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On the calculation of the righting lever curve for a damaged ship

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ABSTRACT

The current damage stability criteria for ships are mainly based on the characteristics of the righting lever curve. The related calculations for different intermediate stages during the flooding process, and for the final equilibrium condition, are generally considered trivial. However, with the increased computing capacity the regulations are developing towards a more realistic assessment of the intermediate stages of flooding. Most notably, time-domain flooding simulation has become a viable option. Consequently, the practices and assumptions related to the calculation of the righting lever curve for a damaged ship need to be addressed. This paper presents these challenges from different perspectives, and reviews available numerical methods for assessment of damage stability. Sample calculation results with different methods are presented for various damage scenarios, and the results are thoroughly analyzed and discussed. Finally, some recommendations on using the different methods are given.

1. Background

Safety of life at sea has had an increasing priority in the maritime industry ever since the catastrophic RMS Titanic accident in 1912, and the development of the regulations has been mainly accident driven. In this publication, we are focusing on practical methods of assessing the safety of a ship after the hull has been breached, i.e. the residual or damage stability. The number of passengers in modern cruise vessels is of thousands, Levander (2011), and thus the society wants to ensure the safety of people in the case of a flooding accident. Regulatory or statutory requirements for the computational methods of assessment of the damage stability need to be clear and concise for the fair comparison of alternative designs. Consequently, the numerical methods for damage stability analyses are of special interest.

The righting lever curve, or simply stability curve, for an intact ship was introduced in the pioneering work of Atwood and de Clairbois (1798). Yet, the first criteria for intact ships were developed much later by Rahola (1939). Since then, the righting lever curve, and its characteristics, have been applied to determine the safety level of ships in various regulations. Initially this concerned only intact stability, but later the righting lever curve has been adopted also for damage stability regulations. A detailed overview of this development is presented in Francescutto and Papanikolaou (2011).

The first Safety of Life at Sea (SOLAS) regulation in 1914 concerned only the subdivision and ensuring sufficient reserve buoyancy after a breach in the hull, but the later upgrades of SOLAS in 1948 and 1960 introduced requirements for a minimum metacentric height (GM) and maximum heel angle in damaged conditions. Eventually the SOLAS 1990 introduced criteria for various properties of the righting lever curve. In the current SOLAS regulations, the s-factor that represents the survivability level is calculated from the properties of the righting lever (GZ) curve. In addition, alternative methods for measuring the survivability have been presented recently, e.g. within the GOALDS project, Papanikolaou et al. (2013) and by Cichowicz et al. (2016). Even these new approaches are based on the characteristics of the GZ curve, and consequently, the calculation procedure for obtaining this curve is of special interest.

The real sequence of flooding progression can only be calculated with a time-domain simulation of progressive flooding. A review of this development has been presented in Papanikolaou (2007). Since then, time-domain flooding simulation has proven to be a useful tool also for accident analyses, Krüger (2016). With the increased computing capacity, simulation has become a viable option for regulatory damage stability calculations, especially for cross-flooding analyses, Ruponen et al. (2012), but also for a more realistic assessment of progressive flooding inside the flooded compartments, Ruponen and Lindroth (2016). Recently, an advanced approach for combining time-domain simulation results and the traditional s-factor into a Survivability Performance Index (SPI) was introduced by Dafermos and Papanikolaou (2016). In addition, simulation can be used onboard a damaged ship for a rapid assessment of

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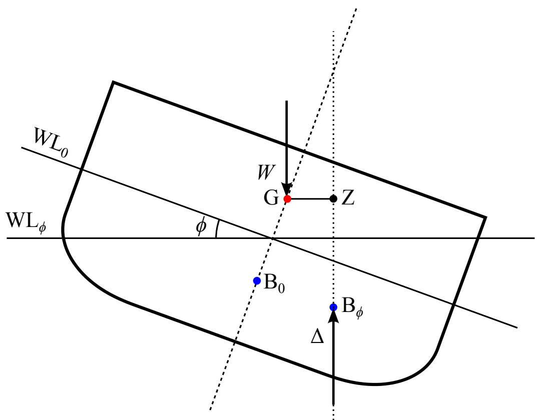

Fig. 1. Definition of the righting lever GZ when the ship is heeled to an angle ϕ.

progressive flooding and the development of stability, Ruponen et al. (2017).

Despite the fact that the recent development allows for a more realistic assessment of the flooding process, the stability criteria in the regulations still mainly rely on the characteristics of the stability curve. The calculation of this curve is generally considered trivial, but the treatment of floodwater, especially in the intermediate filling phases, leaves room for different interpretations. In this paper, the concept of the righting lever curve is revisited, with a review of alternative approaches for evaluating the progress of flooding in a damaged ship. Finally, case studies are presented with discussion and analyses of the results.

2. Calculation of the righting lever curve

The righting lever curve represents a ship's ability to withstand external heeling moments, e.g. due to wind and waves. When a ship heels to an angle ϕ, the center of buoyancy is shifted from the point B_0 to the point B_ϕ. The center of gravity G may also shift, if there are liquid loads. The lifting force of buoyancy Δ is equal to the weight of the ship W, but the directions of these forces are opposite. This pair of forces results in the righting moment, and the righting lever GZ is the lateral distance between the center of gravity and the center of buoyancy in the global coordinate system, as illustrated in Fig. 1. This is evaluated numerically by fixing the heel angle and balancing the trim angle (**free trim**) and the draft, so that the buoyancy equals the weight, and reaching an equilibrium between the trimming moments. In practice, iterative procedures are needed, but the required calculations are rapidly performed with modern computers. By repeating this procedure for a range of heel angles, the righting lever curve is obtained by fitting a smoothed curve to the set of evaluated points. For an intact ship, this procedure is trivial, but for a damaged ship with flooded compartments, the evaluation of the righting lever curve becomes more complex.

Especially for a damaged ship, it is essential that also the trim angle is balanced in the calculation of the GZ curve in order to avoid over-optimistic results, as pointed out by Pawlowski (2016). For ships the assumption of a constant heeling direction is quite realistic, but for floating offshore structures the evaluation of the GZ curve, even in intact condition, should allow for free twisting of the structure, as described in van Santen (2011).

In principle, the GZ curve for a damaged ship is evaluated with the same procedure, but the floodwater needs to be considered in the evaluation of the center of gravity and/or the center of buoyancy. In literature, two different methods for analysis of damage stability are presented, the method of **lost buoyancy** and the method of **added weight**. The basics of both approaches are well-known to naval architects, and are described in most of the distinguished text books, such as Nickum (1988), Tupper (2013) and Biran and López-Pulido (2014). For convenience, a short description of both approaches is given in the following.

In the lost buoyancy method, the flooded compartments are reduced from the buoyant hull with the permeability taken into account. The situation is illustrated in Fig. 2. The mass and the center of gravity of the ship are unchanged, unless there were liquid loads in flooded tanks that may have flown out. Thus the flooded compartments are in free communication with the sea, meaning that the floodwater can freely flow between the flooded compartments and the sea if the ship moves, e.g. due to an external heeling moment. This assumption implies that the time available for equalizing the water levels in flooded compartments is infinite, as the water levels are in hydrostatic balance with the sea. Furthermore, the method cannot account for accumulated water above the sea level, such as firefighting water or water on a ro-ro deck.

In the added weight method, the floodwater is treated as additional liquid cargo. For compartments that are connected to the sea, this method requires iterations for evaluation of the final equilibrium condition. For example, the accumulated water on the vehicle deck must be treated as an added weight since the method of lost buoyancy would result in an immediate draining of the water back to the sea if the floodwater level is above the sea level. The same applies also for firefighting water.

For the final equilibrium after flooding, both methods result in exactly the same floating position and static righting moment, but the actual GM in damaged condition and the righting lever curve are different. In principle, with the added weight method (subscript *aw*) the static righting moment at heel angle ϕ is:

$$M_{st}(\phi) = GZ_{aw}(\phi)\cdot(W+w) \tag{1}$$

where W is the total weight of the intact ship and w is the total weight of floodwater.

With the lost buoyancy method (subscript *lb*) the righting moment is:

$$M_{st}(\phi) = GZ_{lb}(\phi)\cdot W \tag{2}$$

Since the displacement is constant in this approach. Consequently, the following relation between the two calculation methods can be presented by combining the equations (1) and (2):

$$GZ_{lb} = GZ_{aw}\frac{W+w}{W} \tag{3}$$

For extensive flooding cases the difference between the methods is considerable since w is large. However, the treatment of the amount of floodwater with different heeling angles can even have a bigger impact. The lost buoyancy method limits the floodwater to the sea level in all flooded compartments, but with the added weight method such a limitation is not usually applied, and e.g. Vermeer et al. (1994) have used fixed amounts of floodwater at each intermediate phase (time step) of flooding.

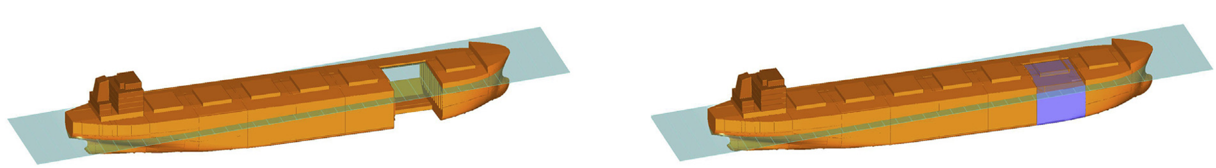

Fig. 2. 3D visualization of the lost buoyancy (left) and the added weight (right) methods.