Towards real-time identification of initial stability from ship roll motion analysis

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ABSTRACT

Stability related failures are known to represent an important cause of accidents involving fishing vessels, and are usually related to the crew lack of capability for assessing the stability level of their ships in an objective way. The use of simplified guidance systems could be adopted as a possible risk control option for trying to address this problematic situation. However, the need for manual interaction with the crew, is one of the major drawbacks of such systems. In this paper, a sample application of a methodology based on spectral analysis of roll motion for obtaining the natural roll frequency of the vessel is presented. The final intention is to have a tool which, from roll frequency estimation, could be used for the estimation of initial ship stability characteristics. The proposed methodology is tested by using roll motion results from a nonlinear one degree of freedom roll model, under the excitation of beam irregular waves and lateral gusty winds. The obtained results are promising, but some open aspects, relevant to the real application of such approach, require further discussion and investigation.

Keywords: *Fishing vessels, Intact stability, stability monitoring, Guidance systems.*

1. INTRODUCTION

Operational guidance systems are common and broadly used today among the commercial fleet, including within them loading and intact stability guidance systems, weather routing systems, damage stability analysis software and dynamic stability evaluation codes (Palmquist and Nygren, 2004). The use of these systems has helped crews to increase the safety of their vessels and their economic performance. Although their operation is usually non-straightforward and their working principles require a more-than-average knowledge of naval architecture, dedicate crew training programs can be put in place among shipping companies to familiarize crews with such systems (Huss, 2016). In fact, the importance of guidance to masters has been already highlighted by the IMO and the Classification Societies, as could be seen, for example in the IMO bad weather sailing guidelines (IMO, 2007). In addition to this, the development of direct stability assessment regulations is also under consideration in the framework of the IMO second generation intact stability criteria (Umeda and Francescutto, 2016). In Bačkalov et al. (2016) and references therein, a discussion on the importance, potentialities and open issues related to operational guidance can be found.

The case of fishing vessels is largely different to that described above. Crews of fishing vessels are not usually trained in risk and stability analysis, especially in the smallest vessels. Guidance systems are not common at all onboard those vessels and most regulators have not tackled the problem of guidance in fishing vessels (Míguez González et al., 2012). This issue is particularly relevant if the number of casualties which occur within the fishing sector is taken into account (Gudmundsson, 2013). A relevant amount of these deaths is due to stability issues, being the crew lack of objective capability for determining the risk level of the vessel one of their main causes (Jensen et al., 2014).

However, some national authorities and institutions proposed in the last years their own alternatives of simplified stability guidance systems, with different degrees of success and levels of implementation among the corresponding fleets (Wolfson Unit, 2004; Viggosson, 2009; Womack, 2002). The authors have also proposed a tool based on a naval architecture software that, together with an IMU module and a simplified user interface, analyzes the ship motions and the ship loading condition, and provides the master with real-time information of the safety level of the ship in the current sailing situation (Míguez González et al., 2012; Míguez González et al., 2016). Within the mentioned tool, this safety level is presently obtained by using the intact stability characteristics of the vessel and the maximum wave to capsize approach proposed by Deakin (2006).

Most of the nowadays available proposals fulfill a given set of basic requirements, including ease of use, simplicity of implementation and reduced cost of implementation and maintenance. However, all of them rely, up to some extent, on subjective interaction with the crew. Such interaction can occur, for instance, through the comparison of the current situation of the vessel to those provided by a suitable stability poster (Deakin, 2006; Womack, 2002), or through the inputting of information within a stability guidance software (Míguez González et al., 2012).

In this paper, a sample application of a methodology focused on the final intention of providing the crew with realistic stability data of their vessel in real time, minimizing the need for user interaction and the influence of subjective analysis, is presented. This approach is based on the estimation of the vessel natural roll frequency in real time from the analysis of its roll motion spectrum. The underlying idea is that this information can then be used for the estimation of the initial metacentric height of the vessel. This information is in fact fundamental for any guidance system relying on ship motions prediction, irrespective of whether such approach is based on short-term deterministic assessment (e.g. Míguez González et al., 2011), more classical linear-seakeeping-based weather forecasting (Nielsen et al., 2006), or more advanced approaches intended to address also potentially dangerous dynamic stability phenomena in waves (Ovegård et al., 2012). In order to test the proposed methodology, a nonlinear model of a medium sized stern trawler, under the excitation of beam irregular waves and lateral gusty winds, has been applied.

2. REAL TIME ESTIMATION OF NATURAL ROLL FREQUENCY

As it has been already mentioned, the proposed methodology relies on the estimation of natural roll frequency in real time, as a basis for obtaining the vessel metacentric height ($\overline{GM}$), which would be of major importance if the stability condition of the ship wants to be monitored. From the well-known roll natural frequency formula, obtained under the simplifying assumption of 1-DOF uncoupled linear roll model,

$$\omega_0 = \sqrt{\frac{\Delta \cdot \overline{GM}}{I_{xx} + I_{add}}} \tag{1}$$

it can be observed that, apart from the natural roll frequency, the vessel displacement (Δ), the dry inertia (I_{xx}) and the hydrodynamic added inertia term (I_{add}) are unknown parameters that are also necessary for obtaining the vessel $\overline{GM}$. Although this work focuses on ω_0, some comments regarding the other parameters can be found in (Míguez González et al., 2016).

The method proposed herein for the estimation of natural roll frequency is based on the analysis of the roll spectrum, obtained in real time from the analysis of the vessel roll motion time series. A different approach was proposed in the past by Terada et al. (2016), based on an autoregressive procedure and a general state space modelling.

Míguez González et al. (2016), reported some results applying an approach similar to that presented herein to a set of towing tank tests of a medium sized stern trawler in longitudinal regular waves, under parametric roll resonance conditions. In that work, *Fast Fourier Transform* (FFT) analysis was directly applied to a single chunk (180 seconds) of each of the analyzed roll motion time series, with the goal of obtaining the roll spectrum for that given chunk. The length of these chunks was defined considering that, under operational conditions, the stability characteristics of such a vessel could be assumed to be invariant within that time. Once the spectrum was obtained, the natural roll frequency of the ship could be estimated from the location of the spectrum maximum value, taking as a basic assumption that most of the energy would be concentrated around the roll natural frequency.

In addition to this, the performance of the system if windowing was applied to the spectra computation was also investigated, concluding that no significant improvement was obtained with these techniques.

Although the obtained results were satisfactory, there were some points which remained open for discussion. On the one hand, the tested cases were limited to the head waves case. Under these conditions, roll excitation was just limited to that due to small misalignments of the model in the tank or, if the conditions were likely, to parametric excitation in roll (and so, approximately at the vessel roll natural frequency). Roll energy was then mainly concentrated around natural roll frequency, which lead to clear single – peaked spectra. On the other hand, the studied conditions, under regular waves, represented an idealized scenario. Both issues lead to the fact that the tested conditions were far from realistic operational situations.

Proposed methodology

In this paper, some of the aforementioned drawbacks are tackled, proposing a refined and improved methodology, and a more realistic test condition. This approach is, as the previously described one, based on the fundamental assumption that the peak frequency of the roll spectrum corresponds, at least approximately, to the roll natural frequency. Such assumption is herein made as a consequence of the peculiar dynamical characteristics of roll, which tends to cut the effect of those excitations which are not leading to roll oscillations close to the roll natural frequency. However, it is clear that this is an approximation and this assumption requires further analysis.

Although the proposed methodology also relies on the estimation of the vessel roll spectrum using FFT analysis, it is more onboard-implementation oriented and three main considerations have been taken into account, which have not been previously considered. Firstly, there is the FFT frequency resolution. Secondly, there is the consideration of the variation of the roll spectrum with time. And finally, there is the need for overlapped analysis in real time.

Regarding the FFT frequency resolution, it is well known that the frequency resolution which a FFT analysis can provide and that determines the accuracy of the spectrum shape, is only related to the length of the time series under analysis (T (s)) (Oppenheim et al., 1999). This resolution can be obtained as:

$$\delta\omega = \frac{2\cdot\pi}{T} = \frac{2\cdot\pi\cdot f_S}{N} \ (rad/s) \qquad (2)$$

where $\delta\omega$ is the FFT frequency resolution (rad/s), f_S is the sampling frequency in Hz, T is the analysis time in seconds, and N is the number of samples analyzed by the FFT. As it can be appreciated, if the aforementioned 180 seconds analysis time is applied, it will result in a $\delta\omega = 0.035\ (rad/s)$. This is not a neglible magnitude and, for the fishing vessel described later in the paper, it amounts to more than a 6 % of the natural roll frequency. This fact makes it difficult to accurately estimate the natural roll frequency from the location of the peak of a roll spectrum which is so scarcely discretized.

Taking into account that roll motion data will be available in real time and that the roll spectrum shape of each analyzed time chunk could be different from each other, a strategy based on overlapped measures and averaging of spectra has been adopted. Based on this methodology, the analyzed spectrum will be, instead that of a given time chunk, the one obtained from averaging a number of spectra, obtained from a set of overlapped measures (of an "*Analysis Time*" length), sampled at a defined "*Sample Time*". The resulting spectrum will be an average spectrum along a given "*Averaging Time*", which will be representative of the roll spectrum of the vessel during that time. The proposed methodology is represented in Figure 1.

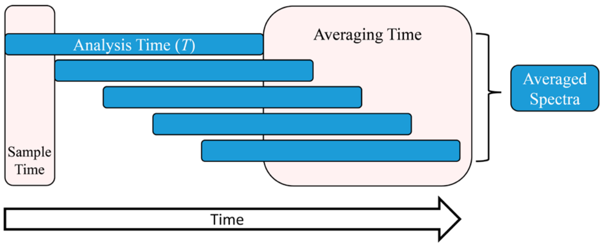

Figure 1. Proposed methodology.

However, the resulting averaged spectrum is still affected by the aforementioned lack of frequency resolution, which is of course independent of the averaging process. In order to try to increase the frequency resolution of the intended results, a fitting process of the averaged spectrum with a simple parametric model based on the superposition of three Gaussian functions has been implemented. The parametric model has 9 parameters, which correspond to three for each of the three Gaussian functions. The number of functions has been selected as to allow the fitting of up to three superimposed spectra, which could correspond with the wind and wave excitation, and the natural roll motion of the vessel. The simplified parametric model takes the following form:

$$S_{roll}(\omega) = a_1 \cdot e^{-\left(\frac{(\omega - b_1)}{c_1}\right)^2} + a_2 \cdot e^{-\left(\frac{(\omega - b_2)}{c_2}\right)^2} + \\ + a_3 \cdot e^{-\left(\frac{(\omega - b_3)}{c_3}\right)^2} \tag{3}$$

It is important to note that the main purpose of the model is not to provide a very accurate fitting of the roll spectrum, but to be a robust model for the identification of the most prominent peak, which is assumed herein to be associated to the roll frequency.

The fitting process has been divided into two steps; the first one is done by a minimization process by applying a genetic algorithm, which provides a first set of fitting parameters. In the second step, this set of parameters is used as starting guess point for a Nonlinear Least Squares Fitting process, which is used to determine the final parameters of the fitting function. Once the fitting is completed, the analytical expression (3) is used for the identification of the maximum peak which is associated with the vessel natural roll frequency. This latter step is no longer bound by the frequency resolution associated from the Fourier analysis.

In order to improve the performance of this process, a previous smoothing of the average spectrum has been done by applying a 5-point moving average technique. Thus, the previously described fitting process is applied to this smoothed spectrum.

Regarding the selection of the Analysis, Sample and Averaging Times, the typical operational profile of the tested vessel (a medium sized stern trawler, which will be later described), has been taken into account. Regarding the Analysis Time, it has to fulfil two main requirements. On the one hand, it has to be sufficiently long as to provide a minimum basic frequency resolution. And on the other hand, it has to be short enough to allow the detection of changes on the vessel stability characteristics, which is in fact the main objective of the proposed methodology. Under these premises, an analysis time of 180 seconds have been considered, taken the comments in (Míguez González et al., 2016) also into account.

Regarding Sample Time, its selection is only determined by the speed of the analysis algorithm and the possibility of being able to track any possible variation on ship natural frequency in real time. In this case, a 10 seconds Sample Time has been selected.

Finally, Averaging Time is the period in which the spectral information of the roll motion is averaged, and so "stored" by the system. Very long averaging time will lead to a hiding of possible changes in the vessel condition, while if it is too short, the results will be largely affected by the very short term estimations. In this case, Averaging Time has been taken as 120 seconds.

3. TEST ENVIRONMENT

Fishing vessel model

In order to test the proposed methodology under more realistic conditions, the ship roll motion in irregular beam seas has been simulated by applying a one degree of freedom nonlinear model, where the excitation due to waves, mean wind and wind gustiness, has been taken into account. The details of this model, which has been already applied to the case of a small fishing vessel, can be found in (Bulian and Francescutto, 2004). The structure of this model is the following,

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

where υ and β are, respectively, the linear and nonlinear quadratic damping coefficients, ω_0 is the natural roll frequency of the ship, $\overline{GM}$ is the still water metacentric height and $\overline{GZ}(\phi)$ is the nonlinear righting lever as a function of the absolute roll angle. $m_{wave}(t)$ and $m_{wind}(t)$ represent the time dependant nondimensional moments due to the effect of beam waves and lateral wind.

Regarding wave excitation, it has been modelled through the "Absolute Angle Approach" (Bulian and Francescutto, 2006). The effective wave slope coefficient ($r(\omega)$) has been obtained from linear hydrodynamic analysis of the proposed vessel

(Bulian and Francescutto, 2009). Finally, a Bretschneider spectrum has been selected to model irregular waves (ITTC, 2002).

Wind speed excitation has been divided into a steady component (mean wind speed) and a fluctuating one (wind gustiness), which reflect in a time dependent, non-zero-mean heeling moment. In order to obtain the total wind moment, aerodynamic coefficients have been obtained using experimental data from Blendermann (1996). Mean wind speed is obtained as a function of significant wave height applying the relationship used in the Pierson – Moskowitz spectrum (ITTC, 2002). Finally, wind gustiness has been modeled by applying a Davenport spectrum (Davenport, 1961).

The selected test vessel is a medium sized stern trawler, which details are reported in Table 1, hull sections are shown in Figure 2, *GZ* curve in calm water in Figure 3 and effective wave slope coefficient in Figure 4.

Test condition

As a sample test case, the aforementioned model has been used to generate a 3600 seconds roll motion time series, to which the proposed methodology has been applied.

The tested wave conditions have been obtained from historical data (period 1997–2015) of a set of four SeaWave buoys placed in Galician coastal area (Spain) (FOM, 2017). From these data, an average scatter diagram was constructed. The conditional mean value of significant wave height for each characteristic period was then determined, leading to a limited set of sea scenarios (T_P, H_S).

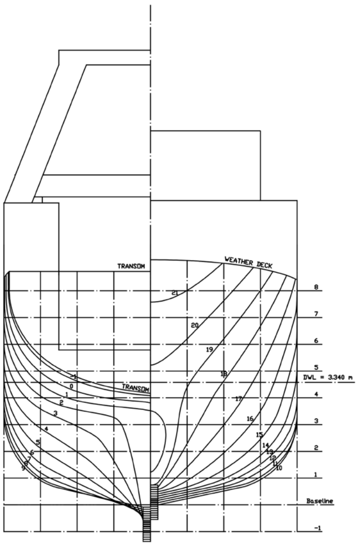

Figure 2. Test vessel: hull sections.

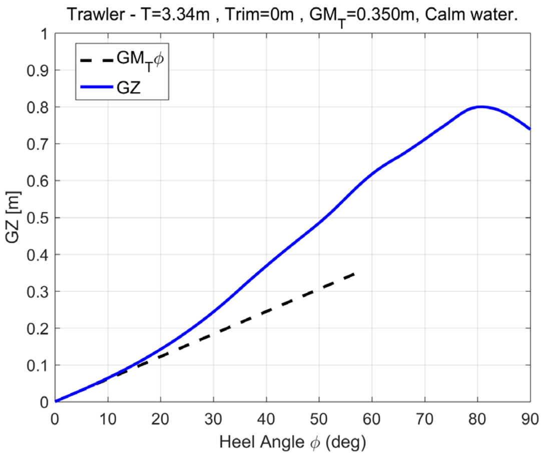

Figure 3. Test vessel: *GZ* curve in calm water.

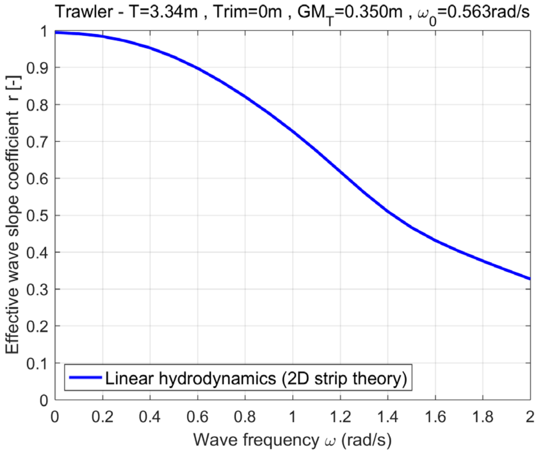

Figure 4. Test vessel: effective wave slope coefficient.

Table 1. Test vessel: main characteristics.

Overall Length	34.50 m
Beam	8.00 m
Depth	3.65 m
Draft	3.340 m
Hull Volume	448 m^3
Metacentric Height (*GM*)	0.350 m
Natural Roll Frequency (ω_0)	0.563 rad/s
Natural Roll Period (s)	11.16 s
Linear Roll Damping Coefficient (υ)	0.0187
Quadratic Roll Damping Coefficient (β)	0.393 1/rad
Lateral Area (A_{lat})	163.19 m^2
Vertical center of A_{lat} over waterline (H_{up})	2.670 m

Table 2. Tested wave and wind conditions.

Significant wave height (H_S)	1.971 m
Peak period (T_P)	10 s
Mean wind speed ($\overline{V}_W$)	9.375 m/s

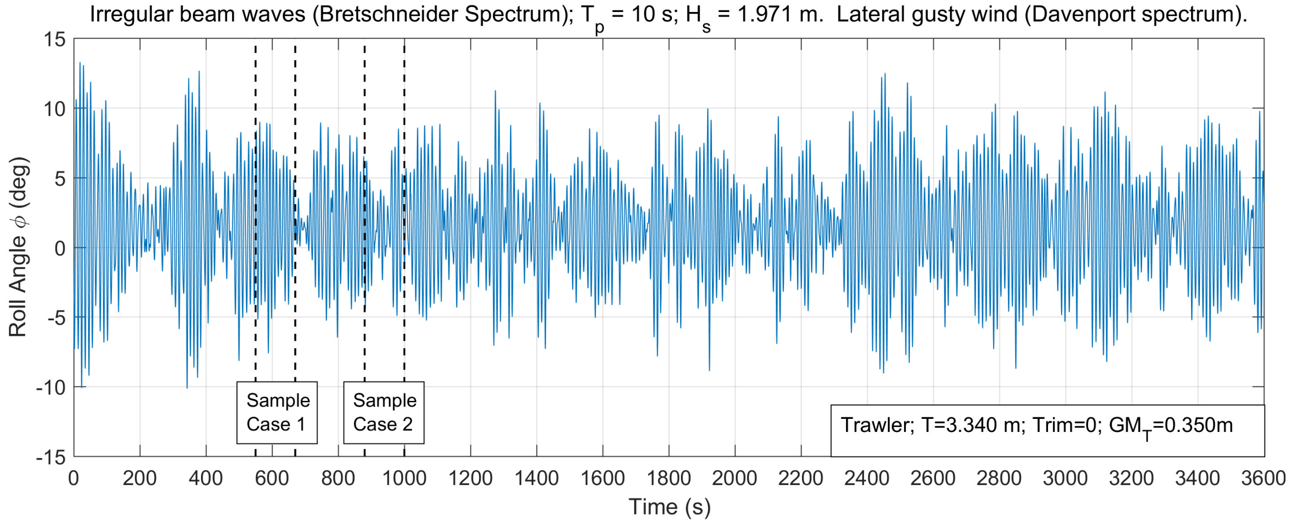

Figure 5. Analyzed roll motion time series. Irregular beam waves. Lateral gusty wind.

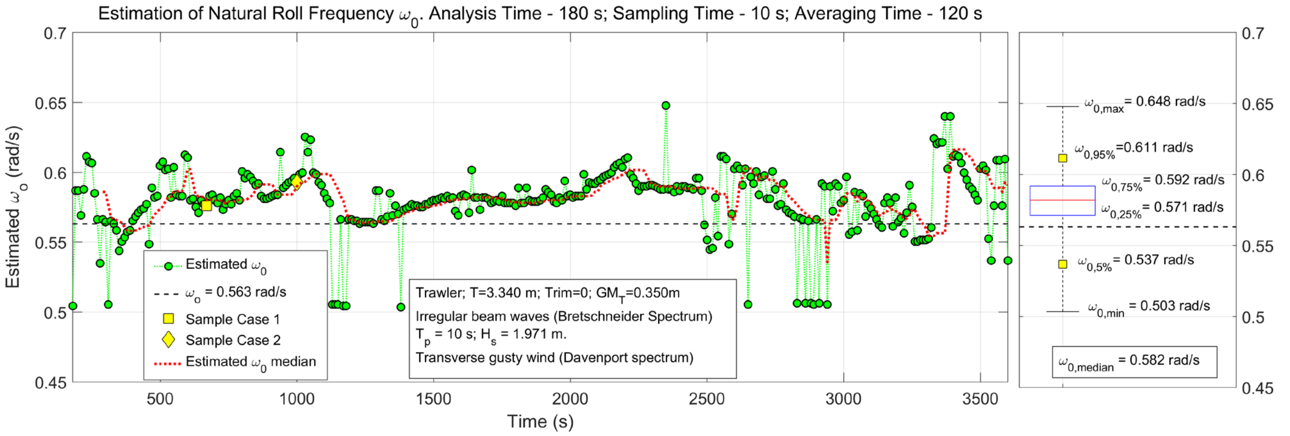

Figure 6. Left: Natural roll frequency estimation results. Right: representation of estimated natural roll frequency distribution through minimum observed value, 5%, 25%, 50%(median), 75% and 95% estimated percentiles, and maximum observed value.

From these, the one associated with the characteristic period with maximum marginal probability of occurrence, has been selected. Its parameters are shown in Table 2. 1000 components were used for generating irregular wave and wind moments, and a 20 Hz sampling rate has been selected.

The obtained roll time series is shown in Figure 5. As it can be appreciated, the ship roll motion presents an asymmetric behavior due to the effect of mean wind pressure. In addition, some low frequency motion, caused by wind gustiness, can also be observed. The wave spectrum peak period is relatively close the vessel natural roll period, thus some relatively large amplitude motions due to harmonic resonance were expected, and in fact, can be observed in the roll time series.

4. RESULTS

In order to test the performance of the described methodology, it has been applied to the test time series which has been already described. The spectrum analysis algorithms have been executed in a continuous way, following the same procedure as it would have been done in a real case. In Figure 6, the obtained results are presented. The green dots in this figure represent the estimated natural roll frequency, obtained every 10 seconds (Sample Time)

These values are obtained from the averaging of the previous spectra (120 seconds of Averaging Time), which were estimated from the analysis of 180 seconds time chunks (Analysis Time).

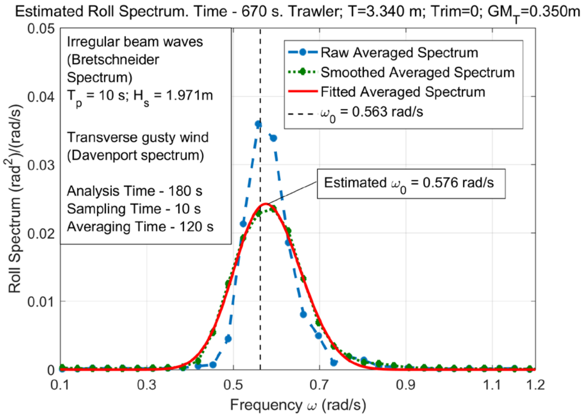

Figure 7. Sample Case 1. Estimated roll spectrum.

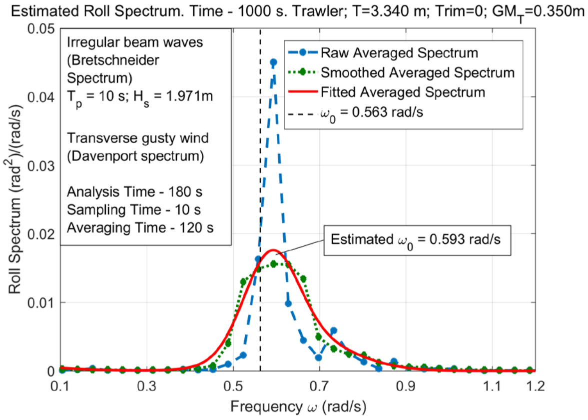

Figure 8. Sample Case 2. Estimated roll spectrum.

In addition to the above, and for a better understanding of the proposed strategy, two sample cases taken from the Figure 6 results are shown in Figure 7 and 8 (highlighted in yellow in Figure 6).

These two spectra correspond to the time instants 670 s and 1000 s respectively. In both figures, the dashed blue lines represent the raw averaged spectrum (for the time intervals shown in Figure 5 between the black dashed lines). As it can be appreciated, the frequency resolution, in the range of interest, is quite low.Dotted green lines represent the smoothed spectrum, aimed at reducing the secondary peaks that could appear in the raw spectra. And finally, the red continuous line represents the spectra obtained after the fitting process of the smoothed spectra using Gaussian functions.

Regarding the general results shown in Figure 6, it can be appreciated that, although the obtained estimations do not exactly match the real natural frequency, they remain continuously on the vicinity of the target value $\omega_0 = 0.563\ \text{rad/s}$, with the exception of some outlier values, as those present around 1100 s and 2900 s. Even though these outliers are taken into account, the 90% of the estimated roll frequency samples remains in the range [0.537 – 0.611] rad/s (corresponding to estimated 5% and 95% percentiles). This range corresponds to a percentage difference with respect to the target value in the range [-4.6%, +8.5 %].

Regarding the aforementioned outliers, and as it can be appreciated from Figure 6, they are values which do not last in time, as the situation only lasts for a single Sample Time (10 seconds in this case). This fact makes it relatively easy to discard such points, always verifying that these values do not extend in time (which, otherwise, could instead represent a real change in the vessel state). One option for robustifying the approach is to use, at each Sample Time, a moving median, where the reference estimated frequency value is determined as the median of the estimated natural roll frequencies from a group of past local estimations. Such an approach, which is based on the assumption of slowly varying ship stability characteristics, allows to disregards the outliers of short duration. An example result from this approach is shown as the red dotted line in Figure 6, where the median is calculated from the group of past 12 local estimations.

The systematic average over prediction of ω_0 observed along the whole time series in Figure 6, could be partially explained by the fact that, under the relatively large roll motions present in the simulated condition, nonlinear effects in restoring (which is of the hardening type, see Figure 3) become more noticeable, and thus the observed dominant roll oscillation frequency tends to be slightly increased.

5. DISCUSSION

It is worth mentioning that, although the obtained estimation ranges in natural frequency could seem to be relatively accurate, the main final target of this methodology, which is to estimate the vessel metacentric height ($\overline{GM}$), has to be kept in mind. If only the possible error in the estimation of the natural roll frequency is taken into account (from all the needed parameters in Equation (1)), and the [5%-95%] percentiles range of estimated natural frequency are considered $\left(\omega_0 \cdot \left(1 + \left[-4.6\%, 8.5\%\right]\right)\right)$, this will lead to a range of error in the $\overline{GM}$ estimation of $\left[-9.1\%, 17.8\%\right]$.

These errors in the estimation of $\overline{GM}$, combined with the unavoidable uncertainties in the estimation of the other relevant parameters (vessel displacement and dry and added inertias), could lead to overestimations of $\overline{GM}$. Such overestimations of the metacentric height are of course non-conservative from a safety perspective and, if too large, they could be not acceptable.

In addition to this, it is also important to remark that the performance of the proposed methodology is largely dependent on the selected Analysis and Averaging times. A detailed analysis of the real operation of these vessels would be needed to determine, in a more accurate way, which is the maximum length of time series chunk which could track loading condition changes.

Finally, further work regarding statistical analysis of the natural roll frequency estimation in different realistic seaways, exclusion of outlier points and error propagation, is therefore needed before a conclusion regarding the applicability of this methodology could be achieved.

6. CONCLUSSIONS

In this paper, a methodology based on the spectral analysis of medium sized fishing vessels roll motion, for the estimation of the vessel roll natural frequency while in operation, has been described. This methodology represents one step towards the development of a technique for the on-board real-time identification of $\overline{GM}$.

A demonstration case of the aforementioned methodology has been presented, taking as a test case the roll motion of a mid-sized stern trawler under the effect of beam irregular waves and gusty lateral wind, applying a one degree of freedom nonlinear uncoupled roll mathematical model.

Although the obtained results seem to be promising, further work is needed to reduce the levels of error in the estimation of natural roll frequency, especially when such errors can potentially lead to unacceptable overestimations of metacentric height of the vessel.

Finally, some points remain open for discussion, including the level of error in the estimation of $\overline{GM}$ which can be considered to be acceptable if such a system is installed onboard a ship, and the maximum analysis time which would be acceptable for accurately tracking the possible variations in the vessel loading condition (and subsequently on its risk level).

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