Quantitative Assessment of Ship Behaviour in Critical Stern Quartering Seas

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Abstract: Following and stern quartering seas, combined with a relatively high speed of vessel, represent the operational conditions which may lead the ship to dangerous situations in adverse weather. Recently, IMO efforts were addressed to the development of the Second Generation Stability Criteria, based on three different safety levels.

The third level requires a direct assessment of ship stability, based mainly on numerical simulation of ship motions in waves. The numerical simulation tool is expected to reproduce vessel dynamics, in order to allow detailed design analysis when assessing ship safety.

The proposed paper presents an application of the numerical model called LaiDyn to the investigation of ship large amplitude motions, in critical conditions typical for a conventional RoPax vessel.

LaiDyn is a six-degree of freedom dynamic model, in time domain, that works on a discrete representation of the hull, using panels. The non-linear restoring generalized forces and the Froude-Krylov wave loads are evaluated, at each time, on the instantaneous ship wetted surface. Radiation and diffraction forces are derived using linear model. The ship resistance and the propeller thrust are also implemented into LaiDyn.

For the purpose of the numerical applications, stern quartering irregular sea is assumed.

Key words: Ship stability, roll resonance, parametric rolling, dynamic simulation.

1. Introduction

The need to upgrade the General Stability Criteria led to a revision of the Intact Stability Code [1], trying to focus more on ship dynamics, with particular emphasis on nonlinear aspects. The so-called Second Generation of Intact stability criteria have been planned to have a multi-tiered structure consisting of three levels [2]. The criteria in level 1, named vulnerability criteria consist of relatively simple methodologies to be applied at the very preliminary phase of the stability assessment in the design process. If a possible vulnerability is detected, then the vulnerability second level criteria are used, referred also as severity criteria.

The final third level, to be applied in case of failure of the previous ones, is called direct assessment, based on numerical simulation tools or, as alternative, experimental tests.

Stability criteria should address three fundamental modes of stability failures [3]: restoring arm variation problems, (such as parametric excitation and pure loss of stability), stability under dead ship condition and maneuvering related problems in waves (such as broaching-to).

Despite several research works dealt with various proposals for the first two levels regarding the several stability failures [4] [5] [6] [7], the third one is still under development.

Direct assessment procedures for stability failure are intended to employ the most advanced state-of-the art technology available being sufficiently practical to be uniformly applied, verified, and validated [8].

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The numerical simulation tool is expected to reproduce vessel dynamics, in order to allow detailed design analysis when assessing ship safety [9]. Moreover, simulation is expected to provide ship-wise guidance for a safe operation also in adverse sea conditions. The operational limitations came out during SLF 55 [10], with the proposal to use operational limitations if the ship fails to comply with the second level vulnerability criterion.

Some proposal for simulation tools to be used for the direct assessment criteria have been developed by several authors [11] [12] [13] [14], regarding parametric rolling analysis.

Parametric rolling is perhaps the most complicated phenomena to understand and manage by officers onboard, partly because it may lead to a sudden heavy roll, from nowhere, in otherwise apparently calm and controllable conditions.

The proposed paper presents an application of the numerical model called LaiDyn to the investigation of ship large amplitude motions, with particular attention to the parametric rolling resonance in stern quartering sea. Following and stern quartering seas, combined with a relatively high speed of vessel, represent the operational conditions which may lead the ship to dangerous situations in adverse weather [15] [16].

LaiDyn is a six- degrees of freedom dynamic model, in time domain, that works on a discrete representation of the hull [17] [18] [19]. The ship resistance in still water and the propeller characteristics are also implemented into LaiDyn, while the ship resistance due to the wave pressure, is computed during the simulation.

Ship speed is obtained by taking into account the propeller behavior in waves; this allows performing a more realistic simulation of ship operational conditions. In the following sections a brief description of LaiDyn architecture is presented, with particular attention on the propeller implementation.

Experimental tests and numerical simulations for a turning circle manoeuvre, in irregular long-crested waves, are carried out and the results by the two different approaches are compared. This investigation is intended to qualitatively validate LaiDyn result, by checking ship rolling behaviuor for several encounter frequencies.

For the purpose of the applications, stern quartering irregular sea is assumed by means of JONSWAP spectrum. The operational conditions that yield to resonant roll motion and to parametric rolling are identified and then analyzed through the simulation.

2. The LaiDyn Simulation Code

The LaiDyn code has been developed for the ship dynamics in waves; the ship is regarded as a rigid intact body.

It could be defined as a hybrid non-linear simulation model in six- degrees of freedom in time domain, for regular and irregular seas.

Wave action on ship hull is represented by two components: the so-called Froude-Krylov component and the so-called diffraction component. The former is evaluated by integrating the pressure over the wetted portion of hull surface. In the linear approximation the integration is conducted up to the still water level and a steady ship motion is assumed. The non-linear model, implemented in LaiDyn, allows instead six-degrees-of-freedom for ship motions. The same non-linear approach is applied in computing the hydrostatic actions.

The diffraction component takes into account the disturbance caused by a ship to oncoming wave. The diffraction actions are evaluated instead according to the linear model for small amplitude oscillatory motions. Radiation forces, i.e. added mass and damping terms come out from the same linear model.

LaiDyn implements also rudder actions, allowing to simulate manoeuvring tasks [18].

The main coordinate systems used for describing ship motion are presented in Fig.1, i.e the inertial system fixed to Earth, with the X-Y plane coincident with the still water level, and the body-fixed reference frame having its origin at ship center of gravity.

For more details about the code, please refer to the following papers [17] [18].

2.1 Propeller Model

There are two ways to model ship resistance and propeller action. The simplest way is to assume that resistance and thrust are of the same magnitude and do not change. The other model takes into account the resistance with an operating propeller.

One of the main goals achieved by LaiDyn is the capability to simulate the ship operational condition taking into account the ship velocity given by the propeller behavior, together with ship resistance in wave.

The code gives the possibility to implement several kinds of propellers as: fixed pitch or controllable pitch propellers and podded propulsion system. The following elaboration refers mainly to fixed pitch propeller, used for the carried out applications.

For still water condition, the thrust that the propellers have to supply for keeping the ship at the operational speed V is given by:

$$X_{resistance} = -R_T/(1-t) = -0.5\rho u^2 S C_T/(1-t) \tag{1}$$

where R_T is the total resistance, t is the thrust deduction factor, S is the wetted surface and u is the forward velocity of the ship in the body-fixed co-ordinate system.

The total resistance coefficient C_T is given in tabular form as a function of Froude number.

The total thrust provided by the propellers is evaluated from a known open water characteristic of the propeller, $K_T = K_T(J)$, as follows:

$$X_{prop} = Z\rho n^2 D^4 K_T \tag{2}$$

where J is the advance number, Z is the number of the propellers, n is the propeller revolutions per second and D is the propeller diameter.

The required propeller revolution, for still water and constant forward speed, is set in order to obtain the condition:

$$X_{prop} = X_{resist} \tag{3}$$

The propeller characteristic curve $K_T(J)$, in the application model, has been assumed and implemented as a linear function.

$$X_{prop} = \frac{P_D \eta_0 \eta_R}{V(1-w)} \tag{4}$$

Keeping in mind that X_{prop} depends on propulsion power P_D, according to (4), it may happen to have unrealistic high thrust values at low speed. The terms η_0 and η_R that figures in (4) are respectively the open water and the rotational efficiencies of the propeller, while w is the wake fraction.

The maximum attainable thrust of a propeller, known as the bollard pull, is evaluated and checked by applying:

$$T = 0.5\rho \frac{\pi D^2}{4}\left(\frac{16 P_D}{\rho\pi D^2}\right)^{2/3} = \sqrt[3]{\frac{\rho\pi}{2}}\left(P_D D\right)^{2/3} \tag{5}$$

Once the initial propeller set up in still water is made, the simulated ship dynamics in waves will affects also propeller behavior.

Propeller actions are expressed in body fixed reference frame and move with the hull (see Fig.1). If the propeller, due to ship motions and wave profile, is instantaneously out of the water, its thrust is set as zero. Moreover, when evaluating thrust, the kinematics of water flow in waves are taken into account.

Added resistance in waves is evaluated as a result of dynamic pressures forces, acting on the wetted panel on the ship, projected on x-direction.

There are two possible approaches to deal with the ship resistance in wave: one possible way is to keep the revolution, set for the still water conditions, as constant. In this way the added resistance in wave will reduce the initial ship speed according to (3).

In order to keep the desired velocity as constant, a different approach can be used. It consists of introducing a feedback control law on the ship speed, adjusting the revolutions during the simulation. For the purpose of the application a simple proportional controller is used.

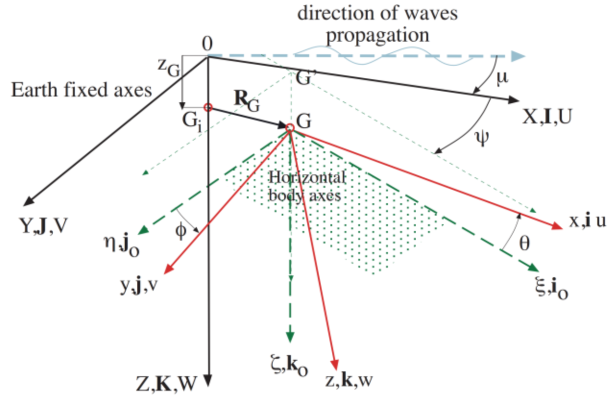

Fig. 1 – Co-ordinate systems used in ship dynamics

3. Roll Resonance in Quartering Sea

Parametric rolling is a critical phenomenon that leads ship, under certain conditions, to quickly develop large roll amplitudes, due to parametric excitations. Hulls with large bow and stern flare, such as container and Ro-Ro vessels, are especially sensitive to this phenomenon: this is link to the significant variation of the metacentric height in waves.

Ordinary linear strip theory in the frequency domain does not capture this phenomenon. One of the possible ways of predicting and assessing parametric rolling is by means of nonlinear simulation model in the time domain.

A ship can experience resonance between the natural period of roll and stability variation if the wave encounter period is half (or less critical, equal to) the roll period [7].

Parametric roll is a resonance phenomenon but it is distinct from "normal" resonance between external periodical forces and natural period of the system, characterized by $T_e{=}T_n$ [20].

Parametric roll resonance for a ship is driven out by the variation in time of the restoring moment, usually expressed as change of the metacentric height (GM) in wave, together with low roll damping and high wave amplitude. The resonance between stability variation and ship's natural period of roll requires $T_e{=}0.5T_n$. It is clear that this kind of unstable behavior cannot be predicted by applying linear analysis.

Linear method, assuming a constant GM value, can instead predict roll resonance but only a non-linear simulation would give a quantitative assessment of ship behavior in that condition. In particular the roll resonance in stern quartering sea coupled with the variation in time of the restoring actions in wave, would lead to unexpected higher amplitude rolling motions.

The applications of LaiDyn code have been performed on a modern fast twin-screw Ro-Pax vessel, named SeatechD, whose main characteristics are shown in Table 1.

Table 1 Main particulars of the vessel SeatechD

	Full Scale	Model Scale
L (m)	158.0	4.049
B (m)	25.0	0.123
T (m)	6.1	0.156
D (m)	15.0	0.384
∇ (m^3)	13766	0.232
S (m^2)	4356	2.860
C_B	0.571	0.571

An extensive experimental research study was carried out at the Ship Laboratory of the Helsinki University of Technology on SeatechD model (see Fig.2), concerning with the dynamic stability.

Fig. 2 – SeatechD model

These model test series allowed validating LaiDyn regarding pure loss of stability and parametric roll resonance in regular and irregular waves [21] [22].

In irregular seas, as the roll response is very sensitive to the period of excitation, only the part of the encountered wave spectrum that coincides with the natural period of roll will be effective.

In order to evaluate an approximate value of the mean period of the encountered waves, the following formula can be used:

$$T_e = \frac{T_1}{1 - 2\pi V \cos\mu/(gT_1)} \qquad (6)$$

The inception of parametric roll depends on the frequency of encounter being in the frequency range where the parametric roll is possible [4]. Therefore, the development of parametric roll depends on speed and heading.

According to (6) it is possible to tune velocity and heading of the vessel in order to get an encounter period that would lead to parametric roll. This analysis set the initial condition of the simulated cases in LaiDyn.

3.1 Turning circle manoeuvre

Experiments and simulations regarding a turning circle manoeuvre in irregular long-crested waves were conducted, in order to observe the ship rolling behaviuor for several encounter frequencies, checking the agreement of the LaiDyn responses with the experimental ones.

The model tests were carried out on the SeatechD model in the multifunctional model basin of Aalto University.

The turning circle tests were run with selfpropelled and radio-controlled model, in irregular waves, given by the Jonswap-type wave spectrum; the significant wave height and the average period were assume respectively H_S=4.8 (m) and T_1=5.9 (s). The speed of the model, with a target value of V_S=16.5 (kn) in full-scale, was controlled manually by adjusting the revolutions of propellers.

The height of Center-Of-Gravity for the model was adjusted to obtain a natural roll period close to its natural rolling period. In performing the turning circle, this creates a dangerous situation of roll resonance in stern quartering seas.

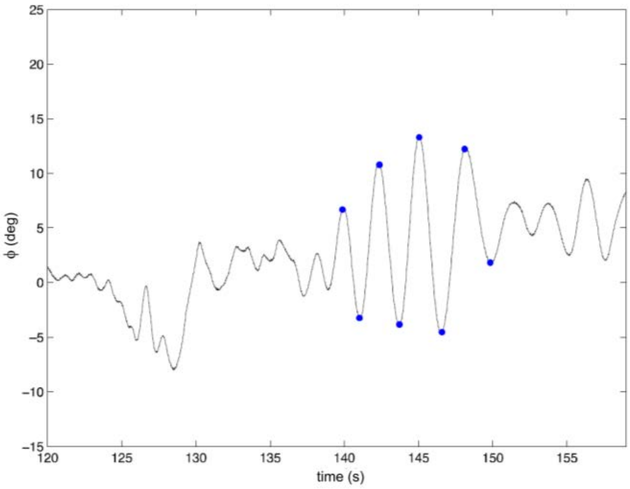

Fig. 3 – Experimental turning circle sample

A sample of the roll motion in turning circle manoeuvre, measured for a single realization of irregular waves, is presented in Fig. 3; roll motions develop in stern quartering seas as an unfavourable effect of change in encountered frequency. The simulated maxima and minima of roll amplitude, for the critical encounter condition, are marked with blue dots; peak-to-peak roll angles exceed 8°.

The simulated ship motion, corresponding to the condition of the model test, was obtained by means of LaiDyn, for a qualitatively comparison of the results. The numerical simulation of the turning circle test is presented in Fig.4. As can be noticed, roll motion, obtained from the same wave spectrum, but for a different wave realizations, develops according to the behavior of the experimental result, showing simulated maxima close to the measured ones.

More details, about the turning circle manouvre investigation, can be found in [18].

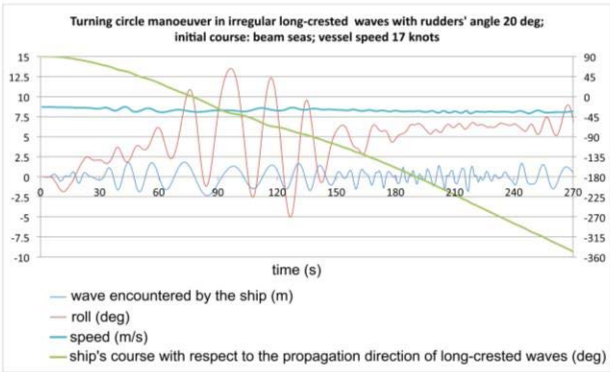

Fig. 4 – Simulated turning circle sample

4. Application and Results

The numerical applications carried out on SeatechD model regard roll resonance, with T_e=T_n and parametric roll resonance with T_e=0.5T_n.

The simulation was performed by assuming a stern quartering irregular sea, described by the JONSWAP spectrum of significant wave height H_S=4.6 (m) and mean period T_1=6.5 (s).

The critical resonant situation were tuned, based on the considerations explained in the previous section (see Table 2).

Table 2 Simulated Conditions in LaiDyn

Case	Speed (m/s)	Heading (deg)	Encountered period (s)
1	8.5	42	16.3
2	8.5	22	22.6
3	5.65	42	11.8
4	2.85	42	9.3

In Fig.5 the results obtained from the application of the LaiDyn code to the Case 1 are shown.

The whole time history of ship motions is presented. Focusing on the rolling motion it is possible to observe the resonance that lead to large roll amplitudes.

Moreover, Fourier analysis of the encountered waves was conducted and the results are presented in Fig.6. It is possible to notice an interesting feature of the encountered waves: compared to the stationary spectrum, the amplitude of the encountered wave changes while the period of the wave train seems to be nearly constant. Its mean value is close to the natural roll period of the ship, as expected by applying (6).

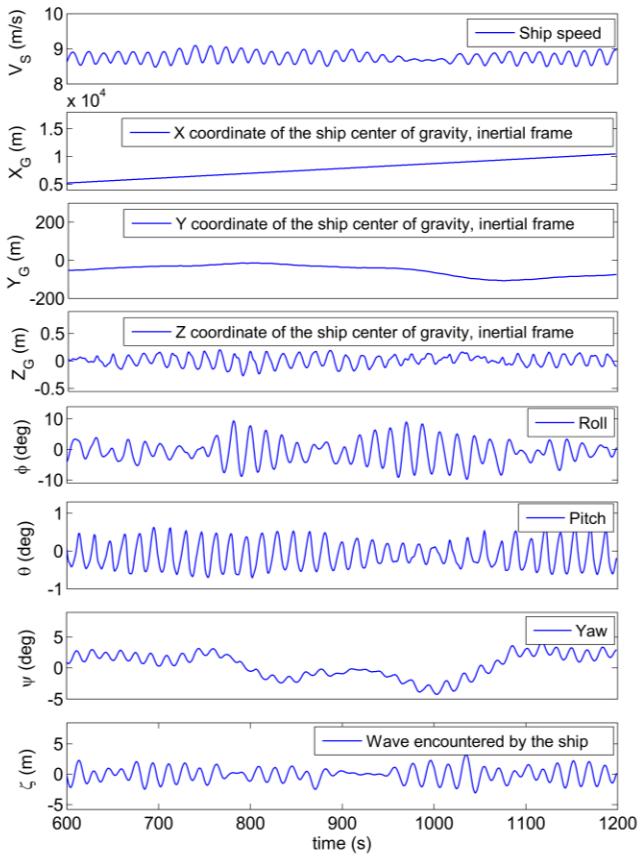

Fig. 5 – Time History of Ship Behavior for Case 1

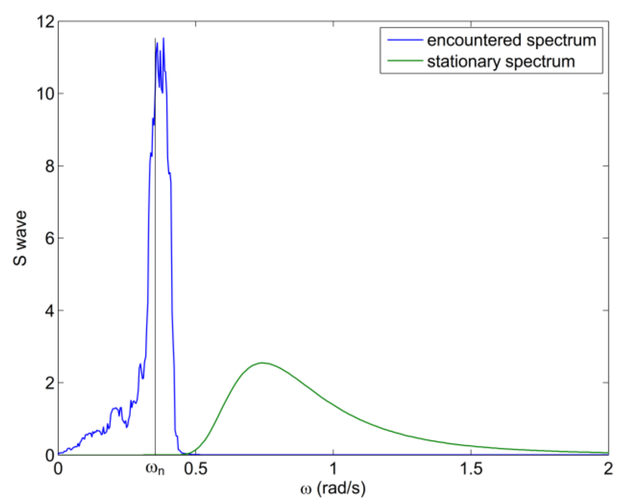

Fig. 6 – Spectral Analysis of irregular sea for Case 1

Further simulations, named Case 2 and Case 3 (see Table 2), were carried out with LaiDyn in order to drive the ship out of the resonant condition, by changing respectively the heading and the speed.

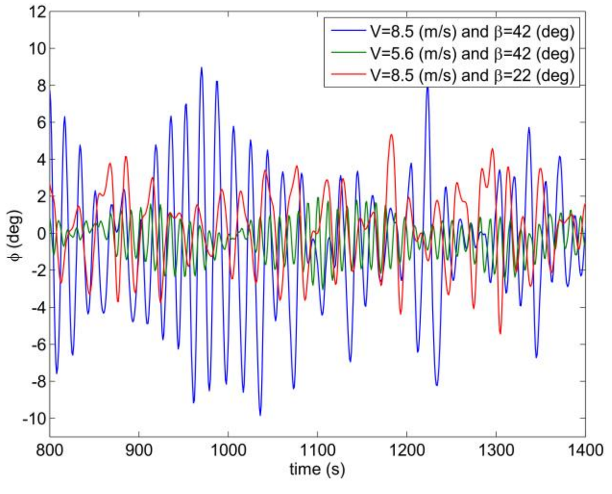

Fig. 7 – Roll Response Comparisons

The main results are shown in Fig.7, where the rolling responses for the three cases are compared.

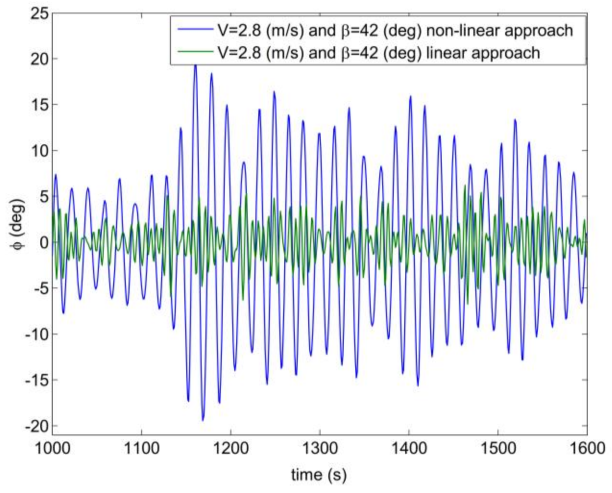

Fig. 8 – Simulated Parametric Roll

As could be noticed, the rolling motions are significantly mitigated, out of the resonant region, in particular for the reduced speed case.

For the Case 4 simulation, with lower speed and with $T_e \approx 0.5 T_n$, the phenomenon of parametric rolling can be easily observed in Fig.8. The parametric resonance was checked by means of the spectral analysis and reported in Fig.9.

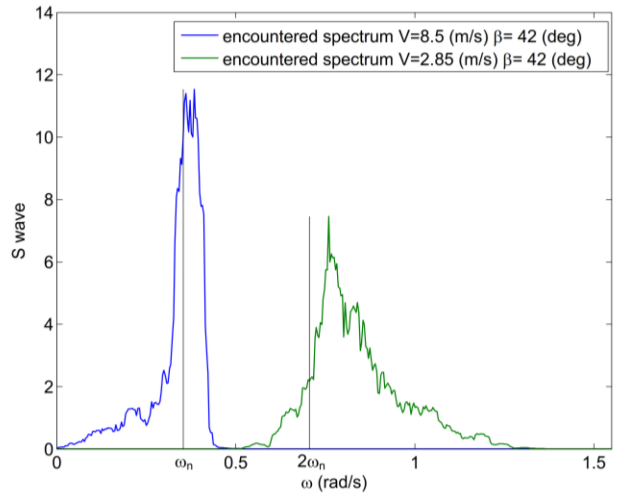

Fig. 9 – Spectral Analysis with resonance frequency

Due to the lower speed of the vessel, the decreased effects of the rolling damping, together with the parametric resonance, lead the ship to larger amplitude rolling motions (see Fig. 8). Moreover the showed results confirm that the linear analysis is not capable to simulate parametric resonance.

From the application of the numerical simulation it is possible to notice that the parametric rolling started for a lower value of T_e, compared to the theoretical value, in terms of frequencies, of $\omega_e \approx 2\omega_n$.

6. Conclusions

In this study a proposal, regarding direct assessment numerical tool, for stability failure, was presented. The numerical simulation tool is expected to reproduce vessel dynamics and provide ship-wise guidance for a safe operation also in adverse sea conditions.

The non-linear numerical model in six- degrees of freedom, LaiDyn was briefly presented and applied to simulate roll resonance in stern quartering irregular waves.

The simulations were performed by assuming a stern quartering irregular sea, described by the JONSWAP spectrum and critical resonant situations were tuned by means of speed and heading.

In order to allow a more realistic simulation of ship operational conditions, the ship speed was obtained by taking into account the propeller behavior in waves.

The applications were carried out on a Ro-Ro vessel. The roll resonance, with $T_e = T_n$ and parametric roll resonance with $T_e = 0.5T_n$ were simulated in time domain. The same ship was also used, in previous research works, to validate LaiDyn, by means of experimental test, regarding pure loss of stability and parametric roll resonance in regular and irregular waves.

Fourier analysis of the encountered waves was conducted and the results analyzed. For the roll resonance condition, with $T_e = T_n$, a large amplitude rolling motions were observed in time domain. From the spectral analysis it was possible to notice that the encountered waves spectrum, presented its mean value close to the natural roll period of the ship.

The application of the numerical simulation on parametric rolling, with $T_e \approx 0.5T_n$, for a lower speed and thus for a lower damping condition, showed larger rolling motions. By means of the spectral analysis it was also possible to observe that the parametric rolling started for a value of T_e, a somewhat lower than the theoretical value.

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