Challenges of Dead Ship condition Vulnerability Criteria Development

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ABSTRACT

The dead-ship condition is one of five stability failure modes for which second generation intact stability criteria (SGISC) is being developed by the International Maritime Organization (IMO). SGISC consists of three levels of successive assessment that are of increasing complexity: Levels 1 and 2 vulnerability criteria are intended to identify loading conditions that are not vulnerable to the given failure mode. The third level – a Direct Stability Assessment (DSA) -- is envisioned to involve the application of sophisticated, proprietary computer software that meet IMO agreed specifications. These assessment levels should be consistent: an assessment outcome of "not vulnerable" for a loading condition in Level 1 or 2, respectively, should not have an opposite outcome for Level 2 or DSA, respectively.

However, the dead-ship condition failure mode is different from the other failure modes since it is the only one that includes existing mandatory criteria (first generation) at the Level 1 assessment (the severe wind and rolling criterion – Weather Criterion, 2008 IS Code, part A, 2.3). Hence, consistency between Levels 1 and 2 in the dead-ship condition assessments is important to maintain the integrity of the 2008 IS Code. Otherwise, the potential exists for an unsafe situation if the SGISC vulnerability criteria are significantly less restrictive than the Weather Criterion because then motivation would exist to design for loading conditions beyond the applicability ranges of the Weather Criterion. This paper addresses these challenges.

Keywords: *dead-ship condition, second generation intact stability criteria (SGISC), vulnerability criteria, Weather Criterion,2008 IS Code.*

1. INTRODUCTION

The second generation intact stability criteria (SGISC) under development by the International Maritime Organization (IMO), consists of three levels of successive assessment. Level 1 vulnerability criteria is intended as a simple assessment to identify loading conditions that are not vulnerable to the given failure mode. Level 2 is intended as a more complex analytical assessment applied to those loading conditions that do not satisfy the Level 1 standard. Loading conditions that do not satisfy the Level 2 standard may be subject to the third level – a Direct Stability Assessment (DSA), which is envisioned to involve the application of sophisticated, proprietary computer software that meet IMO agreed specifications. These assessment levels should be consistent: an assessment outcome of "not vulnerable" for a loading condition in Level 1 should not have an opposite outcome for Level 2. Likewise, a "not vulnerable" Level 2 outcome should not have an opposite outcome for DSA.

The dead-ship condition failure mode, however, is different since it includes existing mandatory criteria (first generation) as the Level 1 assessment (the severe wind and rolling criterion – Weather Criterion, 2008 IS Code, part A, 2.3). As a result, consistency between Levels 1 and 2 in the dead-ship condition assessments is important to maintain the integrity of the 2008 IS Code. In the case where the SGISC vulnerability criteria are significantly less restrictive than the Weather Criterion, the potential exists for an unsafe situation because motivation would exist for designers to choose loading conditions that are beyond the applicability ranges of the Weather Criterion.

Internal consistency is the first challenge of the dead-ship condition vulnerability criteria in Levels

1 and 2. The Weather Criterion is used as the Level 1 criteria and has the following characteristics:

1. it uses a deterministic model for the wind gust as 1.5 times the mean wind speed.
2. it uses a semi-empirical method to determine the roll-back angle.
3. it defines failure as a physical possibility of exceedance of an unacceptable level resulting from a single wind gust.

The Weather Criterion was developed based on ships with loading conditions with certain characteristics (B/d <3.5 and -0.3 < (KG/d-1) < 0.5 and T <20s) and when the loading condition is beyond those ranges. Model tests can be used to assess the wind heeling and the roll-back angle. Otherwise, for Level 1 vulnerability criteria, the Weather Criterion model is extended up to T<30s.

On the other hand, the Level 2 vulnerability criteria has been developed using a probabilistic model for the wind gust based on the spectrum of wind velocity in which the roll-back angle is assessed from ship motion calculations, and stability failure is defined as a probability of exceeding an unacceptable level within one hour's duration. Because the Level 2 model is expected to be more advanced and detailed than the Level 1/Weather Criterion model, some degree of inconsistency can be expected. However, partly because the Weather Criterion is mandatory, there is no information about an accident involving the dead ship condition to assist with setting the standard for the Level 2.

To address these challenges, three objectives can be established:

- Ensure that the calculation methods used for the vulnerability criteria Level 2 are robust and are used within their applicability range.
- Choose the standard to ensure the integrity of the 2008 IS Code and consistency between the Levels 1 and 2 vulnerability criteria.
- Accept a certain probability of inconsistency and treat this probability as a safety level to then be used to set the standard.

The inconsistency of the analysis procedure and some preliminary results are described below.

2. ASSESSMENT OF INCONSISTENCY

How can the consistency between the Weather Criterion and the Level 2 vulnerability criteria be assessed?

Consider a ship in a critical condition on the Weather Criterion, such that any increase of the KG will mean the criterion is not satisfied. This critical condition means that either area a exactly equals area b, or the angle of heel under steady action of wind exactly equals its limit value (16 degrees or 80% of deck edge immersion, whichever is less).

The Level 2 vulnerability criterion is formulated probabilistically. The result of the calculation for Level 2 is a probability of at least one exceedance of the prescribed roll angle within an hour. The Level 2 vulnerability criterion can be applied to loading conditions of several ships where the Weather Criterion is fully applicable and are in a critical condition. If the Weather Criterion and Level 2 vulnerability criterion are absolutely consistent, the calculated probabilities should be exactly the same.

However, as a result of using different mathematical models for ship rolling under wind and wave action, those probabilities cannot be the same. Variation of these probabilistic values can be used to assess the inherent level of inconsistency between Levels 1 and 2.

Applicability of the Weather Criterion

The first step in this procedure is to ensure that B/d < 3.5, which can be achieved by selecting a draft. A ship where no operational draft corresponds to the condition B/d < 3.5 should be excluded from the sample.

Initial KG value is computed as:

$$KG_0 = BM + KB - GM_{\min} \tag{1}$$

Here, the lowest $GM_{\min}$ = 0.15 m is taken from the requirements in the paragraph 2.2.4 of part A of the 2008 IS code.

Using accepted draft, KG_0 and assuming zero trim, one can compute the GZ curve. However, it is not guaranteed this KG_0 is realistic as it may not satisfy the other requirements of the 2008 IS code, part A/2.2. Nevertheless, there is sufficient information to compute the maximum KG based on the requirements of the 2008 IS code, A/2.2. This maximum KG is subsequently referred to as KG_1.

There are limiting values of the KG based on the draft that can be easily derived from satisfying the inequality -0.3 < (KG/d-1) < 0.5:

$$KG_2 = 1.5d \tag{2}$$

$$KG_3 = 0.7d \quad (3)$$

Finally, there is the roll period condition T <20s. Having in mind that the roll period is computed as described in paragraph A/2.3.4, 2008 IS Code:

$$T = \frac{2 \cdot C \cdot B}{\sqrt{GM}} \quad (4)$$

Where B is the moulded breadth and C is computed as:

$$C = 0.373 + 0.023\frac{B}{d} - 0.043\frac{L_{wl}}{100} \quad (5)$$

Where L_{wl} is the waterline length of the ship (m).

Thus, the KG meeting the requirement T = 20s can be computed as:

$$KG_4 = BM + KB - \frac{C^2 \cdot B^2}{100} \quad (6)$$

The KG value for further computation can be chosen as:

$$KG = \min(KG_1, KG_2, KG_4) \quad (7)$$

However if the chosen KG is less than KG_3, the ship should be excluded from the sample as the applicability ranges of the Weather Criterion cannot be achieved. The result of formula (7) also has to be checked for practicality – if such a KG value can be actually encountered on the ship.

Because the KG-value is defined by the conditions of applicability of the Weather Criterion, it may be used to achieve the critical condition of the Weather Criterion. Those critical conditions are frequently achieved by artificially increasing the windage area and height of its center until either area *a* exactly equals area *b*, or the angle of heel under steady action of wind exactly equals 16 degrees or 80% of deck edge immersion, whichever is less.

Calculation Process

The choice of the draft and KG value together with the assumption of zero trim defines all the input data needed for the calculation of the Level 2 vulnerability criteria. The calculation flow follows the description provided in Annex 4 of IMO document SDC 4/5/1 with the exception of two elements:

1. Instead of using the "standard" methodology for the estimation of the effective wave slope, a direct pressure integration method is used, as described in Annex 10 to IMO document SDC 4/INF.

2. Instead of using the relative response amplitude operator (RAO), H_{rel}, the asolute RAO, H, is used in the formula 3.3.2.7-2 from Annex 4 of IMO document SDC 4/5/1.

The Level 2 vulnerability criteria value, C, is computed as described in paragraph 2.13.3.2.1 of Annex 1 of IMO document SDC 3/WP.5. Each criterion value, C, represents one point in a further statistical assessment.

3. INITIAL RESULTS

To check the feasibility of the procedure described in section 2. above, it was applied to 15 sample ship loading conditions; the characteristics of these ship's loading conditions, as well as the calculation results are given in Table 1. If the Weather Criterion and Level 2 vulnerability were totally consistent, all the C values would be the same. The fact they are not indicates the inconsistency between the Weather Criterion and Level 2 vulnerability criterion. The question then becomes how much inconsistency can be tolerated? The remainder of this section provides the quantification of the probability of inconsistency.

To facilitate setting the Level 2 probability criterion, a normal distribution is assumed for the results. Q-Q plot of the centered and standardized criteria value is shown in Figure 1. While agreement is not perfect, the assumption of a normal distribution still can be accepted in the first expansion. If further collection of data rejects the normal distribution assumption, the next candidate would be a log-normal distribution. Setting the standard based on a direct estimate of the quantiles is also possible, if sufficient sample size is available.

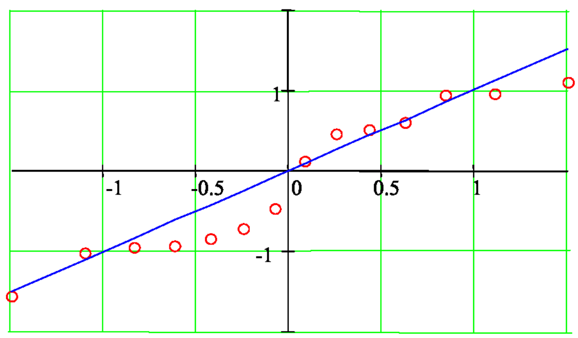

Figure 1: Q-Q Plot of the Criterion Values.

Estimations of the mean and standard deviation of these data points are, respectively:

$$\hat{E} = \frac{1}{n}\sum_{i=1}^{n} x_i = 0.219 \quad (8)$$

$$\hat{\sigma} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \hat{E})^2} = 0.0107 \quad (9)$$

As the distribution of the data is assumed to be normal, the distribution of the estimate of the mean value follows the Student-t distribution, while the variance estimate distribution is related to the chi-square, χ^2, distribution. The boundaries of the estimates (8) and (9) with the confidence probability $\beta = 0.95$ are:

$$\hat{E}_{low,up} = \hat{E} \mp \frac{\sigma}{\sqrt{n}} Q_t = [0.0159, 0.278] \quad (10)$$

Where Q_t = 2.145 is a quantile of Student-t distribution, computed for the probability $0.5(1+\beta)$ and n - 1 = 14 degrees of freedom.

$$\hat{E}_{low,up} = \hat{\sigma}\sqrt{\frac{n-1}{\chi^2_{n-1}(0.5(1\pm\beta))}} = [0.00785, 0.0169] \quad (11)$$

Where $\chi^2_{n-1}(0.5(1\pm\beta))$ is a quantile of the χ^2, distribution, computed for the probabilities $0.5(1\pm\beta)$ and n – 1 = 14 degrees of freedom.

To show how the standard can be set with this data, a suggestion to accept a probability of inconsistency as p = 0.05 is studied. Then, the standard can be proposed as:

$$R_{DS0} = \hat{E} + \hat{\sigma}\cdot Q_N(1-p) = 0.0395 \quad (12)$$

Where Q_N is a quantile of a standard normal distribution computed for the probability 1 - p.

The confidence interval computed in equation (10) and (11) can be propagated further to evaluate how uncertain the results of these calculations are:

$$S_{low,up} = \hat{E}_{low,up} + \hat{\sigma}_{low,up}\cdot Q_N(1-p) = [0.0289, 0.0557] \quad (13)$$

Indeed, as more ships are added as data points to these calculations, the confidence interval decreases. A decreasing p will increase the proposed standard. A noteworthy point is that this analysis (even performed on so few ships) produced a value close to what was proposed in the paragraph 2.13.3.1 at Annex 1 of IMO document SDC 3/WP.5.

CONCLUSIONS

This paper considered one of the main challenges of the vulnerability assessment in the dead ship condition, the consistency between the mandatory requirements in Part A of the 2008 IS Code/ Level 1 and the IMO Level 2 second generation intact stability criteria for the dead-ship condition. The particular difficulty for the dead-ship condition is that the process of ship rolling under the action of irregular waves and gusty wind is described with different mathematical models in the Weather Criterion and the Level 2 vulnerability criteria.

The proposed idea is to accept a certain probability of inconsistency and from this probability find the standard for the Level 2 vulnerability criteria. This approach uses statistics generated with a number of ships that are in a critical condition on the Weather Criterion and for which the Weather Criterion is fully applicable.

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Table 1: Summary of Calculations

Type	L (m)	D (m)	L/B	B/d	KG/d-1	T (s)	C_B	C_M	C_W	GM (m)	ϕ_{max} (deg)	GZ_{max} (m)	ϕ_v (deg	Criterion, C
Cargo ship	159	9.8	6.95	2.34	-0.12	16.21	0.59	0.99	0.72	1.02	26	0.42	56	0.017
Containership	274	10.6	8.53	3.04	0.19	20.00	0.54	0.92	0.67	1.09	46	1.35	79	0.042
RoPax	140	5.8	6.93	3.49	0.50	12.64	0.59	0.93	0.80	1.59	73	2.01	129	0.032
Bulk Carrier	149	10.8	6.47	2.13	-0.16	20.00	0.80	0.99	0.87	0.68	42	0.67	65	0.012
Containership	262	11.5	6.55	3.48	0.50	15.56	0.56	0.96	0.77	3.06	44	2.23	76	0.013
LNG carrier	257	12.0	6.17	3.47	0.36	20.00	0.78	0.98	0.83	2.04	38	2.11	63	0.032
Passenger	248	10.3	6.90	3.50	0.50	16.14	0.72	0.98	0.87	2.39	36	1.40	74	0.005
Cargo ship	122	7.0	7.01	2.50	-0.05	20.00	0.70	0.99	0.79	0.43	56	1.21	111	0.014
Bulk Carrier	280	17.6	5.96	2.67	-0.14	14.21	0.82	1.00	0.89	4.31	26	1.63	59	0.027
Containership	283	12.1	8.80	2.66	0.14	20.00	0.64	0.95	0.83	1.01	39	1.22	60	0.034
Containership	330	15.1	7.24	3.01	0.31	20.00	0.65	0.98	0.84	1.88	38	1.84	59	0.023
Tanker	320	21.1	5.52	2.75	-0.01	20.00	0.80	1.00	0.88	3.00	28	1.54	48	0.012
Containership	327	13.2	7.17	3.47	0.50	17.90	0.58	0.90	0.77	2.53	34	1.68	54	0.011
Containership	376	16.5	6.53	3.49	0.46	20.00	0.61	0.95	0.80	2.82	49	3.15	78	0.027
Containership	198	10.4	6.66	2.86	0.20	20.00	0.60	0.98	0.78	1.11	51	1.88	89	0.028