Identification of a conservative spreading angle to realize operational roll polar plots

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ABSTRACT

The spreading angle of a sea state is a common input value in time domain simulations. It is hardly operationally evaluated from the bridge. However, it has a direct influence on the ship motion. Therefore, it is necessary to specify it as accurately as possible when conducting simulations to evaluate the vulnerability of a vessel. When building operational roll polar plots, a unique value of the spreading angle is used to limit computational time. This study aims to present a method to identify the value of the most conservative spreading angle. A monochromatic sinusoidal wave and its energy are considered as references. An equivalent set of waves constituted of several monochromatic sinusoidal waves from different directions providing altogether the same energy to the vessel are built. The height of each wave is calculated considering a cos^8 spreading function such as recommended in the parametric roll assessment NR 667 (Bureau Veritas, 2019). Each resulting equivalent set of waves is validated by comparison of its implementation in a time domain solver with its analytical formula. The study is conducted by 6-degree-of-freedom simulations for a container vessel, on the reference monodirectional wave and the equivalent spread sets of waves. The comparison of roll motions leads to identify the most conservative spreading angle. Rare phenomenon such as parametric or synchronous roll are treated with special care.

Keywords: *Spreading angle, Time domain simulation, Sea state, Sinusoidal waves, Energy*

1. INTRODUCTION

Analytical sea state definition is quite complex to reflect its encountered diversity. Thus, sea states are defined by their spectrum, significant wave height and period on which their spreading function is added. The spreading function reflects how the sea state definition is spread from the main wave direction. It is associated with the spreading angle which is the angle on which this spreading occurs on either side of the main wave direction. Operationally, several wave systems may appear such as sea and swell coming from different directions. Each wave system is described by a sea spectrum, a main direction, and a spreading angle. The sea spectrum is not established by the officer of the watch. However, the wave period and height can be estimated. Further, the spreading angle is not operationally defined from the bridge; only the main direction of the wave is estimated. In these conditions, the information provided to the officers of the watch on the possible vessel roll motions based on its evaluation of the sea state are to be the most conservative. Therefore, when evaluating the vessel seaworthiness by realizing operational roll polar plots, simulations in 6 degrees of freedom (DoF) should be conducted considering the most conservative spreading angle. Thus, the aim of this paper is to define the value of this most conservative spreading angle.

When conducting time domain simulations, the spreading is defined as the spreading angle (denoted by $\Delta\alpha$), the discrete number of considered waves directions and the associated spreading function. A conventional spreading function used is a “cos^n” function, where n = 8 such as proposed by Bureau Veritas (2019a). An increase of the number of wave directions is important because this increases the time needed for the calculation of the resulting sea state.

First the method to generate equivalent set of waves providing the same energy to the vessel is proposed and validated. The implementation of the set of waves in the time domain solver is validated by comparison with its analytical description. Then, the evaluation method of the impact of the spreading angle on the vessel roll motion is presented based on 6-degree-of-freedom simulations realized with the time domain solver Fredyn. Finally, the results are compared and discussed, and the most conservative spreading angle is identified.

2. EQUIVALENT SET OF WAVES

Definition of the reference wave

A reference wave from which other set of waves are calculated is required. A sinusoidal monochromatic wave which length is arbitrary chosen and of steepness 0.0167 is considered as a reference. The energy provided by such single wave is easily calculated using Equation (1) .

$$E_0 = \frac{1}{8}\rho g {H_0}^2 \quad (1)$$

Where E_0 denotes the energy density in J/m^2, ρ denotes the water density in kg/m^3, g denotes the acceleration of gravity in m/s^2 and H_0 denotes the wave height in m.

The energy of the reference wave is calculated, and an equivalent set of waves are built to develop the same energy.

Equivalent set of waves

A set of waves is defined as the overlay of several monochromatic sinusoidal waves of different height coming from several directions.

Method

This section presents how to calculate the equivalent set of waves for any spreading angle. The energy provided by the reference wave has to be distributed to each wave component of the set of waves. The number of directions (denoted by N) is calculated depending on the spreading angle ($\Delta\alpha$) to obtain a maximum spacing of 10 degrees between two waves (N shall be odd to keep a wave component in the main direction). The resulting wave spacing (denoted by $\delta\alpha$) is calculated using Equation (2). As an example, for a spreading angle of ± 30 degrees, N equals 7 and $\delta\alpha$ equals 10 degrees. The main direction is identical to the direction of the reference wave and the other waves directions are calculated relative to this main direction, using the spreading angle and the number of considered directions.

$$\delta\alpha = \frac{2\Delta\alpha}{N-1} \quad (2)$$

The energy of the reference wave E_0 (Equation (1)) is distributed in the N directions based on a cos^n spreading function (Bureau Veritas, 2019b). Thus, N areas are defined within the space ± π/2 under the cos(x)^n function. The sum of the N areas is considered to be equivalent to the total energy E_0. Each area is associated to its main direction (denoted by α_i in radians, where i defines the wave number) and to its percentage χ_i of the total area (Equation (3)).

$$\chi_i = \frac{A_i}{A_{tot}} \quad (3)$$

Where, A_i denotes the associated area to the i^{th} direction, A_{tot} denotes the area total from - π/2 to π/2.

Figure 1 provides a graphic representation of the areas to consider associated to the wave's directions (main wave direction equals 0) for a spreading angle of ± 30 degrees and 7 waves directions ($N = 7$) with a cos^8 spreading function.

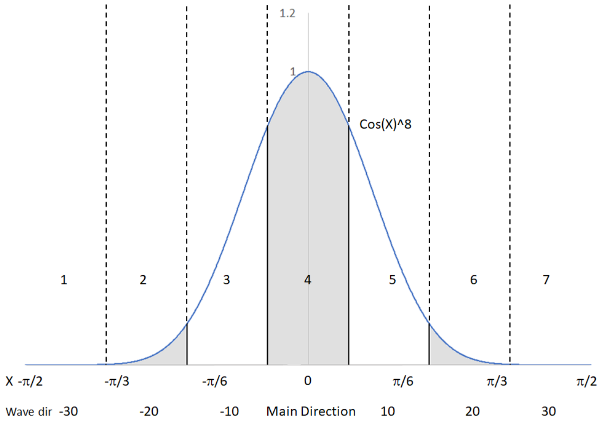

Figure 1: Energy distribution

A monochromatic sinusoidal wave of length equal to the one of the references and of height H_i is associated to each wave direction α_i. The wave height H_i is calculated considering the energy partition (Equation (4) and (5)).

$$\chi_i E_0 = \frac{1}{8}\rho g {H_i}^2 \quad (4)$$

$$H_i = \sqrt{\frac{\chi_i E_0}{\frac{1}{8}\rho g}} = \sqrt{\chi_i} H_0 \quad (5)$$

Therefore, the total energy developed by the equivalent set of waves (composed of N waves) is equal to the energy of the reference wave.

Analytic description

An analytic description of the wave system is required to validate the simulated set of waves. A native wave phase angle is programmed in the time domain solver Fredyn. This native phase angle (denoted by γ) is reintroduced in the analytic description of the free water surface (denoted by η) in a cartesian system (x; y), which is provided in Equation (6).

$$\eta(x;y;t) = \sum_{i=1}^{N} \frac{H_i}{2} cos(kx\,cos(\beta_i) + ky\,sin(\beta_i) - \omega t - \gamma_i) \tag{6}$$

Where, β_i denotes the wave direction of the i^{th} wave from the main direction, k denotes the wave number (rad.m^{-1}, same value for each direction), ω denotes the frequency of the wave (rad.s^{-1}, same value for each direction), γ_i denotes the phase angle of each direction native from Fredyn, x and y are the coordinates of the observer in the cartesian system and t denotes the time.

Validation of the representation in the time domain software

The description of the set of waves is compared to the one provided by Equation (6) to validate the implementation of the set of waves in the time domain solver. The mean observed error between the simulation and its analytical description is 1 cm with a maximum of 5 cm. As an example, Figure 2 represents the free water surface amplitude for an equivalent set of waves composed of 5 waves (5 directions) from minus 90 to plus 90 degrees from the main direction based on a reference wave of length λ. The amplitude of free surface is analytically obtained by varying the time element in Equation (6) for different positions of the observer. Figure 3 represents the elevation of the free surface at an instant " t " for the same set of waves. The blue grey surface defines the limit of the free surface in calm water. Figure 2 and Figure 3 are provided here for a field of 2λ*2λ.

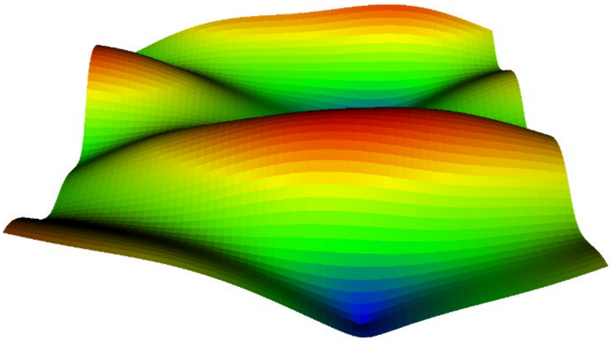

Figure 2: Free surface amplitude

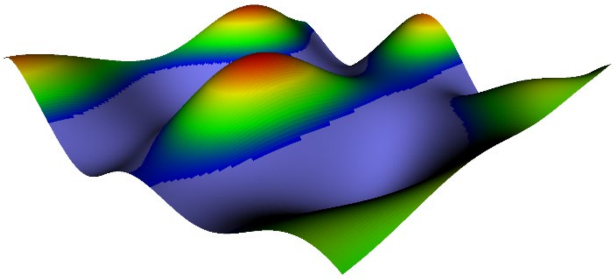

Figure 3: Instantaneous free surface

Results obtained in the time domain solver are almost identical (less than 1% difference) to the one obtained with the analytic description. Each set of waves used in the solver Fredyn throughout this paper is validated with this method.

3. INFLUENCE OF THE SPREADING ANGLE ON THE ROLL MOTION

Simulations conditions

Simulations on a container ship are conducted for several sets of waves (Table 1) using the time domain solver Fredyn. Each simulation is one hour long. Since there is no possibility to change the phase of the wave in each direction, a unique simulation is sufficient to obtain a representative maximum roll angle for each set of waves, loading condition, vessel heading and speed.

Table 1: Set of waves parameters

Case number	Spreading angle [deg]	Number of waves	Comment
1	0	1	Reference
2	± 30	7	-
3	± 90	21	-

The selected vessel is a C11 class container ship of length 262 m, known for its vulnerability to parametric roll (France et al., 2001). Three different loading conditions are considered corresponding to drafts of 10, 11 and 12 metres. The length of the reference wave is equal to the ship length and of a steepness 0.0167. A second reference wave of steepness 0.025 is also considered for the draught of 12 metres.

Roll polar plots

Roll polar plots representing the 1-hour maximum roll angle are realized for the sets of waves presented in Table 1. The speed discretisation is 0.5 $m.s^{-1}$ from 0 to 10 $m.s^{-1}$ and the heading discretization is 7.5 degrees from head sea to following sea. Half of the roll polar plots are calculated since the results are symmetrical (symmetrical hull shape, centre of gravity located on the centreline).

The maximum roll angles obtained on the different set of waves presented in Table 2 are compared with each another, for each reference wave and loading condition. Special care is provided when heavy roll motions appear to detect parametric roll: If the roll period is nearly twice the pitch period (image of the encounter period) when the simulation maximum roll angle is reached, then the maximum roll angle is considered to be associated with the phenomenon of parametric roll. The boundaries of the parametric roll area (in which the maximum roll angle is considered to be due to parametric roll) are overlayed with a black line on the roll polar plots. This permits a closer look to be taken on the influence of the spreading angle on the parametric roll area.

4. RESULTS AND DISCUSSIONS

Results and validations

The results are provided as roll polar plots presenting the maximum roll angle observed during one-hour simulations in 6-DoF. Three loading conditions were evaluated, representing a total of 11,025 simulations. Figure 4 to Figure 6 present the roll polar plots obtained for the C11 class container ships with a draught of 12m and a *KG* of 18m, for the three sets of waves presented in Table 1 considering a reference sinusoidal wave of steepness 0.0167.

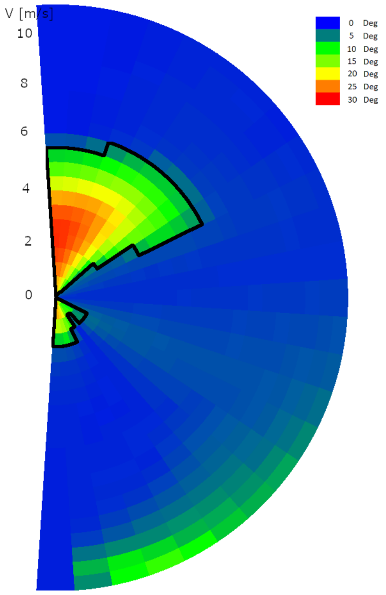

Figure 4: Roll polar plots, case n°1 (reference wave)

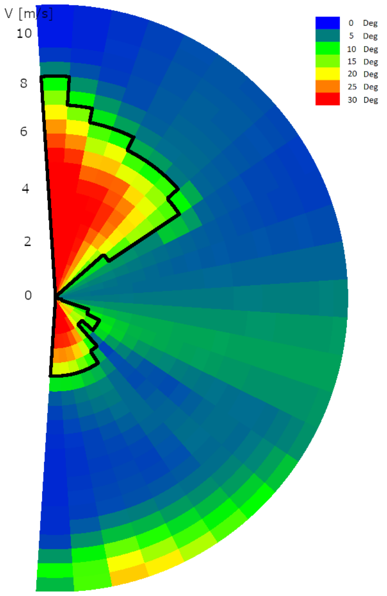

Figure 5: Roll polar plots, case n°2 (spreading ± 30 degrees)

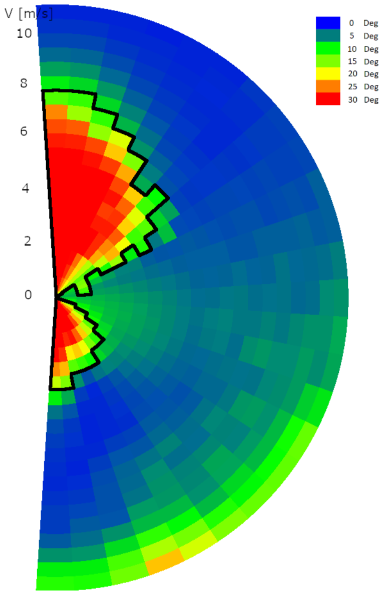

Figure 6: Roll polar plots, case n°3 (spreading ± 90 degrees)

The simulation is performed three times, for the three spreading cases (0 degree, ± 30 degrees, ± 90 degrees). The spreading case leading to the highest value of the maximum roll angle is identified for each vessel speed and heading in the polar plot. Table 2 presents the results obtained for each loading condition and wave steepness. The column "±90° v. ±30°" presents the percentage of simulations for which the maximum roll angle observed with a spreading angle of ± 90 degrees is larger than the one obtained with a spreading angle of ± 30 degrees. As well, the column "±90° v. 0°" presents the percentage of simulations for which the maximum roll angle observed with a spreading angle of ± 90 degrees is larger than the one obtained without spreading angle.

For speeds lower than 2.5m.s^{-1} the vessel may not keep its course in waves. Therefore, simulations in 5-DoF (yaw is frozen) are conducted in addition to the one in 6-DoF and lead to equivalent results.

Table 2: Compared percentage of maximum roll angle

Draft [m]	*KG* [m]	Wave Steepness	±90° v. ±30°	±90° v. 0°
12	18	0.0167	62%	95%
12	18	0.025	69%	87%
12	17	0.0167	80%	97%
12	17	0.025	71%	93%
11	18	0.0167	66%	95%
10	19	0.0167	74%	96%
10	17	0.0167	76%	99%
Average			71%	95%

Discussions

The method used to build equivalent sets of waves developing an equivalent energy is validated for each selected case in the time domain solver. The roll polar plots presented in Figure 4 to Figure 6 refers to the first line of Table 2. In this case, 62 % of the maximum roll angles are larger when the spreading angle is ± 90 degrees than when the spreading angle is ± 30 degrees, and 95 % of the cases larger than the ones without any spreading. In average (for all the conditions in Table 2), 71 % of the maximum roll angles are larger when the spreading angle is ± 90 degrees than when the spreading angle is ± 30 degrees, and 95 % of the cases are larger than the ones without any spreading.

The wavelength is equal to the ship's length. This maximizes the appearance of parametric roll in longitudinal seas. The ratio of the wavelength over ship's breadth is equal to 6.6, which is too large to observe synchronous roll in beam seas.

In theory, considering parametric roll, the case without spreading (monodirectional wave) should lead to the largest GM variation in head seas, and therefore to the largest roll angle. However, results are counterintuitive: The largest roll angle is mostly observed when a non-zero spreading angle is considered.

Figure 4 to Figure 6 show that parametric roll area (contoured in black) extends when the spreading angle increases. This extension of parametric roll area is observed in all cases assessed in Table 2.

Therefore, the spreading angle leading to the largest roll angle is ± 90 degrees, which is identified as the most conservative.

5. CONCLUSION

The aim of this paper is to identify the most conservative spreading angle for equivalent sets of waves. The equivalent sets of waves are built to develop the same energy as a reference wave. The set of waves are validated in the time domain solver prior to being introduced in 6-DoF simulations by comparison with their analytical description. Then, roll polar plots for the C11 class container vessel are traced using the maximum roll angle observed during 1-hour 6-DoF simulations on reference waves in which the wavelength is equal to the ship length. Roll polar plots are generated for the equivalent set of waves and compared with each other. The chosen wavelength permits the appearance of parametric roll to be maximized in longitudinal seas and reduces synchronous roll in beam seas. The roll polar plots show that the area of parametric roll extends as the spreading angle increases. The roll angle reached when the set of waves is built for a spreading angle of ± 90 degrees is larger in 95 % of the cases than when no spreading is considered. The study validates the use of a conservative spreading angle of ± 90 degrees for the C11 container vessel. The authors assume that this conclusion can be extended to other vessels with similar hull shape. Further work needs to be conducted to validate these results on a real sea state based on spectrum description.

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