Real-Time Stability Assessment in Mid-Sized Fishing Vessels

Marcos Míguez González, *Integrated Group for Engineering Research, University of A Coruña*
A Coruña, Spain, mmiguez@udc.es
Vicente Díaz Casás, *Integrated Group for Engineering Research, University of A Coruña*
A Coruña, Spain, vdiaz@udc.es
Lucía Santiago Caamaño, *Integrated Group for Engineering Research, University of A Coruña*
A Coruña, Spain, lucia.santiago.caamano@udc.es

ABSTRACT

Fishing is one of the most dangerous occupations worldwide. Most of the accidents involving mid-sized fishing vessels are due to static and dynamic stability failures, and one of the main reasons is the crew lack of training in these matters. If stability guidance systems want to be used in this type of vessels, they have to fulfil three main requirements: they have to be based on simplicity, they have to be very easy to use and to interact with and their installation and maintenance have to be inexpensive. Within this framework, the authors proposed their own alternative, consisting on an onboard stability guidance computer system.

In this paper, some alternatives for overcoming the main drawback of this system, which is the manual interaction with the crew, are presented. A methodology based on the frequency analysis of the ship roll motion, together with an estimation of roll inertia applying a breakdown method is proposed for determining the vessel intact stability levels in an automatic and unattended way. The performance of this methodology has been verified using data from a towing test campaign of a mid-sized stern trawler, showing accurate results.

Keywords: *Onboard stability guidance, Fishing vessels stability, Stability monitoring*

1. INTRODUCTION

Fishing is well known for being one of the most dangerous industrial sectors in many countries, such as the U.S., the U.K. or Spain, and accounts, according to ILO, for more than 24.000 casualties a year (Petursdottir et al., 2001).

Most of the accidents involving fishing vessels affect the medium-small range of the fleet, and are mainly due to stability issues, both static and dynamic, including large heel and capsizing, pure loss of stability or broaching. Several authors and studies coincide in that one of the main reasons for this large stability-related accident rate is the crew lack of training in stability matters (Míguez-González et al., 2012a).

Fishing vessel masters usually rely in their experience to determine the stability level of their vessels, and this subjective analysis is not often a good approximation. The only element available onboard which provides some information regarding stability to them is the stability booklet, but this is only present in the larger vessels of some countries, taking into account that under 24 m fishing vessel regulations are country-dependent. But in addition, and even in the largest vessels, crew training is not enough to let them understand the information within the booklet.

The issue of stability/operational guidance is a deeply studied topic, and its regulatory framework (including SGISC) and its application onboard large commercial vessels are attracting a lot of attention in the last years. However, when it comes to small fishing vessels, its application, due to the difference in level of training of the crews, is not so straightforward.

Regulators and administrations are aware of these facts, and some programs and publications focused on increasing the training of the masters/crewmembers of these type of vessels have been ran worldwide (MAIB, 2008; Gudmundsson, 2009). However, and although these training programs are of paramount importance, onboard guidance provides masters with even more information to complement their knowledge and to carry out an objective analysis of the risk level of their ships in real time.

Within this last group, there are two main approximations. One is to provide masters with weather guidance, including updated information regarding sea state, which is transformed into a safety of navigation index based on ship dynamic stability curve, obtained for the design loading conditions. This methodology was implemented by the Icelandic Maritime Administration, and together with a compulsory inclining test program, it proved to drastically reduce the number of accidents involving the Icelandic fleet (Viggosson, 2009). The second alternative consists on providing the crews with an approximation of the stability level of their ship in real time, based on measurements or on a group of possible alternatives where to choose from, i.e. real time stability guidance, together or not with some input regarding sea state.

Up to date, just a few authors have dealt with the topic of developing fishing vessel oriented stability guidance systems, which have some differences to those installed onboard larger vessels: they have to be based on simplicity; they have to be very easy to use and to interact with; and their installation and maintenance has to be inexpensive. Some examples are the well-known stability matrix, the stability posters, and some others (Womack, 2002; Deakin, 2005), which provide the risk level of the ship according to the loading condition, that in some cases include the influence of the sea state and which show the obtained results using a static interface (a poster placed on the navigation bridge).

Following this premises, the authors (within the Integrated Group of Engineering Research) have proposed their own alternative, consisting on an onboard stability guidance computer system. It provides the minimum essential information related to the stability of the vessel in the current loading condition, in a very clear and understandable way, even for users with no specific training in the use of computer software (Míguez-González et al., 2012a). However, this system has one major drawback, which is a common issue to all the aforementioned fishing vessel stability guidance systems: in order to determine the stability characteristics of the vessel (metacentric height and righting lever curve), it relies on the information that the crew manually introduces in the system (weight items and their positions and tank filling levels). Although the interface is very simple and it is designed to account for inaccuracies, it requires the crew interaction, which is not always guaranteed.

This paper will present one alternative for trying to overcome these major drawback, which consists on a methodology based on the frequency analysis of the ship roll motion, together with an estimation of roll inertia, for determining the vessel intact stability levels in an automatic and unattended way. The objective of this proposal is to minimize the need of external data and to maximize the accuracy of the obtained risk level.

2. METHODOLOGY

The aforementioned guidance system is composed of a naval architecture software that, from the hull forms, hydrostatic data and weight distribution, and from a sea state estimation, computes a stability index based on IMO Intact Stability criteria and maximum wave to capsize (Deakin, 2005). From this data, both weight distribution and approximate sea state have to be manually introduced by the crew. In order to automate this system, it would be a great improvement to be able to monitor dynamic stability, so that basic initial stability parameters (transverse metacentric height) could be determined.

Considering the uncoupled linear equation of roll motion of the ship,

$$(I_{xx} + A_{44})\ddot{\emptyset} + B_{44}\dot{\emptyset} + g\Delta GM\emptyset = M_{ox} \quad (1)$$

where M_{ox} is the external excitation, I_{xx} is the ship transverse mass moment of inertia, A_{44} is the added mass in roll, B_{44} is the damping coefficient, Δ is the ship displacement and GM is the transversal metacentric height, the roll natural frequency for the case of small amplitude linear oscillations could be estimated by:

$$\omega_N{}^2 = \frac{g\Delta GM}{I_{xx} + A_{44}} \quad (2)$$

And rewriting the previous formula, the metacentric height would be:

$$GM = \frac{{\omega_N}^2 (I_{xx} + A_{44})}{g\Delta} \tag{3}$$

If the Weiss formula based in the roll gyradius of the vessel (k_{xx}) is applied to obtain the transverse mass moment of inertia, the *GM* estimation is reduced to (Krüger and Kluwe, 2008):

$$GM = \frac{{k_{xx}}^2 {\omega_N}^2}{g} \tag{4}$$

Considering the ship as a rigid body oscillating in just one degree of freedom (roll), the problem of real time estimation of the initial stability is reduced to determining the parameters involved in this motion: natural roll frequency, transverse moment of inertia (both dry and added inertia) and vessel displacement.

Ship displacement is obtained by means of the guidance system from the weight data introduced by the crew, although this value could be also obtained in real time by means of a draft monitoring system or draft marks observation by the crew. Transverse moment of inertia is obtained using the proposed estimation of the lightship weight inertia and the data introduced by the crew in the stability guidance software. This value could be also estimated using the aforementioned Weiss formula. Added inertia in roll is precomputed for different drafts by using a strip theory code, and then the needed data is interpolated for the actual draft of the vessel. Natural roll frequency is obtained by analyzing ship roll motion, following the methodology described in the corresponding section. Once all the variables have been obtained, the estimated initial stability of the ship could be computed by means of equations (3) or (4).

The employed methodology is summarized in Figure 1.

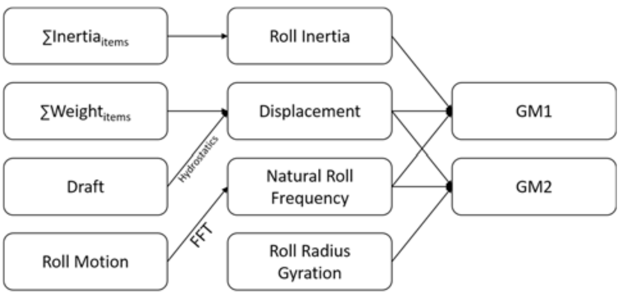

Figure 1: Applied methodology.

Roll natural frequency

In order to estimate the roll natural frequency, the vessel roll motion is analysed. The spectrum of roll motion has a peak around the roll natural frequency, which is more acute if a resonance phenomenon is taking place (Enshaei, 2013; Terada, 2014). Regarding the sampling frequency, the time series length has to be such that it contains enough information to be able to determine the position of this peak with certain accuracy. This procedure is similar to that applied in wave buoys to obtain wave height and direction; in this cases, 20 minutes intervals are usually applied, that is the minimum time window in which the sea is considered stationary (Nielsen, 2007). However, this time window is too large for the case under analysis. In 20 minutes, the ship condition could be significantly modified, even leading to a dangerous situation. In the case of stability guidance, the results are considered in real time when data are obtained at least every 3 minutes (Pascoal et al., 2007; Tannuri et al., 2003). In addition, the sampling frequency should also satisfy the Nyquist theorem (Medina, 2010).

The power spectrum of a signal shows how its energy or power is distributed throughout each component of the frequency and consequently, it permits to identify the natural frequency of the system under analysis. In order to be able to compute it, it is necessary that the signal is represented in the frequency domain. There are several tools that permit the time-frequency analysis, but to be implemented in the onboard stability guidance system is an indispensable condition that the calculation algorithm would be able to obtain the results easily in what we have considered real time. For this reason and because it is the most common way of generating a power spectrum, the Fast Fourier Transform (FFT) was chosen (Medina, 2010). Therefore, the calculation procedure will be the following:

$$g = fft(x) \tag{5}$$

$$S(\omega) = |g(\omega)|^2 \tag{6}$$

As a consequence of the discrete sampling of the signal, the “spectral leakage” may appear. The spectral leakage is no more than energy dispersion. It is usually related to the discontinuities that exist at the beginning and the end of the signal, and that could degrade the signal-noise ratio and mask other smaller signals at different frequencies. The effects of spectral leakage can be reduced decreasing the discontinuities at the edges of the signal. A possible solution is to apply a window function. The process consists of multiplying the signal by a function that reduces the signal to zero at the edges and that it is known as windowing.

Windows generally cause a reduction in the accuracy of the measured peak amplitude of the signal and also introduce damping. However, this is not a problem given the fact that the main objective is to determine the natural frequency of the system, and not to compute the exact amplitude of the spectrum peaks.

There are numerous window functions, of which we will focus only on those that offer more accuracy and, therefore, better results. These are Hanning, Blackman and Blackman-Harris windows (Boashash, 1992; Harris, 1978; Oppenheim et al., 1999).

Transverse mass moment of inertia and displacement

The transverse mass moment of inertia calculation by direct integration is a complex and time consuming process given the fact that the shape of the vessel and its density varies from one point to another. For this reason, the process is usually simplified by considering the ship as a single object with known shape and uniform density or by breaking it down into its most relevant components and approximating them to known shapes with constant density (Aasen and Hays, 2010). In this study, the lightweight mass moment of inertia has been obtained by integrating the midships structure along the length of the vessel and weighting it using the curve of areas, and also considering the weight, position and shape of the most representative lightweight elements (such as winches, main engine, diesel generators, etc.). Tanks and other cargo elements which have to be considered in the loading conditions of the vessel, have also been taken into account using their weights, location and approximate shape.

For the sake of comparison, the Weiss formula approach (Krüger and Kluwe, 2008) has been also considered:

$$I = {k_{xx}}^2 \Delta \quad (7)$$

Where k_{xx} is the roll gyradius, usually taken as a percentage of the vessel's beam.

In addition, the added mass in roll, which may be expressed as an increase in percentage over the total value, must be kept in mind. In this case, the added mass was computed by using a strip theory code.

Finally, the ship displacement can be obtained by the sum of the load items considered in the calculation of the inertia or by the vessel hydrostatics if the draft is known. This fact makes necessary the interaction with the crew in both cases. Although introducing the vessel draft in the application after checking the draft marks seems to be easier than defining all the load items, the use of draft sensing could help solving this issue and avoiding any interaction, although this alternative seems to be out of range due to cost of installation.

3. RESULTS

In order to check the proposed methodology, results from a towing test campaign of a mid-sized stern trawler had been used. These tests include regular and irregular head waves of different frequencies and heights. In some of the cases, parametric roll resonance took place. Their detailed description can be found in (Míguez-González et al., 2012b).

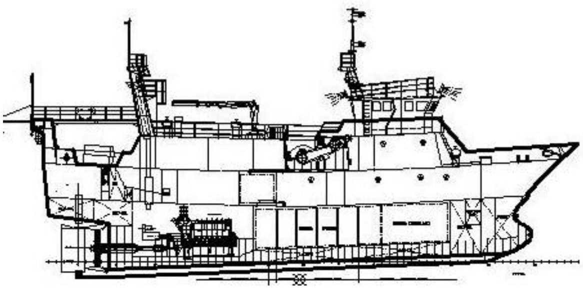

Figure 2: Test vessel.

Table 1: Test vessel main characteristics.

Overall Length	34.50 m
Beam	8.00 m
Depth	3.65 m
Draft	3.340 m
Displacement	450 t
Metacentric Height (*GM*)	0.350 m
Natural Roll Frequency (ω_ϕ)	0.563 rad/s

The tested model is a 1/18.75 scale trawler; roll decay tests at different speeds and an inclining test were carried out to determine the vessel metacentric height, displacement and natural roll frequency, together with roll moment of inertia. The vessel main characteristics are shown in Table 1.

Transverse mass moment of inertia

From the data above, and applying a strip theory code to determine the vessel roll added mass, the roll dry mass moment of inertia and the roll gyradius were determined. Results are shown in Table 2.

Table 2: Test vessel mass distribution. Towing tank tests.

Load condition	Δ *(t)*	I_{xx} $(t{\cdot}m^2)$	k_{xx}/B	A_{44} $(t{\cdot}m^2)$
Towing Tank Tests	448	4383.60	0.391	469.26

These values were compared to those calculated by using the previously described breakdown methodology, corresponding to the four mandatory loading conditions of the vessel, taking into account the tank filling levels, the positions of the different load items and the cargo stowage in the hold of the vessel. These data would be computed by the onboard system based on the actual loading condition introduced by the crew. These results are shown in Table 3.

Table 3: Test vessel mass distribution. Breakdown method.

Load condition	Δ *(t)*	I_{xx} $(t{\cdot}m^2)$	k_{xx}/B
Fully loaded departure. No cargo	492	4450.88	0.376
Ground departure, 35% consumables, 100% catch	489	4102.09	0.362
Arrival at port, 10% consumables, 100% catch	465	3734.43	0.354
Arrival at port, 10% consumables, 20% catch	411	3545.94	0.367

The values of the roll radius of gyration obtained following this procedure are slightly smaller than those measured in the towing tank tests, and also than the reference value for this type of vessel (0.4 (Krüger and Kluwe, 2008)); roll decay and inclining tests should be carried out to verify the accuracy of the method.

However, as is indicated in Figure 1, two alternatives for the computation of the metacentric height will be considered in the onboard system. On one hand, that based on the inertia obtained using the direct calculation method including crew inputs. And on the other hand, that based on the reference value of 0.4 for the roll gyradius. These will allow us to choose the less favourable alternative.

Roll natural frequency

In this section the results obtained after applying the proposed estimation method to the roll time series in four different test runs are presented, including results using Hanning, Blackman and Blackman-Harris windows. In Table 4, the values of the obtained natural frequencies and the corresponding *GM* values for the four test cases are shown.

In Figure 3, the results from a test run in regular waves and where parametric resonance takes place are presented in real scale. On the top, a record of the roll motion and the application of the window functions are presented. As it was expected, the signal is reduced to zero at the edges due to windowing and its amplitude is damped. This effect is more or less pronounced depending on the type of window used. On the bottom, the results of applying the FFT to the different time series are displayed. It can be seen that most of the energy of the spectrum is concentrated in the natural frequency of the vessel. Nonetheless, there is a little scattering around it, likely produced by the discontinuities in the edges, which is reduced with the use of window functions.

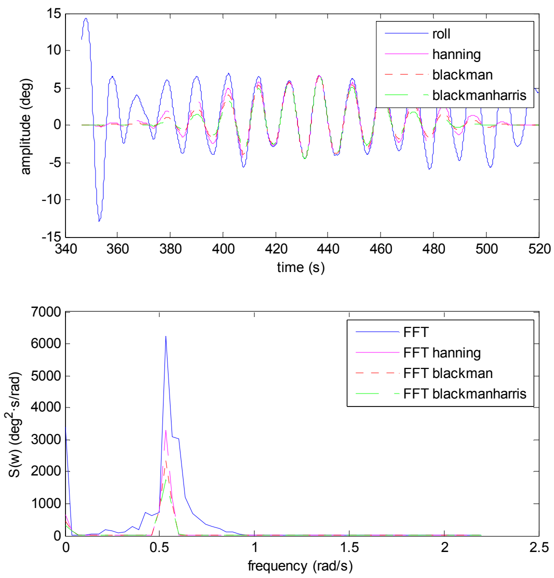

Figure 3. Test 1. Regular waves. Fn 0.1. Parametric roll occurs.

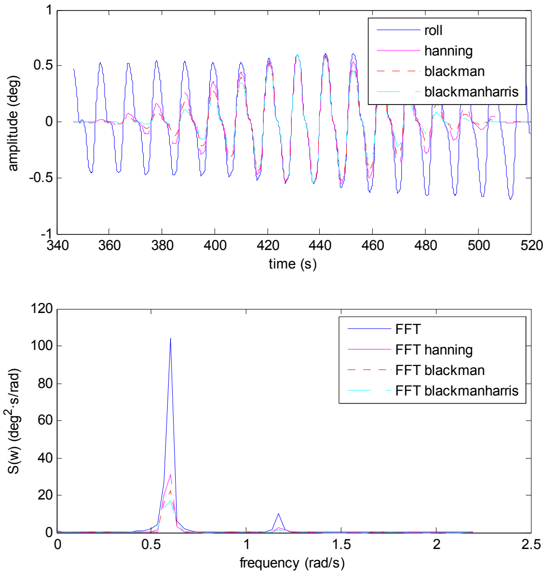

Figure 4. Test 2. Regular waves. Fn 0. No parametric roll.

In Figure 4, results from a regular wave case with no parametric rolling are presented. In contrast to the previous case, due to the absence of the resonance phenomenon there is a greater dispersion of energy, and more than one peak have been identified, although of lower intensity than the one corresponding to the natural frequency. However, the quality of the estimation of the natural frequency remains satisfactory.

In the case of irregular waves, the results are similar to those obtained for regular waves. When the resonance phenomenon takes place (Figure 5) there is no energy dispersion of the spectrum and a clear single peak appears in the solution. If no resonance occurs (Figure 6), the degree of dispersion is increased, and results obtained applying the windowed time series are not satisfactory. However, the frequency of the system can still be identified using the not windowed solution.

The values obtained in all the tests are very close to the actual value of natural frequency (ω_n = 0.563 rad/s). The relative error does not exceed 8% and in the irregular wave cases, the most realistic ones, is below 1%. The application of window functions showed no improvement in the obtained results.

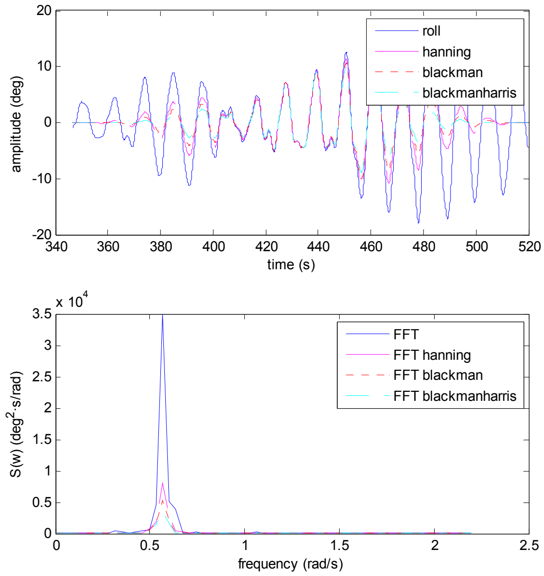

Figure 5. Test 3. Irregular waves Fn 0. Parametric roll occurs.

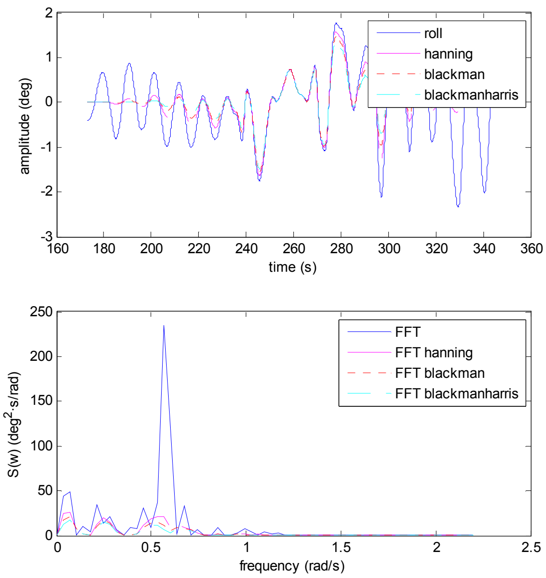

Figure 6. Test 4. Irregular waves. Fn 0.1. No parametric roll.

Table 4: Natural frequency results.

	Regular Waves		Irregular Waves	
	Test 1	Test 2	Test 3	Test 4
Fn	0.1	0	0	0.1
Parametric resonance?	Yes	No	Yes	No
$\omega_{n\ \text{no windowing}}$ (rad/s)	0.531	0.602	0.567	0.567
$\omega_{n\ \text{hanning}}$ (rad/s)	0.531	0.602	0.567	0.071
$\omega_{n\ \text{blackman}}$ (rad/s)	0.531	0.602	0.567	0.071
$\omega_{n\ \text{blackman harris}}$ (rad/s)	0.531	0.602	0.567	0.071
Resulting *GM* (no windowing)	0.311	0.400	0.355	0.355

Metacentric Height

The *GM* values corresponding to the natural frequencies obtained from the time series analysis, which are shown in Table 4, have been calculated by using the real value of the mass moment of inertia which was determined in the towing tank tests of the vessel.

Although the obtained relative error is small (less than a 15 % in all cases), to evaluate the quality of the results obtained for the *GM* it is necessary to focus not only on the final value, but also on the percentage of induced error. As the results are values obtained from the combination of other variables, which have uncertainty themselves, it will be necessary to carry out an error propagation analysis that will let us know which are the variables that have more influence on the correctness of the solution (vessel displacement, mass moment of inertia or natural roll frequency).

4. DISCUSSION

The results of roll natural frequency have been validated for head seas, so the effectiveness of the proposed method is only demonstrated for this case. If the wave direction changes, the forces acting on the vessel are modified and the accuracy of the results may be affected. For this reason, it would be necessary to carry out another test campaign in which more wave incidence angles were considered, including not only head waves, but also stern and oblique ones, to analyze how the performance of the method changes with wave incidence.

Another point of concern is how the transversal moment of inertia is determined. If the breakdown method is applied, the crew have to input the load items in the system, and therefore it would carry on depending on manual data. A possible solution would be to install a remote sounding system, but the problem will be the same regarding hold stowage and individual load items (such as nets, etc.). A possible solution would be the one stated in the text that is to also apply the Weiss formula, to approximate the roll gyradius and to choose the worst situation from both alternatives. Of course, this would lead to a level of uncertainty in the computation of *GM* that has to be evaluated by carrying out an error propagation analysis.

Finally, the last parameter to be considered is ship displacement. The case of the displacement is similar to that of the mass moment of inertia, as both of them have to rely on the interaction with the crew. Regarding the displacement, it could be determined by considering the loading condition defined by the crew, or by the input of the draft in the guidance system, which seems to be a less bothering alternative. In any case, the aforementioned uncertainty analysis will be needed to quantify the influence of the estimation of ship displacement in the calculation of *GM*.

5. CONCLUSIONS

In this paper a real time onboard estimation method of ship’s initial stability, intended to be used in small and medium sized fishing vessels has been presented. The main objective of the proposed methodology was to overcome some of the drawbacks of these type of systems and to try to minimize the need for crew interaction.

In order to obtain the vessel *GM*, the natural roll frequency has been estimated by applying windowed FFT to a group of roll motion time series from a towing tank test campaign, including both regular and irregular head waves. The results show a good agreement with the real values in all the tested cases; the performance of the estimation has not been increased by the use of three different windows, Blackman, Hanning, and Blackman – Harris. However, it is necessary to complement the obtained results with those from a broader towing tank test campaign, including also stern, beam and oblique waves.

For the estimation of roll mass moment of inertia, a breakdown method is proposed based on the different load items which compose the vessel loading condition. However, this approximation still relies in manual data introduced by the crew; the use of the Weiss formula and the estimation of the vessel roll gyradius to determine the inertia implies a simplification in the calculation, although results in both cases have been very similar.

Considering that two of the premises of this system are simplicity and low cost of installation, the use of draft sensing and tank sounding for determining the vessel displacement is not a feasible option; draft manual input seems to be the best alternative.

Finally, the need for an uncertainty analysis has been also stated in the paper. Due to the fact that the values of both roll mass moment of inertia and vessel displacement rely up to some extent on data introduced by the crew, it is necessary to determine which is their contribution to the obtained solution and the influence of the uncertainty of these data in the computation of *GM*.

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