On the feasibility of a real time stability assessment for fishing vessels

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ABSTRACT

Fishing is one of the sectors with the highest number of accidents worldwide. Many of them are related to stability failures and affect mostly small and medium sized fishing vessels. One of the main reasons is the crew lack of training in stability matters. Due to this, guidance systems have emerged in the last years as a solution to this matter, complying with three main requirements: being simple, being easy to use and being inexpensive to install and maintain. The authors have proposed their own alternative consisting on an onboard stability guidance system. However, it has some weak points. The aim of this paper is to propose an alternative to overcome one of them, the need for crew interaction. In order to do this, and to try to set up a fully automated system, a methodology to estimate ship's stability in an automatic and unattended way based on a frequency analysis of roll motion and on the estimation of the ship's inertia is presented. The results have been compared with data from a towing tank test campaign showing good performance.

KEYWORDS: Onboard stability guidance, Fishing vessels stability, Stability monitoring

1. INTRODUCTION

Fishing is one of the main industrial sectors in Spain; the size of the fleet (tonnage and power) and the volume of catches indicate it. At European level, the Spanish fishing fleet represents the largest number of registered tons, reaching 372,617.02 GT, representing 22.46% of the total value by the end of 2013, according to the European Register of Ships (Ministerio de Agricultura Alimentación y Medio Ambiente, 2014). If global data are considered, Europe would be located in fifth place in the ranking of fisheries production (3.4%) behind China, Indonesia, India and Peru (European Market Observatory for Fisheries and Aquaculture Products, 2014).

Regarding the technical aspects of the fishing vessels, the main characteristic of this fleet is that it is very heterogeneous. There are many different typologies of fishing vessels depending on their size, fishing distance to the coast, type of fishing, etc. However, two main groups may be defined, according to their operation model: coastal-artisanal fleet and industrial fleet. The first group is characterized by vessels with a low degree of mechanization and specialization among crew members. Productivity depends on human strength and the workers' skills. The number of crew members rarely exceeds 10 people and the vessels fish close to their base port. The industrial fleet consists of deep-sea fishing. The vast majority of vessels exceed 24 meters in length and fish far from their base port. The degree of mechanization and specialization of the crew is high and the number of crew members ranges between 12 and 60 (Álvarez-Santullano, 2014). The total number of fishing vessels in the world is about 4.36 million; from these, more than the 85% of the engine-powered fishing vessels are less than 12 meters in length, a 13% are between 12 and 24 meters length and only a 2% are over 24 m (Gudmundsson, 2013).

On the other hand, fishing has been, and continues to be, one of the most hazardous occupations worldwide. In 2001, the International Labour Organization estimated about 24,000 fatalities per year and in many countries, such as Spain, USA or UK, fishing has one of the highest fatal injury rates in comparison with the rest of the sectors (Buerau of Labor Statistics, 2014; Ministerio de Empleo y Seguridad Social, 2013; Petursdottir et al., 2001; Roberts, 2002). Most frequent accidents include the incorrect operation of the ship, modifications of the weight distribution of the vessel, sailing in very adverse weather conditions that can lead to foundering or capsizing or a combination of all of them. Despite of the fact that capsizing is a rare event at sea, it is one of the main causes of loss of human life and fishing vessels. Capsizing is usually related to stability failures, both static and dynamic (Krata, 2008; Míguez González et al., 2012; Roberts, 2002; Wolfson Unit, 2004).

The aforementioned accidents mostly affect small and medium length fishing vessels (Krata, 2008; Míguez González et al., 2012) and the main reason is the crew lack of training in stability matters. Only few fishermen have a deep knowledge of ship stability, especially in small-medium sized fishing vessels. They usually carry out a subjective analysis to determine the ship's stability level based on their previous experience. In fact, the only objective information available onboard is the stability booklet. However, this has shown to be quite useless and unpractical. On one hand, because of its complexity. And on the other, because it is only mandatory on those ships of more than 24 m length. If this lack of training and information is put together with the huge economical pressure over fishermen, one of the main causes of the high accident rate affecting these vessels could be explained (Míguez González et al., 2012; Petursdottir et al., 2001).

Having being recognized as a principal cause of accidents, both stability and operational guidance have been a main research topic in the last years. Onboard guidance together with training programs, provides masters more information to complement their knowledge and to carry out an objective analysis of the risk level of their ships, minimizing this probability of accident (Deakin, 2005; Marine Accident Investigation Branch (MAIB), 2008; Varela et al., 2010).

In order to improve the performance of these stability guidance systems, there are some main premises that have to be fulfilled. These are ease of use and understanding, low cost of acquisition, installation and maintenance and minimum need for crew interaction (Deakin, 2005; Womack, 2003). The first approach to these kind of systems was proposed by Koyama in 1982, who used a pendulum for estimating the roll period and the safety level of the vessel (Varela et al., 2010). The proposal of Köse in 1995 consisted in using sensors for providing weather data and applying these data for analysing the risk of capsizing of the vessel (Varela et al., 2010). In 2001 Womack proposed a simple and fast application based on a colour coded matrix, where different loading and weather conditions were included. Its main disadvantage was the difficult understanding in vessel with a large number of compartments (Wolfson Unit, 2004; Deakin, 2005; Míguez González *et al.*, 2010, 2012). A similar approach is applied by the Norwegian Maritime Directorate, which requires all small fishing vessels to carry a simple poster, where some stability guidance is provided by using diagrams and a colour code (Deakin, 2005; Míguez González et al., 2012, 2010; Wolfson Unit, 2004). Finally, the Icelandic Administration has successfully applied a methodology which includes a compulsory inclining test program, which in combination with real time weather data and ship specific stability-related weather limitations, has largely reduced the number of accidents (Viggosson, 2009).

Within this framework, the authors, belonging to the Integrated Group for Engineering Research, have developed their own alternative fulfilling the aforementioned premises. This guidance system consists of a naval architecture software that, installed on a touchable screen PC, from the hull forms and weight distribution of the ship, performs all necessary calculations regarding to vessel stability, generating and displaying in a clear and understandable way the current situation of the vessel and its risk levels. Crew interaction and ease of use premises are dealt with by using an optimized user interface, which usability levels have been tested and verified (Míguez González et al., 2012).

However, the weak point of this system, as in most guidance systems, is that its full and correct operation relies on the information manually introduced by the crew. For example, these data include the weight items and their positions, the tank filling levels and the sea state.

The methodology presented in this work is part of the author´s research in trying to minimize the need for crew input in the aforementioned guidance system. In particular, its main objective is to make a real-time estimation of the vessel natural roll frequency that, together with an estimation of the vessel transverse mass moment of inertia and displacement, could lead to the determination of the ship's initial stability in an automatic and unattended way.

2. METHODOLOGY

Considering the one degree of freedom uncoupled linear equation of roll motion of the ship (Taylor et al., 2008),

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

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.

From equation (1), the roll natural frequency for the case of small amplitude linear oscillations could be estimated by:

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

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

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

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 aforementioned formula, a real time estimation of the initial stability characteristics of the vessel may be done by obtaining the parameters involved in these equations: natural roll frequency (ω_N), transverse moment of inertia and added inertia ($I_{xx} + A_{44}$) and ship displacement (Δ).

In this work, natural roll frequency is estimated using signal processing techniques, following a procedure that will be described in the next section.

Regarding the transverse mass moment of inertia, two alternatives are applied. On one hand, a methodology based on the approximation of the lightship mass inertia and the use of weight data introduced by the crew. And on the other, the inertia is approximated using the Weiss formula. In both cases, added inertia in roll is computed by using a strip theory code for different vessel drafts, so the needed value is obtained by interpolation between those previously computed (Neves and Rodriguez, 2006).

Finally, estimation of the vessel displacement is a remaining issue which will be dealt with in future work. In this paper it is obtained from data which are manually introduced by the crew within the system. Nevertheless, this value could also be automatically obtained using a draft monitoring system.

Once all the variables have been obtained, the metacentric height could be estimated by applying equations (3) or (4).

The described methodology is summarized in Figure 1.

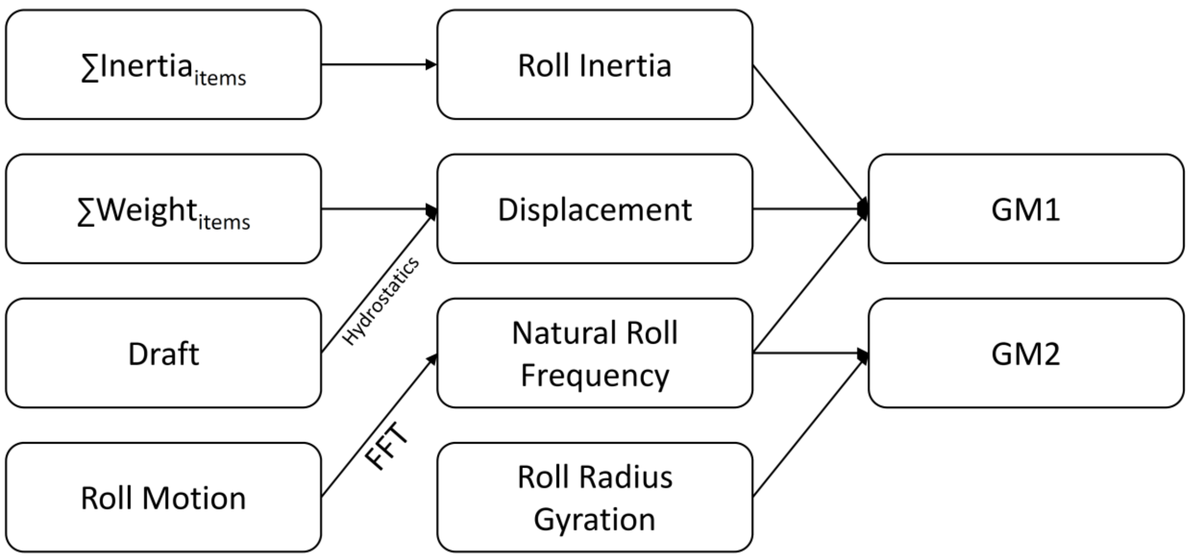

Figure 1. Metacentric height estimation methodology.

2.1. Roll natural frequency estimation

Natural roll frequency is estimated by analyzing the roll motion and considering that its spectrum has a peak around this frequency. This effect is increased when the resonance phenomenon exists (Enshaei, 2013; Terada, 2014). The roll motion time series has to be long enough as to ensure that it contains the minimum information needed to determine this frequency with certain quality. For example, in the case of wave buoys, the length of this time window is 20 minutes, as in this interval the sea is considered to be stationary. However, this is too long for the case under analysis; a vessel may capsize or sink in a much shorter time, and the system would not have been able to analyze the real situation and to generate an alert in this conditions. The objective of a real-time stability assessment system is that the changes in ship behavior could be detected, analyzed and, if needed, an alert issued, in a time window long enough as to allow the crew to take corrective measures and avoid the risk situation. It is generally considered (Pascoal et al., 2007; Tannuri et al., 2003) that time windows of 3 minutes could be used for real time systems.

In addition to the above, the sampling frequency has to also comply with the Nyquist theorem (Medina, 2010).

The power spectrum of a signal provides information about how the energy of the signal is distributed into frequencies. So, from the analysis of this frequency distribution, it is possible to identify the natural frequency of the system by determining the frequencies in which the main peaks are located. In order to be able to compute this power spectrum, it is necessary to represent the signal in the frequency domain carrying out a time-frequency analysis. There are several tools to perform this transformation. However, in order to fulfill with the real time premise, the Fast Fourier Transform (FFT) was chosen was chosen (Medina, 2010). To increase the simplicity of the process and without degrading the results, the signal power spectrum $S(\omega)$

is computed by multiplying the FFT results (g(ω)) by their complex conjugate and averaging it. In consequence, the proposed computation is the following:

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

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

If the FFT is applied in a finitely sampled signal, the "spectral leakage", which is no more than energy dispersion, may appear. Its main cause are the discontinuities that exist at the beginning and the end of the signal and it could degrade the signal-noise ratio and mask other smaller signals at different frequencies. These effects can be mitigated by applying a window function, which takes the signal to zero at the ends. 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 in our case, as the main objective is to estimate the frequency in which the peaks are located, and not their amplitude. There are numerous window functions; in this work, only those which have shown to be more accurate will be used. These are Hanning, Blackman and Blackman-Harris windows (Boashash, 1992; Harris, 1978; Oppenheim et al., 1999).

2.2. Transverse mass moment of inertia and displacement

Considering the shape of the vessel and the variation of its mass characteristics along the length, the computation of the transverse mass moment of inertia by direct integration is not a feasible alternative. The process of mass moment of inertia computation is usually simplified either by reducing the ship to a single object with a known shape and constant density or by breaking down the vessel into the most representative mass items and approximating them to known shapes with constant density (Aasen and Hays, 2010). In this paper, the latter alternative has been selected.

The breakdown has been done considering the steel weight, tanks and some specific and added weights which have large influence in the inertia's value. The steel weight is supposed to represent the largest percentage of the inertia and it is obtained calculating the transverse inertia of the amidship section and integrating it along the overall length using the hull form curve of areas.

The inertia of the tanks is estimated approximating their shape to a parallelepiped with their dimensions and with the mass manually introduced by the skipper. The relevant specific weights are the engine and the fishing gear and they were estimated as parallelepipeds located in their center of gravity. In addition, we have also included the weight of ice, boxes, etc. They were calculated as if they were point loads and we have supposed that the transversal position of the items was in the side of the vessel to take into account the most unfavorable condition in the calculation of the ship's stability.

The other proposed methodology for estimating the transverse mass moment of inertia, is by applying the Weiss formula (Krüger and Kluwe, 2008).

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

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

Regarding the added mass, it has been computed by using a strip theory code, for different values of the vessel draft. Intermediate values for the actual draft, are obtained by lineal interpolation from the precomputed data.

Finally, the ship displacement can be obtained by the sum of the load items considered in the calculation of the inertia which requires the crew interaction unless draft sensors are installed.

2.3. Uncertainty analysis

In order to determine the accuracy of the results, and how the errors in the estimation of the different parameters affect the obtained value of natural roll frequency, and so the stability levels of the vessel, an uncertainty analysis has to be carried out.

In the case of roll natural frequency, it was done considering that the obtained values are directly measured quantities. So, following U_{95} model, as described by (Dieck, 2007):

$$U_{95} = \pm t_{95}\left[(b)^2 + \left(S_X/\sqrt{N}\right)^2\right]^{1/2} \tag{8}$$

U_{95} = the 95% confidence uncertainty

t_{95} = is a function of ν and found in a Student's table. For ν≥30 t_{95} = 2.000.

b = the uncertainty of the standard (at 68% confidence). It is the systematic standard uncertainty of the instrument under calibration. In this case, it has been considered as the difference between the mean of the roll natural frequency obtained values in the different tests and the reference value of natural frequency (obtained from a roll decay test).

N = the number of data points in the average calibration constant or the number of data points in the calibration line fit. In this case, 64 towing tank tests have been performed.

S_X = the standard deviation of the calibration data.

$$S_X = \left[\frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)}{N-1}\right]^{1/2} \tag{9}$$

Where:

X_i = the ith data point used to calculate the calibration constant, i.e. the value obtained after applying the proposed methodology to each test.

$\overline{X}$ = the average of the calibration data (the calibration constant). Here, the average of obtained values from each test.

N = the number of data points used to calculate S_X, in this case, the number of tests.

N-1 = the degrees of freedom for S_X.

On the other hand, as the GM are values obtained from the combination of other variables, which have uncertainty themselves, it will be necessary to carry out an error propagation analysis, as described by (Dieck, 2007). Using this error propagation analysis, besides knowing the accuracy of the results, the variables that have more influence on the correctness of the solution can be recognized (vessel displacement, mass moment of inertia or natural roll frequency).

Applying error propagation to equation (3), the uncertainty of the metacentric height is related to the estimated parameters by:

$$U_{GM}^2 = \left(\frac{\partial GM}{\partial \omega_N}\right)^2 \left(U_{\omega_N}\right)^2 + \left(\frac{\partial GM}{\partial I}\right)^2 (U_I)^2 + \left(\frac{\partial GM}{\partial \Delta}\right)^2 (U_\Delta) \quad (10)$$

Where $U_{\omega n}$ is the natural frequency uncertainty, U_I is the uncertainty of the inertia and U_Δ is the displacement uncertainty.

If the Weiss formula is used to calculate the metacentric height, the uncertainty can be computed by:

$$U_{GM}^2 = \left(\frac{\partial GM}{\partial k}\right)^2 (U_k)^2 + \left(\frac{\partial GM}{\partial \omega_N}\right)^2 \left(U_{\omega_N}\right)^2 \quad (11)$$

Where U_k is uncertainty of the gyradius.

3. RESULTS

In order to check the proposed methodology, results from a towing test campaign of a mid-sized stern trawler have 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. A detailed description of these tests can be found in (Miguez Gonzalez et al., 2012).

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

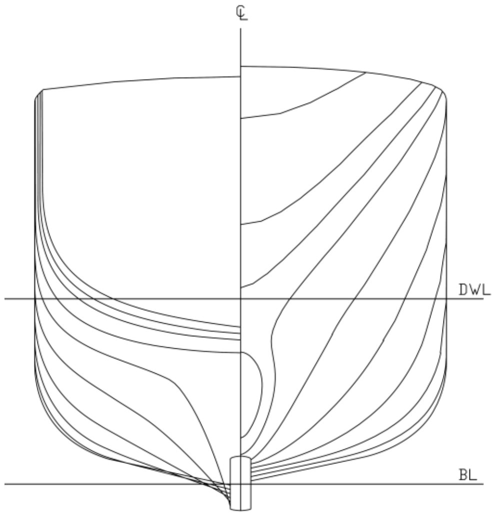

Figure 2: Test vessel

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

3.1. Transverse mass moment of inertia

As it was mentioned in Section 2, the transverse moment mass of inertia was estimated applying the breakdown method. The four considered loading conditions were the following:

1. Fully loaded departure. No cargo.

2. Fishing ground departure, 35% consumables, 100% catch.
3. Port arrival, 10% consumables, 100% catch.
4. Port arrival, 10% consumables, 20% catch.

The considered items and how their values in the different loading conditions are included in the Table 2. In this table, the total values of the transverse mass moment of inertia of the vessel resulting from applying the breakdown methodology in the different loading conditions and its displacement and roll gyradius, are also shown.

Table 2: Dry inertia of load items considered in the breakdown methodology.

		Loading condition 1	Loading condition 2	Loading condition 3	Loading condition 4
Dry Inertia ($t \cdot m^2$)	Steel	3515.80	3515.50	3520.84	3570.04
	Tanks	485.73	178.80	53.43	47.93
	Fishing gear	71.473	71.71	69.40	63.17
	Main engine	8.863	8.928	8.292	6.62
	Ice in hold	11.48	0.00	0.00	0.00
	Fish boxes	2.30	0.00	0.00	0.00
	Fish cargo in hold	0.00	292.89	262.49	35.69
	Supplies	1.94	1.90	2.35	4.19
	Nets	346.03	344.64	358.85	404.99
Total dry Inertia I_{xx} *($t \cdot m^2$)*		4443.61	4414.44	4275.66	4132.53
Δ *(t)*		492	489	465	411
k_{xx}/B		0.376	0.376	0.379	0.396

In order to check the correctness of these results, data from a roll decay test, together with those from the inclining experiment, were used to determine the vessel mass moment of inertia (including added inertia). From this test, natural roll frequency was obtained; added mass was estimated applying a strip theory code, and the dry mass moment of inertia of the vessel was subsequently computed. The obtained results are shown in Table 3.

Table 3: Test vessel mass distribution. Towing tank tests.

Loading condition	Δ *(t)*	I_{xx} *(t·m²)*	k_{xx}/B	A_{44} *(t·m²)*
Towing Tank Tests	448	4383.60	0.391	469.26

As it can be appreciated, the values of the dry mass moment of inertia obtained applying the breakdown method are slightly different than those in the test. Likewise, the values of roll gyradius are smaller than those from tests and also than the widely used reference value of 0.40 (Krüger and Kluwe, 2008). This difference, especially in the two arrival conditions, could be explained due to the fact that in the breakdown method a more realistic distribution of the weights has being done (considering cargo in holds, tanks and other weight items), which are not present in the tested scale model.

3.2. Natural roll frequency

The results of natural roll frequency obtained in the 64 test by means of the proposed estimation method are shown in the figures 3-10, separated depending on the Froude number and in regular or irregular waves. In some tests resonance phenomena took place and it was represented by a red triangle. When resonance does not exist, it was represented by green circles. The dashed line represents the target value.

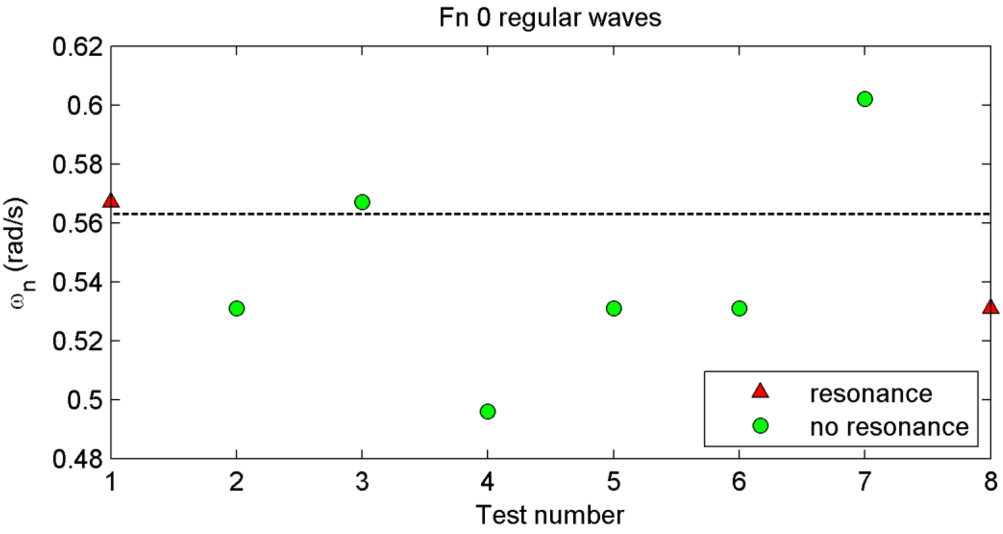

Figure 3. Results for regular waves and Fn 0.

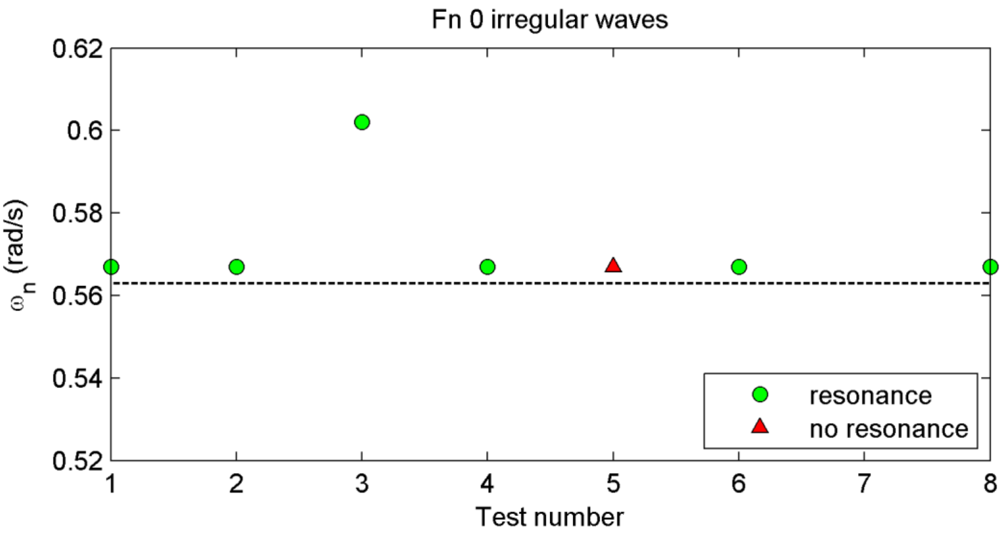

Figure 4. Results for irregular waves and Fn 0.

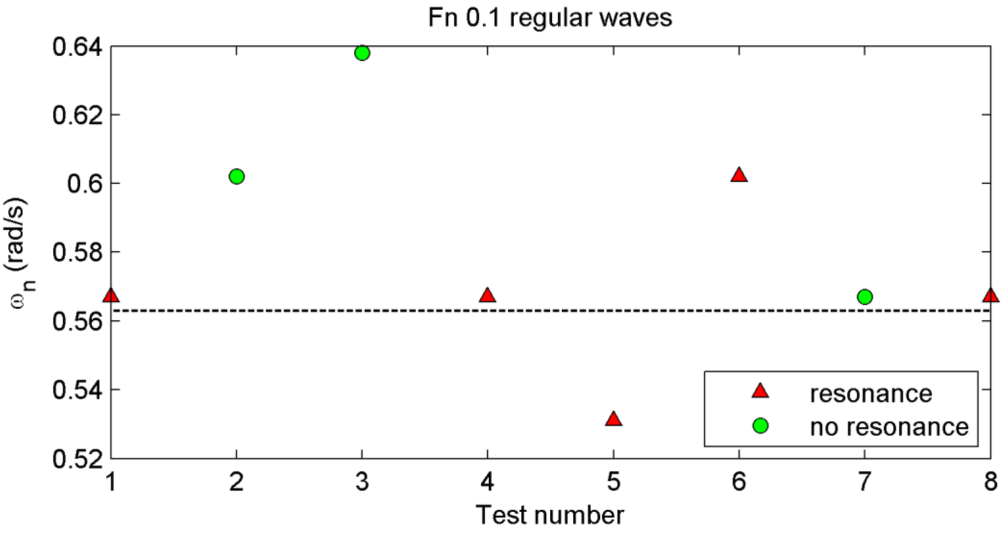

Figure 5. Results for regular waves and Fn 0.1.

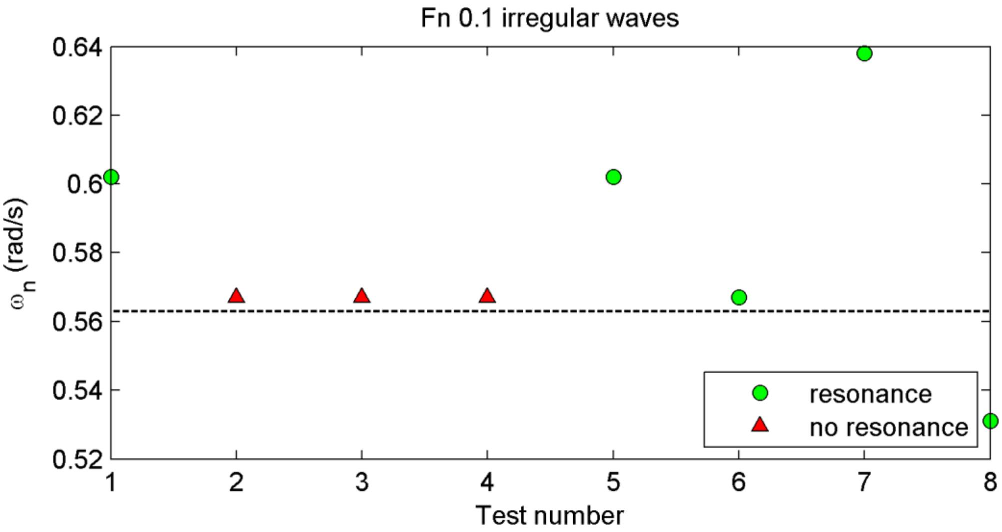

Figure 6. Results for irregular waves and Fn 0.1.

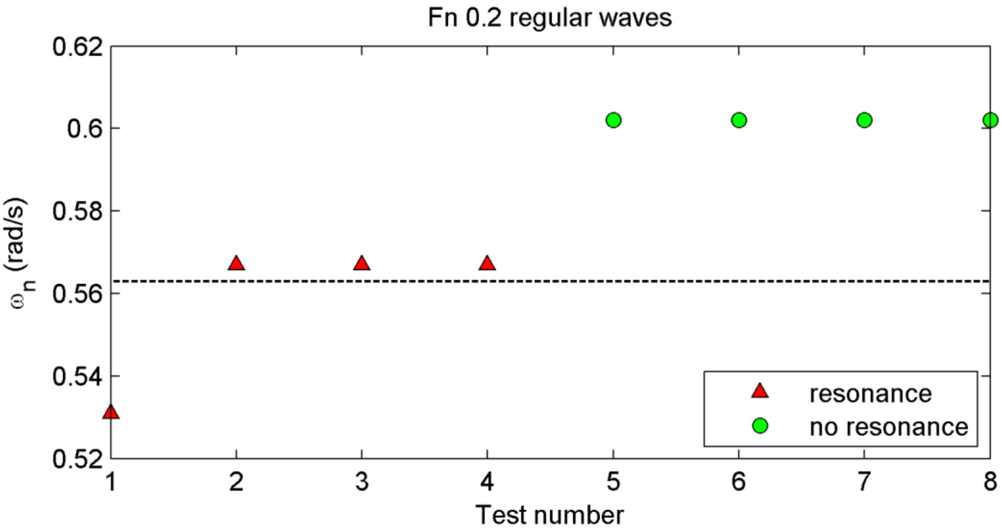

Figure 7. Results for regular waves and Fn 0.2.

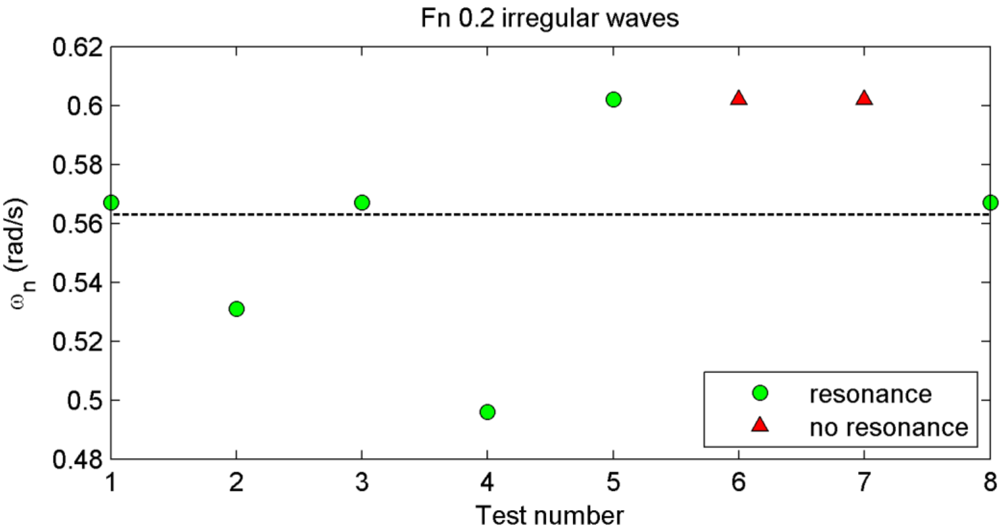

Figure 8. Results for irregular waves and Fn 0.2.

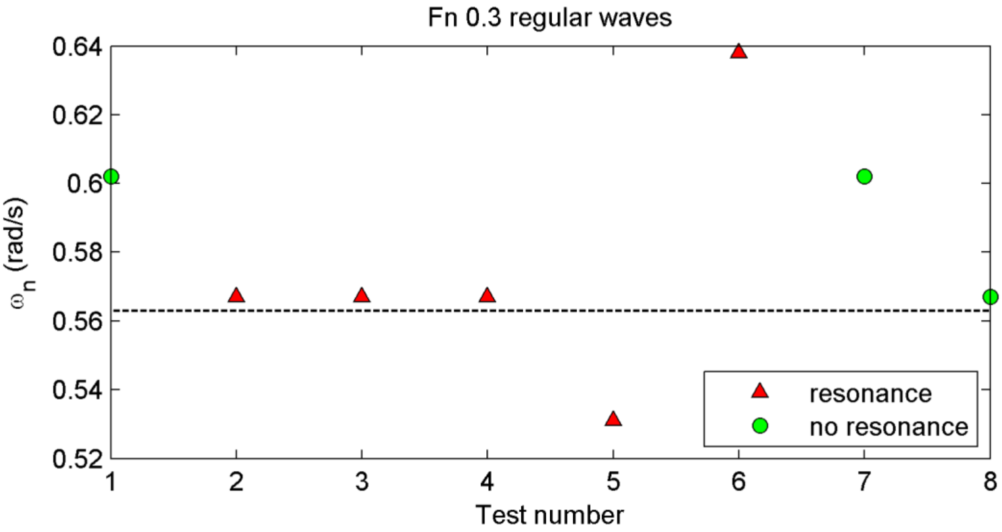

Figure 9. Results for regular waves and Fn 0.3.

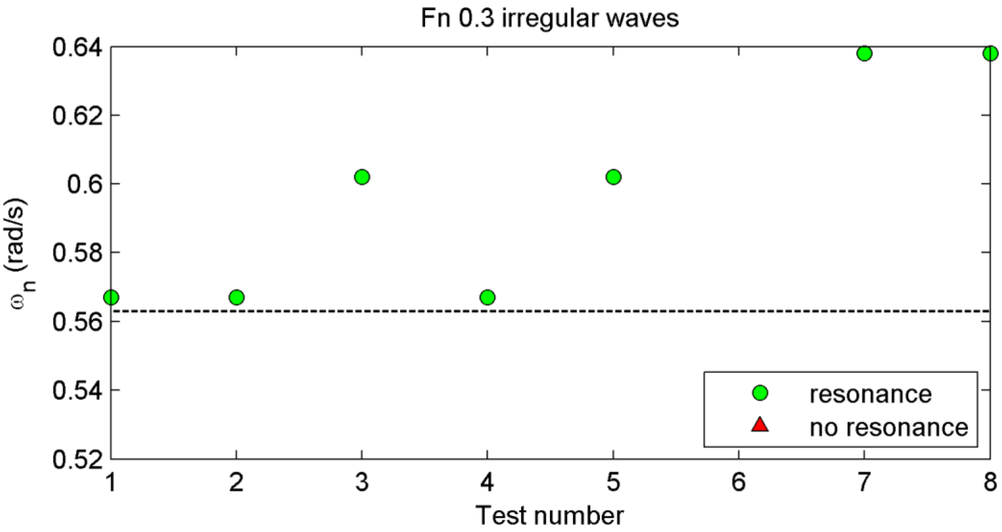

Figure 10. Results for irregular waves and Fn 0.3.

In order to see how the estimation method works and how the use of windowing affects the results of four sample cases, selected between the 64 tests already presented, are going to be explained in depth. Case 1 corresponds to Test 5 in Figure 5 and Case 2 corresponds to Test 7 in Figure 3. Both correspond to regular wave conditions, but the first one was carried out at Froude number 0.1 and the second at 0. The next two cases are in irregular waves. Case 3 is at Froude number 0 and corresponds to Test 5 in Figure 4 and Case 4 is at 0.1 and corresponds to

Test 6 in Figure 6. . The values including the use of Hanning, Blackman and Blackman-Harris windows and the estimation of GM for each case are shown in depth in Table 4.

Table 4: Natural frequency results.

	Regular Waves		**Irregular Waves**	
	Case 1	**Case 2**	**Case 3**	**Case 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

Hereunder, the graphical results in real scale of these tests are presented.

Figures 11 and 12 show the results of Case 1, a test run in regular waves where parametric resonance exists. In figure 11, the measured roll motion and the application of the window functions are presented. As it was expected, the signal is reduced to zero at the edges with windowing and its amplitude is damped. This effect is more or less pronounced depending on the type of the window used. In figure 12, the results of applying the FFT to the previous signals are included. The concentration of most of the energy of the spectrum around the natural frequency of the vessel can be seen, and is mainly due to the resonance phenomenon. Nonetheless, there is a little scattering around it, likely produced due to the discontinuities at the edges, which is less pronounced with the use of window functions.

Figures 13 and 14 show the results from another test in regular waves, but in which parametric rolling does not take place. This last fact makes that there is a greater dispersion of energy and so, another frequency peaks have been detected. Nonetheless, a good accuracy in the result is obtained.

The other tests were run in irregular waves. When there is resonance, the energy dispersion is negligible and a single peak appears in the solution (Figures 15 and 16). On the contrary, if no resonance occurs, the degree of dispersion is increased, although the frequency of the system can still be clearly identified except if windowing is applied (Figures 17 and 18).

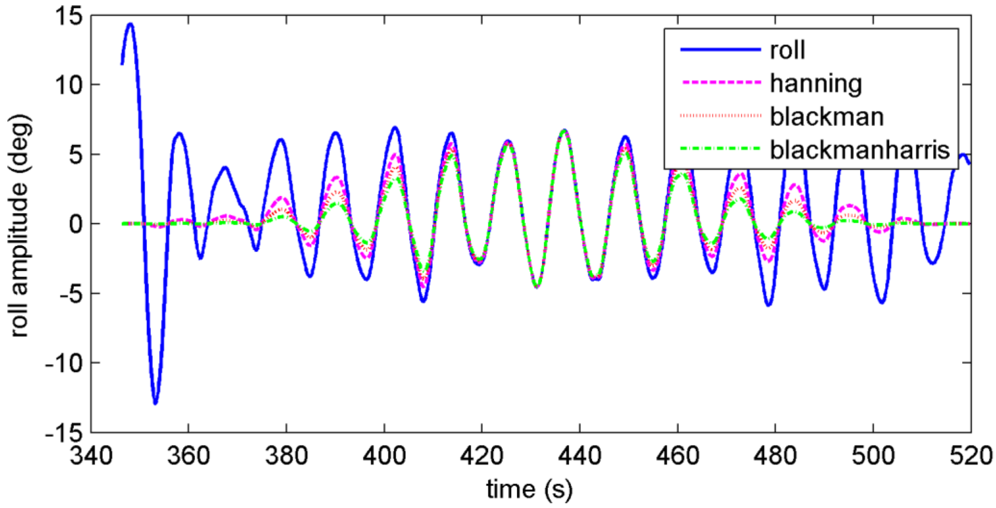

Figure 11. Case 1. Regular waves. Fn 0.1. Parametric roll occurs.

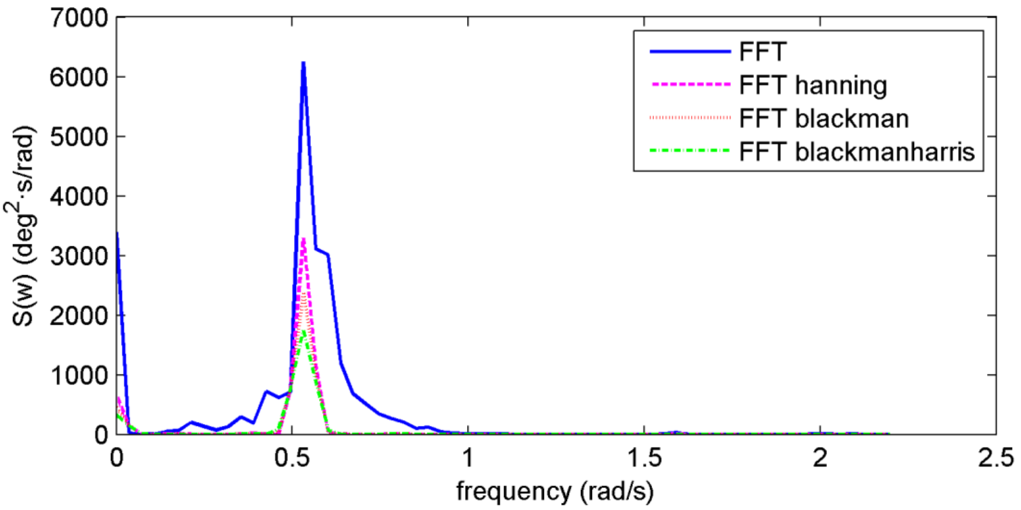

Figure 12. Case 1. Regular waves. Fn 0.1. Parametric roll occurs.

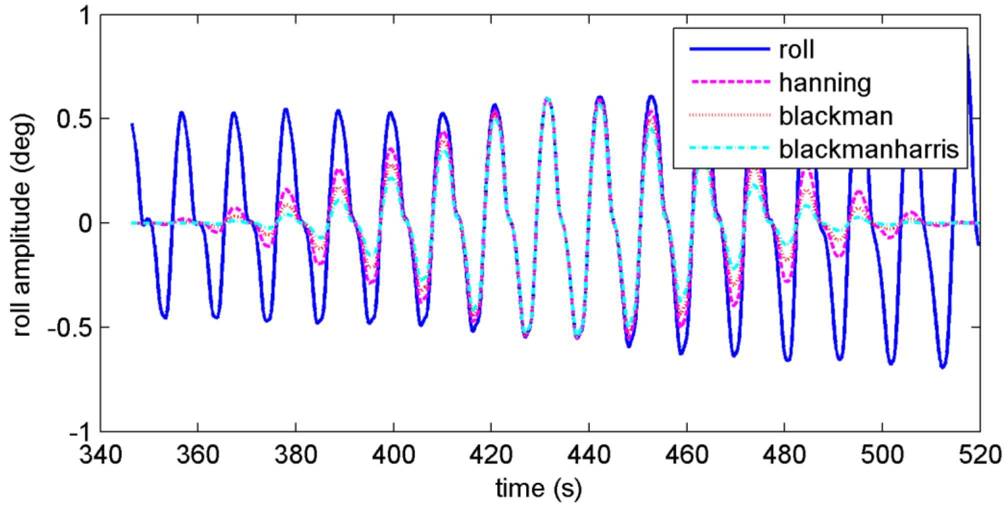

Figure 13. Case 2. Regular waves. Fn 0. No parametric roll.

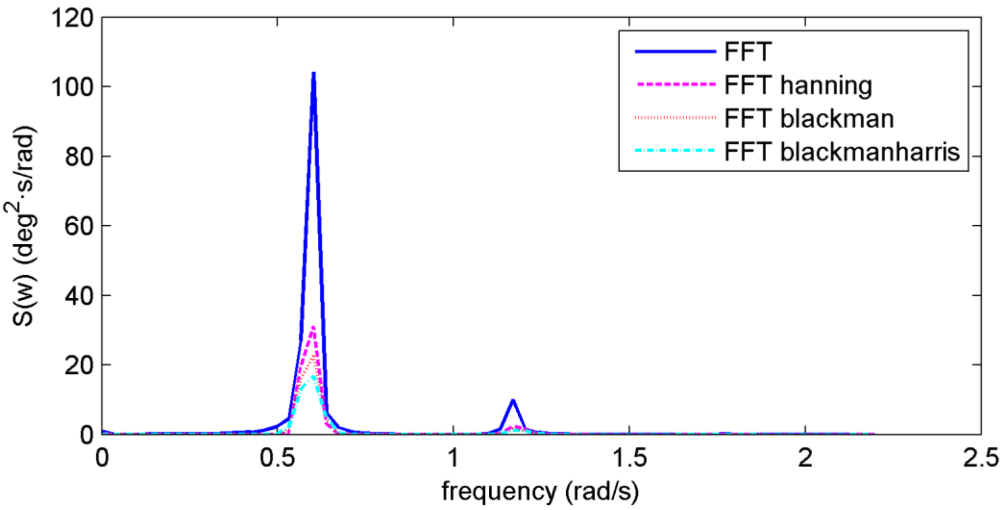

Figure 14. Case 2. Regular waves. Fn 0. No parametric roll.

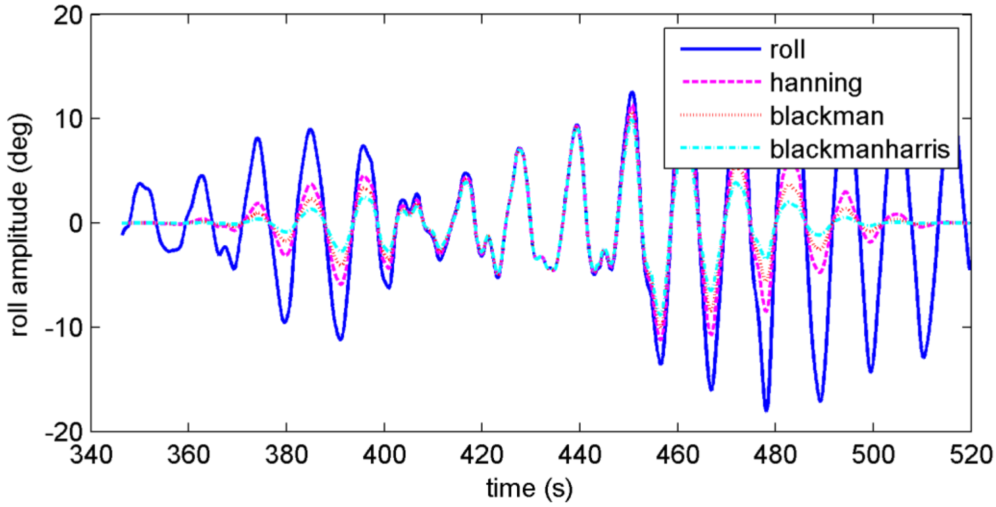

Figure 15. Case 3. Irregular waves Fn 0. Parametric roll occurs.

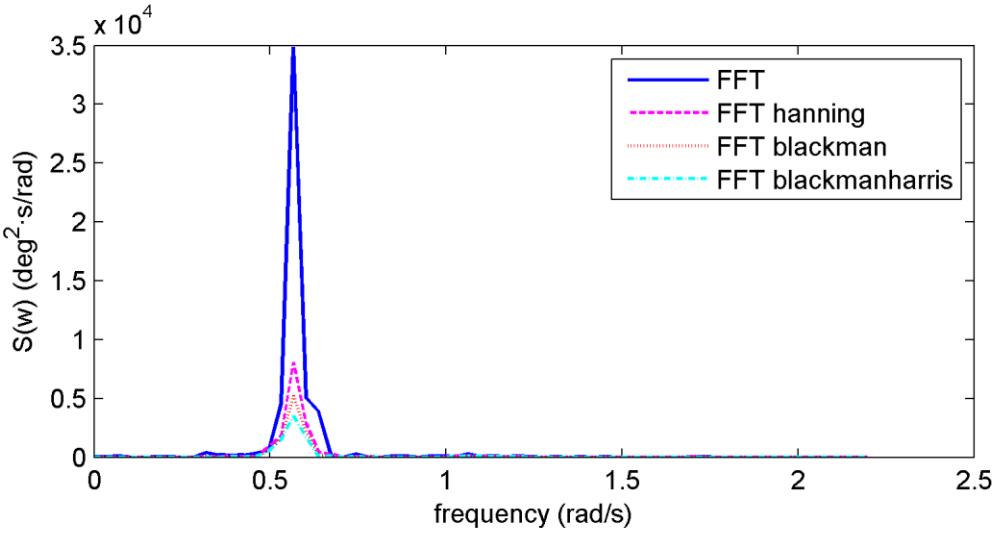

Figure 16. Case 3. Irregular waves Fn 0. Parametric roll occurs.

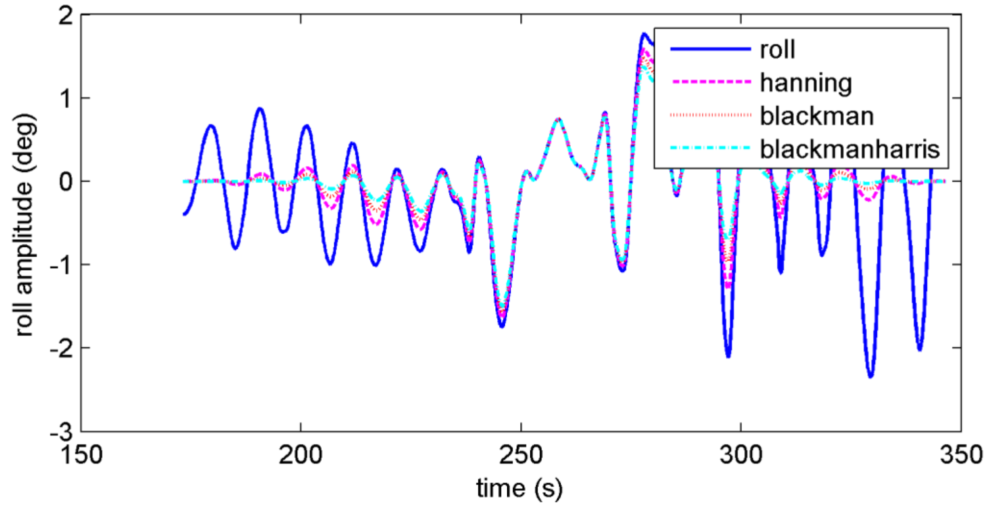

Figure 17. Case 4. Irregular waves. Fn 0.1. No parametric roll.

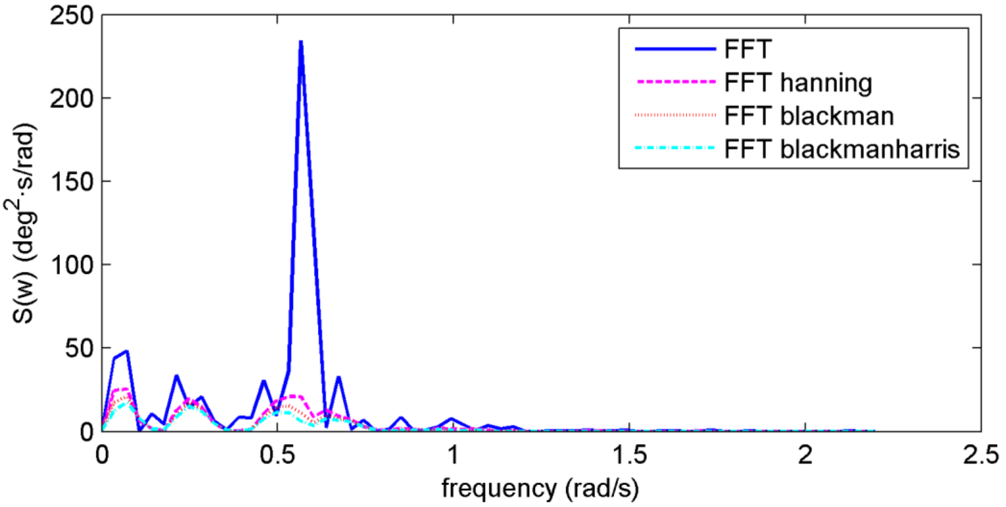

Figure 18. Case 4. Irregular waves. Fn 0.1. No parametric roll.

The values obtained in all the tests are very close to the actual value of natural frequency (ω_n = 0.563 rad/s).

The obtained uncertainty for the different values of estimated natural frequency for both windowed and non-windowed cases are shown in Table 5.

Table 5: Uncertainties in percentage of Nominal Level Units.

Uncertainty source	Systematic Standard Uncertainty (b)	Random Standard Uncertainty ($S_{\bar{X}}$)	U_{95} ±
ω_n	1.857%	0.713%	3.978%
$\omega_{n\ hanning}$	1.230%	5.426%	11.128%
$\omega_{n\ blackman}$	0.252%	2.373%	4.773%
$\omega_{n\ blackman\ harris}$)	0.043%	2.554%	5.108%

The uncertainty results do not exceed the 5% except in one case, so the results could be considered to be satisfactory. The application of window functions showed no improvement in the obtained results, being the best estimation the one obtained by the direct application of the FFT and the use of no windows.

3.3. Metacentric height

In this section, the GM values which correspond to the natural roll frequency values previously estimated, will be obtained, including the corresponding error propagation analysis.

The GM values corresponding to the natural frequencies obtained from the time series analysis, which are shown in Table 5, have been calculated by using the real value of the mass moment of inertia and displacement which were determined in the towing tank tests of the vessel.

If the error propagation is applied to equation (3), the values of the partial derivative terms are:

$$\frac{\partial GM}{\partial \omega_N} = \frac{2\omega_N I}{\Delta g} = 1.143 \tag{12}$$

$$\frac{\partial GM}{\partial I} = \frac{{\omega_N}^2}{\Delta g} = 7.470 \cdot 10^{-5} \tag{13}$$

$$\frac{\partial GM}{\partial \Delta} = \frac{-{\omega_N}^2 I}{\Delta^2 g} = -7.310 \cdot 10^{-4} \tag{14}$$

As it can be seen only the first partial derivative has a real influence in the solution, being the rest of partial derivatives negligible. In conclusion, the relative error in the GM estimation only depends in the uncertainty of the roll natural frequency.

As it can be seen, the weight on the solution only remains in the first partial derivative, so only the uncertainty in the natural frequency has a real influence on the *GM* result. Neglecting the rest of partial derivatives, the relative error in the *GM* estimation is 7.951%.

If we use the Weiss formula to calculate the uncertainty of the metacentric height, the partial derivative terms become:

$$\frac{\partial GM}{\partial k} = \frac{2k\omega_N}{g} = 0.214 \qquad (15)$$

$$\frac{\partial GM}{\partial \omega_N} = \frac{2k^2\omega_N}{g} = 1.196 \qquad (16)$$

And the uncertainty value obtained in this case is 8.163%.

4. DISCUSSION

The proposed methodology to obtain the natural roll frequency has only been verified for the case of head seas. If wave direction changes, the accuracy of the method is not guaranteed because the forces acting on the vessel change with the wave angle of incidence and they could affect the results. Thus, to extend the validity of the method to any wave direction and to analyze how it performs under the different conditions it would be necessary to carry out another test campaign in which following, quartering and beam seas are included as well.

The next point of discussion is the estimation of the transverse mass moment of inertia. By the breakdown method crew interaction is still necessary. The interaction could be decreased installing a remote sounding system, but the problem remains with some items as individual load or cargo in hold. An alternative is proposed in this paper which consists in applying the Weiss formula. This approach has two major drawbacks; on one hand this value is an estimate obtained from literature. Andon the other, the gyradius is kept constant for all loading conditions. These two facts lead to a value of uncertainty that, although has to be taken into account, it is not much higher that the one observed by applying the breakdown method. The case of ship displacement is very similar to the previous one. A possible solution to avoid the need of crew interaction would be to also use the Weiss formula. Another possibility would be installing a draft monitoring system.

5. CONCLUSIONS

An alternative to overcome some of the drawbacks of the stability guidance systems for small and medium sized fishing vessels has been presented in this paper. The goal is to avoid or to minimize the crew interaction with the system, applying a methodology to obtain ship's initial stability in real time.

In order to compute the metacentric height, the natural roll frequency has been estimated applying a spectral analysis based on FFT to a group of roll motion time series from a towing tank test campaign in head seas. The results show a good agreement with the real values, considering that the uncertainty in the estimations is less than 10%. Three types of windowing alternatives (Hanning, Blackman and Blackman-Harris) have been employed to try to improve the accuracy of the estimation, with no success.

The transverse mass moment of inertia has been obtained by two different ways. The first one consisted in breaking down the ship in her main load items. Data from these items have to be manually introduced in the system by the crew. The second one consist on using the Weiss formula to estimate the inertia, thus avoiding the need for any crew interaction. This second option induces a little more error, but still the results remain satisfactory. The estimation of ship displacement has been tackled in a very similar way. The crew interaction issue may be overcome installing remote sounding systems and draft monitoring systems. However, and considering the three initial premises of these simplified stability guidance systems, this is not a feasible option.

In conclusion, the best option seems to be use the Weiss formula in the estimation of metacentric height, at least in the case of head seas.

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