DYNAMIC STABILITY ASSESSMENT IN EARLY-STAGE SHIP DESIGN

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ABSTRACT

The appearance of novel vessel designs have raised a number of problems related to dynamic stability; as some of the new designs have a tendency to exhibit undesirable behavior in waves. The primary reason for this behavior is a radical departure from conventional hull shapes. Existing stability criteria were developed for conventional hull shapes and there is a need for tools to assess if there are problems with dynamic stability, preferably early in the design process. This situation has motivated the International Maritime Organization (IMO) to start development of the next generation of stability criteria, which includes tools for early assessment of the vulnerability of a new design to dynamic stability failure. This paper considers the second level of vulnerability assessment, when simple but physics-based approaches are used to assess the modes of stability failure, still early in the design process. A framework is discussed to address the problems concerning the choice of wave conditions and determining the probability of failure for each stability mode.

Keywords: stability criteria, vulnerability criteria, dynamic stability, capsize, pure-loss, parametric roll, surf-riding, dead-ship condition

1. INTRODUCTION

The assessment of ship stability remains an essential component of determining safety and operational effectiveness for all ship types. Static stability criteria have been used for many decades to determine the level of safety for new ship designs. Dynamic stability related phenomena, not adequately covered by static stability criteria, have remained problematic to address in a systematic yet practical method useful for ship designers and regulators. Hull form designs in the past half century have resulted in a radical departure from the population of ships considered for the development of modern stability criteria. The margin of safety associated with these criteria for these ship types when applied to complex dynamic stability phenomena is not known. Acknowledging this deficiency, the IMO has begun work on the development of next generation intact stability criteria to address problems related to dynamic phenomena and expand the applicability of criteria to the current and future ship designs.

The IMO defines and intact stability failure as *a state of inability of a ship to remain within design limits of roll and combination of rigid body accelerations* (SLF 51/WP.2, 2008). Intact stability failures are divided into two categories: partial and total stability failures. Partial stability failures result in the impairment of normal vessel operations and danger to crew, passengers, cargo or equipment. Total stability failures result in the total loss of ship operability with likely loss of life. The major modes of stability failures were listed in the section 1.2 of the 2008 Intact Stability (IS) Code, part A. They include restoring arm variation problems such as parametric excitation and pure loss of stability; stability under dead ship condition defined by

SOLAS regulation II-1/3 and maneuvering related problems in waves such as broaching-to. This paper considers four modes of stability failure, including pure-loss of stability, parametric roll, surf-riding, and dead-ship condition.

The IMO also distinguishes between conventional and unconventional ships. Unconventional ships are *ships that are vulnerable to stability failures neither explicitly nor properly covered by the existing stability regulations* (SLF 51/WP.2, Annex 2, 2008).

The next generation intact stability criteria are envisioned to consist of a multi-tier evaluation process. For a given ship design, each of the four identified stability failure modes will be evaluated using vulnerability criteria and performance based criteria. Vulnerability criteria are intended to provide checks for susceptibility to particular stability failure modes and enable differentiation from ships adequately covered by existing intact stability regulations. A ship that passes a vulnerability assessment for a given failure mode may be considered safe, despite only a minimum amount of technical and operational data being available (SLF 51/WP.2, Annex 1, 2008).

As currently envisioned, vulnerability criteria may be split into two or more levels. The first level may consist of simple geometry-based criteria which will probably be quite conservative to compensate for their simplicity. This would provide a conservative filtering process based on the simplest method available for each stability failure mode — to enable designers to differentiate between conventional and unconventional ship designs.

The second level may consist of more robust, yet still simple, physics-based methods to enable further differentiation for those ship designs on the margin of vulnerable or not vulnerable. If vulnerabilities are still observed on this next level for a particular stability failure mode, then the ship should be further evaluated using performance based criteria. These performance based criteria may consist of model tests and numerical methods, which may be probabilistic or deterministic for short-term or long-term assessment. The process is shown in Figure 1.

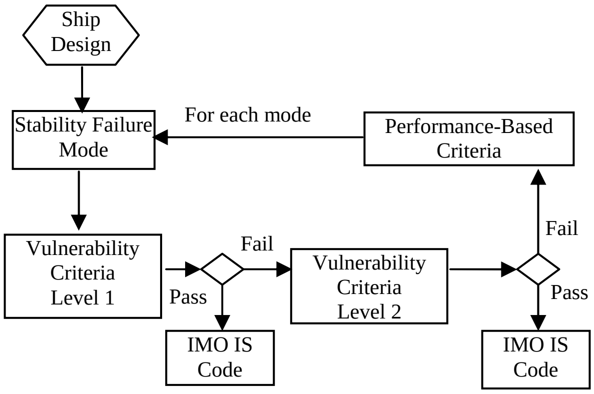

Figure 1. The proposed assessment process for next generation intact stability criteria.

Because it is difficult to determine absolute risk of a stability failure for a given vessel, the vulnerability criteria are intended to provide a tool for relative comparisons of new ship designs to historical or existing ship designs, where the risk is better known from experience.

Following a review of ideas and possible methods for the second level vulnerability criteria (Bassler, et al., 2009), this paper examines the idea that the vulnerability criteria can be formulated as probabilistic — based on consistent application of up-crossing theory and a long-tem approach for the wave environment.

2. CONCEPTUAL FRAMEWORK: CHOICE OF WAVE CONDITIONS

In order to provide practical and consistent vulnerability criteria, stability failures must be evaluated for reasonable environmental and operational conditions. It is almost always possible to find a combination of these conditions which results in a stability failure.

While excluding unrealistic operational conditions is relatively obvious, determination of appropriate wave conditions is more difficult, due their stochastic nature.

This can be illustrated by an example with ABS susceptibility criteria (ABS, 2004; Shin, et al., 2004). It was shown that in order to satisfy conditions for parametric resonance, a VLCC would have to maintain speed about 19-20 knots. While such speed for a supertanker is obviously impossible, encountering a wave with length equal to the length of such a vessel is not impossible. Moreover, the theoretical height of such a wave could exceed 30 meters, as it does not violate a condition of hydrodynamic stability of the wave. This begs the question if it is reasonable to use such wave for vulnerability assessment? If not, what kind of wave is reasonable and how this can be determined?

Obviously, realistic waves are irregular. Even if a regular wave is used for criteria, it is explicitly or implicitly related to some sea state or corresponds to a certain cell in a scatter diagram. For example, ABS used scatter table from IACS Recommendation 34 (2001) to choose height for a regular wave in the Susceptibility Criteria (ABS, 2004; Shin, et al., 2004).

Because irregular waves are a stochastic process, they can only be characterized with statistical parameters; significant wave height and mean zero crossing period, (or spectral modal period, or mean period) are typically used for scatter diagrams. The very fact that these parameters are used implies an assumption of quasi-stationarity. This means the process of irregular waves is assumed to be stationary, its statistical characteristics do not change over time, for some limited period — usually three to six hours which is a typical weather update interval. In reality, waves are not stationary due to weather changes, but these changes are generally slow in comparison with wave period, which justifies this commonly used assumption. Changes in weather and corresponding changes in waves are considered using another time scale, sometimes called a synoptic scale. These changes are reflected in the statistical frequency of observation of certain combinations of significant wave height and mean zero-crossing, modal or mean period and are used to populate the cells of a scatter diagram.

A scatter diagram may correspond to a certain area of the ocean and to a certain season or month. Alternatively, a scatter diagram may represent averaged figures for all seas, based on data from a region known for bad weather, like the scatter table from IACS Recommendation 34 (2001) and NATO standard 4194 (1983). As vulnerability criteria are expected to be reasonably conservative and simple, an average scatter diagram approach will be used throughout this paper. For the following discussion, the scatter diagram is assumed to represent some severe conditions averaged through all the seasons.

Each cell of the scatter diagram corresponds to wave conditions that can be further used in a form of stationary stochastic process; or even a regular wave, seen as equivalent or representative of the chosen wave conditions. Then each wave condition is associated with statistical frequency. The fundamental question becomes, which one should be chosen for vulnerability criteria?

Two potential approaches to answer this question are identified. One possibility is to use the condition that leads to the highest probability of stability failure. Another possibility is to calculate the long-term probability of stability failure, such as a year or lifetime, and then find the wave conditions that correspond to the same probability of failure determined for the long-term. Both methods can be used concurrently and are meant to be applied separately for each mode of stability failure.

Application of either of these approaches requires a method to evaluate the probability of stability failure. Candidates for these methods are discussed later in the paper. These methods are meant to be simple, the only requirement is consistency, and the probability of failure in heavier sea conditions must be higher that in more benign sea conditions — provided the wave spectra are the same.

The final stage of application of any criteria is a comparison of its value with a standard and performing an assessment. Because the probability of stability failure is already available for each cell in a scatter diagram, it is logical to create a standard also in a form of a probability of stability failure. The level of probability for the standard can be calculated using exactly the same methods but using a vessel, or family of vessels, known for its historically safe stability performance. In this case the standard represents the level of safety that has been historically achieved. However, the actual number still cannot be compared with statistics, as mathematical models used for these assessments are intended to be very simple.

Additionally several possible methods of comparison are identified. The first compares the long term probability of failure of unconventional and conventional vessels. The second method uses the comparisons of the largest probability of failure of an unconventional vessel vs. the largest probability of failure of a conventional one over all of the cells of a scatter diagram. The third method compares the largest probability of failure of an unconventional vessel vs. the probability of failure for a conventional ship in the same cell of the scatter diagram, identified by where the unconventional vessel had the largest probability of failure.

Discussion of how to determine a reasonable choice of wave conditions leads to a somewhat paradoxical conclusion; there is no practical way to make such a choice. The amount of information needed is practically sufficient to solve the entire problem of vulnerability.

Nevertheless this way of choosing of wave conditions is still useful as they may be useful for further analysis, limiting the scope of conditions to consider for performance-based assessment.

3. CONCEPTUAL FRAMEWORK: PROBABILITY OF A STABILITY FAILURE

In general, stability failure can be considered in terms of conventional reliability theory (Sevastianov, 1963, 1994). Stability failure is considered as a random event of Poisson flow and is assumed to satisfy three conditions: the probability of occurrence at a specific moment of time is infinitely small, only one failure can occur at the same moment of time, and if there are two or more consecutive failures, they are independent of each other.

The first two conditions are always satisfied. Since the number of time instances is infinite even during finite time duration, the probability of something occurring for a specific time instance is always infinitely small. Also each stability failure is always associated with one stochastic process, such as roll or lateral acceleration, etc. This process can only have one value at any instant in time and two failures of the same type cannot occur simultaneously. Two failures of different type can occur at the same time, but this will correspond to two different Poisson flows.

Satisfying the third condition is also trivial when considering total stability failure, because there can only be one capsize. A problem may arise for partial stability failures with satisfying the independence condition, as there may be a series of consecutive large roll angles or acceleration values, especially for resonance modes of stability failure such as parametric roll.

Assuming all three conditions are satisfied, the probability that at least one stability failure occurring during time T is expressed as:

$$P(T) = 1 - \exp(-\lambda T) \tag{1}$$

where λ is rate of failures, meaning the average number of stability failures per unit of time.

The formula (1) also represents the cumulative distribution of time before the failure. If there is at least one stability failure during time T, then the time before the failure is less then T and the probability of a random number taking a value less then the argument is defined as the cumulative probability distribution function. Another advantage of application of (1) for the probability of failure is its explicit connection with time of exposure.

The rate of failures, λ, depends on the mode or physical mechanism of a failure. This includes whether it is total or partial stability failure, as well as loading condition, wind/wave environment, speed and heading. Further assuming that consideration of (l) is made for a particular mode and type of failure (partial/total), the dependence on the environment and loading conditions can be expressed as (Sevastianov, 1994):

$$\lambda = \lambda(\vec{S}, \vec{L}) \tag{2}$$

$\vec{S}$ is a vector describing the "assumed situation," including environmental (significant wave height, H_s, and zero-crossing period, T_z) and operational data (wave direction, ψ, and speed, V_s); $\vec{L}$ is the vector of loading conditions, including displacement, KG, etc. For simplicity, consideration should be limited to only one loading condition at a time.

$$\lambda = \lambda(\vec{S}) = \lambda(H_S, T_Z, \psi, V_s) \tag{3}$$

Significant wave height, H_s, and zero-crossing period, T_z, are defined for each cell in the chosen scatter diagram, while wave direction, ψ, and speed, V_s, are results of decision made by human operator.

It was shown in SLF 49/Inf.7 (2006) that it is essential to take into account the operator, even a simple model for the choice of speed and course can lead to reasonable results. Ignoring the operator may lead to unrealistically large value of probability of failure, as it was found to be quite sensitive to the choice of speed for a given heading.

A model for the operator can be formulated based on a very simple principle. Below a certain threshold, which depends on the size of a vessel, the wave direction can be considered as a uniformly distributed random variable. Above this threshold, bow quartering waves have a higher probability and above the second threshold, only near head waves courses are possible. A similar model can be envisaged for speed. Here service speed can be considered below the first threshold and then random voluntary speed reduction, expressed in terms of a probability distribution, and the finally a deterministic speed loss above the second threshold. Characteristics of both models may be determined by the statistical processing of the response to a questionnaire distributed among operators of various types of ships.

This discussion results in the formulation of the rate of failures, (3), as a deterministic function of four variables. Two of them: wave height, H_s, and zero-crossing period, T_z, are a deterministic characterization of the environment and are taken from the scatter diagram. Other two variables, wave direction, ψ, and speed, V_s, are random variables modeling the decision making of the human operator. Therefore, the rate of failure for the given condition is, also a random number and should be averaged over its random arguments to be used in further analysis:

$$\lambda(H_S, T_Z) = \sum_i \sum_j \lambda_{ij}(\psi_i, V_{Sj}) W_i W_j \tag{4}$$

where W_i and W_j are statistical weights of speeds and wave direction that are calculated from their distributions and depend on the seas state, as discussed above.

It is clear from (4) that a large number of failure rate calculations will be required for this analysis. Therefore, when considering methods for their calculation, one should be reminded that simplicity of these methods is essential for the very feasibility of the discussed approach to second level vulnerability criteria.

Probability of stability failure for each cell of the scatter diagram is associated with the probability of at least one random event of Poisson flow. The only parameter of Poisson flow is the rate of failures, which must be calculated for each mode and type (partial/total) of stability failure. Speed and wave directions are associated with human decisions and simple statistical models may be implemented for these values which lead to the necessity of averaging of rates of failure within each cell.

4. PURE-LOSS OF STABILITY

This failure mode is primarily associated with stability degradation in stern-quartering and following seas. Because of the rapid change in waterplane, this stability failure mode may be considered as a single wave event. It is also well known that the worst-case wavelength is close to the length of the ship, $\lambda/L \approx 1.0$.

One may consider an envelope presentation of waves. If a narrow banded spectrum is assumed, the wave elevation can be presented in a form of a cosine function with slowly changing amplitude and phase:

$$\zeta(t) = a(t)\cos(\omega_m t + \varphi(t)) \tag{5}$$

where $a(t)$ is an amplitude and $\varphi(t)$ is a phase, and both of these figures are random processes. ω_m is the modal frequency of the spectrum. It is known that with the narrow-band assumption, the amplitudes have a Rayleigh distribution, while phases are distributed uniformly. Envelope theory also offers an expression for the distribution of their derivatives and autocorrelation functions.

If a ship is moving, the instantaneous profile of a wave around the ship depends on speed and wave direction, which usually results in an encounter frequency different from the true frequency:

$$\omega_{em} = \omega_m - kV_S \cos\psi \qquad k = \frac{\omega_m^2}{g} \tag{6}$$

As a result, the instantaneous wave profile at the centerline of the ship, corresponding to time, t, is expressed as:

$$\zeta(t,x) = a(t,x)\cos(\omega_{em} t - kx + \varphi(t,x)) \tag{7}$$

Here x is wave profile distance measured along the ship length. The value of instantaneous GM in wave can be evaluated using (7) as a water line. Note that amplitude and phase also depend on x, as the profile of an irregular wave does not remain the same in space.

To simplify the calculations even further the time history of the changing GM in waves can be described:

$$GM(t) = GM_0 + GM_a(t)\cos(\omega_{em} t + \varphi(t)) \tag{8}$$

This change in GM can be used as an indicator of vulnerability to pure loss of stability, which can be associated with dropping GM below a critical level. Determining this critical level is a subject of further research. As a first guess, the following may be considered.

It is assumed that the GM “modulates” the entire GZ curve as it changes while the wave passes the ship. A value of GM_{cr}, corresponding to “critical” state of the GZ curve from the point of view of current stability standards, can be determined. One of the existing criteria will be satisfied without a margin, while the other criteria will still be above the minimum required level. In other words, a small change of *GM* will lead to violation of the existing stability regulations.

The indication of vulnerability may then be associated with the down-crossing of *GM* at this critical level. Assuming Poisson applicability for such down-crossing, the probability can be estimated using formula (1) with the rate of events equal to:

$$\lambda = f(GM_{cr}) \int_{-\infty}^{0} GM' f(GM') dGM' \qquad GM' = \frac{dGM}{dt} \tag{9}$$

Further simplification of the problem includes the assumption of linear dependence of *GM* on instantaneous wave elevation and therefore, a normal distribution for both *GM* in waves and its derivative. This relation is known be nonlinear and therefore, the distribution is non-normal and the main essence of the phenomenon can still be captured. A similar assumption was made by Dunwoody (1989). Of course the consequences of such assumptions will need to be checked numerically.

Another important issue is the time of down-crossing, where stability is reduced below the dangerous level. It is intuitively clear that a very short-interval decrease of stability cannot be very dangerous — during the time ship will attain dangerous roll angle, the stability will be restored. The simplest measure of the length of the down-crossing is the mean value of its duration:

$$M(T \mid GM < GM_{CR}) = \frac{\int_{-\infty}^{GM_{cr}} f(GM) dGM}{f(GM_{cr}) \int_{-\infty}^{0} GM' f(GM') dGM'} \tag{10}$$

The equation (10) allows the formulation of an additional condition for vulnerability to pure loss of stability, the comparability of the mean value with the natural roll period. If this condition is not satisfied, the rate of failure for pure loss stability can be reduced or set equal to zero.

Numerical deviations of the estimated rate of failures from the true value are acceptable if they are consistent. This allows one to distinguish between ships that are vulnerable to pure loss of stability and ships that are not.

5. PARAMETRIC ROLL

Development of parametric roll, as with any other resonance phenomenon, requires consecutive action of waves. These waves must satisfy the frequency ratio requirement and also be capable of inducing enough change in stability to result in a failure. Therefore, the parametric roll cannot be considered a single wave event. The use of wave groups seems to be appropriate approach for irregular waves (Themelis & Spyrou, 2007)

Consideration of the vulnerability of a ship to parametric roll in irregular waves is preferable not only because it is consistent with the probabilistic approach discussed above, but also because the use of regular waves may be too conservative. Regular waves are a wave group of infinite length; therefore, the time to develop large amplitude is also infinite (SLF 48/4/12, 2005). In a real seaway, parametric roll development is the response to a particular wave group, which contains waves capable of generating parametric resonance. Not all wave groups possess such a quality and this is the reason why parametric roll can start and stop.

Vulnerability to parametric roll may be associated with the largest amplitude a ship develops when under action of a typical wave group. This is associated with a series of waves exceeding a certain threshold, a_g. The mean value of the length of such a group can be evaluated using a formula from up-crossing theory, similar to (10), but applied to an envelope of wave elevation, $a(t)$.

$$m(T_g)=\frac{\int_{a_g}^{\infty} f(a)da}{f(a_g)\int_0^{\infty}\dot{a}f(\dot{a})d\dot{a}} \qquad (11)$$

The typical wave group here is considered as a group of length equal to mean time of up-crossing of the envelope. The number of waves in the typical wave group is defined as

$$n=\frac{m(T_g)}{T_m} \qquad (12)$$

Here T_m is the mean period that corresponds to the envelope presentation frequency from (5).

To find the maximum for a typical wave group, one may assume that this maximum occurs at the moment corresponding to half of typical group length or the half of the corresponding mean value

$$t_2=0.5\cdot m(T_g) \qquad (13)$$

Consider the conditional distribution of amplitude at the moment t_2, under the condition that at the moment t_1 it has up-crossed a_g. It is possible to prove formally that such distribution is equivalent to the generic conditional distribution of two amplitudes:

$$f(a_{\max})=f(a_2\,|\,a_1=a_g) \qquad (14)$$

Envelope theory gives the following formula for generic conditional distribution of the amplitude:

$$f(a_2|\,a_1)=\frac{a_2}{\sigma^2 p^2}\exp\left(-\frac{a_2^2}{2\sigma^2 p^2}\right)\times I_0\left(\frac{a_1 a_2\sqrt{1-p^2}}{\sigma^2 p^2}\right)\exp\left(-\frac{\left(1-p^2\right)a_1^2}{2\sigma^2 p^2}\right) \qquad (15)$$

Here σ is standard deviation of waves, I_0 is Bessel function of the first type and zero order of the imaginary argument. The value p is defined using the autocorrelation and cross-correlation:

$$p=\sqrt{1-r^2-k^2} \qquad (16)$$

here k is correlation coefficient and r is cross-correlation coefficient for the complimentary stochastic process calculated at the moment t_2. Finally the maximum value of the group can be found as a mean value of distribution (15)

$$a_{\max}=m(a_2)=\int_0^{\infty} a_2 f(a_2\,|\,a_1=a_g)da_2 \qquad (17)$$

Assuming a sinusoidal form of the group with the time above the threshold a_g equal to $m(T_g)$ with amplitude a_{max} completes the definition of the typical wave group.

The response should be evaluated numerically starting from a standard initial condition, such as 10 degrees. If the maximum value of response at the end of the group exceeds an agreed threshold, the vulnerability to parametric roll is established.

Stability failure, then, can be associated with the encounter of a typical wave group. The probability of encounter of a typical wave group can be calculated as the probability of the wave envelope up-crossing the threshold a_g by.

$$\begin{aligned} P(T)&=1-\exp(-\lambda T)\\ \lambda&=f(a_g)\int_0^{\infty}\dot{a}f(\dot{a})d\dot{a} \end{aligned} \qquad (18)$$

The response threshold can be defined differently for various ships and whether partial or total stability failure is considered. However, it may be necessary to relate the level of practical failures with specific damages to ship machinery structure or cargo. For example, the threshold of 22-25 degrees may be related to lubrication failure of low speed diesel engine. The level for total stability failure may be associated with down-flooding or other elements (like icing or cargo shift) that take the problem out of domain of intact stability.

6. SURF-RIDING AND BROACHING

Methods of assessment for surf-riding and broaching are reviewed in the companion paper of Bassler, et al. (2009). An approach for a practical probabilistic formulation, within the theoretical framework presented in this paper, is outlined next. This section concentrates on high-speed broaching that develops after the occurrence of surf-riding. Moreover, the vulnerability to this type of broaching is evaluated on the basis of the likelihood of surf-riding.

The essence of surf-riding phenomenon is the attraction to equilibrium. The simplest model of surf-riding consists of just a surge equation that gives a qualitatively adequate description of surf-riding only in following waves. In irregular seas, the surf-riding equilibrium does not exit all of the time. It begins when the surging excitation provides enough additional force to compensate for additional resistance and causes the ship to move with the wave celerity. As the surging excitation in irregular waves is a stochastic process, the existence of surf-riding equilibrium becomes a random event. As the existence of equilibrium is prerequisite for surf-riding and surf-riding is prerequisite for broaching, the existence of the surf-riding equilibrium for a relatively long duration could considered as an indicator of vulnerability to this type of stability failure.

Recalling that surf-riding is often a one-wave event, a profile of an irregular wave along the ship may be considered with the envelope formula (7) while the time is fixed.

$$\zeta(t,x) = a(t,x)\cos(\omega_{em}t - kx + \varphi(t,x))$$

Taking into that $x = (c - V_S \cos\psi)t$ where c is wave celerity, the surging force can be written just as a function of time

$$F(t) = F_A(t)\cos(\omega_{em}t - \varphi(t)) \qquad (19)$$

Every time the surging force is greater or equal to the balance between thrust and resistance created by an attempt to propel the ship with wave celerity, the surf-riding equilibrium comes into existence. Therefore, the random event of the appearance of surf-riding equilibrium can be associated with the down-crossing of the force process. Here there is a constant level of balance, Bl, between resistance at wave celerity $R(c)$ and thrust T(c,n) with the commanded number of propeller revolutions, n, at calm water speed equal to the wave celerity:

$$Bl = R(c) - T(c,n) \qquad (20)$$

Then, mean value of time while the equilibrium exists is

$$M(T \mid F < Bl) = \frac{\int_{-\infty}^{Bl} f(F)dF}{f(Bl)\int_{-\infty}^{0} F' f(F')dF'} \qquad (21)$$

The distribution of the surging force and its derivative can be assumed normal, as the surging force can be expressed as a linear function of wave elevation. Evaluation of the probability of encounter with the surf-riding equilibrium during time T may be attempted using Poisson flow:

$$P(T) = 1 - \exp(-\lambda T)$$
$$\lambda = f(Bl)\int_{0}^{\infty} \dot{F} f(\dot{F})d\dot{F} \qquad (22)$$

Very short appearances of surf-riding equilibrium may not represent a significant danger of surf-riding, as the ship will not have enough time to be attracted to the equilibrium. Therefore, an additional “post-critical” condition for the mean duration of appearance of the surf-riding equilibrium could be formulated, comparable to the period, which could be considered as the natural time scale for the problem.

7. DEAD-SHIP CONDITIONS

Vulnerability for the dead ship condition can be interpreted as when a subject vessel in dead ship conditions is exposed to a greater danger in comparison with conventional ship, because of its unconventional design. To perform such analysis, a simple method is needed to evaluate probability of partial and total stability failures.

When a ship loses power, its positioning relative to wind is defined by a balance of aerodynamic moments caused by wind and hydrodynamic moments caused by drift. For ships of traditional geometries, which feature a superstructure at midships, this position is close to beam seas, the reason why dead ship conditions are usually associated with beam seas. This is no longer correct for modern ships, where a variety of hull form types may lead to variety of positions relative to the wind.

Nevertheless, for the purposes of assessing vulnerability, the simplest 1-DOF roll equation can still be used, as the beam seas assumption is generally conservative. If during comparative calculation, it is found that this assumption is too conservative, a correction for deviation from the beam seas position can be applied.

Mean wind speed is statistically related to significant wave height. For simplicity, the wind direction is assumed to coincide with wave direction. In principle, the coefficients of aerodynamic moment, hydrodynamic drift moments, and roll damping could be extracted from current weather criterion. Despite all of the simplifications and schematics of the weather criterion, it still can be used as an initial reference, especially for a comparative vulnerability check.

Partial stability failure in the dead ship condition can be associated with exceeding some roll angle, ϕ_f, leading to damage, as was discussed above. The exceedance of this angle can be safely considered as a Poisson event, and up-crossing theory can be applied to determine the probability of partial stability failure

$$P(T \mid \phi > \phi_f) = 1 - \exp(-\lambda T)$$
$$\lambda = f(\phi_f) \int_0^{\infty} \dot{\phi} f(\dot{\phi}) d\dot{\phi} \tag{23}$$

Practical application of (23) requires knowledge of the distribution of roll, at least at the level of the angle ϕ_f, and distribution of roll rate. The latter distribution may be assumed normal, as roll rate is related with relatively weak roll damping. The distribution of roll may be very different from normal, as it is related to the significant nonlinearity of the *GZ* curve. Consideration of the distribution of nonlinear roll is too complex for vulnerability criteria, so methods of statistical linearization can be applied. Application of statistical linearization is not limited by small motions, as it is not based on asymptotic methods, and it allows the use of normal distributions for roll and roll rate.

Total stability failure can be modeled with a piecewise linear method. Described in a number of references (e.g. Belenky, 1993; Paroka & Umeda, 2006), it can be integrated into the considered scheme. The piecewise linear method associates capsizing with the up-crossing of the maximum of *GZ* curve which creates initial conditions for another linear solution resulting in the progression of the system to a capsized equilibrium. The condition of capsizing after the up-crossing occurred can be expressed in a very simple formulation. One of the arbitrary constants of the linear solution for describing the decreasing part of the *GZ* curve must be positive

$$P(T) = 1 - \exp(-\lambda P(A > 0)T)$$
$$\lambda = f(\phi_{\max}) \int_0^{\infty} \dot{\phi} f(\dot{\phi}) d\dot{\phi} \tag{24}$$

The probability of the arbitrary constant to be positive is expressed trivially through the roll rate at up-crossing. The distribution of roll rate at up-crossing, f_{cr}, can be found as:

$$f_{cr}(\dot{\phi}_{cr}) = \frac{\dot{\phi}_{cr} f(\dot{\phi}_{cr})}{\int_0^{\infty} \dot{\phi} f(\dot{\phi}) d\dot{\phi}} \tag{25}$$

where f represents the general distribution of roll rates. For a normal distribution of roll rates, (25) becomes a Rayleigh distribution (Belenky, et al., 2008). Linearization on the decreasing part of the *GZ* curve can be done using equalizing potential energy.

Similar to other vulnerability criteria, the probability of capsizing in (24) is understood as conditional and schematic. Only small vessels can capsize being truly intact. For a larger ship, a number of other damages will occur at large angles and a simple model can no longer be applied. The practical meaning of probability of capsizing in (24) is as basis for comparison between conventional and unconventional vessels.

8. SUMMARY AND CONCLUDING COMMENTS

This paper presents a possible framework which may be applicable for the second-level vulnerability criteria for the IMO next generation intact stability criteria. The discussion demonstrates that the development of second-level vulnerability criteria is feasible based on currently available knowledge and technology.

A reasonable choice of wave conditions for assessing vulnerability can be made only after the probability of stability failure in all modes is already known. Therefore, the probability of failure must be calculated for each cell of a scatter diagram and the methods of calculation of probability must be fast and simple.

A stability failure is considered as random event described by Poisson flow. This allows explicit relation with the time of exposure. However, it requires assurance that the events are independent. Only one parameter, the rate of failures – an average number of events per unit of time, is needed. The rate of failures depends on operational parameters, such as speed and course relative to waves. A simple model accounting for the operator is proposed. It is an empirical relation of the distribution of wave direction and speed for a sea state. This model accounts for normal navigational practice to have “waves on the bow” in heavy weather. Then, it becomes possible to average the rate of failure for each wave conditions, the cell of a scatter diagram, and also account for operational factors.

Further discussion focused on the evaluation of the rate of failures for particular stability failure modes is needed:

- Pure loss of stability is associated with down-crossing by the stochastic *GM* value through a level associated with partial or total stability failure. An additional condition for comparison is the mean time while below the threshold with the natural period of roll.
- Vulnerability to parametric roll is associated with exceeding a threshold of roll response while encountering a “typical” wave group. The probability of failure is calculated as the probability of up-crossing a threshold of the wave envelope.
- Consideration of the vulnerability to maneuvering related problems in waves is limited to surf-riding. Vulnerability to surf-riding is associated with prolonged periods of existence of the surf-riding equilibrium. Stability failure is associated with the down-crossing of the stochastic wave surging force through the threshold of

balance between thrust and resistance at wave celerity. An additional condition for comparison is the average duration of the down-crossing with the period of oscillation about stable surf-riding equilibrium.

- Vulnerability in dead ship conditions is understood as greater-than-conventional danger of stability failure. Partial failure is associated with up-crossing by roll of a given threshold. The probability of total failure is calculated using a piecewise linear method, where the probability of up-crossing the maximum of the *GZ* curve results in a condition leading to capsizing.

The discussion of stability failures for particular modes demonstrated that up-crossing theory can be applied for all of them, to calculate the rate of both partial and total stability failures, with exception of surf-riding where partial and total stability failures were not distinguished. However, application of this method is limited and intended only to provide simple probabilistic-based mathematical models which have the possibility to assess vulnerability in irregular waves.

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