Risk Based Analysis of Inland Vessel Stability

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ABSTRACT

The authors continue to investigate the problem of inland container vessel rolling due to influence of beam gusting wind. Previously developed risk based tools are used for the critical analysis of the new version of European Directive for Technical Requirements for Inland Waterway Vessels. It is shown that the Directive, concerning stability, freeboard and safety clearance of container vessels, is not strict enough. The vessels, satisfying all the requirements of the Directive, could be flooded through the open cargo hold, in some extreme but realistic storms. In addition, the risk based approach is applied to investigate the probability of sliding of unsecured containers, due to wind action and vessel rolling.

KEYWORDS: Probabilistic ship stability rules; Inland container vessels; Coupled nonlinear rolling; Stochastic wind action.

INTRODUCTION

Severe rolling is commonly connected to the seagoing ships in waves, and not to the vessels sailing along inland waterways. However, inland vessels could also roll heavily, not due to waves, but due to (chaotic) gusts of strong beam wind. This especially applies to inland container vessels, as they have large lateral areas that could be exposed to wind. The problem of inland vessel rolling has already been investigated by the authors in a series of papers (Hofman et al 2005, 2006, Bačkalov et al 2008, 2010, Bačkalov 2010). A novel tool for risk based analysis of inland container vessel stability was developed, consisting (basically) of two parts: firstly, the coupled nonlinear equations of motion are solved numerically, giving the time history of vessel rolling due to beam gusting wind. Secondly, the vessel motion is analyzed statistically, and the probability of flooding of open container hold, found. It was shown that the method is especially applicable to critical analysis of the existing stability rules. For instance, it was found (by a surprise) that the vessels satisfying some of the respectable inland stability standards could be flooded and eventually capsized due to severe gusts of beam wind!

The present paper continues the investigation of inland vessel rolling due to gusting beam gales. It is focused on critical analysis of the new version of European Technical Requirements for Inland Waterway Vessels (Directive of the European Parliament and the Council 2006/87/EC), and checks in detail the part of the Directive prescribing stability, freeboard and safety clearance of inland container vessels. It shows that the Directive, even more than some other stability standards analyzed previously, is (in this part) not strict enough. In aim of harmonization and simplicity, the dynamic wind effects are oversimplified, so the vessels satisfying the requirements of the Directive were found (in some extreme cases) unsafe from the probabilistic point of view.

In addition to the critical analysis of EC Directive, the paper investigates the possibility of sliding of unsecured containers due to vessel rolling and the wind influences. Thus, for the first time, the usual practice on inland waterways – the transportation of unsecured (unlashed) containers – is put to test by the novel risk based tools.

BASIC TOOLS

In the present investigation, vessel motion due to the influence of beam wind gusts is modelled by coupled, nonlinear differential equations of roll and sway, developed and explained in detail in Bačkalov et al (2010). So called "course keeping model" is used, in which the vessel is not allowed to drift freely due to the beam wind, but is forced to sway oscillatory about her prescribed straight route. The main feature of the approach is the treatment of the wind effects. The wind force and moment depend on the variable wind speed, which is obtained from the known, semi-empirical wind spectrum. More precisely, wind speed is presented as[1]

$$v(t) = \bar{v} - \dot{\eta} + v' = \bar{v} - \dot{\eta} + \sum_{n=1}^{N} v_n \cos(\omega_n t + \alpha_n),$$

and the amplitudes of gusting wind components v_n are obtained from the wind spectrum by the relation

$$v_n = \sqrt{2S(\omega_n) \cdot d\omega}$$

which follows from the definition of the spectrum.

As in the previous papers (Hofman et al 2005, 2006, Bačkalov et al 2008, 2010, Bačkalov 2010), Davenport wind spectrum is applied

$$S(\omega) = \frac{4\kappa \cdot \bar{v}^2 X^2}{\omega\left(1 + X^2\right)^{\frac{4}{3}}} \;, \quad X = \frac{600\omega}{\pi \cdot \bar{v}} \quad .$$

On the basis of the discussion given in Hofman et al (2006), the coefficient of terrain roughness appropriate for suburban areas $\kappa = 0.015$ is applied.

The differential equations of motion are solved numerically by classical Runge-Kutta method, and the vessel roll and sway motions $\varphi(t)$, $\eta(t)$ are obtained. Stochastic analysis of these motions gives the mean value of roll, its standard deviation, and other statistical characteristics of vessel nonlinear, irregular rolling. Then, the most probable maximal heel in N cycles would be

$$\varphi_{max} = \bar{\varphi} + \sigma_\varphi \sqrt{2 \ln N} \;,$$

while the probability that the angle of roll would reach some prescribed value ϕ is

$$P \approx N \exp\left[-\frac{1}{2}\left(\frac{\phi - \bar{\varphi}}{\sigma_\varphi}\right)^2\right].$$

In the case that ϕ is angle of flooding of the open cargo hold, the probability P would be called ***the index of flooding***.

In addition to maximal heel and the index of flooding, the present investigation analyzes the condition in which the unsecured containers would slide due to the vessel motion and the wind influences. The analysis is straightforward once the vessel motions are known, so only the final formulas would be presented here.

The components of acceleration of centre of container mass could be obtained from vessel motion, in the form

$$a_y = \ddot{\eta}\cos\varphi - y_C \dot{\varphi}^2 - z_C \ddot{\varphi} \;,$$

$$a_z = -\ddot{\eta}\sin\varphi + y_C \ddot{\varphi} - z_C \dot{\varphi}^2 \,.$$

The total container reactions in y and z direction follow from Newton low as

$$F_y = m a_y + mg\sin\varphi - F_w \cos\varphi \,,$$

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[1] The nomenclature is given at the end of the text

$$F_z = ma_z + mg\cos\varphi + F_W \sin\varphi \, .$$

The container is unsecured, just freely leaned to the box below, so the following restrictions in the supports apply

$$F_z \geq 0, \quad \left|F_y\right| \leq \mu F_z \, .$$

This leads to the condition under which the container would not slide:

$$\frac{\left|F_y\right|}{F_z} = \frac{\left|ma_y + mg\sin\varphi - F_W \cos\varphi\right|}{ma_z + mg\cos\varphi + F_W \sin\varphi} = f_s \leq \mu \; ,$$

giving the probability of sliding of an unsecured container as

$$P_s \approx N \exp\left[-\frac{1}{2}\left(\frac{\mu - \overline{f}_s}{\sigma_s} \right)^2 \right] .$$

FREEBOARD AND STABILITY RULES

As said, the present investigation offers a critical analysis of the new version of European Technical Requirements for Inland Waterway Vessels, which was accepted in 2006 and is obligatory since the beginning of 2009. The paper checks, by the risk based approach, the part of the Directive prescribing stability, freeboard and the safety clearance of inland container vessels.

The requirements prescribed by the Directive are, very briefly, the following.

The freeboard of vessels with open cargo holds should be, at least, ***0.15 m***. This basic freeboard could be (somewhat) reduced on the account of the deck sheer and watertight superstructure.

The safety clearance (vertical distance from the waterline to the first unsecured opening) should be, at least, ***0.5 m***.

Concerning stability, the Directive supposes that the vessel is subjected to the beam wind and (simultaneous) turning on a circular path. It recognizes the case of secured (fixed, lashed) and unsecured (non fixes) containers. For the case of unsecured containers (which is the usual practice on the major European inland waterways), the mean wind speed is supposed to be ***18 m/s***, and the radius of the turning trajectory equal to *2.5L*. Under such joint action of wind and centrifugal force, the maximal static heel is restricted to **5°**. In addition, the edge of vessel deck should not be submerged, and the metacentric height should not be less than ***1 m***.

It should be noticed that the stability requirements are (for the sake of simplicity), reduced to the static requirements, only. Unlike some other inland stability rules, the Directive neglects all the dynamic effects. For instance, the Recommendations of UN Economic Commission for Europe, or Serbian Register of Shipping, do account wind gusts through (simplified) inland weather criterions. However, the requirement of the Directive that the edge of the main deck should not be submerged, does give some safety margin to cover the neglected dynamic effects. One of the tasks of the following analysis is to clarify if such simplified approach is sufficient and properly adjusted to insure the vessel's safety.

SAMPLE VESSEL

The sample vessel of the present investigation is a typical European inland container vessel ***110 m*** long, ***11.4 m*** in beam, designed to carry up to *208* TEU containers in *13* bays, *4* rows and *4* tiers, in a single open cargo hold. The vessel has designed draught of ***3.1 m*** (typical for the Rhine vessels). In such, fully loaded condition, the average mass of TEU containers onboard is about *12.8 t*.

It is supposed that the vessel has freeboard of *0.15 m*, which is the minimal value required by the Directive. To satisfy the safety clearance requirement, the vessel would have to have watertight hatch coamings, at least, *0.35 m* high. However, the actual height of watertight hatch coamings is not yet specified, as it would be one of the variables in the oncoming calculations.

Since the angle of the deck edge submergence of the sample vessel equals *1.5°* (less than *5°*) it is the critical heeling angle according to the Directive. The angle of flooding of the cargo hold, in the case of minimal safety clearance (minimal watertight hatch coaming height) is *5.7°*. The residuary righting arm of the vessels, defined as

$$h' = h - GM \cdot \sin\varphi ,$$

is presented in Fig. 1 and approximated by an odd polynomial of high order for the sake of numerical calculations. From the known h' curve, one can easily obtain total righting arm h for any prescribed value of *GM*. The critical heeling angles depend on the height of watertight hatch coamings, so are not yet specified.

It was found that the critical requirement - static heel smaller than *1.5°* under combined action of wind, was satisfied if ***GM > 1.2 m***. Being larger than *1 m*, that is the actual stability limitation prescribed the Directive.

To prevent eventual falling of crew into the cargo hold, the Directive (in the part not connected to freeboard, safety clearance or stability requirements) defines the minimal height of hatch coamings as *0.7 m*. However, there is no specific requirement for their water tightness, once the minimal safety clearance is satisfied!

To resume, the sample vessel, in the case of metacentric height over *1.2 m* and watertight hatch coaming height over *0.35 m*, would satisfy all the stability, freeboard and safety clearance requirements prescribed by the Directive.

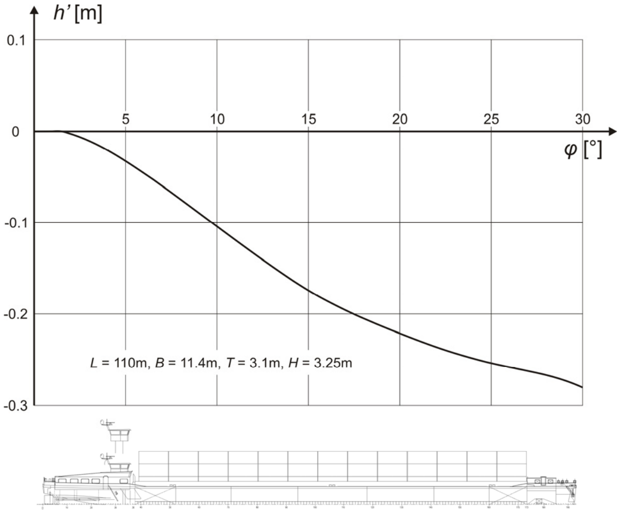

Fig. 1: Residuary righting arm of sample vessel

NUMERICAL EXPERIMENTS

The explained risk based procedure was applied on the sample vessel, supposing that the mean wind speed is *18 m/s*, which is exactly the one prescribed by the Directive. In applying the procedure, it was necessary to assess the appropriate period in which the vessel is exposed to the wind action. The choice of storm duration is closely related to the assessment of acceptable (permitted) index of flooding, as one of the most delicate tasks in the following analysis. In the present analysis, as in the previous investigation done by the authors, it is accepted that the storm lasts for *2* hours, and that in such circumstances the acceptable index of flooding is of $\mathbf{O}(10^{-3})$. Although such choice is somewhat arbitrary, it is believed (as explained in Hofman at el 2006), that it provides a similar level of safety to inland vessels, as does the classical Weather Criterion to the seagoing ships.

The most probable maximal heel of the vessel satisfying the minimal requirements of the Directive, in two hours of storm, is obtained to be *7°*. It is larger than *5.7°*, implying that the cargo hold of such vessel would be flooded! So, the height of watertight hatch coamings has to be increased over the minimal value prescribed by the Directive, to ensure the vessel safety.

The obtained index of flooding of sample vessel for different metacentric heights and for different hatch coaming heights is presented in Fig. 2. Concerning the requirements of the Directive and the imposed risk based criterion, these diagrams could be divided into four Regions:

	Region **I**	Region **II**	Region **III**	Region **IV**
EC Directive Criterion	✓	✓	✗	✗
Risk based Criterion	✓	✗	✗	✓

The results falling into Region II demonstrate a possible situation in which the requirements of the Directive are fulfilled, while the risk based approach indicates that the vessel is not safe enough! In the case of examined vessel, this happens if the watertight hatch coamings are less than *0.85 m* high.

The part of the curves in Region IV show the opposite situation: there are cases in which the metacentric height could be reduced below the requirements of the Directive, without endangering the vessel safety.

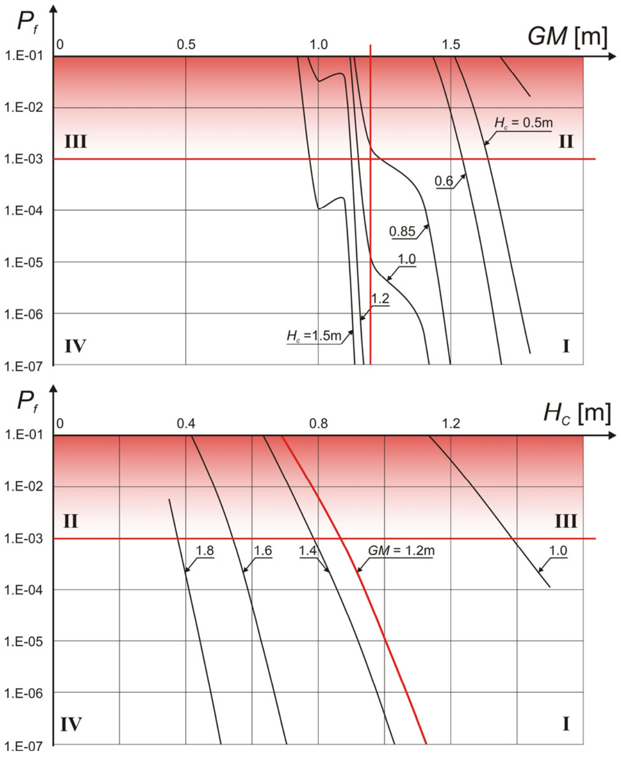

Fig. 2: Index of flooding of a typical inland container vessel

In addition to the index of flooding of the cargo hold, the probability that unsecured containers could slide in 2 hours of gusting wind action was calculated. A container in a side row of the highest tier was chosen as an example.

The results for the probability of sliding in case of different mean wind speeds, as a function of container mass and metacentric height, is presented in Fig. 3. The friction coefficient between the containers is supposed to be *0.4* (steel to steel, wet).

As expected, the diagrams show that the probability of sliding decreases with the increase of container mass. The most vulnerable are, therefore, the empty, *2 t* containers. Still, even these containers do have acceptably small probability of sliding at mean wind speeds up to *18 m/s*. It should be remembered: that is the wind speed prescribed by stability criterion of the Directive; at the stronger winds, the inland transportation is (usually) stopped. So, normally there is no danger of container sliding. However, if the vessel (for some reason) sails in a bit stronger winds, the probability of sliding of containers could be dangerously increased.

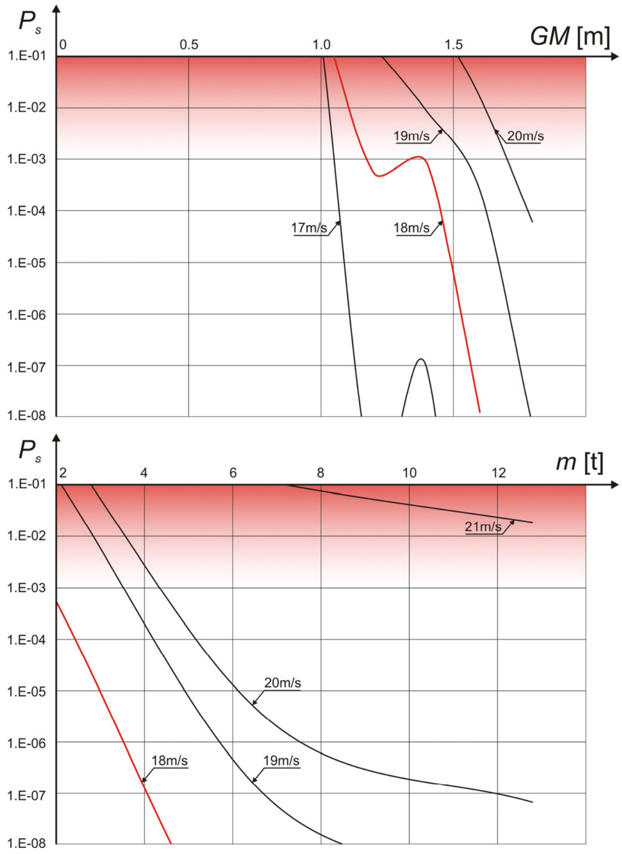

Fig. 3: Probability of sliding of unsecured container

CONCLUSIONS

Introduced risk based procedure was applied on a typical, *110 m* long inland container vessel, satisfying the minimal safety requirements of the European Directive for Technical Requirements for Inland Waterway Vessels. It was supposed that the vessel sails in beam storm prescribed by the Directive (mean wind speed *18 m/s*), and found by numerical experiments that her cargo hold would be flooded in two hours due to heel and rolling caused by the gusting wind!

To prevent the flooding, the vessel's safety clearance would have to be increased over the minimal requirement prescribed by the Rules. The proposed risk based criterion (minimal index of flooding of $\boldsymbol{O}(10^{-3})$), indicates that such increase should be, at least, *0.5 m*. This could be done (for instance), by increasing the height of watertight hatch coamings.

In spite of disturbing findings of the numerical experiments, there seems to be no accidents that such results anticipate. Is that just a good fortune or the obtained results involved some improper assumptions and modelling?

The answer seems to lie in typical hatch coaming heights used on inland container vessels. Namely, apart from the safety clearance requirement, the vessels usually have hatch coamings of over *1 m* because of strength (and other) reasons. Such high hatch coamings are typically made watertight, so they (unintentionally but fortunately) increase the vessel safety to the desired level!

The risk based approach proved that, in winds of mean speeds up to *18 m/s*, there is no practical danger of container sliding. However, the results also show a high sensitivity of sliding risk on the wind speed. In the winds just a bit stronger than *18 m/s*, the probability of sliding of empty containers in the upper tiers becomes dangerously high. So, the usual practice to stop inland traffic in wind speeds exceeding *18 m/s*, seems to agree surprisingly well with the obtained risk based result.

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NOMENCLATURE

A_n	wind-gust amplitude
a_y , a_z	acceleration components of container centre of mass
C	container centre of mass
F_B	vessel freeboard
F_w	wind force
F_y , F_z	container reactions
g	gravitational acceleration
f_s	container sliding function
$\bar{f}_s$	mean value of f_s
G	vessel centre of mass
GM	metacentric height
h	total righting arm
h'	residuary righting arm
H_c	hatch coaming height
L	vessel length
m	container mass
N	number of cycles
P	probability
P_f , P_s	index of flooding and probability of container sliding
S	wind spectrum
σ_φ , σ_s	standard deviations of φ and f_s
t	time
v, $\bar{v}$	wind speed, mean wind speed,
v'	fluctuating wind speed
v_n	amplitude of n-th wind component
x, y, z	moving coordinate axes (centre in G)
y_C , z_C	coordinates of centre C
α_n	phase shift of n-th wind component
ϕ	prescribed angle of heel
φ , $\bar{\varphi}$	roll angle, heel, mean value of roll
φ_f , φ_{max}	flooding angle, most probable maximal heel
η	sway
κ	coefficient of terrain roughness
μ	friction coefficient
ω, ω_n	wind frequency, frequency of n- th wind component