Increasing performance of real-time stability assessment through ship motion analysis

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ABSTRACT

Stability guidance systems have been acknowledged by the sector as a feasible and effective way of improving ship safety regarding stability. In fact, some approaches have been already implemented, showing good results and being accepted not only by designers and ship operators but also, and more important, by ship crews.

In recent years, the authors have proposed their own alternative aimed at being used onboard fishing vessels, which could operate with no need of crew interaction (Míguez González et al., 2018, 2017). The system consists of a methodology for assessing the stability from measured roll responses. This methodology is based on the recursive use of the Fast Fourier Transform (FFT). Although the performance of this system was acceptable, there were some specific situations where the influence of external excitations reduced the accuracy of the stability estimations.

The work presented here is aimed at trying to overcome this issue. In order to do this, the aforementioned FFT-based methodology will be complemented with the analysis of pitch and heave motions, which will be used to increase the system performance. Towing tank tests of a mid-sized stern trawler in different wave conditions were used to analyze the improvements obtained with this approach.

Keywords: *Fishing vessels, intact stability, stability monitoring, wave encounter frequency estimation, towing tank tests.*

1. INTRODUCTION

Guidance systems arose as a feasible alternative to reduce the number of incidents related to stability in fishing vessels. Despite not being the most frequent, stability failures are responsible of the largest fatality rate (Transportation Safety Board of Canada, 2012). Taking into account the type of fishing gear and the size, trawlers and vessels under 24 meters in length can be considered more likely to suffer this kind of accident (European Maritime Safety Agency, 2018; Marine Accident Investigation Branch (MAIB), 2008).

Simplified guidance systems consist of a group of procedures to provide clear information about the stability level, including a description of a set of safe and non-safe loading conditions. In order to be accepted by designers, ship operators and ship crews, guidance systems have to fulfil three main requirements: be easy to use and to understand, low cost of acquisition installation and maintenance and no need for crew interaction (Míguez González et al., 2012).

Initial ones were based on posters or diagrams representing the different loading possibilities with some recommendations. Good examples are the Womack matrix and the Norwegian stability poster (Deakin, 2005). One of their main drawbacks was that, as loading conditions were described approximately, the safety margins were not very precise and, for intermediate situations, it was needed to perform calculations.

Along the time, they have evolved into more sophisticated computer based systems, such as the Safe Skipper or the SEMPEO (Míguez González et al., 2012; Varela et al., 2010). The only inconvenience of these systems is that manual data is required to fully operate them. Thus, the requirement of no interaction is not fulfilled.

As a consequence, in recent years, a new group of decision support systems have been proposed. The purpose of these systems is to provide an automatic assessment of stability in real-time from ship motions.

Within this framework, some of the authors have developed their own alternative based on measuring roll motion and then, applying recursively the FFT to compute the roll spectrum. The peak of this spectrum has been assumed as the natural roll frequency (ω_0) of the vessel and, hence, the metacentric height could be computed (GM). This methodology has been validated with simulated roll motion time series and also with sea trials, showing promising results. Nevertheless, in some situations the external excitations (such as waves, wind, etc.) decreased its performance (Míguez González et al., 2018, 2017).

In this work, an improvement in the real-time stability assessment methodology is presented. This approach additionally uses an estimation of the wave encounter frequency (ω_e) from ship motions and also removes this component from the roll signal before computing its spectrum. This proposal has been tested with a roll motion time series from a campaign of towing tank tests of a fishing vessel.

2. WAVE ENCOUNTER FREQUENCY ESTIMATION

The estimation of wave parameters is essential to improve the efficiency of stability guidance systems. In order to obtain them in real-time, the wave buoy analogy can be used, i.e., measure the ship responses as it was a buoy and from them obtain the wave spectrum. For sea state estimation two main approaches could be differentiated: parametric modelling and non-parametric modelling (Nielsen, 2006; Ren et al., 2021).

In this work, as only the wave encounter frequency is needed, a simpler methodology is proposed. It is based on the assumption that heave acceleration (a_z) and pitch spectra have a peak nearby this frequency (Pascoal et al., 2007). Thus, measuring these responses and computing their spectra, ω_e could be obtained.

The procedure to obtain the a_z and the pitch spectra is the same as the one developed in previous works (Míguez González et al., 2018, 2017) for computing the roll spectrum and it can be seen in Figure 1, highlighted in orange color. It consists of, firstly, measuring the response during 180 s and, then, applying the FFT to the signal and calculating its spectrum as:

$$S(\omega) = \frac{\left|FFT\big(x(t)\big)\right|^2}{N} \quad (1)$$

Where $x(t)$ is the heave acceleration or the pitch time series and N is the length of the signal.

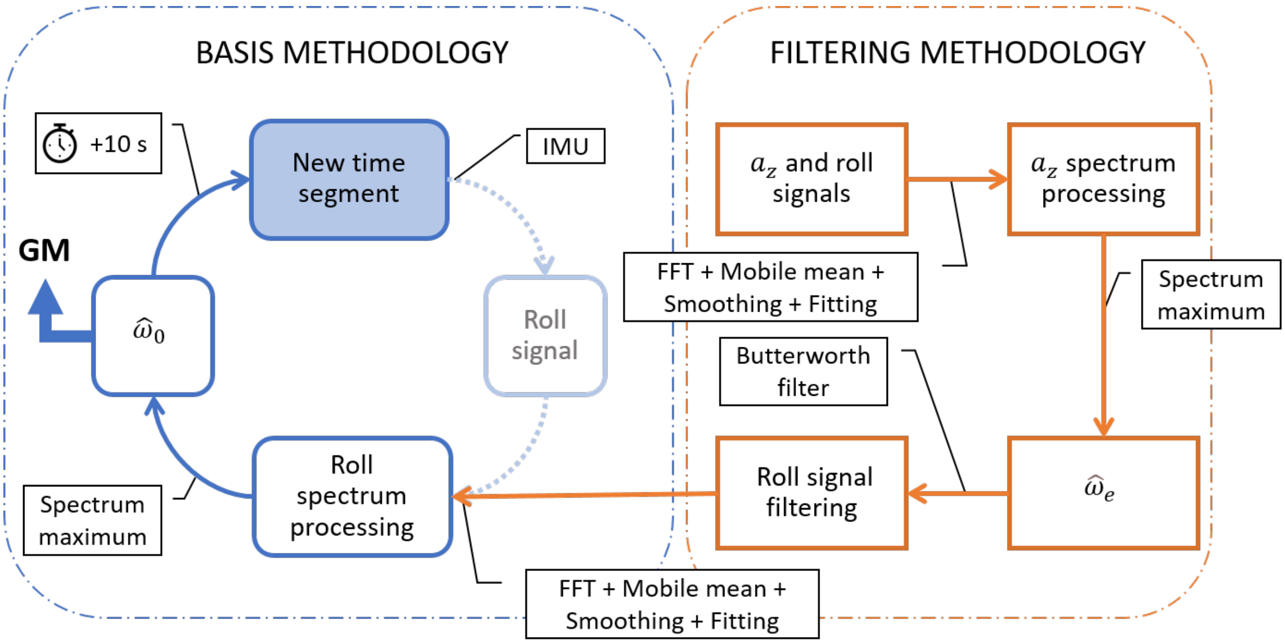

Figure 1. Architecture of the proposed methodology.

Once the spectrum is generated, a mobile mean which considers the 12 previous spectra is implemented.

After that, this spectrum is smoothed, using a moving average technique. This function utilizes a mobile mean to recalculate each spectrum's point, $S(\omega_i)$, by using the following expression:

$$S_{smooth}(\omega_i) = \frac{1}{5}\sum_{j=i-2}^{i+2} S(\omega_j) \qquad (2)$$

The next step is to fit the spectrum with a parametric model. The fitting is based on three superposed Gaussian functions, which may consider situations where roll, encountering waves and encountering wind would be involved. Finally, the main peak of the fitted spectrum is supposed to be the estimated wave encounter frequency ($\hat{\omega}_e$).

In order to determine which is the best performing alternative for estimating ω_e (using pitch motions or using heave acceleration), a comparison between both proposals has been made. The results have been compared studying the deviation of each estimated value from the real wave encounter frequency during the tests. The deviation of each estimation is defined by the following expression, where ω_e is the real value and $\widehat{\omega_e}$ is the estimation:

$$Dev.[\%] = \frac{(\widehat{\omega_e} - \omega_e)}{\omega_e} \times 100 \qquad (3)$$

As it is shown in 'Wave encounter frequency results', in section 4, better results – i.e., smaller $\hat{\omega}_e$ deviations – are provided by a_z. Due to this fact, the analysis of this response is used for filtering the roll motion in the natural roll frequency estimation methodology.

3. IMPROVED STABILITY MONITORING SYSTEM

The proposed stability monitoring system results in the combination of the original methodology (Míguez González et al., 2018, 2017) plus a wave encounter frequency estimation and a filtering of roll motion. The objective of the filter is to remove the ω_e component from the spectrum, that in some sea states masks the peak of the natural roll frequency, providing wrong results.

The new methodology, summarized in Figure 1, works with roll and heave acceleration segments, with a 10 s lag between consecutive segments.

Initially, the wave encounter frequency is estimated following the procedure described in Section 2.

Once the $\hat{\omega}_e$ has been obtained, the roll motion is filtered. The filtering process considers three different situations, depending on the $\hat{\omega}_e$ value relation with the minimum and maximum expected natural roll frequency of the ship – $\omega_{0,min}$ and

$\omega_{0,max}$, respectively. On one hand, $\omega_{0,min}$ is considered as the natural roll frequency of the ship when its metacentric height is the minimum required to keep the heel under 15 deg with a 30 kn beam wind. On the other hand, $\omega_{0,max}$ is taken as 15% over the natural roll frequency of the ship corresponding to the loading condition with the largest GM contained in the stability booklet.

Three different Butterworth filters are configured in the system, each one of them modifying the roll signal depending on the $\widehat{\omega}_e$ value. If the $\widehat{\omega}_e$ is less than the minimum considered ω_0, i.e., $\widehat{\omega}_e < \omega_{0,min}$, a 3rd order high-pass Butterworth filter is applied. In this situation, the roll signal components associated with frequencies under $\omega_{0,min}$ are removed – or at least reduced. The higher the difference between a specific frequency under $\omega_{0,min}$ and this one, the more it is reduced. Otherwise, if $\widehat{\omega}_e$ is over the maximum ω_0 considered – $\omega_{0,max} < \widehat{\omega}_e$ – then a 3rd order lowpass Butterworth filter acts, reducing the roll signal components associated with frequencies greater than $\omega_{0,max}$. Finally, a 2nd order stopband Butterworth filter is used when the $\widehat{\omega}_e$ value is among the roll natural frequencies range – $\omega_{0,min} \le \widehat{\omega}_e \le \omega_{0,max}$ –, reducing the signal components associated with a specific range of frequencies under $\widehat{\omega}_e$ and over it. The limits of the range (a, b) have been defined as $a = 0.9 \times \widehat{\omega}_e$ and $b = 1.1 \times \widehat{\omega}_e$. All filtering orders have been selected as the maximum value that does not increase the gain of any spectrum component. Figure 2 shows the response curve of the three filters.

After the filtering process, the roll spectrum is computed applying the FFT and the mobile mean. Then it is smoothed and fitted. The main peak is assumed to be the natural roll frequency of the vessel and the GM can be calculated from this value. Finally, the whole process is repeated every 10 seconds.

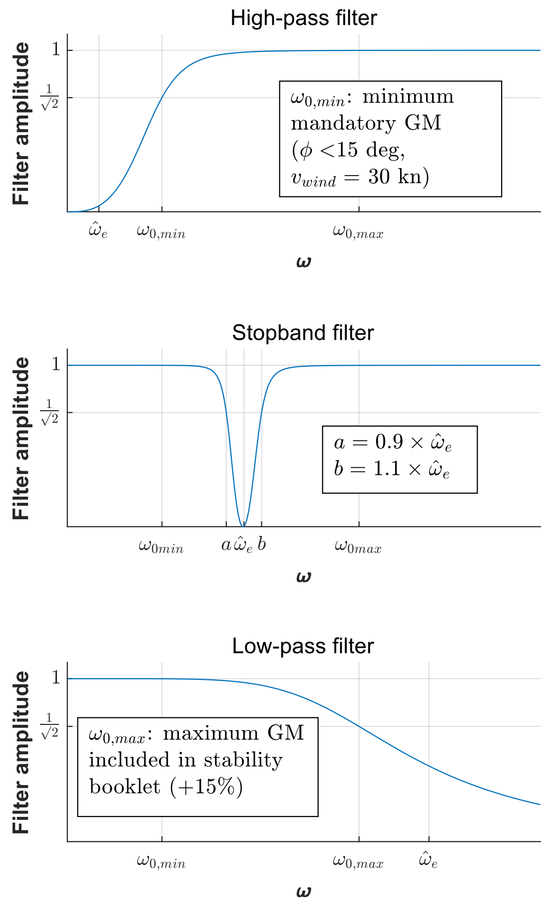

Figure 2: Response curves of Butterworth filters employed in the system

4. VALIDATION

Test vessel

The vessel under analysis is a mid-sized stern trawler. Its main characteristics and loading condition details can be seen in Table 1 and Figure 3. This vessel has been already used by the authors in previous works (Míguez González et al., 2018, 2017; Santiago Caamaño et al., 2019).

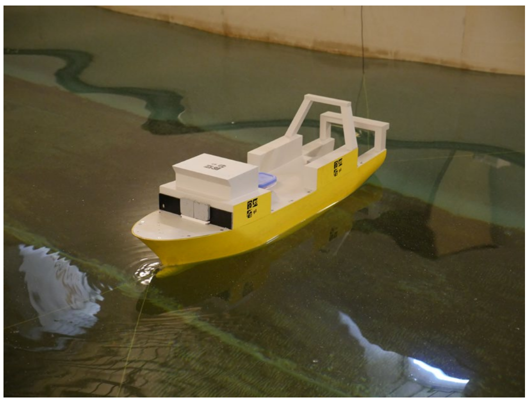

Figure 3: Test vessel.

Table 1: Test vessel main characteristics and loading condition details.

L_{OA} (m)	34.50
L_{pp} (m)	29.00
B (m)	8.00
$D_{main\ deck}$ (m)	3.65
T (m)	3.34
Δ (t)	448
GM (m)	0.350
ω (rad/s)	0.563
$\omega_{0,min}$ (rad/s)	0.300
$\omega_{0,max}$ (rad/s)	0.925

Test conditions

In order to analyze the performance of the proposed methodology, towing tank experiments to obtain ship motion time series have been carried out.

The test conditions were regular beam waves with the same wave height and different wave period. The purpose of these tests was to verify if the wave encounter frequency has any impact in the performance of the methodology. Furthermore, the tests were run at zero forward speed.

The test wave conditions are show in Table 2.

Table 2: Test wave conditions.

Sea state	H_W (m)	T_W (s)
1	3.000	5.477
2	3.000	6.573
3	3.000	7.668
4	3.000	8.764
5	3.000	9.859
6	3.000	10.954
7	3.000	12.050
8	3.000	13.145

Wave encounter frequency results

In this section, the results obtained after applying the proposed methodology for estimating the wave encounter frequency are presented.

Figure 4 shows the obtained spectrum from pitch motion (in red color) and from heave acceleration (in blue color) in Sea state 1. The black dashed line represents the wave encounter frequency target value. As can be seen, the peak of both spectra coincide with the target value.

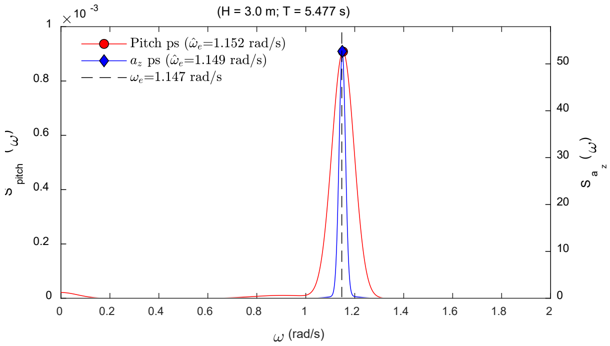

Figure 4: Pitch and a_z spectra and $\hat{\omega}_e$ for sea state 1.

Another case is illustrated in Figure 5 and, again, the peaks of both spectra are very close to the target value. It should be mentioned that in this figure the spectra have two spikes. This is a consequence of the fitting process as it uses three Gaussian functions that represent the three possible main frequency components contained in the signal (the vessel roll motion itself, wave and wind excitations).

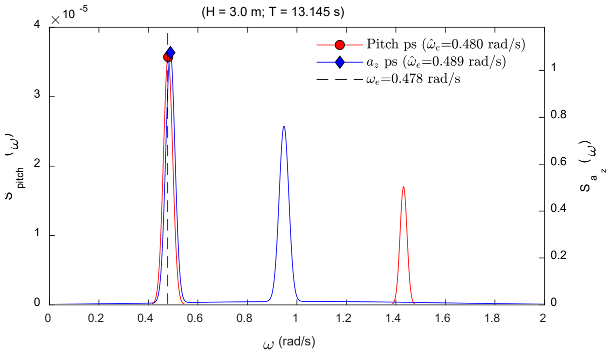

Figure 5: Pitch and a_z spectra and ω_e estimations for sea state 8.

Table 3: Estimated wave encounter frequency results.

Sea state	ω_e (rad/s)	Pitch results		a_z results	
		$\hat{\omega}_e$ (rad/s)	*Dev.*	$\hat{\omega}_e$ (rad/s)	*Dev.*
1	1.147	1.152	0.42%	1.149	0.16%
2	0.956	0.961	0.53%	0.958	0.21%
3	0.819	1.633	99.29%	0.824	0.56%
4	0.717	1.440	100.85%	0.726	1.26%
5	0.637	1.274	99.90%	0.637	-0.05%
6	0.574	1.154	101.19%	0.567	-1.15%
7	0.521	0.514	-1.43%	1.046	100.60%
8	0.478	0.480	0.42%	0.489	2.31%

Table 3 summarizes the obtained results after analyzing heave acceleration and pitch motion. The deviation from the target value is also included. As can be appreciated, the heave acceleration provides better results. Except in one case, the deviation never exceeds the 3% threshold. By contrast, the pitch motion only gives accurate results in four of the sea states.

To conclude, Figure 9: Deviation of $\widehat{\omega}_0$ from target ω_0 for each Figure 9 plots the real ω_e values for each sea state against the $\widehat{\omega}_e$ values obtained from each test. The red dots represents $\widehat{\omega}_e$ using pitch and the blue diamonds $\widehat{\omega}_e$ using heave acceleration. In light of the graph shown in Figure 6, the vertical acceleration signal analysis is considered to be the best way to obtain accurate $\widehat{\omega}_e$ values when it is compared with the results obtained during pitch signal analysis. Although in one of the studied cases (sea state 7) a large deviation is presented during the a_z analysis: this situation is more commonly observed during pitch analysis. Hence, a_z is proposed for filtering out ω_e from the roll signal.

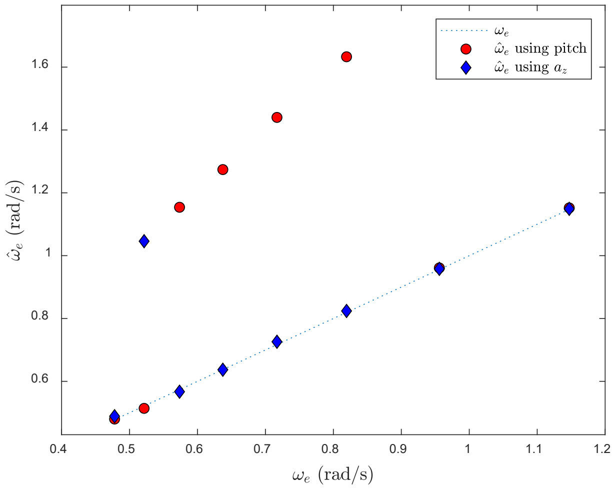

Figure 6: Comparison between ω_e and $\widehat{\omega}_e$.

Improved stability monitoring system results

Before presenting the obtained results for the natural roll frequency estimation, several considerations have to be presented. The short duration of the towing tank tests after removing transitory parts of the signals conditioned the number of temporal segments available for analyzing in each experiment. In many cases test duration was not long enough to reach the analysis time, and no test had enough duration to properly apply the averaging time – i.e., none of them calculated spectrum mobile mean considering the previous 12 segments.

Therefore, an unique segment to get the estimated value of wave encounter and natural roll frequencies has been considered – i.e., no mobile mean was applied to the spectrum obtained after the *FFT* application.

Figure 7 shows the roll spectrum (blue dashed line), the spectrum of the filtered roll motion (blue continuous line), the main peak of both spectra (represented by a triangle and filled triangle respectively), the target value of the wave encounter frequency (black dashed line) and the target value of the natural roll frequency (red dashed line) for sea state 1. In this wave condition, ω_e is larger than $\omega_{0,max}$, consequently the employed filter is a lowpass. As can be appreciated, both spectra contain two peaks. One corresponds to the natural roll frequency and the other one to the wave encounter frequency. For the non-filtered roll spectrum, the highest peak is the wave encounter frequency. Hence, the stability monitoring system would provide erroneous results. On the contrary, the application of the lowpass filter substantially decreases this peak making possible to correctly identify the natural roll frequency of the vessel.

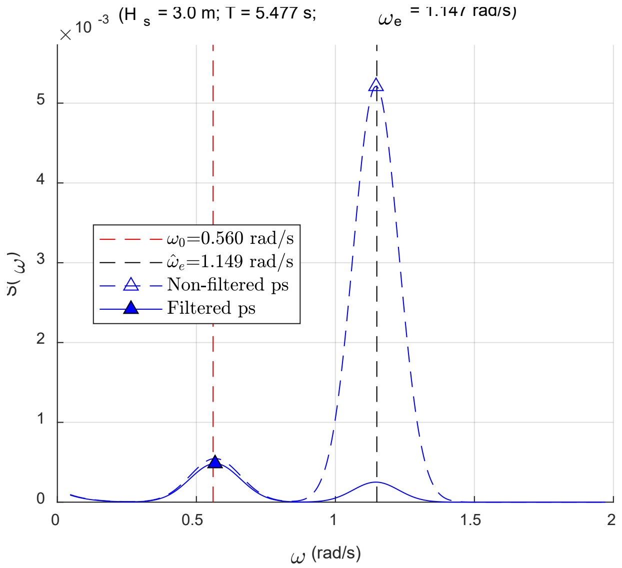

Figure 7: Roll spectrum and $\widehat{\omega}_0$ for sea state 1.

In Figure 8 the same output but for sea state 8 is presented. In this case, ω_e is between $\omega_{0,min}$ and $\omega_{0,max}$. For this reason, the applied filter is a stopband. It can be observed that for the non-filtered roll motion both peaks in the spectrum are very close to the target values. Nevertheless, again the wave encounter frequency masks the natural roll frequency. For the filtered roll motion, the amplitude of the spectrum is much lower and the peaks are shifted as a side-effect of the stopband filter. Therefore, in this situation, the filter does not significantly improve the performance of the monitoring system.

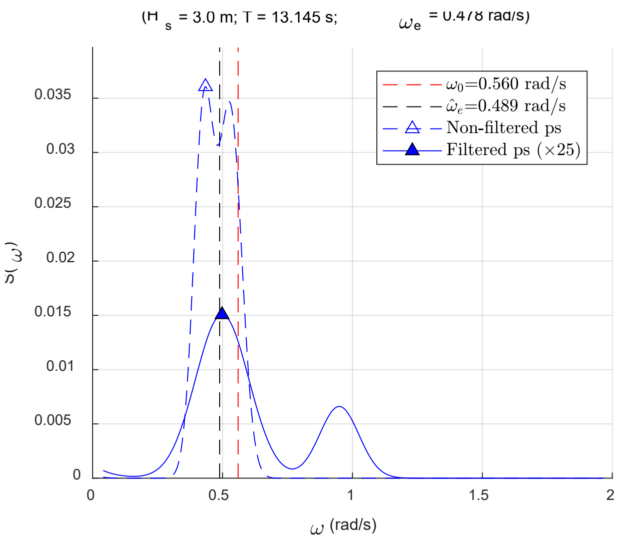

Figure 8: Roll spectrum and $\hat{\omega}_0$ for sea state 8.

The results for all sea states are included in Table 4. In general, the integration of the filter provides better estimations of ω_0. Nevertheless, in sea states that fall inside the interval $(\omega_{0,min}, \omega_{0,max})$ the performance of the stopband filter is not as good and the deviations are still significant. One of the reasons could be the slow cutoff of the Butterworth filter and that could be enhanced choosing another type of filter. In addition, it has to be taken into consideration that, when ω_0 and ω_e are very close to each other, it is very difficult to remove ω_e without affecting ω_0.

Special mention has to be paid to sea state 7, in which a lowpass filter is applied instead of a stopband. The explanation is a wrong estimation of the wave encounter frequency, $\hat{\omega}_e = 1.046\, rad/s > \omega_{0,max}$.

Table 4: Natural roll frequency estimations results (ω_0=0.560 rad/s).

Sea state	Applied filter*	Filtering		Non-filtering	
		$\hat{\omega}_0$ (rad/s)	*Desv.*	$\hat{\omega}_0$ (rad/s)	*Desv.*
1	LP	0.527	-5.86%	1.146	104.67%
2	LP	0.912	62.90%	0.914	63.25%
3	SB	0.930	66.05%	0.802	43.25%
4	SB	0.713	27.30%	0.723	29.05%
5	SB	0.651	16.23%	0.631	12.63%
6	SB	0.615	9.82%	0.613	9.47%
7	LP	0.513	-8.41%	0.567	1.17%
8	SB	0.510	-8.95%	0.435	-22.41%
*LP=lowpass; SB=stopband					

Lastly, a graphical comparison between the deviations of $\hat{\omega}_0$ obtained for each sea state is represented in Figure 9. Except in three cases, the improved stability monitoring system provides a better estimation.

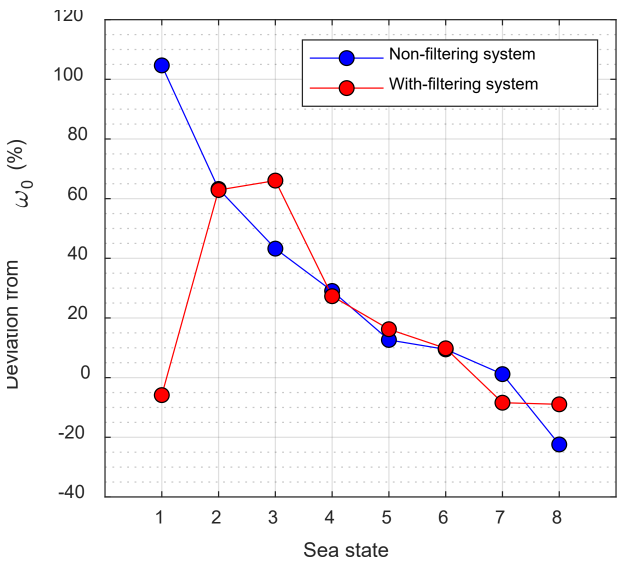

Figure 9: Deviation of $\hat{\omega}_0$ from target ω_0 for each sea state.

5. CONCLUSIONS

In this work, a methodology for estimating in real-time the wave encounter frequency from ship motions has been presented. In particular, pitch and heave accelerations have been analyzed in order to determine which one provides a more accurate estimation.

Then, this methodology has been validated using time series from towing tank tests showing that, in most of the situations, the processing of heave acceleration leads to better results.

The last step was the integration of this methodology into an existing monitoring system, previously developed by some of the authors. The performance of the new proposal has been tested with the same time series obtained from the towing tank experiments.

The incorporation of the wave encounter frequency estimation into the stability monitoring system has resulted in an improvement in most of the cases. However, more validation is needed. In particular, this is needed for a wider range of sea states and different wave directions.

REFERENCES

Deakin, B. (2005). Development of simplified stability and loading information for fishermen. *RINA, Royal Institution of Naval Architects International Conference - Fishing Vessels, Fishing Technology and Fisheries*, 37–46.

European Maritime Safety Agency. (2018). Annual overview of marine casualties and incidents 2018. *European Maritime Safety Agency*, 1–135.

Marine Accident Investigation Branch (MAIB). (2008). *Analysis of UK Fishing Vessel Safety 1992 to 2006*.

Míguez González, M., Bulian, G., Santiago Caamaño, L., & Díaz Casás, V. (2017). Towards real-time identification of initial stability from ship roll motion analysis. *Proceedings of the 16th International Ship Stability Workshop (ISSW 2017)*, 221–229.

Míguez González, M., Santiago Caamaño, L., & Díaz Casás, V. (2018). On the applicability of real time stability monitoring for increasing the safety of fishing vessels. *Proceedings of the 13th International Conference on the Stability of Ships and Ocean Vehicles*.

Míguez González, M., Sobrino Caamaño, P., Tedín Álvarez, R., Díaz Casás, V., Martínez López, A., & López Peña, F. (2012). Fishing vessel stability assessment system. *Ocean Engineering*, *41*, 67–78. https://doi.org/10.1016/j.oceaneng.2011.12.021

Nielsen, U. D. (2006). Estimations of on-site directional wave spectra from measured ship responses. *Marine Structures*, *19*, 33–69. https://doi.org/10.1016/j.marstruc.2006.06.001

Pascoal, R., Guedes Soares, C., & Sørensen, A. J. (2007). Ocean wave spectral estimation using vessel wave frequency motions. *Journal of Offshore Mechanics and Arctic Engineering*, *129*(2), 90. https://doi.org/10.1115/1.2426986

Ren, Z., Han, X., Verma, A. S., Dirdal, J. A., & Skjetne, R. (2021). Sea state estimation based on vessel motion responses: Improved smoothness and robustness using Bézier surface and L1 optimization. *Marine Structures*, *76*(June 2020), 102904. https://doi.org/10.1016/j.marstruc.2020.102904

Santiago Caamaño, L., Míguez González, M., Galeazzi, R., Nielsen, U. D., & Díaz Casás, V. (2019). On the application of change detection techniques for the stability monitoring of fishing vessels. *Proceedings of the 17th International Ship Stability Workshop (ISSW 2019)*.

Transportation Safety Board of Canada. (2012). *Marine investigation report. Safety issues investigation into fishing safety in Canada. Report Number M09Z0001*.

Varela, S. M., Guedes Soares, C., & Santos, T. (2010). Monitoring system for safety of fishing vessels subjected to waves. *The Portuguese Maritime Sector*, 1–10.