STABILITY OF EUROPEAN INLAND VESSELS: DETERMINISTIC REGULATIONS VS. PROBABILISTIC APPROACH

Igor Bačkalov

1University of Belgrade, Faculty of Mechanical Engineering, Department of Naval Architecture, Belgrade, Serbia (ibackalov@mas.bg.ac.rs)
(*) Corresponding author

ABSTRACT

This paper presents an overview of stability requirements contained in various safety regulations for inland vessels that coexist in Europe. A range of national, regional and international rules that are presently in force, comprise diverse criteria and use different stability assessment methods. Using typical European inland vessels, the differences between regulations are emphasized through numerical examples, with specific focus on inland container vessels and river cruisers. It is demonstrated that existing deterministic regulations fail to provide sufficient level of safety in a number of relevant cases. Therefore, a probabilistic alternative to present regulations is proposed and discussed. Particular attention is paid to appropriate modelling of ship motions and weather conditions (gusting wind).

Keywords: intact stability; inland container vessels; inland passenger vessels; probabilistic ship stability regulations; coupled nonlinear rolling; stochastic wind.

RESUMEN

Este escrito presenta una visión general de los requisitos de estabilidad contenidos en diferentes normas de seguridad para los buques de navegación interior que coexisten en Europa. Una gama de normas nacionales, regionales e internacionales, que son actualmente en vigor, comprenden diversos criterios y utilizan métodos de evaluación de estabilidad diferentes. Si se utilizan típicos buques de navegación interiores europeos, las diferencias entre las normas están subrayadas por ejemplos numéricos, con una atención específica a los buques de contenedor interior y cruceros fluviales. Está demostrado que las normas deterministas existentes dejan de proporcionar un nivel suficiente de seguridad en una serie de casos relevantes. A consecuencia de esto, aquí se propone y se discute una alternativa probabilística a las normas actuales. Se presta una atención particular al modelado adecuado de movimientos de la nave y a las condiciones meteorológicas (ráfagas de viento).

Palabras clave: estabilidad intacta; buques de contenedor interiores; buques de pasajeros interiores; probabilísticas normas de estabilidad de la nave; acoplado no lineal del balanceo; viento estocástico.
INTRODUCTION

Intact Stability Code [1] represents a set of regulations universally applicable to seagoing ships worldwide. Contrary to that, common stability requirements for inland vessels presently do not exist. Even on the European level, there is an array of national, regional and international rules that contain different criteria and use diverse stability assessment methods. The situation is comparable as far as other ship safety aspects are concerned too.

Historically, the most important set of regulations for inland vessels in Western Europe is issued by the Central Commission for Navigation on the Rhine (CCNR). The CCNR adopts, updates and implements regulations that are concerned with construction and outfitting of vessels, transportation of dangerous goods, boat-masters’ licenses, and so on. Technical standards are contained in the Rhine Vessel Inspection Regulations (RVIR) [2]; the first version of RVIR was issued in 1905, while the latest significant revision of the regulations took place in 2006. Inland vessels are not allowed to navigate the Rhine unless they comply with the CCNR rules. In Central and Eastern Europe, national registers such as Yugoslav Register of Shipping (JR)¹ and Russian River Register (RRR) issued their own rules for classification of inland vessels. The registers of former Eastern bloc (including JR and RRR) were associated in OTNK, the joint research and rule development body. As far as ship stability is concerned, the regulations of OTNK registers were more complex than provisions of the RVIR, reflecting stricter scientific approach to the problem.

Described conditions could have been sustained until the construction of the Main-Danube canal enabled access to the Rhine to inland vessels that were not certified by the Rhine Commission rules. Following the enlargement of European Union, it was required to establish conditions under which vessels from other EU Member States (for instance Austria and Hungary), that did not have CCNR certificates, could operate on the Rhine as well. These developments amplified the need for harmonization of the technical regulations for inland vessels in Europe.

The harmonization process in EU is implemented through the directives of European Parliament and the Council. The Directive 2006/87/EC [3] is the most recent effort in this process on the EU level. Nevertheless, not all the European states with significant inland waterways and fleets are members of European Union. Russia, Ukraine and Serbia make the most prominent cases. Therefore, it was considered that the harmonization of technical standards should be simultaneously stimulated through a larger pan-European organization. United Nations Economic Commission for Europe (UNECE) provided such platform. In 2006, based on the efforts of working groups of Inland Transport Committee, UNECE has published Resolution No. 61 “Recommendations on harmonized Europe-wide technical requirements for inland navigation vessels” [4]. As it is going to be demonstrated later in the paper, the Resolution No. 61 and in particular the Directive 2006/87/EC contain (to a large extent) exactly the same rules as CCNR’s RVIR. This way, the “harmonization” actually implied the transpose of the Rhine shipbuilding practice to other inland waterways. Similarly, the transportation of dangerous goods on inland waterways is regulated by three synchronized documents: “Regulation for the Carriage of Dangerous Substances on the Rhine (ADNR)”, adopted by the CCNR in 1972, “European Agreement concerning International Carriage of Dangerous Goods by Inland Waterway (ADN)”, adopted by UNECE in 2000 and EU Directive 2008/68/EC on the Inland Transport of Dangerous Goods, that entered into force in 2008. Ship stability provisions contained in these documents are identical.

Unfortunately, such an approach fails to provide sufficient level of safety regardless of waterway characteristics. Inland waterways may significantly differ between each other. For instance, the

¹ Classification society of the former Yugoslavia nowadays operates as Serbian register of shipping.
depth of the fairway on the Rhine is often 3.5m. Contrary to that, the Danube has many shallow-water sections, and the fairway depth only occasionally reaches 2.5m. Furthermore, the Rhine hinterland is characterized by developed infrastructure and accompanying logistics chains, while in the Danube area both the infrastructure and the logistics concepts are still being developed. The share of the high-value goods (i.e. containers) transported by inland vessels is considerably larger on the Rhine than on the Danube, where the cargo is predominantly transported in bulk, etc. (for more detailed description of differences between the Rhine and the Danube, see for instance [5]). These differences affect the fleet composition and vessel design and, consequently, the ship safety.

In an effort to overcome the shortcomings of deterministic regulations, a group of researchers from the University of Belgrade put forward a probabilistic approach to assessment of inland vessels stability. Proposed probabilistic analysis was based on the works of Francescutto and Vassalos (see, for instance papers [6] by Bulian & Francescutto and [7] by Vassalos et al.), but it was further extended so as to include inland navigation conditions. One of the focal points of the research was a proper modeling of gusting wind and its impact on ship safety. The results were reported in a series of papers, addressing the shortcomings of existing stability regulations (papers [8], [9], [10] and [11]), appropriate modelling of inland container vessel rolling in realistic weather conditions [12] and risks related to transport of non-secured containers [11], which often takes place on European inland waterways.

The paper will present an overview of stability requirements given in both Eastern and Western European rules, as well as in the documents intended for pan-European harmonization of technical standards for inland vessels. The main aspects of the proposed probabilistic alternative to present regulations will be outlined and demonstrated through stability assessment of inland container vessels and an inland cruise ship. Finally, it should be noted that the literature on safety of European inland vessels is quite scarce and, for the most part, not internationally published. Although rather old, study [13] still represents an important reference. With particular relevance for the present topic, recently published studies [14] and [15] could be pointed out.

**PRESENT STABILITY REGULATIONS FOR INLAND VESSELS**

Existing stability regulations for inland vessels comprise basic criteria, valid for all vessels within the scope of application of rules, and specific requirements for particular ship types: container vessels, pushers, passenger vessels, river-sea ships and so on. Safety requirements depend on the vessel type and the navigation zone. All regulations divide vessels into three main types: vessels with hatch covers (Type A), tankers (Type B) and open-hold vessels (Type C). European inland waterways are divided in navigation zones 1, 2 and 3, usually related to wave heights of up to 2m, 1.2m and 0.6m respectively. The EU Directive 2006/87/EC distinguishes between zones 1, 2, 3 and 4, as well as the zone R (the Rhine), but does not link navigation zones to wave heights. Russian River Register [16] defines O, R and L navigation areas corresponding to zones 1, 2 and 3, respectively. However, some important inland waterways are differently classified by various rules. For instance, the Danube and the Rhine are classified as the zone 3 waterways both by Resolution 61 and Directive 2006/87/EC, while rules of Yugoslav Register [17] consider the Danube as the zone 2 waterway and consequently apply stricter stability requirements. Furthermore, environmental conditions prescribed for the same zones of navigation by different rules may considerably vary.

When compared to the CCNR and EU regulations, the most distinct feature of the rules of Russian River Register and Yugoslav Register of Shipping is an effort to take into account the dynamic

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2 Russian River Register also recognizes zone M which corresponds to river-sea navigation.
effects, both by dynamic stability calculations and by introducing safety margins in static stability analysis. The regulations also reflect shipbuilding and operational practice in the area of origin. For instance, the regulations of the Rhine commission outline standards for different options for carriage of containers, while the Russian River Register contains extensive rules for river-sea navigation and special vessels (multihulls, air supported vessels, hydrofoils, etc.). The present paper focuses on stability regulations for container and passenger vessels.

**Stability regulations for inland container vessels**

Inland container ships are Type C vessels (vessels without hatch covers or watertight means of closing of exposed openings). It should be emphasized that inland waterway transport of containers in Europe predominantly takes place on the river Rhine. Therefore, the technical regulations of the Rhine Commission were taken as the basis for development of the safety rules for container vessels on the European level. Effectively, the RVIR requirements were simply transposed to the Directive 2006/87/EC. On the other hand, Yugoslav Register and Russian River Register do not contain provisions explicitly intended for container vessels. Instead, basic stability criteria, valid for all ship types, are amended by specific conditions that ought to be met by vessels carrying the cargo on deck, “with the center of lateral area positioned more than 2m above the waterline”.

As it was previously pointed out, the UNECE regulations were envisaged as the instrument for Europe-wide (beyond EU borders) harmonization of technical standards for inland vessels. As a result, the Resolution 61 contains both the RVIR requirements and the rules typical for registers previously associated in the OTNK.

The regulations of the Rhine Commission distinguish between vessels carrying secured (fixed) and non-secured (non-fixed) containers. Minimal metacentric height of vessels carrying non-secured containers should not be less than 1m. The static heel of a vessel exposed to simultaneous action of heeling moments caused by beam wind force and the centrifugal force due to turning should not exceed 5° or the angle at which the deck enters the water (Fig. 1a). Wind moment corresponds to 18m/s wind speed. Vessels carrying secured containers should attain metacentric height not less than 0.5m. Additionally, no hull opening should be submerged in case that vessel is simultaneously exposed to heeling moments due to wind and the turning (Fig. 1b).

![Figure 1: Stability requirements of the Rhine Commission for transport of (a) non-fixed and (b) fixed containers](image)

Yugoslav Register applies the so called Inland Weather Criterion as the basic stability requirement. The vessel heels to the angle of static equilibrium due to the steady wind moment $M_{\text{ws}}$; after the sudden increase of the wind speed (the wind gust), the vessel attains the dynamic angle of heel that
must not exceed the downflooding or capsize angle (Fig. 2a). The static and dynamic wind moments are calculated as follows:

\[ M_{ws} = p_{ws} \cdot A_w \cdot \left( l_w + \frac{T}{2} \right) \]  

and

\[ M_{wd} = \left( p_{wd} - p_{ws} \right) \cdot A_w \cdot l_w, \]  

where \( l_w \) represents the vertical distance between the centroid of exposed lateral area and the waterline. Although the similarity to the IS Code Weather Criterion is apparent, there are several important differences. The wind speed profile is taken into account when calculating wind moments. The specific dynamic pressure \( p_{wd} \) is roughly 70% higher than static \( p_{ws} \), thus making the wind gust stronger than it was foreseen for the maritime environment by IMO’s Weather Criterion. Physically, this corresponds to higher roughness of surrounding terrains on the inland waterway network (suburban areas, industrial zones, city centers, etc.) in comparison to the open sea.

Figure 2: Stability requirements of Yugoslav Register applicable to container vessels: Inland Weather Criterion (a) and additional requirement for vessels with large exposed lateral area (b)

Figure 3: Inland Weather Criterion, basic stability standard as prescribed by the Russian River Register (a) and UNECE Resolution 61 (b)
Additional stability criterion of JR that could apply to container vessels requires that static heel of vessel exposed to beam steady wind does not exceed 80% of the flooding angle (Fig. 2b).

Russian River Register requires the verification of the dynamic stability as the basic safety criterion, valid for all inland vessels considered by the rules. For vessels operating in R and L navigation zones the following applies. The angle of heel of the vessel subjected to the dynamic impact of the wind moment $M_{wd}$ should not exceed the angle of capsize or the downflooding angle, whichever is less (Fig. 3a). Wind moment corresponds to 17m/s wind speed; however the change of the wind speed profile is taken into account. Additional criterion for vessels with centroid of the exposed lateral area higher than 2m is similar to the one given in Yugoslav Register (Fig. 2b). Yet, it seems to be stricter: the angle of heel is limited to 80% of the flooding angle or to the angle at which deck enters the water.

UNECE regulations require the verification of the dynamic stability in an Inland Weather Criterion scenario, too. This provision clearly originates from the rules of former OTNK classification societies (which are parties to the UNECE working groups). The vessel, initially in the upright position is subjected to the dynamic impact of the wind moment $M_{wd}$:

$$M_{wd} = p_{wd} \cdot A_w \cdot l_w. \tag{3}$$

The resulting heeling angle should not exceed the critical angle or the capsize angle (Fig. 3b). Critical angle is rather stringent: it is defined as the angle of flooding through unsecured openings, but this angle must not be greater than the angle at which freeboard deck enters the water (for container vessels, the latter is normally critical). Just as in the JR rules, specific dynamic wind pressure $p_{wd}$ depends on the navigation zone; wind speed profile is taken into account as well.

Supplementary stability provisions for container vessels given in Resolution No. 61 contain two groups of requirements that could be alternatively used: Method A and Method B. The Method A essentially represents the afore-mentioned stability criteria of the Rhine Commission.

The Method B, in case of non-fixed containers, requires 1m minimal metacentric height as well, but demands the calculation of the dynamic stability in the following scenario. The vessel inclined to static list due to wind moment $M_{ws}$, dynamically heels under the combined action of heeling moments due to turning ($M_{de}$) and the wind. The dynamic angle of heel is limited to 5° or the angle...
at which the deck enters the water (Fig. 4a). Fixed containers could be transported if the vessel exposed to steady beam wind attains the static heel less than 80% of the critical angle (Fig. 4b).

Freeboard assignment is a common safety provision in all regulations. In addition to freeboard, regulations for inland vessels also define “safety clearance” or “safety distance”, as a vertical distance between the water level at maximal draft and the lowest point of water ingress. Required freeboard and safety clearance are also determined by the vessel type and the navigation zone. Minimal safety distance and freeboard of type A and B vessels typically depend on the vessel’s length. For type C vessels these parameters are prescribed regardless of length.

Minimal freeboard and safety distance for Type C vessels operating in zones 1, 2 and 3 are given in Table 1. The following should be noted. Both the RVIR and EU rules prescribe 150mm and 500mm as minimal freeboard and safety distance respectively, for navigation in zone 3. However, each EU country may adopt its own technical requirements, including freeboard, for zones 1 and 2. The certificates for these navigation zones, issued in one EU Member State may not be accepted in another. (For instance, the Polish Register of Shipping [18] prescribes the same freeboard and safety clearance requirements for Type C vessels as UNECE). As for Yugoslav Register, the rules for inland vessels do not foresee the navigation of Type C vessels in zone 1. In general, freeboard values may be further reduced depending on sheer, superstructures, etc. With respect to that, Yugoslav Register allows reduced freeboard of 50mm in zone 3, while according to Directive 2006/87/EC for the same zone, minimal freeboard after reductions may be as little as 0mm!

Table 1: Freeboard and safety distance requirements for Type C vessels in various regulations

<table>
<thead>
<tr>
<th>Zone</th>
<th>FB [mm]</th>
<th>SD [mm]</th>
<th>FB [mm]</th>
<th>SD [mm]</th>
<th>FB [mm]</th>
<th>SD [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>1000</td>
<td>1200</td>
<td>–</td>
<td>–</td>
<td>1000</td>
<td>1900</td>
</tr>
<tr>
<td>Zone 2</td>
<td>600</td>
<td>1000</td>
<td>300</td>
<td>1000</td>
<td>600</td>
<td>1200</td>
</tr>
<tr>
<td>Zone 3</td>
<td>150</td>
<td>500</td>
<td>150</td>
<td>500</td>
<td>450</td>
<td>600</td>
</tr>
</tbody>
</table>

Since the safety distance of container vessels is related to the hatch coaming, the minimal hatch coaming height can be derived from the \( F_B \) and \( S_D \) values given in Table 1. For instance, \( H_{cmin} \) for navigation in zone 2 may vary from 400mm (according to Resolution 61) to 600mm (Russian River Register) to 700mm (Yugoslav Register). Additionally, the provisions for safety in working spaces of the RVIR and the Directive 2006/87/EC require a 700mm high bulwark or coaming as a measure against falling into cargo hold. The Resolution 61 prescribes somewhat higher value (900mm) for the same purpose. However, this rule is not stability related, hence the watertightness is not specifically required (even a guard rail is permitted).

**Stability regulations for inland passenger vessels**

Inland passenger ships are subject to specific safety requirements in all regulations considered. The stability assessment is typically carried out for several loading cases, taking into account the wind effects, the grouping of passengers and the turning, and often restricting heeling to the so called panic angle (10 – 12°).

According to the Rhine Vessel Inspection Regulations, intact stability of passenger ships is deemed as appropriate if a vessel, first of all, satisfies criteria related to the parameters of the righting arm (including minimal metacentric height). Minimal freeboard should not be less than 0.3m. Permitted angle of static heel should not exceed 12° under the combined action of heeling moments due to turning, passenger accumulation and wind (\( M_{dh}, M_p, \) and \( M_w \) respectively) (Fig. 5a) while the residual freeboard in such case should not be less than 0.2m. The accounted wind speed is merely 11m/s. The static heel due to passenger accumulation only is limited to 10° (Fig. 5b).
Figure 5: Stability requirements for passenger ships contained in various regulations: Rhine Vessel Inspection Rules (a, b), EU Directive 2006/87/EC (a, c, d), Yugoslav Register of Shipping (c, d, e) and Russian River Register (f, g, h).
The Directive 2006/87/EC prescribes the same requirements concerning the righting arm parameters and the residual freeboard as the Rhine Vessel Inspection Regulations. Still, there are several differences in comparison to the RVIR. The static heel due to simultaneous action of wind and passenger accumulation on one side of the vessel should not exceed 12° (Fig. 5c). The same criterion would apply if the vessel is subjected to heeling moments due to turning of the vessel and passenger accumulation (Fig. 5d). However, the corresponding wind speed is 18m/s. Instead of minimal freeboard, the rules limit minimal downflooding angle to 15°. The wind moment is calculated just as the static $M_{ws}$ in rules of Yugoslav Register, see formula (1), except that wind pressure does not depend on the height above the water.

Cabin windows are inherent part of the passenger ship design. Both the RVIR and the Directive 2006/87/EC set the minimal residual safety clearance to 0.1m when the vessels with the non-watertight side windows are simultaneously exposed to the moments due to wind, turning and passenger accumulation. The Directive 2006/87/EC however, explicitly refers to windows located below the bulkhead deck, while the CCNR rules denote (all) the windows “that can be opened”.

In addition to basic stability requirement, Inland Weather Criterion (Fig. 2a), Yugoslav Register applies several supplementary stability criteria intended for passenger ships. The static heel due to the most unfavorable grouping of passengers is limited to angle at which 75% of freeboard is submerged (Fig. 5e); this angle, however, should not exceed 10°. Furthermore, the static heel should not exceed the downflooding angle or 12° in the case of the simultaneous passenger accumulation combined with turning (Fig. 5d), or with static wind moment (Fig. 5c).

In addition to basic (dynamic) stability requirement (Fig. 3a), Russian River Register also prescribes the additional stability criteria for passenger ships. The static list due to the accumulation of passengers on one side of the vessel $\phi_s$ should not exceed the critical angle set to 80% of the flooding angle or the angle at which the deck edge is submerged (Fig. 5f). In any case, permitted angle of static heel is limited to 10° for ships longer than 30m. The vessel inclined to angle $\phi_s$ should further withstand dynamic impact of the moment due to turning of the vessel (Fig. 5g). The limiting angle of dynamic heel is defined as the angle at which either the deck, or the waterline positioned 75mm below the exposed opening, enters the water (whichever is less). Furthermore, in case that the center of exposed lateral area is positioned more than 2m above the waterline, static heel of the vessel simultaneously exposed to heeling moments $M_p$ and $M_w$ should not exceed aforementioned critical angle; yet this angle may exceed 10° in given scenario (Fig. 5h).

An attempt to accurately describe the physics of the stability related phenomena is a prominent feature of the rules of Russian River Register. For instance, in contrast to other regulations, the levers of wind moments are defined as follows:

$$M_{wd} = p_{wd} \cdot A_w \cdot (l_w + a_1 a_2 T),$$  \hspace{1cm} (4)

where $a_1 = f(B/T)$ and $a_2 = f(GK/B)$,

$$M_{ws} = p_{ws} \cdot A_w \cdot (l_w + T(1 - a_1)),$$  \hspace{1cm} (5)

The similar applies to the heeling moment due to turning, which in all analyzed regulations has the following form:

$$M_{dr} = C \cdot v^2 \cdot \frac{D}{L_{WL}} \cdot \left(GK - \frac{T}{2}\right),$$  \hspace{1cm} (6)
where constant coefficient $C$ may differ, depending on the rule considered. The rules of Russian River Register, however, prescribe:

$$M_{dr} = C \cdot v^2 \cdot \frac{D}{L_{WL}} \cdot (GK - a_3 T),$$

(7)

where $a_3 = f(B/T)$. Another interesting feature of the RRR rules is that the dynamic wind pressure is considered to be more than two times higher than the static one: $p_{ws} = 0.47 p_{wd}$.

Finally, the Resolution No. 61 contains exactly the same requirements as Directive 2006/87/EC. Still, the basic stability requirement, i.e. Inland Weather Criterion (Fig. 3b) should be satisfied too.

**PROBABILISTIC APPROACH TO STABILITY OF INLAND VESSELS**

For the most part, present stability regulations are based on simplified techniques and outdated tools, whereas contemporary knowledge on ship dynamics, modelling of environmental loads and probabilistic methods enable more accurate ship safety assessment. Following the on-going process of development of probabilistic regulations for intact stability of sea-going ships (see, for instance [19]), a similar approach was proposed for inland vessels (see papers [8] ÷ [12]). In general, probabilistic safety assessment implies evaluation of the probability of a critical event (stability failure) in environmental conditions that could lead towards an incident. Probability is derived by means of statistical analysis of relevant ship motion(s). Therefore, probabilistic analysis would require an appropriate mechanical model of motions of a ship exposed to properly represented weather conditions in a realistic scenario.

For inland vessels the proposed scenario was, to an extent, adopted from the Inland Weather Criterion (see paper [8]). The vessel is exposed to severe beam gusting wind of a prescribed mean speed, over a specified exposure time. The probability that vessel would attain critical angle of heel in such scenario, should not exceed an acceptable value. It should be noted that such scenario covers both classic dead ship condition and the powered vessel. Unlike the sea-going ship, inland vessel could be forced to sail in strong beam winds because master cannot change her route, due to waterway constraints.

The state-of-the-art 2DOF model of inland vessel motions, used in present analysis, was described in detail in paper [12]. Therefore, only the main features of the model will be briefly outlined. Initially, a robust model, single nonlinear differential equation of roll was utilized in papers [8] and [9]. Over the course of the research, it was demonstrated that simplified 1DOF model overestimates the rolling generated by wind gusts, due to several reasons. Consequently it was substituted with the system of coupled nonlinear differential equations of roll and sway:

$$\dot{\eta} + m_{pp} \ddot{\phi} + N_{\eta} (\ddot{\eta}) + m_{pp} \phi = F_w (v_w) - F_r$$

(8)

$$\dot{\phi} + m_{pp} \ddot{\eta} + N_{\phi} (\ddot{\phi}) + m_{pp} \eta = M_{ww} (v_w) + M_r$$

(9)

The constant side force $F_r$ restrains the drift and keeps the vessel “on course”. Otherwise, the vessel would freely drift off, which is very unlikely in realistic circumstances as the master would tend to retain the vessel on her route. Hence the equations (8, 9) are labelled as the “course-keeping” model of sway and roll (in contrast to “free-to-drift” model where $F_r = 0$ and $M_r = 0$). The comparison of models developed throughout research is performed in paper [12]. The course-keeping model is not only considered to be more realistic, but it also proves to be more dangerous one from the safety
point of view when compared to the free-to-drift model. Side force $F_r$ and moment $M_r$ are calculated as follows:

$$F_r = \frac{1}{2} \rho_s A_s c_s \cdot \overline{v}^2,$$  \hspace{1cm} \text{(10)}

$$M_r = \frac{1}{2} \rho A_s c_s/\ell_s \cdot \overline{v}^2,$$  \hspace{1cm} \text{(11)}

where speed $\overline{v}$ should be taken as a few percent higher than the free drift speed $\overline{v}_o$:

$$\overline{v}_o = \frac{k}{1+k} \overline{v}_w \approx k \cdot \overline{v}_w,$$  \hspace{1cm} k = \frac{\rho_s c_s A_s}{\rho c_s A_s}.$$

Proper modelling of forces and moments generated by stochastic beam wind was one of the central points of the research. Wind force and moment are calculated as:

$$F_w = \frac{1}{2} \rho_w A_w c_w \cdot \overline{v}_w^2,$$  \hspace{1cm} \text{(13)}

$$M_w = \frac{1}{2} \rho_w A_w c_w/\ell_w \cdot \overline{v}_w^2,$$  \hspace{1cm} \text{(14)}

where $\overline{v}_w$ represents apparent wind speed (wind speed relative to the vessel):

$$\overline{v}_w(t) = \overline{v}_w - \dot{\overline{v}}_w + \sum_{n=1}^{N} v_n \cos(\omega_n t + \alpha_n).$$

Amplitudes of the fluctuating part of the wind speed $v_n$ are obtained from the Davenport wind spectrum:

$$v_n = \sqrt{2S(\omega_n) \cdot d\omega}, \hspace{1cm} S(\omega) = \frac{4K \cdot \overline{v}_w^2 X_D^2}{\omega (1 + X_D^2)^3}, \hspace{1cm} X_D = \frac{600\omega}{\pi \cdot \overline{v}_w},$$

The choice of appropriate value of the terrain roughness coefficient $K$, which directly affects the wind gust amplitudes, was discussed in detail in paper [9]. In deterministic regulations, the static wind moment lever is usually taken as the distance between centroids of lateral areas above and under water, the latter being approximated by half of the draft (see formula 1). The dynamic wind moment lever is defined as the vertical distance of centroid of lateral area exposed to wind and the waterline, as in the formulas (2) and (3). The rules of the Russian River Register are the only exception as they integrate better physical modelling into formulas (4) and (5). Model (8, 9) enables to implement a correct term for the wind moment lever, from the mechanics point of view, as the distance between the vertical centre of gravity and centroid of vessel’s lateral area above water.

On the left-hand side of roll equation (9), the righting moment is:

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

where $h'$ represents residuary righting arm, approximated by a high-order odd polynomial:
Damping forces and moments contain both linear and nonlinear parts:

\[ N_{\eta}(\dot{\eta}) = n_{\eta}\dot{\eta} + \frac{1}{2} \rho A_s c_s \cdot \dot{\eta} |\dot{\eta}|, \]
\[ N_{\phi}(\dot{\phi}) = n_{\phi}\dot{\phi} + \beta \cdot \dot{\phi} |\dot{\phi}|, \]
\[ N_{\eta\eta} = n_{\eta\eta}\dot{\eta} - \frac{1}{2} \rho A_s c_s l_s \cdot \dot{\eta} |\dot{\eta}|. \]

Finally, added masses \( m_\eta, m_\phi \) and \( m_{\eta\eta} = m_{\eta\phi} \) and potential damping coefficients \( n_\eta, n_\phi \) and \( n_{\eta\eta} = n_{\eta\phi} \) on the left-hand side of equations (8, 9) are obtained using classical strip-theory technique.

System of equations (8, 9) is numerically solved using Runge-Kutta method. Obtained time record of roll is subsequently analysed in order to derive statistical properties: mean roll angle, standard deviation, etc. The probability that the vessel would heel to some prescribed, critical angle of heel in specified exposure time is calculated as:

\[ P = 1 - \exp \left\{-N_c \exp \left[ -\frac{1}{2} \left( \frac{\phi - \phi_0}{s_\phi} \right)^2 \right] \right\}, \]

where \( N_c \) is the number of cycles in analyzed exposure time:

\[ N_c = \frac{t}{T}. \]

Very important aspect of the probabilistic safety analysis is the choice of the appropriate acceptable level of probability of the critical event, \( P_a \). In line with the analysis of safety of sea-going ships done in [8], the permissible probability \( P_a = O(10^{-3}) \) in two hours exposure time was adopted.

**Sample vessels**

In order to highlight the differences between the analyzed regulations, stability assessment of a typical European inland container vessel and a passenger ship intended for river cruises (Fig. 6) is carried out. A common feature of the selected sample ships is the large exposed lateral area which could make them vulnerable to the impacts of beam wind. Both vessel types, although quite dissimilar, have the same principal dimensions (\( L \) and \( B \)) corresponding to the European CEMT Va class [20] (Table 2).

| Table 2: Particulars of the sample vessels |
|-----------------------------------------|----------------------------------|----------------------------------|
| Rhine container vessel | Danube container vessel | RMD passenger vessel |
| \( L \) [m] | 110 | 110 | 110 |
| \( B \) [m] | 11.4 | 11.4 | 11.15 |
| \( T \) [m] | 3.1 | 2.1 | 1.5 |
| \( D \) [t] | 3444 | 2327 | 1486 |
| \( A_w \) [m\(^2\)] | 923 | 1003 | 739 |
Two self-propelled container carrier designs are analyzed: a representative “large Rhine” vessel with 3.1m draft and a container vessel with much smaller 2.1m draft suitable for navigation on the Danube. Regarding the passenger ship, one of the distinctive contemporary designs used in river cruises on the Danube and the Rhine was selected.

![Sample vessels used in the investigation: inland container vessel (a) and river cruise ship (b)](image)

**Probabilistic analysis of stability of inland container vessels**

Stability of inland container vessels from the probabilistic point of view was subject of thorough investigations (see [8], [9], [10], [11] and [12]). One of the goals of the research was to establish the correlation of safety levels attained by present stability regulations to estimated probability of stability failure.

Therefore, the minimal stability requirements for sample container vessels were determined according to the rules [4]. It was assumed that vessels operate in navigation zone 2. Minimal metacentric heights for cases of secured and non-secured containers are indicated in Fig. 7 (taken from [10]). Minimal safety distance, freeboard and consequently, minimal hatch coaming height follow from Table 1. Note that $H_{cmin} = 400$mm applies for zone 2. Mean wind speed was also adopted from the regulations, i.e. 18m/s. As the safety distance of inland container vessels is related to hatch coaming height, the probabilistic safety criterion requires that probability of flooding of an open cargo hold should not exceed acceptable probability $P_a$ in two hours. A series of numerical experiments for a range of realistic metacentric heights and a number of hatch coaming heights was performed. The results of probabilistic analysis are given in Fig. 7.

The Rhine vessel (Fig. 7a) fulfilling the minimal stability provisions ($MG_{min}$ and $H_{cmin}$) cannot be considered as safe in beam gusting wind. This particularly applies to the vessel carrying secured containers. For all hatch coaming heights considered, the risk of flooding is unacceptably high if the metacentric height is at its minimum. $MG$ should be increased by some 0.3m in order to achieve required safety level even with coamings considerably higher than prescribed by the rules. Typical vessels, however, carry non-secured containers and have hatch coamings higher than 1m. So, the minimal metacentric height would suffice to attain adequate safety level in such cases. On the other hand, minimal hatch coaming, i.e. 0.4m, would require the increase of $MG_{min}$ by not less than 0.3m if containers are not secured.

The safety of the Danube vessel is even worse (Fig. 7b). Sufficient safety level cannot be achieved regardless of hatch coaming height, if metacentric height complies with minimal stability requirements. In case that vessel carries non-fixed containers, minimal $MG$ should be increased at
least by 0.1m, or by 0.3m, if containers are fixed. It should be noted the Danube vessel with the same \( MG \) and \( H_c \) as the Rhine one is always exposed to higher risk of flooding. So, the probabilistic analysis indicates that present regulations for container ships are actually tailored for the typical Rhine vessels. They fail to provide adequate safety for shallow-draft ships, such as the examined Danube container vessel.

![Figure 7](image)

**Figure 7**: Probability of flooding of container vessels designed for the Rhine (a) and for the Danube (b), correlated to minimal safety requirements of rules [4]. Each curve corresponds to a hatch coaming height.

The transport of non-fixed containers is a usual practice in European inland navigation. So, it would be interesting to examine another safety aspect, i.e. the probability of loss of containers in strong beam winds. In order to assess the probability of sliding of a side row container in the uppermost tier, a number of numerical experiments were conducted on a Rhine container vessel, complying with safety requirements of the regulations [3] for the zone 3 \((F_{B\text{min}} = 0.15m, MG_{\text{min}} = 1.2m)\). The results were presented in paper [11]. The friction coefficient \( \mu = 0.4 \) corresponding to friction between wet steel surfaces was assumed.

![Figure 8](image)

**Figure 8**: Probability of sliding of an unsecured container in different mean wind speeds as a function of (a) the metacentric height and (b) the container mass, for \( MG = 1.2m \)

Probability of sliding increases as the container mass decreases, but even the empty units \((m = 2t)\) attain the required safety level in winds up to 18m/s (Fig. 8, taken from [11]). Yet, in slightly stronger winds, the probability of sliding dangerously increases. The results or probabilistic analysis
are therefore in good agreement with operational experience, as the inland navigation is usually suspended in winds stronger than 17m/s.

**Probabilistic considerations of inland passenger vessel stability**

For the purposes of the present paper, the application of described method to inland passenger vessels was briefly investigated as well. Several aspects needed to be reconsidered. Rather than downflooding, heeling to the panic angle was regarded as the critical event. Furthermore, within the risk-based framework, not only the probability, but also the consequences of a critical event should be examined. Given that stability failure of a passenger vessel could potentially lead to more fatalities in comparison to an accident of a cargo ship, it remains open to discussion whether instead $P_a = O(10^{-3})$ a lower level of probability should be prescribed.

The probability of flooding ($\varphi_f = 23^\circ$) as well as the probability that vessel would attain $10^\circ$ (the panic angle) were derived as a function of metacentric height (Fig. 9a). On the other hand, minimal metacentric heights were calculated according to analyzed deterministic regulations and given in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>RVIR 2006/87/EC</th>
<th>JR Zone 2</th>
<th>JR Zone 3</th>
<th>RRR Zones R, L</th>
<th>UNECE Zone 2</th>
<th>UNECE Zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MG_{min}$ [m]</td>
<td>0.919</td>
<td>0.949</td>
<td>0.608</td>
<td>0.49</td>
<td>0.557</td>
<td>0.968</td>
</tr>
</tbody>
</table>

The probabilistic analysis indicates that minimal metacentric heights required by the existing regulations should be increased, although present investigation takes into account wind effects only. For instance, if more stringent $P_a = O(10^{-4})$ is adopted as required safety level for passenger ships, metacentric height should be at least 1.5m. Although observed deficiency of rules does not represent a threat to the safety of this particular design of passenger vessels (as they normally operate with considerably higher metacentric heights) it does reveal that deterministic rules may be misleading. The results also suggest that different rules may yield quite dissimilar safety levels for the same vessel.

![Figure 9](image-url)

**Figure 9:** Probability of stability failure of inland passenger vessel: in 18m/s mean wind speed (a) and in varying wind speeds (b).

Previously, it was demonstrated that container vessel safety is rather sensitive to mean wind speed variations. Following that conclusion, susceptibility of the selected passenger vessel to wind changes was examined as well (Fig. 9b). The order of magnitude of estimated probability of heeling
to the panic angle mounts sharply with the increase of mean wind speed. These findings support the afore-mentioned operational practice of suspension of navigation in severe winds.

CONCLUDING REMARKS

Although it is considered that inland navigation in Europe has a good safety record, the stability related accidents do happen, on the Rhine as well as on the Danube or the Russian rivers. Two accidents that recently took place on the Rhine could be outlined. In 2007, container vessel *Excelsior* lost around 30 containers (one third of her load) in an incident near Cologne, due to a combination of inappropriate loading, impact of wind gust and turning. The navigation was suspended for six days, affecting several hundred vessels and causing the damage that amounted to EUR 1 million. In 2011, inland tanker *Waldhof* capsized in intact condition on the Central Rhine. Two persons were reported dead and one missing; 900t of sulfuric acid leaked into the river. The navigation on the Rhine was fully restored after almost five weeks. The total damage was estimated to some EUR 50 million [21]. Sometimes, the consequences are much more severe, with human casualties comparable to the maritime catastrophes. In 1952, due to severe wind in combination with overloading, ferry *Niš* capsized on the Danube, near Belgrade, causing the death of around hundred passengers. In 2011, the sinking of the river cruiser *Bulgaria* in a storm on the river Volga led to over 120 confirmed deaths.

In general, the stability hazards of inland vessels are recognized by the numerous safety regulations presently utilized in Europe. However, the stability rules often rely on doubtful approximations and oversimplified methods. As a consequence, in some cases, the regulations fail to provide sufficient level of safety. It was demonstrated that large Rhine container vessels satisfying minimal safety requirements attain unacceptable risks in extreme, but realistic weather conditions. On the other hand, adequate stability could be achieved unintentionally, by application of another, unrelated rule. The safety of existing container fleet is improved due to structural strength demands and provisions for safety at work that both result in hatch coamings much higher than stability rules for inland container vessels require.

Moreover, the regulations may be based on operational and shipbuilding practice gained in one waterway, which cannot be directly applied on some other, considerably different river. It was shown that container vessels intended for waterways of different depth attain different safety levels, although they comply with the regulations. Container vessels designed for shallow waterways, such as the Danube, are exposed to higher risks. Presently, containers are only occasionally transported on the Danube, but it is expected that container transport volumes are going to rise in the future. Thus the safety issues, caused by inconsistent rules, may yet become evident.

Though a single case is insufficient to draw more substantial conclusions, the probabilistic analysis of an inland passenger ship seems to confirm the safety of this modern design and aligns well with operational experience. However, even though only the effects of beam gusting wind were considered in present study, the results indicated that the vessel fulfilling minimal stability requirements could attain unacceptable risk levels in realistic weather conditions. Hence the sufficient level of safety is not attained by stability requirements of regulations, but comes as a consequence of other design features, much as is the case with inland container vessels.

The sensitivity to gusting winds is noticeable for both sample ship types. The probability of stability failure could rise for several orders of magnitude, due to a relatively small increase of mean wind speed. One of the reasons why accidents on inland waterways do not happen more often is certainly suspension of navigation in strong winds, usually over 17m/s. These findings highlight the importance of proper modelling of often overlooked wind loads.
Despite the harmonization attempts, various technical standards for inland vessels are still being used in Europe. The overall situation is dissatisfying and often confusing. The Author believes that the present state could be substantially improved with the introduction of probabilistic approach to intact stability analysis. The paper presents just a part of the research, carried out over the years in the University of Belgrade, with an aim to thoroughly investigate the safety of inland vessels and to contribute to development of a probabilistic alternative to current deterministic regulations. The research is still on-going and several aspects should be reconsidered and agreed upon (including the reliability of mechanical model, roll damping coefficients appropriate for inland vessel forms, acceptable level of probability of stability failure and so on). The introduction of such regulations in inland navigation would require more complex calculations and advanced software, but also an altered understanding of safety. It is considered, however, that the risk-based regulations could be applied on all inland waterways, regardless of their specific characteristics. Moreover, the probabilistic approach would enable not to learn from the accidents but to avoid them and diminish the risks for vessel, cargo, crew and environment.

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NOMENCLATURE

\( A_s \) \quad \text{underwater lateral area of the vessel (m}^2\text{)} \\
\( A_w \) \quad \text{lateral area of the vessel exposed to wind (m}^2\text{)} \\
\( D \) \quad \text{displacement (t)} \\
\( F_B \) \quad \text{freeboard (m)} \\
\( G_K \) \quad \text{vertical centre of gravity (m)} \\
\( H_c \) \quad \text{hatch coaming height (m)} \\
\( K \) \quad \text{terrain roughness coefficient (-)} \\
\( L \) \quad \text{vessel length (m)} \\
\( I_w \) \quad \text{wind moment lever (m)} \\
\( M_G \) \quad \text{metacentric height (m)} \\
\( M_p \) \quad \text{heeling moment due to accumulation of passengers (kNm)} \\
\( M_{st} \) \quad \text{righting moment (kNm)} \\
\( M_w \) \quad \text{wind moment (kNm)} \\
\( M_{wd} \) \quad \text{dynamic wind moment (kNm)} \\
\( M_{ws} \) \quad \text{static wind moment (kNm)} \\
\( P_a \) \quad \text{acceptable probability (-)} \\
\( P_S \) \quad \text{probability of sliding of an unsecured container (-)} \\
\( P_{wd} \) \quad \text{dynamic wind pressure (kPa)} \\
\( P_{ws} \) \quad \text{static wind pressure (kPa)} \\
\( S \) \quad \text{wind spectrum ordinate (m}^2\text{/s)} \\
\( S_D \) \quad \text{security distance (safety clearance) (m)} \\
\( s_p \) \quad \text{standard deviation of roll (rad)} \\
\( T \) \quad \text{draft (m)} \\
\( \bar{T} \) \quad \text{mean (zero-crossing) period of roll (s)} \\
\( t_e \) \quad \text{exposure time (s)} \\
\( v_n \) \quad n^{th} \text{wind-gust amplitude (m/s)}
\( \bar{v}_w \) absolute mean wind speed (m/s)
\( \bar{v}_d \) constant drift speed (m/s)
\( \phi \) prescribed critical angle of heel (rad)
\( \varphi \) mean value of roll (rad)
\( \varphi \) roll angle, heel (°, rad)
\( \varphi_{cap} \) angle of capsize (°, rad)
\( \varphi_{d} \) angle of dynamic heel (°, rad)
\( \varphi_{deck} \) angle at which deck enters the water (°, rad)
\( \varphi_{f} \) angle of flooding (°, rad)
\( \varphi_{res} \) angle of heel corresponding to prescribed residuary freeboard (°, rad)
\( \varphi_{s} \) angle of static heel (°, rad)
\( \rho \) water density (t/m³)
\( \rho_{w} \) air density (t/m³)

CCNR  Central Commission for Navigation on the Rhine
CEMT  Conference of European Ministers of Transport
EU  European Union
IMO  International Maritime Organization
JR  Yugoslav Register of Shipping
OTNK  International association of technical survey and classification institutions (TSCI)
RRR  Russian River Register
RVIR  Rhine Vessel Inspection Regulations
UNECE United Nations Economic Commission for Europe

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