ISSN 0209-2069

ZESZYTY NAUKOWE NR 2 (74)
AKADEMII MORSKIEJ
W SZCZECINIE

EXPLO-SHIP 2004

Zbigniew Szozda

A Concept of Ship Stability Criteria Based on Cargo Shift Caused by Rolling Due to Gust

Key words: stability, stability assessment, stability criteria

At present, intact ship stability criteria have prescriptive nature. At the 45-th Session of SLF Sub-Committee a decision was made to change IMO attitude concerning intact ship stability from prescriptive rules to performance based rules. This paper aims at providing a basic framework for the development of intact ship stability criteria based on a deterministic scenarios concept. The concept is described in general and one simple scenario is calculated in detail. This scenario concerns shifting of a deck cargo.

Koncepcja kryterium oceny stateczności na podstawie przesuwania się ładunku spowodowanego kołysaniem się statku pod wpływem szkwału

Słowa kluczowe: stateczność, ocena stateczności, kryteria stateczności

Obecnie kryteria oceny stateczności statku nie uszkodzonego oparte są na przepisach wynikających ze statystyki wypadków. Na 45. sesji Podkomitetu ds. Stateczności i Linii Ładunkowych podjęto decyzję o zmianie podejścia IMO do oceny stateczności na podejście uwzględniające zjawiska towarzyszące kołysaniom statków. Niniejszy artykuł przedstawia ideę opracowania kryteriów oceny stateczności na podstawie tzw. „scenariuszy". Opisano ogólne założenia oraz przedstawiono obliczenia dla wybranego scenariusza zakładającego przesunięcie się ładunku na pokładzie.

Introduction

The stability assessment of intact ships is confined at present to the fulfilment of the prescriptive criteria related to the static righting arm curve. These criteria were developed mainly in nineteen sixties. The basis for the rules was the experience with capsized and not capsized ships before that time. Almost 40 years have passed sincethe time when the prescriptive rules were being developed. During this time a great progress in numerical tools, model tests methodologies and measurement techniques has been made internationally. For this reason at 45-th and 46-th Session of SLF Sub-Committee a decision was made to change IMO attitude concerning intact ship stability assessment from prescriptive rules to performance based rules [8, 9]. A very similar approach was examined in nineteen sixties but theoretical and computational limitations stopped this development at that time. There is international agreement that the numerical tools and other methods which are available today, despite of their deficiencies, can be used for direct stability assessment using ship performance approach [3, 5].

At present there are three general concepts (possible approaches) how direct assessment of intact ship stability could be performed:

1. Probability of survival.
2. Formal Safety Assessment (FSA method) [7].
3. Deterministic scenarios.

Each of these concepts has advantages and disadvantages in comparison to the other ones. There is general agreement that the concept of deterministic scenarios seems to be the easiest in application and for approval purposes for the near future [3]. On the other hand this concept gives the smallest step forward towards fully matured and “rational” stability criteria. Consideration of scenario proposed in this paper aims to formulate a procedure for development other scenarios, which will be more complex.

1. Concept of deterministic scenarios

The main goal of stability assessment in ship design and ship operation is to provide acceptable level of confidence that dangerous or undesired heel angles or angular accelerations due to ship rolling will not be met by particular ship in particular loading condition under assumed excitation mainly connected with environment.

The concept of scenarios approach to performance based stability criteria of an intact ship which is described in this paper is a proposition for wide discussion to achieve this goal. The scheme of proposed concept is shown in Figure 1.

It is proposed that the SCENARIO "S" is a set of the following components:

S = {Event, Assumptions, Method, Ship performance, Criteria, Standards for computer programs}

There are three methods of determination of the ship performance:

- Calculations (analytical, numerical),
- Model tests,
- Full scale trials.

If the method used for ship performance determination is other than calculations – standards for computer programs shall be replaced by standards for model tests or standards for full scale trials.

The components of scenario S are listed below (provided that ship performance is determined by calculations).

Event – possible or assumed external excitation leading to the ship rolling (heaving/pitching). The aim of the Event is to describe the identified risk to ships stability (real or simplified model).

Assumptions – description of simplifications related to reality which have to be taken into account because of deficiencies of calculation tools.

Method – detailed description of analytical formulas or numerical solutions used for calculations.

Ship performance – ship motions (amplitudes, accelerations) in function of time.

Criteria – a set of conditions which have to be satisfied in order to judge the ship stability as proper.

Standards for computer programs – a set of conditions to be satisfied by the code of the computer program which is used for calculations in order to assess the ship performance.

There are three cases in the life time of a ship when the stability of a ship is judged: design, before departure, at sea. The answer "YES" in the scheme given in Figure 1 supplies the following information:

1. Design – design of the ship is proper, it may be approved.
2. Before departure – the loading condition of the ship is proper, the ship may proceed to sea.
3. At sea – the course and the speed of the ship (not defined by the scenario but real) is proper, she will not meet excessive rolling.

The answer “NO” means that at least one component of a ship[1] has to be changed in order to satisfy all criteria in the next run of the calculations.

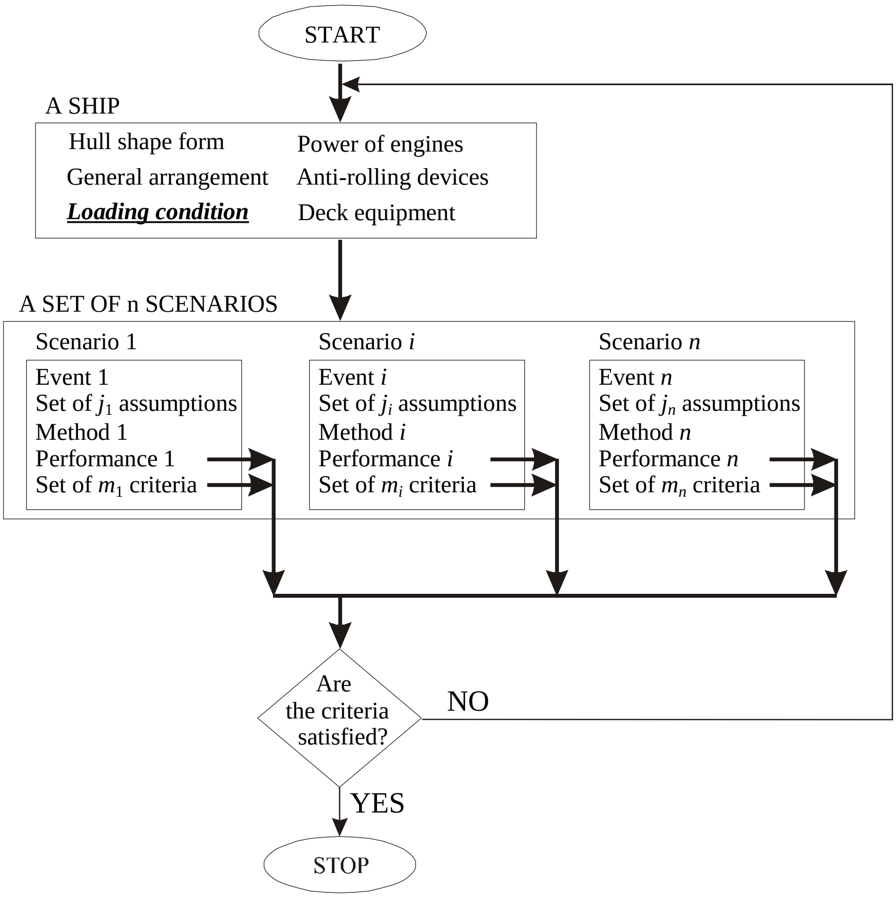

Fig. 1. A diagram of a deterministic scenarios concept
Rys. 1. Schemat koncepcji scenariuszy deterministycznych

Usually a basisof stability assessment of a ship in operation is stability limit curve drawn in the co-ordinates: draft (displacement) versus allowable height of the centre of gravity. For this reason, in this paper the results of example calculations will be correspondingly illustrated.

1 In this case a ship is recognised as a system. Change of one component means change of the hull shape form or change of the loading condition or other.

2. Steady wind scenario

The proposed scenario is very simple, transparent and there is relatively wide range of knowledge gathered in this subject. Besides, with some assumptions, this scenario may be solved by analytical calculations and there is no need for standards for the computer programs.

Table 1 shows components of a ship which are used in the proposed scenario and particular data for calculations obtained on the basis of these components. Other variables describing the ship are not used in this scenario.

Table 1

Components of a ship used in proposed scenario
Składowe statku wykorzystane w proponowanym scenariuszu

Name of a component	Particular data
Hull shape form	Cross curves, hydrostatic characteristics, damping coefficient
General Arrangement	centre of gravity co-ordinates of different loading condition components (effecting on the angle α shown in the figure 2)
Loading condition	V, T, KG, I_{xx}, M

2.1. Event

The ship is subject to gust perpendicularly to longitudinal symmetry plane at zero ship speed.

2.2. Assumptions

The set of assumption for the proposed scenario is as follows. This set aims to enable calculations using numerical method described in 3.3.

- The wind velocity results with the pressure $p = 504$ [Pa] on the lateral windage area above the water line.
- The wind moment does not depend on ship heel.
- The resulting rolling due to wind moment is calculated based on the static calm water righting arm curve calculated for even keel.
- The damping coefficient is linear.
- At the time "zero" the wind pressure is equal to zero and there is no initial rolling (angle of heel or angular velocity).
- The point of attack above the water plane is the centre of lateral area. The point of attack below the water line is the half of mean a draft.
- The axe of rolling goes through the centre of gravity of the ship.

2.3. Method

Ship performance due to excitation given by Event is presented by equation (1).

$$(I_{xx} + m_{\varphi}) \cdot \ddot{\varphi} + N_{\varphi} \cdot \dot{\varphi} + \rho \cdot g \cdot V \cdot GZ(\varphi) = M(t) \qquad (1\text{ a})$$

$$M(t) = \begin{cases} 0 & \text{for} \quad t < 0 \\ M = p \cdot A \cdot z = \text{const} & \text{for} \quad t \geq 0 \end{cases} \qquad (1\text{ b})$$

The solution of the equation (1) is assumed as follows [10]:

$$\varphi(t) = \varphi_{st} \cdot \left[1 - \sqrt{1 + \nu^2} \cdot e^{-\nu \cdot \omega_{\varphi} \cdot t} \cdot \cos(\omega_{\varphi} \cdot t - \nu) \right] \qquad (2)$$

Static angle of heel φ_{st} used in the solution (2) is derived from the condition (3).

$$GZ(\varphi_{st}) = \frac{M}{\rho \cdot g \cdot V} = l_H \qquad (3)$$

Natural damped roll frequency is calculated using Doyere's formula for transverse moment of inertia of the ship:

$$\omega_{\varphi} = \sqrt{1 - \nu^2} \cdot \sqrt{\frac{12 \cdot g \cdot GM_{\varphi}}{k \cdot \left(B^2 + 4 \cdot KG^2 \right)}} \qquad (4)$$

where GM_{φ} is derivative of the righting arm calculated at the angle of heel equal to φ_{st}.

$$GM_{\varphi} = \frac{d}{d\varphi} \left(GZ(\varphi) \right)_{\varphi = \varphi_{st}} = tg(\beta) \qquad (5)$$

Variables φ_{st} and GM_{φ} and β are explained in Figure 2.

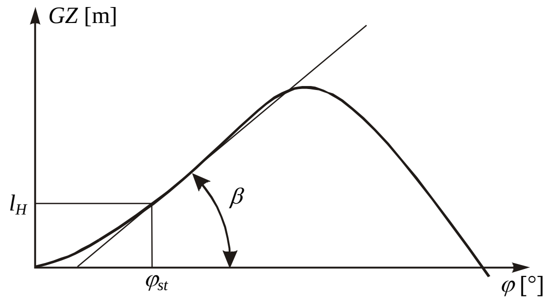

Fig. 2. Explanation of variables: φ_{st}, GM_{φ} and β
Rys. 2. Wyjaśnienie wielkości: φ_{st}, GM_{φ} *i* β

Angular velocity and acceleration are calculated using equations (6) and (7).

$$\omega(t) = \dot{\varphi} = \frac{d(\varphi(t))}{dt} = \\ = \varphi_{st} \cdot e^{-\nu \cdot \omega_{\varphi} \cdot t} \cdot \sqrt{1+\nu^2} \cdot \omega_{\varphi} \cdot \left[\nu \cdot \cos(\nu - \omega_{\varphi} \cdot t) - \sin(\nu - \omega_{\varphi} \cdot t) \right] \tag{6}$$

$$\varepsilon(t) = \ddot{\varphi} = \frac{d(\omega(t))}{dt} = \\ = \varphi_{st} \cdot e^{-\nu \cdot \omega_{\varphi} \cdot t} \cdot \sqrt{1+\nu^2} \cdot \omega_{\varphi}^2 \cdot \cos(\nu - \omega_{\varphi} \cdot t) \cdot \left[1 - \nu^2 + 2 \cdot \nu \cdot tg(\nu - \omega_{\varphi} \cdot t) \right] \tag{7}$$

Variables described above are used in formula (9) for the purpose of assessing ship safety from stability point of view for the criteria: the unlashed cargo will not shift.

2.4. Ship performance

Ship performance herein means rolling angles, angular velocities (rates of turn) and accelerations as the function of time. These variables are calculated using formulas (2), (6), (7) and are shown in Figure 3 (a function of time) and in Figure 4 (phase portrait).

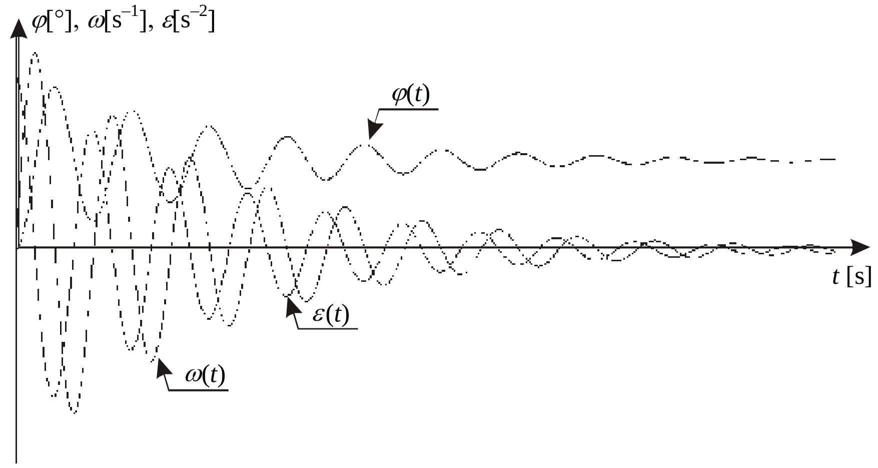

Fig. 3. Ship performance asthe function of time
Rys. 3. Kołysania statku w funkcji czasu

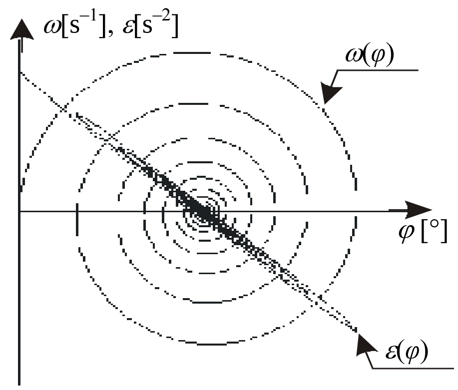

Fig. 4. Phase portrait of the ship performance
Rys. 4. Portret fazowy kołysania statku

2.5. Criteria

The assessment of the intact ship stability might be based on the sentence: the rolling amplitude and angular acceleration should be sufficiently small for preventing the ship from:

- cargo shifting,
- ship capsizing,
- difficulties in ship handling,

- immersion of watertight openings,
- failure of key systems or appliances,
- panic of passengers,
- other dangerous or undesired events.

This list is open for further development.

Each of above mentioned conditions may provide a basis for the mathematical form of the appropriate criteria. Below is an example derived for the first condition: the unlashed cargo shall not shift.

The cargo will shift on a deck if the following condition is satisfied:

$$a_T > f \cdot a_V \tag{8}$$

The analysis of all accelerations acting on the cargo staying on a deck leads to formula (9). This formula, angles φ, α and radius r are clarified in Figure 5.

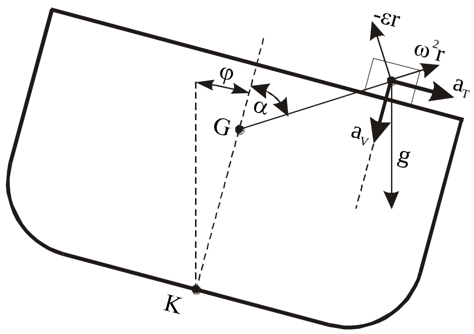

Fig. 5. Acceleration acting on the deck cargo
Rys. 5. Przyspieszenie działające na ładunek pokładowy

$$\begin{aligned} & g \cdot \sin(\varphi) + \omega^2 \cdot r \cdot \sin(\alpha) - \varepsilon \cdot r \cdot \cos(\alpha) > \\ & g \cdot \sin(\varphi) + \omega^2 \cdot r \cdot \sin(\alpha) - \varepsilon \cdot r \cdot \cos(\alpha) > \\ & g \cdot f \cdot \cos(\varphi) - \omega^2 \cdot r \cdot f \cdot \cos(\alpha) - \varepsilon \cdot r \cdot f \cdot \sin(\alpha) \end{aligned} \tag{9}$$

The cargo will shift due to ship rolling if the condition given by formula (9) is satisfied.

2.6. Standards for computer programs

There is no need to define standards for computer programs for this example because the considered criterion is concluded in the analytical formula.

3. Results of calculations

The calculations presented in this paper are conducted for a ro-ro passenger ferry. The cargo presumed to be shifted due to ship rolling is a lorry staying on the highest deck close to the starboard side. The critical height of the centre of gravity of a ship is calculated. If the centre of gravity is higher than calculated, the angle of rolling and angular acceleration are so high that the lorry is suspected to shift. The results of calculations are shown in Figure 6 together with actual stability limits taken from the Information on stability for the master:

a) for damage stability – SOLAS 60 (mandatory),
b) for intact stability (range of righting arm curve and weather criterion),
c) for initial metacentric height GM (only for comparison).

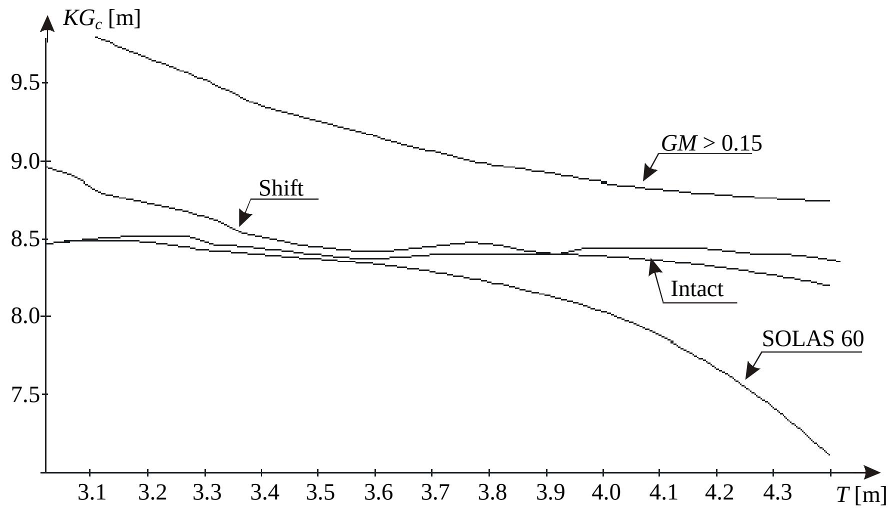

Fig. 6. Results of calculations – stability limit curves
Rys. 6. Wynik obliczeń – dopuszczalne wzniesienia środka ciężkości

Conclusions

One possible way to change the attitude to intact ship stability assessment from prescriptive rules to ship performance criteria is the deterministic scenario concept. The list of different dangerous situations threatening stability safety in ship operation includes cargo shifting. The analytical formula expressing criteria for cargo shifting can be derived if the mathematical model of the ship rolling is simplified. The esults of calculations conducted for a ro-ro passenger ferry show that the curve of allowable centre of gravity of the ferry due to lorry shifting is very close to intact stability limit curve. It suggests that the level of safety obtained from present prescriptive rules for intact stability is similar to this obtained from the presented scenario.

The following general questions remain to be answered:

- What is required level of safety for performance based criteria and how it has to be defined?
- What scenarios have to be taken into account?
- What set of criteria shall be judged to obtain satisfactory level of safety?

Further research is necessary in order to define coherent approach to intact ship stability assessment based on the performance rules and deterministic scenarios concept. This approach might be presented to IMO for consideration.

Abbreviations

Symbol	Meaning
a_T	Acceleration parallel to deck
a_V	Acceleration vertical to deck
A	Lateral windage area
B	Moulded breadth of a ship
GM_φ	Derivative of the righting arm for φ_{st}
g	Acceleration due to gravity
GM_φ	Derivative of the righting arm for φ_{st}
GZ	Righting arm
I_{xx}	Moment of inertia of a ship
k	Coefficient of inertia of added mass
KG	Height of the centre of gravity of a ship
l_H	Heeling lever due to wind pressure

Symbol	Meaning
m_φ	Moment of inertia of added mass
M	Heeling moment due to gust
N_φ	Damping coefficient of ship rolling
p	Wind pressure
t	Time
T	Mean draft
V	Volume of displacement
z	Vertical distance from point of wind attack to half of mean draft
φ	Angle of heel
φ_{st}	Static angle of heel due to wind pressure
ν	Dimensionless damping coefficient
ρ	Sea water density
ω_φ	Natural damped roll frequency of a ship

References

1. Bertaglia G., Serra A., Francescutto A., Bulian G., *Experimental evaluation of the parameters for the weather criterion*, 8-th International Conference on the Stability of Ships and Ocean Vehicles, Madrid, 2003.
2. Bird H., Morral A., *Ship Stability – a Research Strategy*, Proc. 2nd International Conference on Stability of Ships and Ocean Vehicles, Tokyo,1982.
3. Cramer H., Tellkamp J., *Toward the Direct Assessment of a Ship's Intact Stability*, 6-th International Ship Stability Workshop, Webb Institute, 2002.
4. Cramer H., Kruger S., Mains C., *Separate Wind and Wave versus a Weather Criterion for the Evaluation of a Ship's "Dynamic" Stability*, Intersessional Meeting of SLF Group, Hamburg, 2003.
5. Francescutto A., *Intact Ship Stability – The Way Ahead*, 6-th International Ship Stability Workshop, Webb Institute, 2002.
6. Francescutto A., Serra A., *A critical analysis of weather criterion for intact stability of large passenger vessels*, 5-th International Workshop Stability and Operational Safety of Ships, Triest, 2001.
7. Kobyliński L., *Performance oriented intact stability criteria*, Intersessional Meeting of SLF Group, Hamburg, 2003.
8. SLF 45, *Report to the Maritime Safety Committee*, International Maritime Organisation, London, 2002.
9. SLF 46, *Report to the Maritime Safety Committee*, International Maritime Organisation, London, 2003.
10. Wełnicki W., *Mechanika ruchu okrętu* (in polish), Politechnika Gdańska, Gdańsk 1989.

Wpłynęło do redakcji w lutym 2004 r.

Recenzenci

dr hab. inż. Tadeusz Szelangiewicz, prof. PS
prof. dr hab. inż. Bernard Wiśniewski

Adres Autora

dr inż. Zbigniew Szozda
Akademia Morska w Szczecinie
Instytut Nawigacji Morskiej
Zakład Budowy i Eksploatacji Statku
tel. 48 09 311