Real-Time Estimation of Natural Roll Frequency for the Stability Guidance of Fishing Vessels

Marcos Míguez González, Gabriele Bulian, Lucía Santiago Caamaño, Sandra Allegue García, and Vicente Díaz Casás

Abstract Stability failures are known to be one of the major causes of accidents involving fishing vessels. The use of guidance systems, focused on complementing the capabilities of the crews for dealing with the assessment of their vessel stability, have been proposed by many authors as a possible way for reducing the frequency of this type of incidents. Initially, these systems were basically color-coded posters or were relying on subjective data introduced by the crew. However, the use of approaches which operate in real time with no need of interaction could overcome the problems identified for these "first generation" methods. This work presents a methodology based on the analysis of roll spectrum for estimating in real time the metacentric height of the vessel. The integration of the presented methodology within a first generation guidance system could increase its capabilities for providing stability guidance. The performance of the proposed methodology is analysed using the simulated roll motion of a mid-sized fishing vessel in irregular beam waves and lateral gusty wind, computed by a one degree of freedom nonlinear model. Obtained results are promising in most of the analysed conditions, although some open issues regarding the implementation of the methodology still require further analysis.

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1 Introduction

Operational guidance systems are common and broadly used today among the commercial fleet, and include loading and intact stability guidance systems, weather routing systems, damage stability analysis software and dynamic stability evaluation software [22]. 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 [10]. In fact, the importance of guidance to masters has been already highlighted by the IMO and the Classification Societies, as could be seen, for instance, in the MSC.1/Circ.1228 [11]. In addition to this, the development of regulations based on direct stability assessment has also been embedded in the IMO second generation intact stability criteria [12, 27]. In Bačkalov et al. [1] 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 [16]. This issue is particularly relevant if the number of casualties which occur within the fishing sector is taken into account [9]. A relevant amount of corresponding fatalities is due to stability issues, and one of the main causes is the crew lack of objective capability for determining the risk level of the vessel [14].

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 [28–30]. Some of the authors of this work have also proposed a tool based on a naval architecture software that, together with an IMU module and a simplified user interface, analyses 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 [16, 24]. 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 [7]. Most of the nowadays available proposals fulfil 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 condition of the vessel to those provided by a suitable stability poster [7, 30], or through the inputting of information within a stability guidance software [16].

This work presents a sample application of a methodology aiming at 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. This approach is based on the estimation of the vessel natural roll frequency in real time from the analysis of 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 and it could then be eventually embedded in a guidance system such as the one described above [16, 24]. Information regarding the metacentric height of the vessel 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. [15]), more classical linear-seakeeping-based forecasting systems [19], or more advanced approaches intended to address also potentially dangerous dynamic stability phenomena in waves [21]. 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 wind, has been applied. This work updates and complements the findings previously described by Míguez González et al. [17].

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 an estimation of the vessel metacentric height ($\overline{GM}$), which is of major importance if the stability condition of the ship is to be monitored. From the well-known roll natural frequency formula, obtained under the simplifying assumption of 1-DOF uncoupled linear roll model,

$$\omega_0 = \sqrt{\frac{\Delta \cdot \overline{GM}}{I_{xx} + I_{add}}} = \sqrt{\frac{g \cdot \overline{GM}}{k_{xx}^2}} \tag{1}$$

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}) (or the wet roll gyradius k_{xx}) are unknown parameters that are also necessary for obtaining the vessel $\overline{GM}$. In case the vessel could be equipped with draft sensing devices, it could be possible to determine the displacement and to estimate the dry inertia (using a weight breakdown method) and added inertia (using, for example, some potential theory code) with no need for crew interaction. However, in the case of small and medium sized fishing vessels, using these systems is not feasible due to cost limitations. In Santiago Caamaño et al. [23], an analysis of the influence of these parameters in the estimation of ω_0 is done, concluding that reasonably good results could be obtained by obtaining the wet roll gyradius using typical approximate values ($k_{xx} \approx 0.4 \cdot B$) and disregarding the effects of the variation of the other parameters, which is the approach followed in this work.

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. [26], based on an autoregressive procedure and a general state space modelling.

Santiago Caamaño et al. [23], 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 s) of each of the analysed 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 window. 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 case of head waves. Under these conditions, roll motion was just limited to that due to small misalignments of the model in the tank or, in the proper conditions, 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.

2.1 Proposed Methodology

In this work, some of the aforementioned drawbacks are tackled, proposing a refined and improved methodology, and more realistic test conditions. 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, similarly to Santiago Caamaño et al. [23], also the proposed methodology relies on the estimation of the vessel roll spectrum using FFT analysis, the present approach is more onboard-implementation oriented and three main aspects have been taken into account, which have not been previously considered, namely:

the limitations induced by FFT frequency resolution, the variation of the roll spectrum in time, and the use of 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)) [20]. This resolution can be obtained as:

$$\delta\omega = \frac{2 \cdot \pi}{T} = \frac{2 \cdot \pi \cdot f_S}{N} \tag{2}$$

where $\delta\omega$ is the FFT frequency resolution (rad/s), f_S is the sampling frequency (Hz), T is the analysis time (s), and N is the number of samples analysed by the FFT. As it can be appreciated, if the aforementioned 180 s analysis time is applied, it will result in a frequency resolution $\delta\omega = 0.035$ (rad/s). This is not a negligible magnitude and, for the fishing vessel described later in this work, 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 analysed time chunk could be different from each other, a strategy based on overlapped measures and averaging of spectra has been adopted in order to obtain a more robust estimation of the spectrum. Based on this methodology, instead of relying on the spectrum given by a single time chunk, the analysed spectrum is the one obtained from averaging a number of spectra, obtained from a set of partially overlapped measures each one having the same "*Analysis Time*" length, and separated each other by a constant "*Sample Time*". The resulting spectrum is an average spectrum within a given "*Averaging Time*", which will be representative of the roll spectrum of the vessel during that time. The proposed methodology is represented in Fig. 1.

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

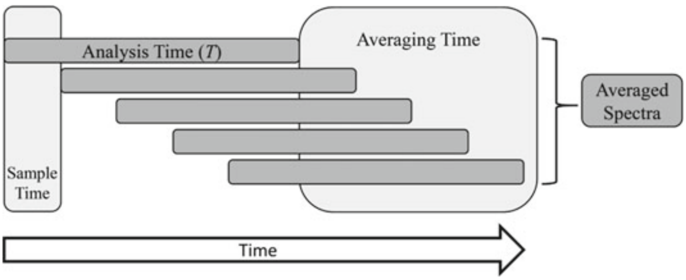


Fig. 1 Proposed methodology

superposition of three Gaussian functions has been implemented. The parametric model has 9 parameters; three parameters for each of the three Gaussian functions. The number of Gaussian functions has been selected as to allow the fitting of up to three superimposed spectra, which could correspond with the roll motion at the principal wind and wave excitation frequencies, and the roll motion of the vessel at its natural frequency. The simplified parametric model for the roll spectrum 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 a_i, b_i and c_i for $i = 1, 2, 3$. 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 assumed to be 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 preliminary smoothing of the average spectrum is carried out 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. 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. From these considerations, and taking into account also the comments by Santiago Caamaño et al. [23], an Analysis Time of 180 s has been considered. Regarding the 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 s Sample Time has been selected. Finally, the Averaging Time is the period in which the spectral information of the roll motion is averaged, and so "stored" by the system. A too long averaging time will lead to hiding possible changes in the vessel condition, while a too short averaging time will not be long enough for sufficiently reducing the variability of the short term estimations. In this case, Averaging Time has been taken as 120 s. However, it has to be highlighted that these values are applicable only to this specific vessel, and that further refinement should be needed after some time of operation in a real scale scenario.

3 Test Environment

3.1 Fishing Vessel Model

In order to test the proposed methodology under 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 are given by Bulian and Francescutto [3], who also applied the model to the case of a small fishing vessel. The structure of this model is the following,

$$\ddot{\phi} + 2 \cdot \upsilon \cdot \omega_0 \cdot \dot{\phi} + \beta \cdot \dot{\phi} \cdot \left|\dot{\phi}\right| + \omega_0^2 \cdot \frac{\overline{GZ}(\phi)}{\overline{GM}} = \omega_0^2 \cdot (m_{wave}(t) + m_{wind}(t)) \quad (4)$$

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" [4]. The effective wave slope coefficient ($r(\omega)$) has been obtained from linear hydrodynamic analysis of the proposed vessel according to Bulian and Francescutto [5]. Finally, a Bretschneider spectrum has been selected to model irregular waves [13].

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 [2]. The mean wind speed is obtained as a function of the significant wave height by applying the relationship used in the Pierson-Moskowitz spectrum [13]. Finally, wind gustiness has been modelled by applying a Davenport spectrum [6].

The selected test vessel is a medium sized stern trawler, which details are reported in Table 1, hull sections and 3D view are shown in Fig. 2, and $\overline{GZ}$ curve in calm water and effective wave slope coefficient in Fig. 3. The same vessel has been studied also by Míguez González and Bulian [18].

Table 1 Test vessel: main characteristics

Length overall	34.50 m
Beam	8.00 m
Depth	3.65 m
Draft	3.340 m
Hull volume	448 m^3
Metacentric height ($\overline{GM}$)	0.350 m
Natural roll frequency (ω_0)	0.563 rad/s
Natural roll period (T_0)	11.16 s
Wet roll gyradius (k_{xx})	3.291 m
Linear roll damping coefficient (υ)	0.0187
Quadratic roll damping coefficient (β)	0.393 rad^{-1}
Lateral windage area (A_{lat})	163.19 m^2
Height of center of A_{lat} above the waterline (H_{up})	2.670 m

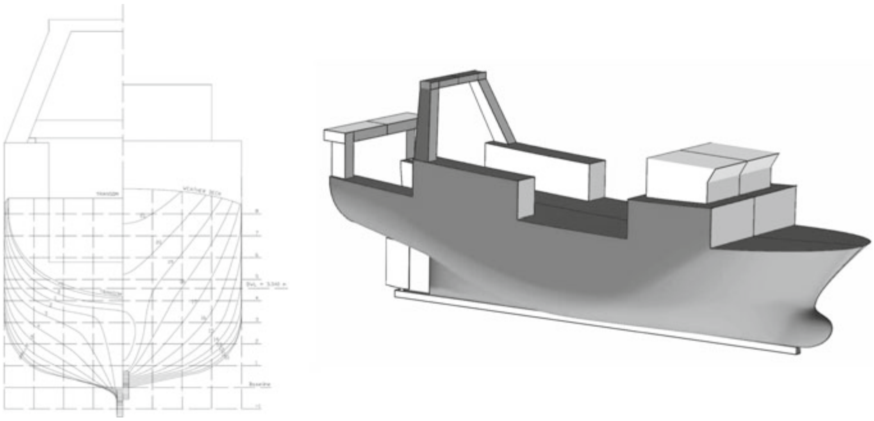


Fig. 2 Hull bodyplan (left) and 3D view (right)

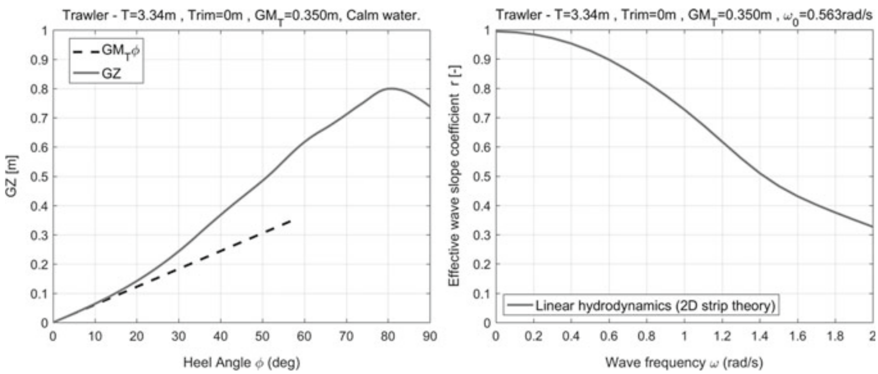


Fig. 3 Test vessel: $\overline{GZ}$ curve in calm water (left) and effective wave slope coefficient (right)

3.2 Test Condition

The vessel under study sails in coastal waters off Galicia, Spain. In order to obtain the typical meteorological conditions for this area, historical data from four Puertos del Estado wave buoys (Silleiro, Vilán, Bares and Peñas SeaWatch buoys) have been used [8]. Wave data from these buoys for the period between 1997 and 2015 were used to generate one scatter diagram for each of the locations. An approximate scatter diagram for the entire Galician Coast area was eventually determined by averaging them. From this average scatter diagram, a series of wave conditions have been selected for being used in this study. For each value of the 9 considered spectral peak periods (T_P), the conditional average significant wave height ($H_{S\,Ave}$) has been determined and taken as reference. This leads to a corresponding limited set of reference wave scenarios (T_P, $H_{S\,Ave}$).

The conditional average significant wave height $H_{S\,Ave\,j}$ for the considered j-th peak period is calculated as:

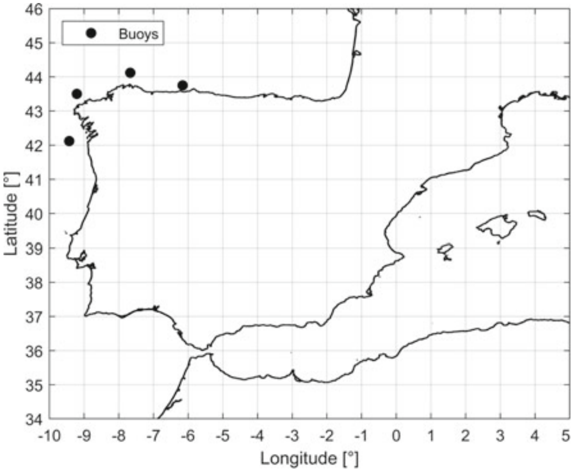
$$H_{S\,Ave\,j} = \sum_{i=1}^{N} \frac{H_{Si} \cdot p_{ji}}{P_j} \text{ with } P_j = \sum_{i=1}^{N} p_{ji} \tag{5}$$

where $H_{S\,i}$ is the centre-cell significant wave height for the i-th interval in the wave scatter diagram, p_{ji} is the probability associated to each combination of significant wave height and peak period, and P_j is the probability for the j-th peak period. The resulting wave conditions (peak period and corresponding significant wave height), which are those used in this work, are included in Table 2, together with a map showing the location of the four considered SeaWatch buoys.

In order to test the performance of the system, the aforementioned model has been used to generate 3600 s roll motion time series for each of the reference sea conditions of Table 2, to which the proposed methodology has been applied. 1000 harmonic components were used for generating irregular wave and wind moments, and a 20 Hz sampling rate has been selected. Results including standard deviation of roll motion (σ_{roll}) and maximum (ϕ_{max}) and mean (ϕ_{mean}) roll values for each of the nine tested sea conditions, are shown in Table 3.

The behaviour of the vessel roll motion under the studied wave and wind conditions is illustrated using as sample case the roll time series corresponding to the case with the characteristic period with maximum marginal probability of occurrence (reference sea condition 4), and which is shown in Fig. 4. As it can be appreciated, the ship roll motion shows an asymmetric behaviour due to the effect of mean wind. The wave spectrum peak period in this case 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 (this phenomenon can also be appreciated in reference sea conditions from 5 to 8). Since the gustiness spectrum is linked to the mean wind speed, wind effects on roll motion overall increase as the mean wind speed increases.

Table 2 Location of SeaWatch buoys (left) and tested wave and wind conditions (right)



Reference sea condition	Peak period (T_P) (s)	Significant wave height ($H_{S\,Ave}$) (m)	Mean wind speed ($\overline{V}_W$) (m/s)
1	4	0.932	6.448
2	6	1.481	8.126
3	8	1.772	8.890
4	10	1.971	9.375
5	12	2.671	10.912
6	14	3.499	12.492
7	16	4.297	13.843
8	18	4.715	14.499
9	20	5.028	14.973

Table 3 Roll motion characteristics

	Reference sea condition								
	1	2	3	4	5	6	7	8	9
σ_{roll} (deg)	0.424	0.848	1.621	3.661	5.202	5.861	5.976	6.165	5.363
ϕ_{max} (deg)	2.120	4.091	6.835	13.275	17.332	21.675	19.36	20.455	20.323
ϕ_{mean} (deg)	0.725	1.148	1.368	1.480	1.975	2.561	3.126	3.406	3.678

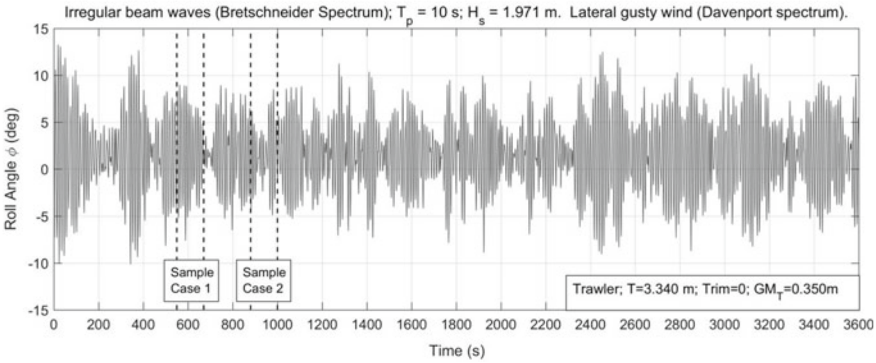


Fig. 4 Roll motion time series. Irregular beam waves and lateral gusty wind. Reference sea condition 4

4 Results

In order to test its performance, the described methodology has been applied to the test time series which have 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 on board.

In Fig. 5, results from the reference sea condition 4, which is used as sample case, are shown. The large grey circular markers in this figure represent the estimated natural roll frequency, obtained every 10 s (Sample Time). These values are obtained from the averaging of the previous spectra (120 s of Averaging Time), which were estimated from the analysis of 180 s time chunks (Analysis Time). In addition to the above, and for a better understanding of the proposed strategy, two sample cases are shown in Fig. 6 (marked using a grey rectangle and diamond in Fig. 5). These two spectra correspond to the time instants 670 s and 1000 s respectively. The dashed grey lines in Fig. 6 represent the raw averaged spectrum for the time intervals shown in Fig. 4 by the vertical black dashed lines. As it can be appreciated, the frequency resolution, in the range of interest, is quite low. Dotted black lines represent the smoothed spectrum, aimed at reducing the secondary peaks that could appear in the raw estimated spectra. Finally, the grey continuous line represents the spectra obtained after the fitting process of the smoothed spectra using Gaussian functions.

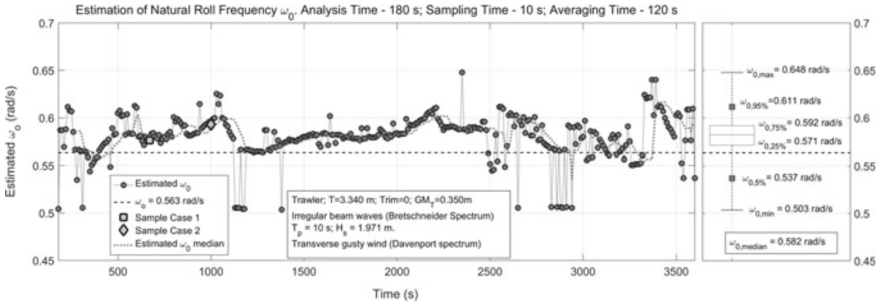


Fig. 5 Left: Natural roll frequency estimation results. Right: representation of estimated natural roll frequency distribution through minimum observed value, 5%, 25%, 50% (median), 75% and 95% estimated percentiles, and maximum observed value. Reference sea condition 4

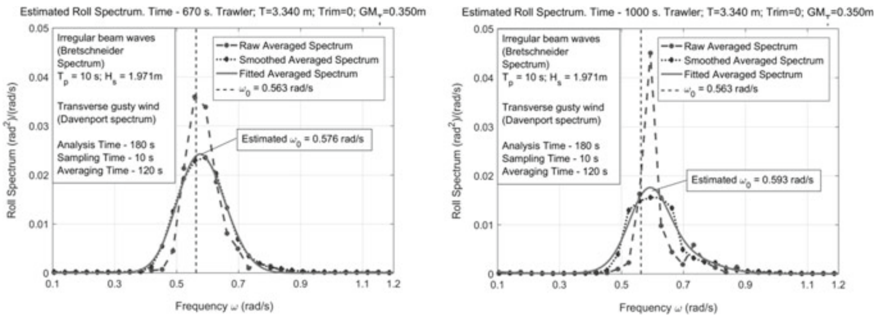


Fig. 6 Estimated roll spectrum. Sample Case 1 (left) and Sample Case 2 (right)

Regarding the general results shown in Fig. 5 for the reference condition 4, it can be appreciated that, although the obtained estimations do not exactly match the real natural frequency, they remain continuously in the vicinity of the target value $\omega_0 = 0.563$ 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 [−4.62%, +8.58%]. Regarding the aforementioned outliers, and as it can be appreciated from Fig. 5, they do not last in time, as the situation only lasts for a single Sample Time (10 s in this case). This fact makes it relatively easy to discard such points, always verifying that these values do not extend in time. In this case, the repetition in time of such points could indicate a true change in stability, and not taking them into consideration (by inappropriate filtering or removing) could lead to missing a possible low stability dangerous situation. 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 disregard the outliers of short duration. The use of the median has been preferred compared to the use of the mean, because of the sensitivity of mean to outliers. An example result from the application of this approach is shown as the dotted line in Fig. 5, where the median is calculated from the group of past 12 local estimations.

Regarding the systematic average over prediction of ω_0 observed along the whole time series in Fig. 5, and in other reference conditions as it will be described later, 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 Fig. 3) become more noticeable, and thus the observed dominant roll oscillation frequency tends to be slightly increased compared to the linear (small amplitude) roll natural frequency. This is a quite classic phenomenon in nonlinear ship dynamics, and it is also described in Míguez González and Bulian [18] for a very similar vessel to the one analyzed in this work in case of regular waves.

The obtained results corresponding to all the tested sea conditions are reported in Table 4.

With reference to the results in Table 4, the considerations done for the reference condition 4 could be extended to sea conditions from 4 to 9, where 90% of the natural roll frequency samples remain in a similar range $[-5.49\%, +11.62\%]$ and again some over prediction of ω_0 is observed. However, results from reference sea conditions 1–3 display larger errors, and that over prediction appears not to be so noticeable (as roll amplitude is much smaller in these cases). These three reference conditions are those corresponding to wave peak periods smaller than the vessel natural roll period, with the smallest wave excitations and also with the smallest amplitudes of vessel roll motions. This behaviour could be explained by the larger dispersion of the roll spectrum, which leads to a multi-peaked shape, which reduces the performance of the methodology. In fact, as it could be appreciated in reference conditions 2 and 3, the value of $\omega_{0,95\%}$ is very close to the wave peak frequency of those cases. This fact is analysed more in detail by Santiago Caamaño et al. [25] where it is shown that, in these conditions, the roll spectrum display several peaks of similar amplitude, where the different wave and wind frequency components mask that corresponding to the vessel natural roll frequency. On the contrary, in those cases with wave peak periods in the vicinity of the natural roll period or higher, the obtained roll spectra show a clear peak close to the vessel natural roll frequency, which explains the better performance of the methodology in these conditions.

5 Discussion

It is worth mentioning that, although the obtained estimation ranges in natural frequency could seem to be relatively accurate in many of the reference sea conditions, the main final target of this methodology is the estimation of the vessel metacentric height ($\overline{GM}$). Considering the results of reference conditions from 4 to 9 and if

Table 4 Full results. Estimated natural roll frequency ($\omega_{0,5\%}$: 5% percentile; $\omega_{0,median}$: median; $\omega_{0,95\%}$: 95% percentile), with correspondingly estimated GM ($GM_{5\%}$, GM_{median}, $GM_{95\%}$). Deviations to target values for 5% and 95% percentiles for estimated natural roll frequency ($\varepsilon_{\omega_{0,5\%}}$, $\varepsilon_{\omega_{0,95\%}}$) and GM ($\varepsilon_{GM_{5\%}}$, $\varepsilon_{GM_{95\%}}$)

	Reference sea condition								
	1	2	3	4	5	6	7	8	9
$\omega_{0,median}$ (rad/s)	0.551	0.555	0.629	0.582	0.582	0.577	0.568	0.572	0.568
$\omega_{0,5\%}$ (rad/s)	0.035	0.519	0.579	0.537	0.541	0.541	0.532	0.539	0.541
$\omega_{0,95\%}$ (rad/s)	0.582	1.032	0.741	0.611	0.619	0.628	0.613	0.617	0.599
$\varepsilon_{\omega_{0,5\%}}$ (%)	−93.80	−7.87	2.82	−4.62	−3.87	−3.85	−5.49	−4.21	−3.98
$\varepsilon_{\omega_{0,95\%}}$ (%)	3.41	83.29	31.67	8.58	9.98	11.62	8.83	9.64	6.32
GM_{median} (m)	0.334	0.340	0.436	0.373	0.373	0.367	0.356	0.361	0.356
$GM_{5\%}$ (m)	0.001	0.297	0.369	0.318	0.323	0.323	0.312	0.321	0.322
$GM_{95\%}$ (m)	0.374	1.173	0.606	0.412	0.423	0.435	0.414	0.420	0.395
$\varepsilon_{GM_{5\%}}$ (%)	−99.62	−15.29	5.52	−9.20	−7.78	−7.74	−10.85	−8.42	−7.98
$\varepsilon_{GM_{95\%}}$ (%)	6.73	235.28	73.03	17.66	20.72	24.34	18.20	19.98	12.82

only the error in the estimation of the natural roll frequency is taken into account (i.e. k_{xx} in Eq. (1) is taken as a constant known value), the [5%, 95%] percentiles range of estimated natural frequency is $(\omega_0 \cdot (1 + [-5.49\%\ ,\ 11.62\%]))$. This leads to a range in the error of $\overline{GM}$ estimation corresponding to $[-10.85\%\ ,\ 24.34\%]$. Although these errors in the estimation of $\overline{GM}$ could seem to be acceptable if adequate safety margins are applied, the situation is different if results from reference conditions 1–3 are taken into consideration. In these cases, errors in the estimation of natural roll frequency and $\overline{GM}$ are much larger. Combined with the unavoidable uncertainties in the estimation of the other relevant parameters, they could lead to underestimations and especially overestimations of $\overline{GM}$. This latter are of particular importance, as they are of course non-conservative from a safety perspective and are therefore 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.

From the above results and considerations, it may be concluded that, although good results are obtained in those situations where wave peak periods are larger than the expected vessel natural roll period, further work is needed to improve the methodology capabilities in the rest of reference conditions. Moreover, an analysis of the performance of the method including the exclusion of outlier points is also needed before a conclusion regarding the practical applicability of this methodology could be achieved.

6 Conclussions

In this contribution, 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 different combinations of beam irregular waves and gusty lateral wind, which has been simulated by means of a one degree of freedom nonlinear roll model.

Although the obtained results seem to be promising in most of the tested conditions, further work is needed to reduce the level of error in the estimation of natural roll frequency, especially when such errors can potentially lead to unacceptable non-conservative overestimations of the 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 initial stability and, consequently, its risk level.

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