PROBABILISTIC SAFETY OF ESTUARY VESSELS BASED ON NONLINEAR ROLLING IN WIND AND WAVES

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(DOI No: 10.3940/rina.ijme.2010.a1.162)

SUMMARY

The author was previously involved in the development of the risk-based stability analysis which is now further extended, and used for the safety assessment of estuary container vessels subjected to stochastic action of beam wind and irregular waves. The study was motivated by the new set of safety regulations for estuary vessels issued by Belgian authorities in cooperation with Lloyd's Register. These regulations introduce very innovative probabilistic ideas to ship stability regulations, and therefore present a significant step forward compared to the classical approach. Still, they do not account properly some important influences, such as wind gusts and motion nonlinearities, so considerably simplify the problem. The present investigation models the vessel motion much more realistically, analyzes the influence of beam wind and beam waves on the probability of a stability failure, and argues whether simplifications proposed by the regulations were justified. It is believed that presented method is not limited to the safety of estuary vessels only, but also gives important guidelines for a more general investigation of ship safety in wind and waves.

NOMENCLATURE

A_n	n-th wind-gust amplitude (m/s)
A_s	underwater lateral vessel area (m^2)
A_w	lateral vessel area exposed to wind (m^2)
B	vessel breadth (m)
B_n	n-th wave amplitude (m)
c_s	water drag coefficient (-)
c_w	air drag coefficient (-)
F_B	vessel freeboard (m)
F_s	nonlinear part of sway drag force (kN)
F_w	wind force (kN)
F_η^{FK}	Froude-Krylov wave force, sway (kN)
F_η^{D}	diffraction wave force, sway (kN)
g	gravitational acceleration (m/s^2)
GM	metacentric height (m)
H	vessel depth (m)
H_s	significant wave height (m)
h	total stability lever (m)
h'	residuary stability lever (m)
J_x	moment of inertia for x axes (tm^2)
j_x	radius of gyration for x axes (m)
K	terrain roughness coefficient (-)
L	vessel length (m)
l_w	wind moment lever (m)
M_{st}	righting (stability) moment (kNm)
M_w	wind moment (kNm)
m_η	added mass of sway (t)
M_φ^{FK}	Froude-Krylov wave moment, roll (kN)
M_φ^{D}	diffraction wave moment, roll (kN)
m_φ	added mass of roll (tm^2)
$m_{\varphi\eta}$	coupling added mass coefficient (tm)
N_c	number of cycles (-)
N_η	sway damping force (kN)
n_η	sway linear damping (t/s)
N_φ	roll damping moment (kNm)
n_φ	potential roll damping coefficient (-)
$N_{\varphi\eta}$	coupling damping force (kN)
$n_{\varphi\eta}$	coupling damping coefficient (tm/s)
P	probability (-)
P_{15}	probability of heeling to 15° (-)
S_T	Truijens wave spectrum (m^2/s)
S_D	Davenport wind spectrum (m^2/s)
s_φ	standard deviation of roll (rad)
T	vessel draught (m)
t	time (s)
t_s	period – duration of storm (s)
v_w	apparent wind speed (m/s)
$\bar{v}_w$	absolute mean wind speed (m/s)
v'_w	wind speed fluctuations (m/s)
x	longitudinal central axes
α_n	phase shift of n-th wind component (-)
β	quadratic damping coefficient (-)
Δ	vessel displacement (t)
η	sway (m)
ϕ	prescribed angle of heel (rad)
ϕ_{fl}	angle of flooding (rad,°)
φ	roll angle, heel (rad,°)
$\bar{\varphi}$	mean value of roll (rad)
μ	linear damping coefficient (-)
ρ	water density (t/m^3)
ρ_a	air density (t/m^3)
ω_n	frequency of n-th component (rad/s)
IMO	International Maritime Organization

1. INTRODUCTION

The present investigation was motivated by the new set of safety regulations developed for the coastal navigation vessels on the sea stretch between Belgian deep-sea ports and West Scheldt estuary [1]-[3]. Although intended just for the local restricted use, these regulations are believed to have much wider relevance: they are (as far as the author knows) the first actual implementation of innovative idea of substituting the classic ship stability rules by the novel risk-based approach. As the author of the present investigation participated in the promotion of such approach in a series of papers [5]-[8], this implementation is regarded as a very significant step in the general improvement of ship safety regulations.

However, the imposed regulations introduce some doubtful approximations. For instance, they omit the effects of gusting wind in seakeeping calculations, but take dynamic influence of wind on rolling indirectly, through a constant (33%) safety margin prescribed to the angle of flooding (or the angle corresponding to the maximum of the stability curve), and through the classical Weather Criterion approach. In addition, the required seakeeping calculations are based on linear equations of ship motion, valid for the small rolling amplitudes, only. In that way, the regulations considerably simplify the problem of ship motion in realistic seaway, provoking some doubts concerning the safety results obtained.

In order to examine whether such shortcomings could hinder the benefits of the novel approach, the author performed a thorough analysis of the problem of rolling of an estuary vessel in beam seas and winds. The techniques developed in previous investigations [5]-[8] were extended in order to model realistically the influences of irregular wind gusts and nonlinearities in equations of motion. So, the rolling motion of an estuary vessel was obtained by solving coupled nonlinear differential equations under the combined action of irregular waves and gusting wind. Wave and wind forces and moments were derived from the appropriate wave and wind spectra. Short-term statistical analysis was used instead of a long-term, life time statistics, prescribed by the rules.

With such tools, the safety of sample estuary vessel was systematically examined through numerous numerical experiments for a range of realistic metacentric heights, wind speeds and sea states. The analysis pointed that the influence of gusting wind depends not only on the mean wind speed, but also on the vessel metacentric height, sea state, etc., and is so complex that it could not be coped by any indirect (simplified) approach. On the other hand, the influence of nonlinearities (due to relatively small rolling amplitudes in the coastal areas) was found not to be crucial.

Although limited to the influence of beam wind and beam waves, and performed on only one (typical) estuary vessel, the analysis showed that, despite its shortcomings, the approach used in regulations appeared to be sufficient for the current navigation practices in the Belgian coastal zone. On the other hand, the author believes that innovative probabilistic approach used in the regulations has much greater potentials. Such potentials, however, could not be shown unless the direct seakeeping calculations, accounting properly for the gusting wind effect are incorporated into the risk-based regulations.

2. PRESENT PROBABILISTIC REGULATIONS

The estuary navigation, which is the subject of the newly imposed safety regulations, represents an alternative transport solution in connecting Belgian deep-sea ports with hinterland. Estuary vessels are basically inland navigation vessels which are allowed to operate on the sea route between port of Zeebrugge and West Scheldt estuary under certain (technical and weather) conditions. The Belgian Shipping Inspectorate has issued the first set of regulations on estuary ships in 1962, limiting navigation to “favourable weather and wave conditions”. In practice, this implied Beaufort 5 wind corresponding to H_s = 1.2m waves, at the most [2]. However, these limits were found to be too restrictive for the present trade demands. In order to foster estuary traffic and improve its safety, Belgian authorities, in cooperation with Lloyd’s Register, have issued a new set of risk-based safety regulations for estuary vessels in 2007 [3]. As of January 2008, *Amberes* – the first estuary container vessel designed according to the new regulations – has started a regular shuttle service between Zeebrugge and Antwerp [4]. During 2008, another two container vessels have obtained certificates for the estuary navigation.

The new Belgian regulations impose several probabilistic requirements related to the seakeeping of estuary vessels. Slamming, bow diving, rolling and strength of ship in seaway are taken into consideration. Operational limits of a vessel are defined by the long-term probabilities of critical events: vertical relative motions, roll amplitudes, bending and torsion moments, etc. [2], [3]. Probabilistic calculations are performed based on the assumption that during 20 years long lifetime, the vessel makes 300 round trips per year.

In general, response amplitude operators (RAOs) of ship motions should be calculated by (classical) linear strip-theory technique, for all relevant wave incidence angles. Therefore, ship response spectra should be computed for departure and arrival trip separately, due to changes in wave heading angles. Response spectra are calculated for a series of directional wave spectra, where each wave spectrum corresponds to an interval of significant wave heights of 0.05m or less. For each interval, conditional minimal, maximal and average number of critical events is determined per round trip. Based on conditional average, cumulative average number of critical events can be determined as a function of significant wave height. Cumulative average number of 1/300 events corresponds to a ‘once a year’ occurrence, while 1/6000 = $\boldsymbol{O}(10^{-4})$ corresponds to a ‘once in a lifetime’ probability, where 6000 = 20·300 is the total number of round trips in a lifetime.

In addition, the regulations define minimum standards for procedure that should assist the master in making a decision whether to start a voyage or not, based on the weather forecast of an approved service provider.

Critical angle of roll and permitted probability of its occurrence are defined by the established regulations as follows:

The probability that the roll angle exceeds 67% of either the angle of flooding or the angle corresponding to the maximum of the stability curve must not be greater than once in a lifetime; in any case, the roll angle should not exceed 15 degrees.

It should be noted that 33% margin is prescribed in order to account for the possible wind effects [1], and to compensate, in that way, for ignoring the wind loads in the motions calculation procedure.

Response amplitude operators of roll should be calculated for the loading condition corresponding to maximal draft, for different values of vertical centre of gravity. Regulations do not prescribe a specific method for calculation of roll damping coefficient, but recommend that a "realistic estimation" of roll damping should be made, taking bilge keels, if present, into account.

Apart from the newly imposed regulations which address behaviour of the estuary vessels in seaway in a probabilistic manner, the vessels should also satisfy common stability requirements for seagoing ships. This includes (somewhat adapted) general intact stability criteria and severe wind and rolling criterion (Weather Criterion) contained in IMO Resolution A749. So, the influence of wind is not (directly) accounted for in the seakeeping calculations and the related risks of the critical events, but only through the classical Weather Criterion approach.

3. PROPOSED RISK-BASED ANALYSIS

The proposed risk-based analysis is a two-phase approach. In the first phase, a record of vessel's rolling is obtained by solving nonlinear differential equations of motions accounting for the influence of gusting wind and irregular waves. In the second phase, the probability of a vessel to reach some critical angle of heel is calculated using statistical analysis of the acquired time-history of vessel rolling.

The problem of nonlinear rolling is often addressed with a single-degree-of-freedom model, i.e. an independent nonlinear equation, as (for instance) in [9], [10]. The authors have already applied such model in their analysis of safety of seagoing ships exposed to beam seas and gusting wind [5]. However, for the purposes of the present investigation, a model consisting of coupled nonlinear equations of roll and sway in beam wind and waves was developed:

$$\begin{aligned}&\left(\Delta+m_{\eta}\right)\ddot{\eta}+N_{\eta}\left(\dot{\eta}\right)+m_{\eta\varphi}\ddot{\varphi}+n_{\eta\varphi}\dot{\varphi}=\\&\qquad=F_{w}\left(v_{w}\right)+F_{\eta}^{FK}+F_{\eta}^{D}\\&\left(J_{x}+m_{\varphi}\right)\ddot{\varphi}+N_{\varphi}\left(\dot{\varphi}\right)+m_{\varphi\eta}\ddot{\eta}+N_{\varphi\eta}\left(\dot{\eta}\right)+M_{st}\left(\varphi\right)=\\&\qquad=M_{w}\left(v_{w}\right)+M_{\varphi}^{FK}+M_{\varphi}^{D}\end{aligned} \tag{1}$$

Although the introduced equations do present ship motions more accurately then the earlier 1DOF approach, a fully nonlinear analysis in beam seas would have to include the coupling of the equations to heave and yaw motions, also. This is, however, left for some future analysis.

The procedure for solving the system of equations (1) is, briefly, the following. Damping forces and moments on the left hand side of the equations contain linear and nonlinear parts:

$$N_{\eta}(\dot{\eta})=n_{\eta}\dot{\eta}+\frac{1}{2}\rho A_{s}c_{s}\dot{\eta}\left|\dot{\eta}\right| \ ,$$

$$N_{\varphi}(\dot{\varphi})=\left(n_{\varphi}+\mu\right)\dot{\varphi}+\beta\cdot\dot{\varphi}\left|\dot{\varphi}\right| \ ,$$

$$N_{\varphi\eta}=n_{\varphi\eta}\cdot\dot{\eta}-\frac{1}{2}\rho A_{s}c_{s}l_{s}\cdot\dot{\eta}\left|\dot{\eta}\right| \ .$$

Added masses $m_\eta, m_\varphi, m_{\eta\varphi}=m_{\varphi\eta}$ and potential damping coefficients $n_\eta, n_\varphi, n_{\eta\varphi}=n_{\varphi\eta}$ were obtained using classical strip-theory techniques. Semi-empirical method of Ikeda [11] was used to calculate linear and nonlinear parts of viscous roll damping μ and β. The restoring term in equation of roll is the righting moment:

$$M_{st}(\varphi)=g\Delta\cdot h(\varphi)=g\Delta\cdot\left[h'(\varphi)+GM\cdot\sin\varphi\right] \ ,$$

where residuary stability lever of the vessel was approximated by an odd polynomial:

$$h'(\varphi)\approx\sum_{n=0}^{N}a_{2n+1}\varphi^{2n+1} \ .$$

From such h' curves, for a given value of GM, the stability lever h and the corresponding stability moment M_{st} directly follow.

Exciting forces and moments due to wind and waves appear on the right hand side of the equations (1). Force and moment generated by the wind are:

$$F_{w}=\frac{1}{2}\rho_{a}A_{w}c_{w}\cdot v_{w}^{2} \ ,$$

$$M_{w}=\frac{1}{2}\rho_{a}A_{w}c_{w}l_{w}\cdot v_{w}^{2} \ ,$$

where the moment lever l_w is the vertical distance of centre of windage area to the centre of gravity, and v_w represents the apparent wind speed (wind speed relative to the vessel)

$$v_{w}\left(t\right)=\overline{v}_{w}+v_{w}'-\dot{\eta} \ .$$

Two realistic alternatives concerning the absolute mean wind speed (the nominal wind speed) $\bar{v}_w$, were analyzed. In one, $\bar{v}_w$ corresponds to the significant wave height for a fully developed wave spectrum (see Table in e.g. [12]).

For the range of significant wave heights

$$1\text{m} < H_s < 5\text{m}$$

the $\bar{v}_w - H_s$ relationship was (roughly) approximated as:

$$\bar{v}_w = f\left(H_s\right) \approx -0.8158 \cdot H_s^2 + 8.9142 \cdot H_s - 7.1291 . \quad (2)$$

In the other, $\bar{v}_w$ was taken as independent of wave height, in aim to cover the undeveloped waves, especially in the case of offshore wind directions.

The gusting part of wind speed v_w' is calculated as

$$v_w'\left(t\right) = \sum_{n=1}^{N} A_n \cos\left(\omega_n t + \alpha_n\right) .$$

The wind gust amplitudes are obtained from the appropriate wind spectrum

$$A_n = \sqrt{2 S_D\left(\omega_n\right) \cdot d\omega}$$

where, as in the previous investigations, well known Davenport spectrum was used

$$S_D(\omega) = \frac{4K \cdot \bar{v}_w^{\,2} X_D^2}{\omega\left(1 + X_D^2\right)^{\frac{4}{3}}} \ , \ X_D = \frac{600\omega}{\pi \cdot \bar{v}_w} \ .$$

In present analysis, terrain roughness coefficient for open sea areas $K = 0.003$ was applied.

Wave forces and moments are consisted of Froude-Krylov and diffraction parts:

$$F_\eta^{FK} = -D \sum_{n=1}^{N} \omega_n^2 B_n \cos\left(\omega_n t - \varepsilon_{\eta n}\right) ,$$

$$F_\eta^{D} = -m_\eta \sum_{n=1}^{N} \omega_n^2 B_n \cos\left(\omega_n t - \varepsilon_{\eta n}\right) ,$$

$$M_\varphi^{FK} = \left(J_x + m_\varphi\right) \frac{\omega_\varphi^2}{g} \sum_{n=1}^{N} \omega_n^2 B_n \cos\left(\omega_n t - \varepsilon_{\varphi n}\right) ,$$

$$M_\varphi^{D} = -m_{\varphi\eta} \sum_{n=1}^{N} \omega_n^2 B_n \cos\left(\omega_n t - \varepsilon_{\varphi n}\right) - \\ - \overline{OG} \cdot m_\eta \sum_{n=1}^{N} \omega_n^2 B_n \cos\left(\omega_n t - \varepsilon_{\eta n}\right) .$$

Wave amplitudes are obtained from the appropriate wave spectra:

$$B_n = \sqrt{2 S_T\left(\omega_n\right) \cdot d\omega}$$

In the present analysis, the Truijens wave spectrum [1] was accepted as appropriate for the Belgian North Sea coastal area.

In order to obtain time records of roll and sway motion, $\varphi(t)$ and $\eta(t)$, the system of equations (1) was numerically solved by the use of Runge-Kutta method. Time history of roll was statistically analyzed in order to acquire mean angle of roll $\bar{\varphi}$ and standard roll deviation s_φ. Finally (as in the previous investigations performed by the author [5]-[8]), the probability that the vessel would heel to a critical angle ϕ in a given period of time t_s , was determined as:

$$P = 1 - \exp\left\{ -N_c \exp\left[-\frac{1}{2}\left(\frac{\phi - \bar{\varphi}}{s_\varphi}\right)^2 \right] \right\} \approx \\ \approx N_c \exp\left[-\frac{1}{2}\left(\frac{\phi - \bar{\varphi}}{s_\varphi}\right)^2 \right] \ , \quad (3)$$

where N_c represents the number of cycles in the analyzed period:

$$N_c = \frac{t_s}{\bar{T}} \ .$$

By the outlined procedure, starting from the coupled nonlinear differential equations of motion (1) follows the probability (3) that the vessel would heel to the prescribed critical angle. Such a probability would be the main target of the succeeding numerical analysis.

4. NUMERICAL TESTS

Present analysis was performed through a series of numerical experiments carried out on a sample vessel 134m long and 14.5m in beam, designed to carry TEU containers in 17 bays, 5 rows and 5 tiers (Figure 1). The assumed speed of the vessel is 16km/h. The vessel is a typical estuary container vessel with an open cargo hold, with no hatch covers and a 1m high hatch coaming. The vessel's draught corresponding to maximal number of containers is 3.8m, the average mass of a TEU being m_{con} ≈ 12t. However, according to regulations, the vessel would not be allowed to sail out for a sea voyage with the draught greater than 3m. Residuary stability moment lever $h'(\varphi)$ of the vessel, corresponding to the draught 3m, is given in Figure 2.

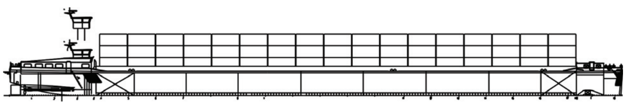

Figure 1: Sample vessel – a typical estuary container vessel

The probability that the vessel would reach the critical angle of heel, if exposed to given beam wind and waves for two hours, was calculated for a realistic range of metacentric heights, wind speeds and sea states. The outlined procedure enables short-term prediction of roll motion when weather conditions are known. The author believes that safety assessment based on such short-term analysis – which takes gusting wind into account – is more adequate than the long term analysis used in the regulations. It is especially suitable for the ship master, who is supposed to make an immediate decision whether to sail out or not. The long-term prediction, which would aim to include the influence of gusting wind, would require (in addition to already used wave scatter diagrams) a proper empirical correlation between wave heights and wind speeds for the operation area.

Concerning the acceptable level of risk attained during the voyage, it was adopted that the maximal allowable probability of a stability failure (heeling to a specified critical angle) in two hours is $\boldsymbol{O}(10^{-4})$, which is in agreement to 'once in a lifetime' accepted in the present regulations.

Regarding the choice of the critical angle, the present regulations aim to prevent flooding of an open container hold. However, they also limit the maximal angle of roll to 15° in order to keep the vessel from excessive rolling. As 67% of the angle of flooding of the container hold, corresponding to the draught 3m, is 18.7° (ϕ_{fl} being 28°), the critical angle was established to be 15° in the present analysis.

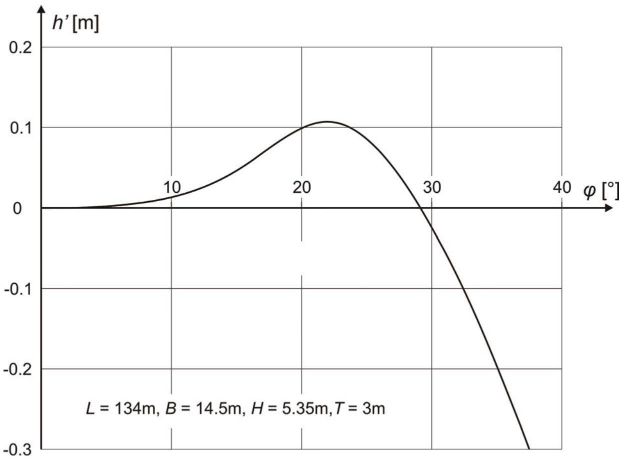

Figure 2: Residual stability lever of the sample vessel

As already mentioned, the two distinctive situations concerning the mean wind speed were analyzed. In case of fully developed waves, the mean wind speed is related to the significant wave height by relation (2). However, it is possible to have strong winds long before the severe waves develop [13]. This particularly applies to coastal areas and offshore wind directions. In order to take such circumstances into consideration, the mean wind speed was alternatively supposed to be independent of wave height.

The results of the investigation are presented and analyzed in the form of the (so called) probability curves, which connect the obtained probability of heeling to 15 degrees in two hours, to some of the main ship's or weather parameters.

The curves presented in Figure 3 connect the probability of heeling of the sample vessel to 15 degrees in given weather conditions, to the metacentric height of the vessel. The results were obtained for a range of significant wave heights (H_s = 1.4 – 2.4m) and wind speeds that were supposed to correspond to the fully developed waves, $\overline{v}_w = f\left(H_s\right)$. These probability curves demonstrate an interesting influence of the metacentric height on the safety of the sample vessel. Namely, the traditional stability concepts limit only the minimal metacentric height. For instance, the classical stability requirements for seagoing ships (Weather Criterion of IMO Resolution A749) restrict just the minimal metacentric height of the sample vessel to $GM \approx 0.8$m. Normally, it is understood that a ship becomes more stable as the metacentric height increases. Contrary to this common belief, the probability curves presented in Figure 3 indicate that there is actually an upper boundary of acceptable metacentric heights for which the vessel may be considered as safe in the given weather conditions. This innovative result was already reported in [5], and previously in [9].

The maximal acceptable metacentric height of the sample vessel depends on the significant wave height. The results show that the increase of significant wave height for 1m decreases the upper limit of metacentric heights (maximal *GM*) for approximately 0.6m.

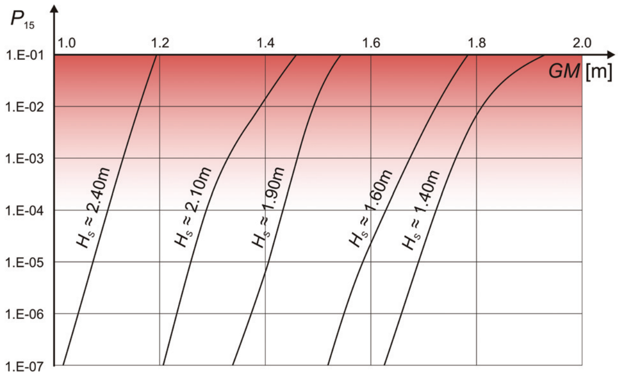

Figure 3: Probability of heeling to 15° vs. metacentric height

The probability curves given in Figure 4 demonstrate that maximal *GM* (obtained for a single value of significant wave height) depends on the wind speed as well, as it additionally decreases with the increase of the mean wind speed. In the given example, the vessel exposed to beam waves and strong beam winds, could be considered as safe only if her *GM* is up to 25cm lower than the metacentric height of the vessel subjected to beam waves only. Even more important, the vessel that could attain the proposed level of safety, clearly has the probability of heeling to 15° higher than acceptable, if the impacts of gusting wind are taken into account. The influence of wind on ship safety is apparent and should not be neglected. The results of probabilistic analysis presented in Figure 4 also indicate that the influence of wind considerably decreases as the metacentric height increases. For instance, if GM = 1.1m, the probability of heeling to 15 degrees would increase for three orders of magnitude due to the increase of mean wind speed from 20 to 25m/s. On the other hand, if GM = 1.5m, the probability P_{15} corresponding to the wind speed of 25 m/s is of the same order of magnitude as in the case of no wind at all. This interesting feature deserves to be examined more thoroughly.

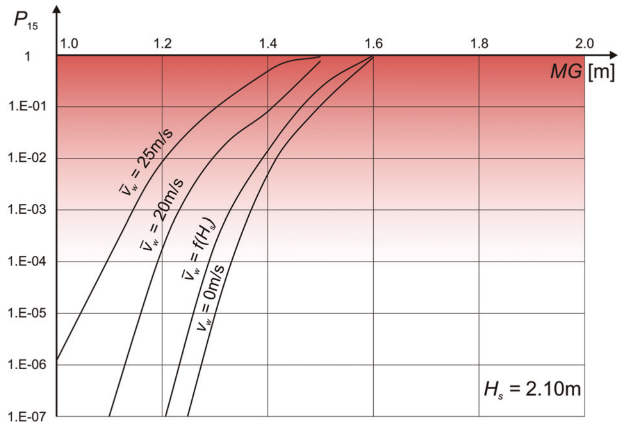

Figure 4: The influence of the beam wind speed on the probability of heeling to 15°

The probability curves shown in Figures 5, 6 and 7, represent the probability P_{15} obtained for a range of wave heights and different wind speeds, in the case that the metacentric height of the sample estuary vessel is 1m, 1.5m or 2m, respectively.

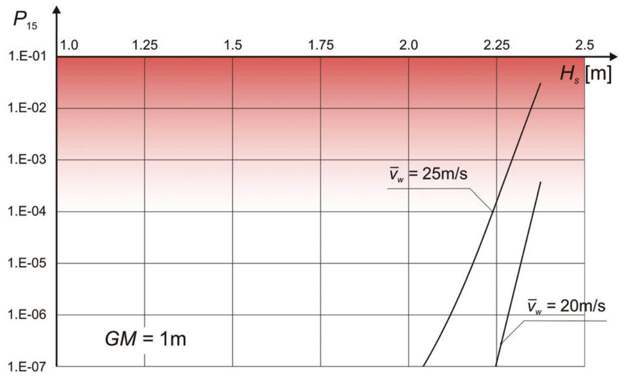

Figure 5: The influence of the beam wind speed on the pprobability of heeling to 15° for GM = 1m

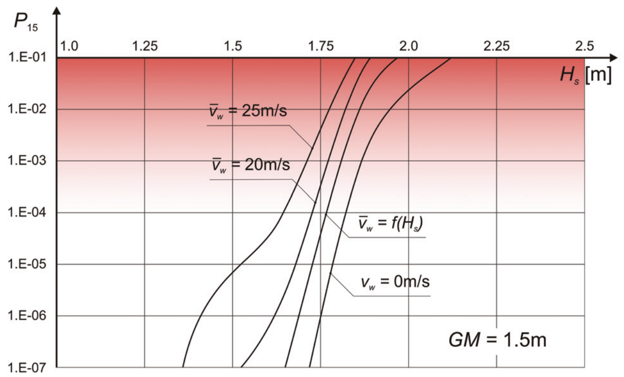

Figure 6: The influence of the beam wind speed on the pprobability of heeling to 15° for GM = 1.5m

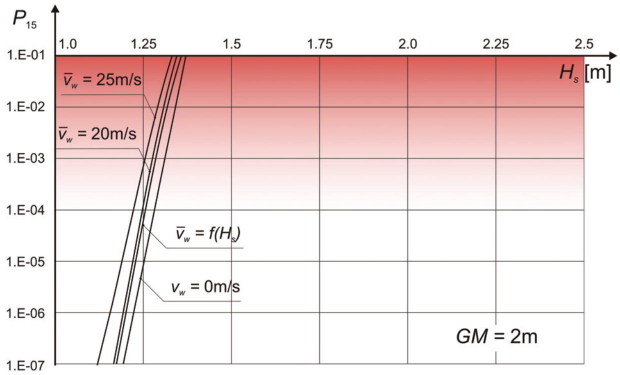

Figure 7: The influence of the beam wind speed on the pprobability of heeling to 15° for GM = 2m

The influence of the beam wind clearly decreases with the increase of the metacentric height. For GM = 1m, the increase of the mean wind speed $\bar{v}_w$ for just 5m/s causes sudden jump of the risk of excessive rolling. For GM = 1.5m, the influence of wind is less pronounced but remains significant. For instance, the vessel that could be considered as safe in beam waves $H_s \approx$ 1.8m and no wind, in fact fails to attain the required level of safety, if the influence of the gusting wind is properly taken into account. The probability P_{15} increases for at least one order of magnitude if the impact of the wind corresponding to the fully developed seas is included in the seakeeping calculations. For stronger winds, the risks are two, three or even more orders of magnitude higher. For GM = 2m, the influence of wind is further decreased. Nevertheless, this does not affect the general conclusion. The P_{15} of the vessel that could be regarded as safe when exposed to the beam waves $H_s \approx$ 1.3m and no wind, is still higher than acceptable for any wind speed.

However, as the influence of wind decreases, the maximal acceptable wave height decreases as well. The navigation conditions become further limited due to the high metacentric height.

Numerical tests, so far presented, were conducted on the sample vessel without bilge keels. As far as the author is aware, the present estuary container vessels are equipped with such anti-roll devices (although the use of bilge keels is not specifically required by the regulations). Therefore, another set of numerical experiments was performed in order to examine the influence of bilge keels on the safety of estuary vessels. It was assumed that the length of bilge keels is 50% of L. The results obtained for a single metacentric height, but for different wave heights and wind speeds, are presented in Figure 8.

The bilge keels, as expected, decrease the safety risks and move the probability curves towards the higher sea states. Interestingly, it seems that bilge keels additionally decrease the influence of wind on rolling in fully developed seas.

The present estuary vessels are restricted to the navigation in the waves which do not exceed H_s = 1.7m.

Figure 8 shows that the sample vessel remains safe according to the present criterion (P_{max} = $\boldsymbol{O}$ (10^{-4}) in two hours) in such waves, even in the case of the strongest winds. In the given example, the influence of the wind did not jeopardize the vessel safety. In spite the fact that this is just one example (a typical vessel with a specified metacentric height), the result goes in favour of the Belgian rules.

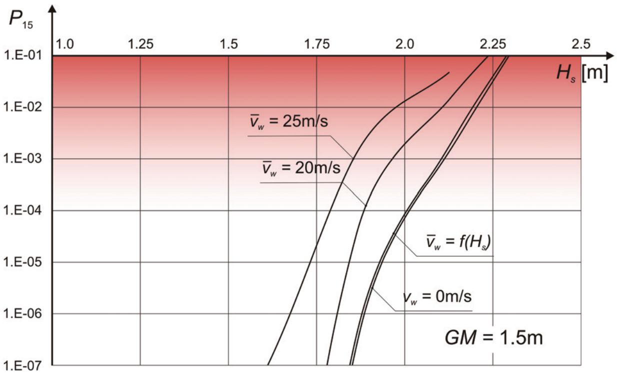

Figure 8: The influence of the beam wind speed on the pprobability of heeling to 15° for *GM* = 1.5m, vessel equipped with bilge keels

In addition to the gusting wind effect, the present analysis accounted for the roll nonlinearities, as another influence omitted in the procedure prescribed by the rules. The influence of this effect, as a function of metacentric height, for significant wave height 2.1m and mean wind speed 25m/s, is presented in Figure 9.

The results show that the overall influence of nonlinearities, in the given weather conditions, is almost negligible in the examined range of metacentric heights. That could have been expected, as the rolling of estuary vessel was not severe, and the mean roll amplitudes did not overcome some 5°.

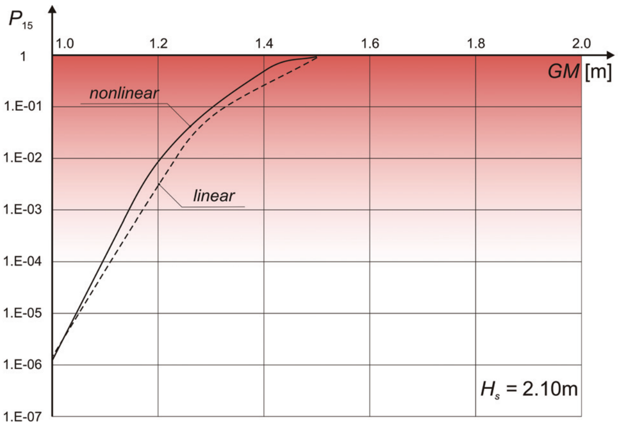

Figure 9: Comparison of linear and nonlinear results

5. CONCLUSIONS

The investigation covered a detailed critical analysis of the new set of safety regulations for estuary vessels imposed by Belgian authorities. Although having just a local character, these regulations are believed to be of a much greater importance: they present the first actual substitution of the classical ship stability rules by the novel, risk-based approach.

The methods used by the author in the previous investigations were extended, the ship motion was modelled by coupled nonlinear differential equations roll and sway, and the action of irregular waves and gusting wind was accounted through the appropriate wave and wind spectra. Then, by the stochastic analysis of the obtained ship motion time-history, the risks that the vessel would heel to a specified critical angle were calculated, for given weather conditions (significant wave height and mean wind speed).

The numerical tests performed on a typical estuary container vessel demonstrated the following.

- When taken into account, the wind effects always increase the probability of stability failure, and, consequently, decrease the safety of the vessel in beam waves. Such decrease of the vessel safety strongly depends on the metacentric height. It is very large in the case of small metacentric heights, and practically negligible at large metacentric heights.
- Therefore, the actual influence of the gusting wind cannot be replaced by a plain method that does not take the metacentric height into account, such as the introduction of a uniform margin to the critical angle of heel. Instead, it should be approached directly, through the proper seakeeping calculations.
- In spite the fact that the examined regulations do not account correctly the effect of beam wind, the results indicate that a typical estuary vessel (satisfying the Belgian rules) is safe enough in beam wind and waves, if the restrictions imposed on the specified waterway (waves under 1.7 m, wind under 17 m/s) are followed.
- As already recognized by the Belgian authorities, the bilge keels have very positive effect on the estuary vessel safety in beam wind and waves.
- The linear approach applied in the regulations was found to be fairly adequate (see Figure 9). For the examined range of metacentric heights, the influence of nonlinearities is practically negligible. It should be emphasized that such conclusion applies to restricted conditions of estuary navigation only, and is certainly not valid for seagoing ships, in general.

The author is, however, aware of one distinctive disadvantage concerning the application of the proposed method. Its incorporation into the rules would imply the seakeeping software which properly accounts for the rolling nonlinearities and the effects of gusting wind. Therefore, not only the regulations, but the commercial seakeeping programs need to be upgraded as well.

However, if a proper seakeeping program is available, there would be a wide range for its application. Not only ship designers and navigation authorities applying the risk-based rules would benefit. The master of the vessel equipped with such tool could immediately verify if vessel's metacentric height is in the safety range, so could make a proper decision whether to sail out to the stormy sea.

Although the present investigation was limited to the influence of beam wind and beam waves, and carried out on just one (typical) estuary vessel, it is believed that the performed critical analysis did provide some essential guidelines for the further improvement of stability regulations. The author strongly promotes such approach (the risk analysis based on direct seakeeping calculations, accounting properly gusting wind effect) and believes that it should not be restricted just to the estuary navigation. It should be imposed to all other types of seagoing ships and inland navigation vessels, substituting in that way the classical stability regulations, based on already outdated theory.

6. ACKNOWLEDGMENT

The paper is a part of long-term project "Development of Safe, Efficient, Ecological (SE-ECO) Ships" executed by Department of Naval Architecture, Faculty of Mechanical Engineering University of Belgrade. The project is partly financed by Serbian Ministry of Science and Technology, Contract No. 14012.

7. REFERENCES

1. Truijens P., Vantorre M., Van der Werff T., "On the Design of Ships for Estuary Service", Transactions of the Royal Instution of Naval Architects Vol. 148 (Part A2), Royal Institution of Naval Architects, London, 2006, pp. 25-39.
2. Vantorre M. et al., "Risk Analysis for Inland Vessels for Estuary Service", The 31st PIANC Congress, Estoril, 2006.
3. "Moniteur Belge / Belgisch Staatsblad", No. 81, Brussels, 16th March 2007.
4. "First Estuary Vessel to Become Operational 'Unlocks' Zeebrugge", ABOARD! Newsletter of Shortsea Promotion Centre Belgium, No. 28, April 2008.
5. Hofman M., Bačkalov I., "Weather Criterion for Seagoing and Inland Vessels – Some New Proposals", Proceedings of International Conference on Marine Research and Transportation, ICMRT '05, University of Naples "Federico II", 2005, pp. 53-62.
6. Hofman M., Maksić I., Bačkalov I., "Some Disturbing Aspects of Inland Vessel Stability Rules", Journal of Ship Technology, New Delhi (India), Vol. 2, No. 2, July 2006, pp 1-14.
7. Bačkalov I., Kalajdžić M., Hofman M., "On Safety of Inland Container Vessels Designed for Different Waterways", FME Transactions, Belgrade, Vol. 36, No. 2, October 2008, pp 51-57.
8. Bačkalov I., Kalajdžić M., Hofman M., "Inland Vessel Rolling due to Severe Beam Wind: a Step towards a Realistic Model", Journal of Probabilistic Engineering Mechanics, Vol. 25, No. 1, January 2010, pp. 18-25.
9. Bulian, G., Francescutto, A., "A Simplified Modular Approach for the Prediction of the Roll Motion due to the Combined Action of Wind and Waves" Proceedings. Inst. Mech. Eng. Vol. 218, Part M, Journal of Eng. for the Maritime Environment 2004, pp. 189-212.
10. Belenky, V.L., Sevastianov, N.B., "Stability and Safety of Ships – Risk of Capsizing", The Society of Naval Architects and Marine Engineers (SNAME), 2007.
11. Himeno, Y., "Prediction of Ship Roll Damping – State of the Art" Report No. 239, College of Engineering, University of Michigan, 1981.
12. Journée, J.M.J., Massie, W.W., "Offshore Hydromechanics", Delft University of Technology, 2000.
13. Ditlevsen O., "Stochastic model for joint wave and wind loads on offshore structures", Structural Safety, Vol. 24, 2002, pp. 139-163.

