wave conditions (T_P, H_S) have been selected to represent a heavy seas condition, according to prevailing conditions in Spanish north-western coastal area. These wave parameters are shown in Table 3. The roll motion time series, obtained from stitching those corresponding to the two loading conditions is shown in top of Figure 6, where it can be appreciated the time instant where conditions have changed. From this time series, the first 20 minutes are used for the calibration/adjusting stage of the detector; during this time, the detector does not generate any result; from this moment on, a result is generated every 3 minutes.

Table 2. Tested loading conditions.

	LC1	LC2
Displacement	489 t	448 t
Metacentric Height (*GM*)	0.501 m	0.331 m
Natural Roll Frequency (ω_0)	0.701 rad/s	0.548 rad/s
Natural Roll Period (s)	8.963 s	11.466 s
Draft	3.484 m	3.294 m
Roll gyradius (k_{xx}) / B	0.395	0.411

Table 3. Tested wave conditions.

Significant wave height (H_S)	8.520 m
Peak period (T_P)	12.8 s

Regarding the estimation of natural roll frequency, the EMD+HHT work in time records of 3 minutes with an overlap between consecutive measures of 75%, thus making a new estimation every 45 seconds. Regarding the detector, its operation time window has been set to 5 minutes with an overlapping of a 40 %, thus generating a new measurement every 3 minutes (which is supposed to be, for this type of vessel, a short enough time as to detect possible sudden changes in stability).

4. RESULTS

In order to analyse the performance of the proposed system, the aforementioned algorithms have been applied to the roll motion time series described above. In Figure 6, the obtained results are displayed.

In Centre top of Figure 6, the green dots illustrate the natural roll frequency estimates obtained by applying the EMD+HHT. In Centre bottom of Figure 6, the results of the W-GLRT detector are included as blue dots. In this figure, the red line represents the limit between safe (values under this line) and non-safe conditions (values over this line). At the Bottom of Figure 6, the results obtained from the colour awareness alarm are included. Finally, in Figure 7, results of the estimations of natural roll frequency obtained by applying the *fft*-based methodology developed by the authors, as described in Míguez González et al. (2017), have been included.

If the obtained results are analysed, it can be appreciated that regarding the estimations of natural roll frequency (Table 4), a very good agreement between the obtained values and the target ones has been observed, not only regarding the median values, but also between the 95% percentiles and the

5% percentiles and the target values. This fact is especially remarkable if results are compared to those obtained with the *fft*-based methodology (Table 6). In these last case, the system had previously shown a tendency to over predicting the natural roll frequency of the vessel, which can be also appreciated in these results (deviations between the 95% percentile and target value close to the 12 %). The newly developed EMD+HHT estimators seem to reduce these values (maximum deviations between the 95% percentile and target value of the 5 %), thus leading to the favourable effect of reducing the tendency of the system to overestimate the stability of the vessel.

On the other hand, at least in the case under analysis, the EMD+HHT has shown a larger tendency to under predicting the vessel stability (bigger differences between the 5% percentile and the target value than in the *fft* case), although this issue is less important, at least from the safety point of view and if under predictions are kept under reasonable levels, than the previous one.

In addition to the above, it also has to be said that the novel approach performs better than the *fft* based one even in those situations (as the one represented by LC1), where roll natural period and wave peak period are far from each other. On this same line, it is also worth to mention that those situations, although safe from a dynamic stability point of view (as wave and natural roll frequencies are far from each other and pure roll resonance are not expected to take place), could be suffering from reduced stability levels and so, they have to be considered as also relevant while stability is being monitored.

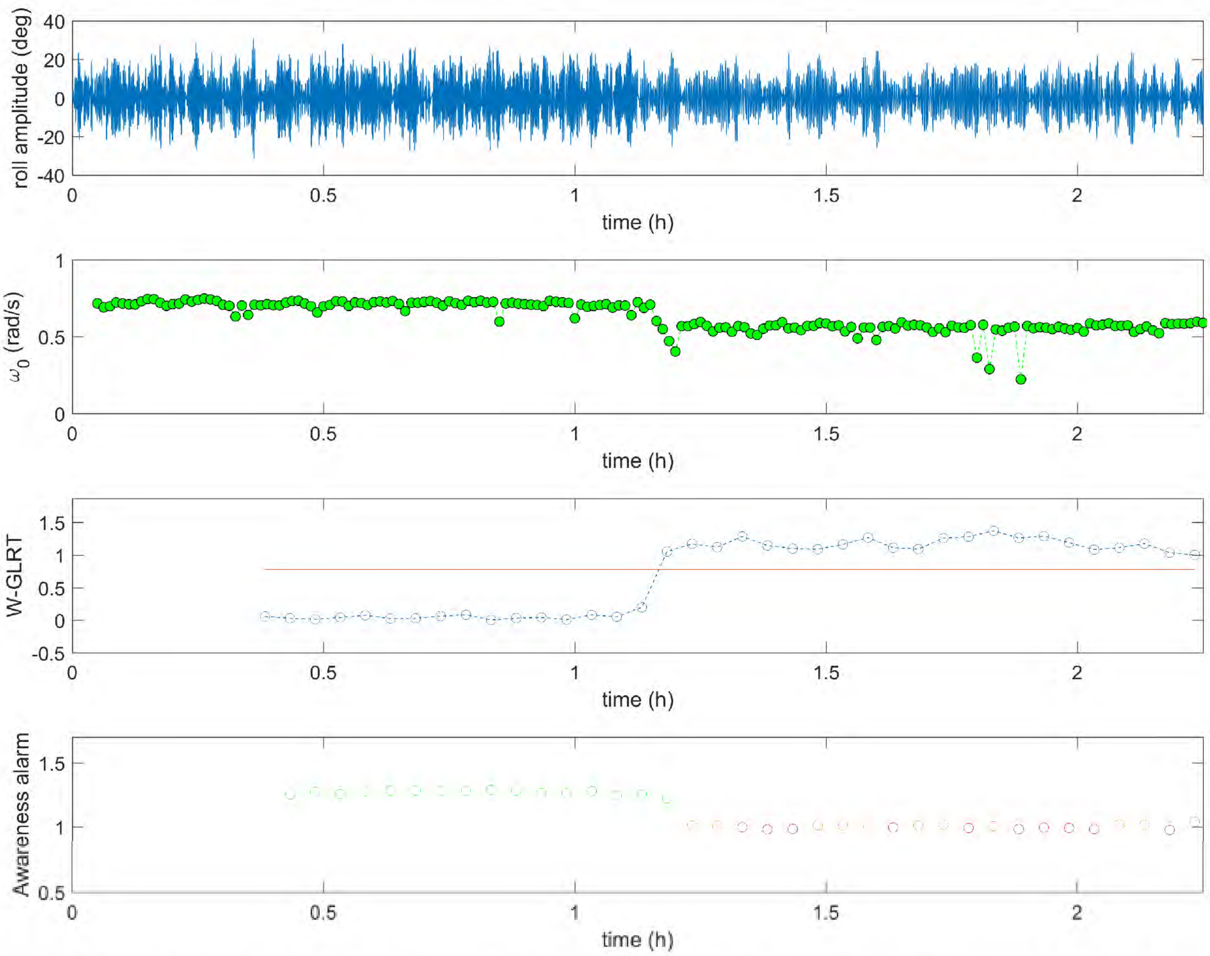

Figure 6. Top: roll motion time series under analysis. Centre top: estimations of natural roll frequency from the EMD+HHT. Centre bottom: output of the W-GLRT detector. Values under the red line indicate a safe situation, while values over the red line generate an alarm due to low stability levels. Bottom: output of the colour – coded situation awareness algorithm.

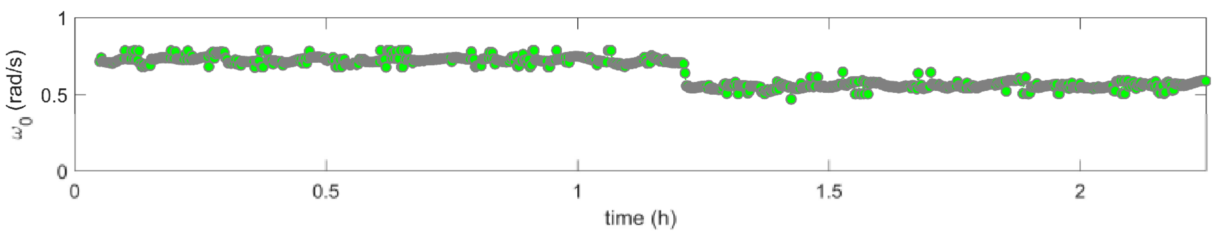

Figure 7. Estimations of natural roll frequency from the *fft* methodology (as described in Míguez González et al., 2017).

Regarding the results obtained from the detector (included in Table 5), it has shown to timely track the changes between the safe and the non-safe condition and has not generated any false alarms (classifying a safe condition as unsafe) or miss-detections (classifying as safe an unsafe condition). Subsequently, the results from the awareness alarm are also quite accurate, although some variation in colour is observed for the second half of the time series, where the detector results tend to slightly oscillate with time.

It is necessary to say that one of the advantages of this proposal is that in addition to the evaluation of the vessel $\overline{GM}$ that could be done from the natural roll frequency estimates (following the same concept that was applied in Míguez González et al., 2017), the detector provides a rougher evaluation of the level of stability (safe / non-safe condition), but that at the same time is less dependent of the level of accuracy of the frequency estimators and represents the minimum information the crew needs for evaluating the level of safety of their vessel.

Table 4. Estimations of natural roll frequency. EMD+HHT.

	LC1	LC2	Deviations to target value (%)	
			LC1	LC2
ω_0 Target Value ($\omega_{0\ target}$) [rad/s]	0.701	0.548	-	-
Estimated ω_0 Median ($\omega_{0\ median}$) [rad/s]	0.695	0.545	0.86	0.55
5% Percentile Estimated ω_0 ($\omega_{0\ 5\%}$)[rad/s]	0.643	0.448	8.27	18.25
95% Percentile Estimated ω_0 ($\omega_{0\ 95\%}$)[rad/s]	0.720	0.575	2.71	4.93

Table 5. W-GLRT detector performance.

	LC1	LC2
True Detections	16	22
False Detections	0	0

Table 6. Estimations of natural roll frequency. *fft*-based methodology (Míguez González et al., 2017).

	LC1	LC2	Deviations to target value (%)	
			LC1	LC2
ω_0 Target Value ($\omega_{0\ target}$) [rad/s]	0.701	0.548	-	-
Estimated ω_0 Median ($\omega_{0\ median}$) [rad/s]	0.725	0.556	3.40	1.45
5% Percentile Estimated ω_0 ($\omega_{0\ 5\%}$)[rad/s]	0.685	0.516	2.28	5.84
95% Percentile Estimated ω_0 ($\omega_{0\ 95\%}$)[rad/s]	0.784	0.613	6.70	11.86

5. CONCLUSSIONS

In this work, a novel proposal for carrying out a real time evaluation of the stability of a vessel has been presented. This proposal relies on two main different methodologies; on one hand, one algorithm aimed at estimating the natural roll frequency of the vessel (EMD+HHT). And on the other hand, a probabilistic detector which analyzes if the current loading condition is safe or not from a stability point of view (W-GLRT).

In order to evaluate the performance of this proposal, 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, one which represents a safe one, and another which is supposed to be non-safe from an initial stability point of view.

The estimations of the natural roll frequency of the vessel obtained by the EMD+HHT, have shown to be quite accurate, performing better than the *fft*-based estimator previously proposed by the authors, at least in the wave conditions under analysis. Regarding the detector, its behaviour 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.

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.

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