Study on the Second Generation Intact Stability Criteria of Broaching Failure Mode

Peiyuan Feng, *Marine Design & Research Institute of China (MARIC)*, pyfeng23@163.com

Sheming Fan, *Marine Design & Research Institute of China (MARIC)*, fan_sm@maric.com.cn

Xiaojian Liu, *Marine Design & Research Institute of China (MARIC)*, cz_liu_xj@sina.com

ABSTRACT

This paper evaluates the vulnerability of sample ships to the broaching stability failure mode according to the current proposal submitted to IMO's Subcommittee on Ship Design and Construction (SDC). Sensitivity analysis is performed to study the influence of input parameters on the assessment result. Sample calculations are then performed and the results are analyzed with an emphasis on the appropriateness of the current proposal. Consequently, some comments concerning the potential impact of the broaching stability criteria on ship design is proposed.

Keywords: *surf-riding, broaching, stability assessment, sample calculations, ship design*

1. INTRODUCTION

The International Maritime Organization (IMO) is currently working on the second generation intact stability criteria of five failure modes to ensure the safety of ships in waves more effectively. Broaching is among the five and is considered to be the most complicated one due to its highly nonlinear and chaotic nature. Broaching occurs when a ship cannot keep a constant course despite the maximum steering effort typically in following and quartering waves. Surf-riding is usually regarded as the prerequisite of broaching, which occurs when a ship is captured by the wave approaching from the stern that accelerates the ship to the wave celerity. Small-size high-speed ships such as fishing vessels are most vulnerable to this stability failure mode.

To investigate the mechanism behind this hazardous phenomenon, significant theoretical and experimental efforts have been made by researchers in the recent decades (Umeda et al., 1999, Spyrou, 2001, Umeda & Vassalos, 1996, Hashimoto et al., 2004, Hashimoto & Stern, 2007, Maki et al., 2010), which form a good foundation for the development of broaching stability assessment criteria.

According to IMO, a three-tiered approach is applied for assessing the five stability failure modes. Level 1 is meant to be simple and conservative, whose purpose is to distinguish ships that are clearly not vulnerable. If found vulnerable, the ship is then required for Level 2 evaluation which is less conservative. The method adopted for Level 2 evaluation is meant to be based on simplified physics and involve calculations with reduced computational efforts. If the ship is found vulnerable again, direct stability assessment using the most advanced state-of-the art technology has to be performed.

The current proposal from U.S. and Japan (SDC 2/INF.X, 2014) follows the three-tiered framework: Level 1 evaluation only needs the ship length and speed information; Level 2 evaluation is based on a simplified surf-riding model, the probability of surf-riding occurrence in irregular seaway is chosen as the criteria for assessment; Level 3 direct stability assessment procedures are still under discussion, the draft guidelines can be found in SDC1/INF.8 (2013).

This study focuses on the Level 2 evaluation. The main purpose is to analyze and verify the current proposal through sensitivity analysis and sample calculations. Concerns towards the appropriateness of the Level 2 criteria such as the threshold value are raised. Consequently, the potential impact of the broaching stability criteria on ship design is discussed.

This study can help designers better understand the second generation intact stability criteria of broaching failure mode and the establishing of the regulation.

2. CURRENT BROACHING STABILITY FAILURE ASSESSMENT PROPOSAL

The following introduction of the current proposal to assess the Level 1 and Level 2 broaching stability failure mode is based on the contents of Annex 32 and Annex 35 in SDC 2/INF.X (2014).

2.1 Level 1 Vulnerability Criteria

A ship is considered not to be vulnerable to the broaching stability failure mode if:

$$L > 200m \quad \text{or} \quad Fn > 0.3 \tag{1}$$

where, $Fn = V_S / \sqrt{Lg}$ is the Froude number; V_s is ship service speed in calm water; L is the length of ship.

If the ship fails to pass Level 1 criteria, Level 2 assessment is needed.

2.2 Level 2 Vulnerability Criteria

For a ship to pass Level 2 assessment, it is required that:

$$C < R_{SR} \tag{2}$$

where, C represents the probability of surf-riding occurrence; R_{SR} is the standard value. Two opinions exist for the value of R_{SR}, with 1e-4 by Japan and 5e-3 by U.S.

C is estimated by:

$$C = \sum_{H_S} \sum_{T_Z} \left(W2\left(H_S, T_Z\right) \frac{\sum_{i=1}^{N_\lambda} \sum_{j=1}^{N_a} W_{ij} C2_{ij}}{\sum_{i=1}^{N_\lambda} \sum_{j=1}^{N_a} W_{ij}} \right) \tag{3}$$

where, $W2(H_s,T_z)$ is the weighting factor of short-term sea state according to long-term wave statistics; H_s is the significant wave height; T_z is the zero-crossing wave period; W_{ij} is a statistical weight of a wave with steepness $s_j=(H/\lambda)_j$ varying from 0.03 to 0.15; and wave length to ship length ratio $r_i=(\lambda/L)_i$ varying from 1.0 to 3.0. Details concerning these factors are specified in SDC 2/INF.X (2014).

$C2_{ij}$ is the key element which represents whether surf-riding/broaching occurs for each wave case, which is defined as follows:

$$C2_{ij} = \begin{cases} 1 & \text{if} \quad Fn > Fn_{cr}\left(r_j, s_i\right) \\ 0 & \text{if} \quad Fn \le Fn_{cr}\left(r_j, s_i\right) \end{cases} \tag{4}$$

where, $Fn_{cr} = u_{cr} / \sqrt{Lg}$ is the critical Froude number corresponding to the threshold of surf-riding (surf-riding occurs under any initial condition); u_{cr} is the critical ship speed determined by solving the following equation:

$$T_e\left(u_{cr}; n_{cr}\right) - R\left(u_{cr}\right) = 0 \tag{5}$$

where, $R(u)$ is the calm water resistance of the ship approximated by N^{th} order polynomial:

$$R(u) \approx \sum_{i=0}^{N} r_i u^i = r_0 + r_1 u + r_2 u^2 + \cdots \tag{6}$$

$T_e(u_{cr};\, n_{cr})$ is the propulsor thrust in calm water:

$$T_e(u_{cr}; n_{cr}) = (1 - t_P)\rho n_{cr}^2 D_P^4 K_T(J) \tag{7}$$

$$K_T(J) \approx \sum_{i=0}^{N} \kappa_i J^i = \kappa_0 + \kappa_1 J + \kappa_2 J^2 + \cdots \tag{8}$$

where, n_{cr} is number of propeller revolutions corresponding to the threshold of surf-riding, which is estimated based on Melnikov method by solving the following equation:

$$2\pi \frac{T_e(c_w; n_{cr}) - R(c_w)}{f} = \sum_{i=1}^{N} \sum_{j=1}^{i} C_{ij} (-2)^j I_j \tag{9}$$

where,

$$C_{ij} = \frac{c_i}{fk^j} \left\{ \frac{i!}{j!(i-j)!} \right\} \frac{(fk)^{j/2}}{(m + m_x)^{j/2}} c_w^{i-j} \tag{10}$$

$$c_i = -\frac{(1 - t_P)(1 - w_P)^i \rho \kappa_i}{n^{i-2} D_P^{i-4}} + r_i \tag{11}$$

$$I_j = 2\sqrt{\pi}\, \Gamma\left(\frac{j+1}{2}\right) \Big/ \Gamma\left(\frac{j+2}{2}\right) \tag{12}$$

$$\Gamma(N) = (N-1)! \tag{13}$$

$$\Gamma\left(N + \frac{1}{2}\right) = (2N-1)!! \frac{\sqrt{\pi}}{2^N} \tag{14}$$

In the above equations, c_w is the wave celerity; k is the wave number; t_P is the thrust deduction factor; w_P is the wake fraction; D_P is the propeller diameter.

The amplitude of wave surging force f in equation (9) is calculated as:

$$f = \rho g k \frac{H}{2} \sqrt{F_C^2 + F_S^2} \tag{15}$$

where,

$$F_C = \sum_{i=1}^{N_S} S(x_i) \exp\{-0.5kd(x_i)\} \sin kx_i \Delta x_i \tag{16}$$

$$F_S = \sum_{i=1}^{N_S} S(x_i) \exp\{-0.5kd(x_i)\} \cos kx_i \Delta x_i \tag{17}$$

where, $d(x_i)$ and $S(x_i)$ are the draft and the submerged area of the ship at station i in calm water, respectively.

3 SENSITIVITY ANALYSIS

Level 2 assessment involves many parameters which might be hard to obtain at the early design stage. Usually, empirical formula and/or model experiment results are used as the initial estimation. Therefore, it is meaningful to perform the sensitivity analysis to evaluate the influence of input parameter variation on the assessment result.

A purse seiner (L_{PP}=42.5m, B=7.8m, d=3.2m, C_B=0.6721) is chosen as the target ship for the sensitivity analysis. The service speed of the ship is 6.5m/s (Fn=0.32), therefore the ship cannot pass Level 1 assessment.

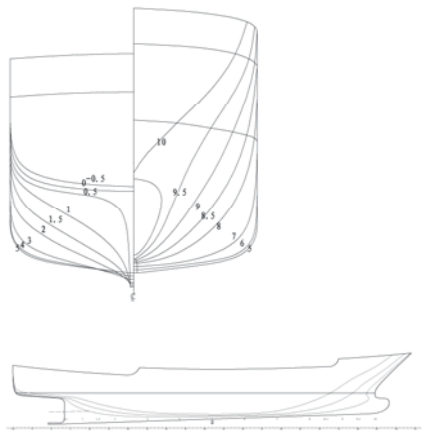

Figure 1 Lines of the purse seiner.

3.1 Influence of Resistance Estimation

Two aspects are studied, one is the influence of the order of polynomials for resistance curve approximation, and the other is the influence of resistance estimation error. The propeller thrust coefficients are approximated by 2nd order polynomials.

Figure 2 demonstrates the influence of order of polynomials for curve fitting. As can be seen, the curve fitting results in low and middle speed region (*Fn*<0.35) have small differences. However, the differences increase between N_{Fit}=3 and N_{Fit}=4 or 5 in the high speed region.

The results are listed in Table 1. As expected, there is a 29.5% difference of *C* value between N_{Fit}=3 and N_{Fit}=5. Therefore, proper choice of the order of polynomials for resistance curve fitting is important for the assessment.

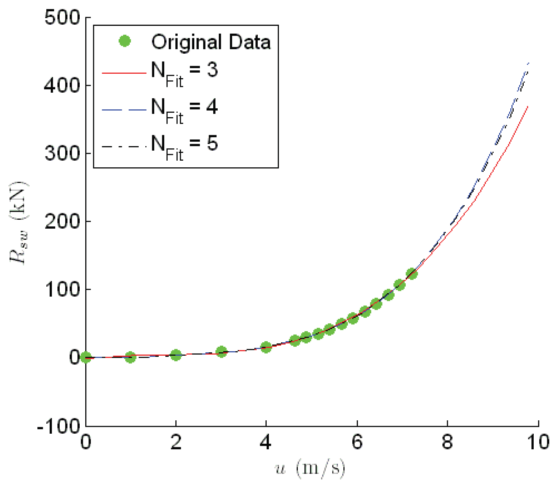

Figure 2 Resistance curve approximation.

The influence of estimation error is also listed in Table 1. According to the results, if there is 1% uncertainty in the estimated data, there will be about 1% difference in the attained *C* value. Moreover, with the increase of estimation uncertainty, the differences in the attained *C* values grow rapidly. Typically, if there is 5% uncertainty in the resistance estimation, which is quite likely in terms of RANS based CFD computations, the resulting difference in the attained *C* value can be up to 16%.

However, it should be pointed out that the lack of data in high speed region (*Fn* around 0.45) may have some influence on the obtained result, which implies that accurate estimation of ship resistance at high speeds is also important.

Table 1 Resistance Estimation Influence

Case	Uncertainty (%)	N_{Fit}	*C*	Δ*C* (%)
1	0	5	1.90E-02	
2	0	4	1.82E-02	4.2
3	0	3	2.46E-02	29.5
4	1	5	1.88E-02	1.1
5	3	5	1.79E-02	6.0
6	5	5	1.59E-02	16.3

3.2 Influence of Propulsion Estimation

Similar studies are performed to investigate the influence of propulsion input data uncertainty, where the resistance curve is approximated by 5th order polynomials.

Figure 3 demonstrates the influence of order of polynomials for K_T curve approximation, and very small differences can be noticed. As shown by the results listed in Table 2, this will cause roughly 2% difference in the attained *C* value. Moreover, it is demonstrated that the result is not very sensitive to the K_T coefficient estimation error. If the uncertainty is within 2%, the final difference can be kept within 1%.

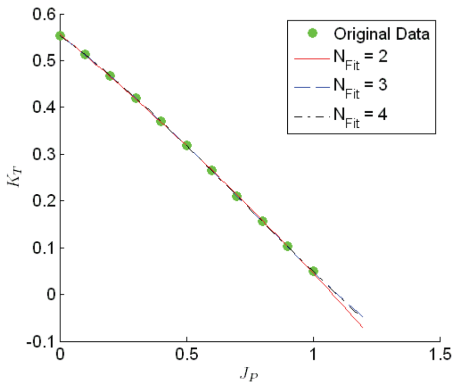

Figure 3 Thrust coefficient approximation.

Table 2 Propulsion Estimation Influence

Case	Uncertainty (%)	N_{Fit}	C	ΔC (%)
1	0.0	2	1.90E-02	
2	0.0	3	1.94E-02	2.1
3	0.0	4	1.94E-02	2.1
4	1.0	2	1.91E-02	0.5
5	1.5	2	1.90E-02	0.2
6	2.0	2	1.91E-02	0.7

Table 3 Influence of w_P and t_P Estimation

Case	w_P	t_P	C	ΔC (%)
1	0.287	0.287	1.90E-02	
2	0.316	0.287	1.84E-02	3.2
3	0.258	0.287	1.94E-02	2.1
4	0.287	0.316	1.88E-02	1.1
5	0.287	0.258	1.92E-02	1.1

The influence of w_P and t_P are also studied by varying them either 10% larger or smaller. The results are listed in Table 3. As can be seen, both parameters have small influence on the final C value. Comparatively speaking, the result is more sensitive to w_P than t_P.

3.3 Influence of Wave Force Calculation

As pointed out by Japan (SDC 2/INF.X, 2014), the wave-induced surge force could often be over-estimated because only the Froude-Krylov component is considered in current procedure. Japan thus proposed an empirical correction factor for the diffraction effect as follows:

$$f = \mu_x \rho g k \frac{H}{2} \sqrt{F_C^2 + F_S^2} \tag{18}$$

$$\mu_x = \begin{cases} 1.46C_b - 0.05 & C_m < 0.86 \\ (5.76 - 5C_m)C_b - 0.05 & 0.86 < C_m < 0.94 \\ 1.06C_b - 0.05 & C_m \geq 0.94 \end{cases} \tag{19}$$

where, μ_x is the empirical correction factor; C_m is the midship section coefficient.

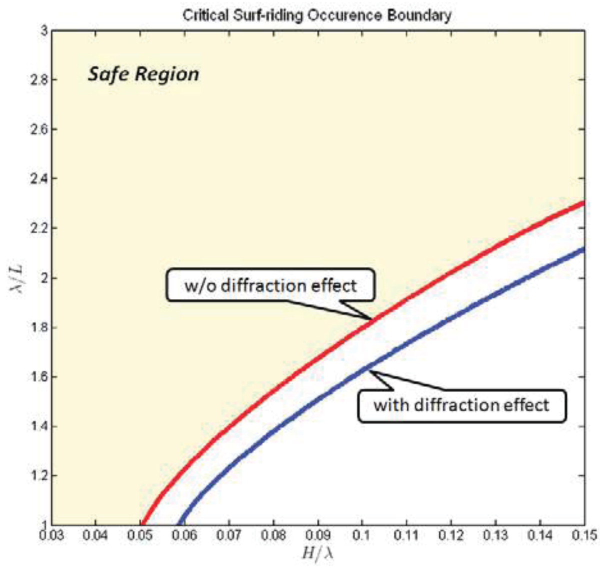

Figure 4 Surf-riding occurrence boundary.

The change of critical surf-riding boundary after correcting for the diffraction effect is illustrated in Figure 4, where the safe region corresponds to $C2_{ij}$=0. As can be seen, the safe region is increased, and correspondingly, the attained C value decreases from 1.90E-02 to 9.40E-03, which is 50.5% smaller. Therefore, the wave force calculation has significant influence on the assessment. Investigations on more accurate wave force estimation methods are crucial in subsequent researches.

4 SAMPLE CALCULATIONS

Based on the sensitivity analysis result, sample calculations are performed to 10 ships. The calm water resistance curve and the propeller thrust coefficient are approximated by the 5th and 2nd order polynomials, respectively. The correction for the diffraction effect is not considered since it has not yet been included in the standard procedure. The results of the sample calculations are analyzed to verify the appropriateness of the current proposal.

4.1 Sample Ships

The main particulars of the 10 sample ships are listed in Table 4.

Table 4 Main Particulars of Sample Ships

NO.	Ship Type	*Fn*	L_{PP} (m)	*B* (m)	*d* (m)	C_B
1	Purse Seiner	0.320	42.5	7.8	3.2	0.6721
2	Purse Seiner	0.285	43.0	8.5	3.7	0.8011
3	Purse Seiner	0.268	54.0	10.0	4.1	0.7396
4	Fishing Boat	0.364	29.5	6.0	1.8	0.4796
5	Fishing Boat	0.290	41.0	7.0	2.8	0.5800
6	Traffic Boat	0.496	16.0	6.0	1.8	0.5277
7	Traffic Boat	0.553	19.5	5.0	1.4	0.4925
8	Gillnet Boat	0.332	27.1	5.4	2.0	0.5610
9	Trawler	0.316	36.8	7.2	2.8	0.5850
10	Crab Boat	0.285	39.0	6.6	2.7	0.5940

Fishing boats and small-size high-speed boats are chosen intentionally because they are most vulnerable to the broaching stability failure. Moreover, the Froude numbers of the sample ships are around 0.3, with four below 0.3 and six over 0.3. However, none of the ship length is over 200m.

The offset data, calm water resistances and propeller open water data of the sample ships are provided by the design institutes, while w_P and t_P are estimated by:

$$w_P = C_B/3 + 0.063 \tag{20}$$

$$t_P = w_P \tag{21}$$

4.2 Assessment Results

The results are shown in Table 5. Four ships can pass the Level 1 assessment because their Froude numbers are below 0.3. When it comes to Level 2 assessment, the setting of the standard value R_{SR} plays an important role. If R_{SR} =1e-4, only two of the four remaining ships (NO.2 and NO.3) can further pass Level 2 assessment while inconsistency occurs to NO.5 and NO.10, even when the diffraction effect is included (NO.5-μ_x and NO.10-μ_x); however, if R_{SR} =5e-3, all the four remaining ships can further pass Level 2 assessment, and the consistency can be guaranteed.

Since Level 2 assessment is meant to be less conservative than Level 1 assessment, the occurrence of inconsistency should be avoided. Therefore, based on the current sample calculation results, R_{SR} =5e-3 seems to be a more proper standard value.

Table 5 Assessment Results

NO.	Level 1	Level 2		
		C	Conclusion	
			R_{SR}=1e-4	R_{SR}=5e-3
1	Fail	1.90E-02	Fail	Fail
2	Pass	0.00E+00	Pass	Pass
3	Pass	0.00E+00	Pass	Pass
4	Fail	3.26E-01	Fail	Fail
5	**Pass**	**3.40E-03**	**Fail**	**Pass**
5-μ_x		**5.43E-04**	**Fail**	**Pass**
6	Fail	9.68E-01	Fail	Fail
7	Fail	1.00E+00	Fail	Fail
8	Fail	1.11E-01	Fail	Fail
9	Fail	1.97E-02	Fail	Fail
10	**Pass**	**1.70E-03**	**Fail**	**Pass**
10-μ_x		**3.30E-04**	**Fail**	**Pass**

4.3 Impact on Ship Design

Some insights concerning the potential impact of the broaching stability criteria on ship design can be obtained through further investigation into the sample ship calculation results.

Taking the NO.10 crab boat as the example, the *Fn*—*C* relation curve is shown in Figure 5. As can be seen, the slope of the curve around *Fn*=0.3 is very steep, which implies that a slight change of *Fn* will cause a significant change in the attained *C*. Therefore, a slight increase of ship length or decrease of ship speed might be helpful for meeting the criteria requirement.

Furthermore, we can see from Table 4 and 5 that NO.6 and NO.7 traffic boats are most vulnerable to the broaching stability failure mode due to their small lengths. The same situation might happen to most ships with small lengths and thus high Froude numbers. If the second generation intact stability criteria come into force, the existing small-size high-speed ships may have to increase their lengths in order to comply with the regulation. Otherwise, they can only operate under much slower speeds, which do not seem to be very feasible for these task-oriented vessels.

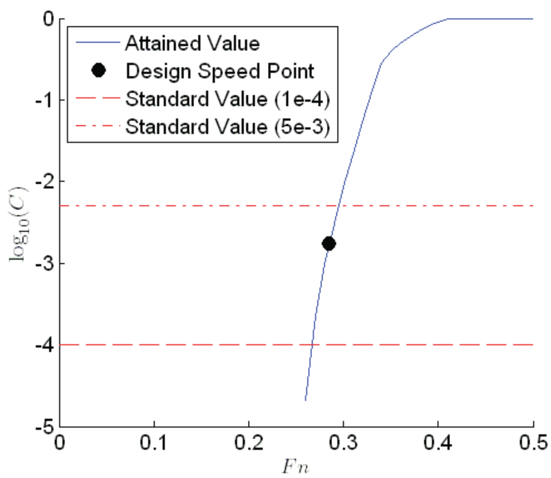

Figure 5 *Fn*—*C* relation curve.

5 CONCLUSIONS

This study tries to identify the most crucial parameters of the broaching stability criteria assessment through sensitivity analysis, and to verify the current proposal based on sample calculations. The main conclusions are summarized as follows:

1) Resistance estimation accuracy has big influence on the attained index value *C*. Calm water resistance estimation at high ship speeds is important for curve fitting. The result is also quite sensitive to the uncertainty level of resistance estimation. A 5% uncertainty in the resistance data may cause a significant difference on the attained *C* value. However, prediction of resistance at large Froude numbers is very difficult and error prone. CFD results for Froude numbers over 0.4 are considered to be unreliable, so the estimation of the resistance at high speeds should be studied.

2) The result of attained *C* value is not very sensitive to the K_T coefficient estimation error, so as the wake fraction w_P and thrust deduction coefficient t_P. The results seem to justify the use of rough approximations for the propeller thrust coefficient as well as w_P and t_P in the initial design stage.

3) The wave force calculation has significant influence on the assessment result. The attained *C* value can be halved if the diffraction effect is taken into account through an empirical correction model. Further studies on this aspect are crucial and definitely necessary.

4) Based on the sample calculation results, R_{SR} =5e-3 seems to be a more proper standard value than R_{SR} =1e-4. To better justify the choice of the standard value, more sample calculations that cover a wider range of ship types are preferable.

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