한국 융합신호처리학회
융합신호처리학회논문지 Vol. 25, No.2 : 86~93 June 2024
DOI : 10.23087/jkicsp.2024.25.2.005

IMO 2세대 비손상 복원성에 의한 서프라이딩/브로칭 평가

강용덕[1], 이상목[2], 김대현[2], 문병영[3*]
[1]해군사관학교 조선공학과, [2]국립군산대학교 조선해양기자재연구센터,
[3]국립군산대학교 조선해양공학과

Evaluation for Surfriding/Broaching of the IMO Second Generation Intact Stability

Yong Duck Kang[1], Sangmok Lee[2], Daehyeon Kim[2], Byungyoung Moon[3*]
[1]Department of Naval Architecture Engineering, Naval Academy
[2]Shipbuilding and Ocean Equipment Research Center, Kunsan National Universty
[3]Department of Shipbuilding and Ocean Engineering, Kunsan National University

요 약 본 논문은 4.99톤급 소형 연안 어선의 안정성을 평가하기 위해 수집된 데이터를 국제해사기구(IMO) 2세대 비손상 복원성 기준에 따라 해석을 수행하였다. 특히, 해상 항해 중 서프라이딩/브로칭 조건에서의 선박 거동에 중점을 두고 국제 기준에 부합하는 평가 과정을 검증하였고, 제시된 데이터 처리 절차는 파랑 중 선박의 비손상 복원성을 평가하기 위해 1세대 비손상 복원성 기준보다 엄격한 기준을 적용하였다. 그러나, 대상 어선의 상태가 표준 상태에서 벗어나는 경우, 실제 적재 조건에 따라 비손상 복원성 평가가 별도로 수행되어야 한다. 서프라이딩/브로칭 데이터 처리 절차는 국립군산대학교 조선해양기자재연구센터에서 개발한 프로그램을 사용하였고, 계산이 수행된 조건, 파라미터 및 기준에 따라 그 결과를 상세히 비교 및 분석 하였다. 또한, 국제해사기구(IMO) 규정에 따른 1단계 및 2단계 평가 결과를 제시하여, 소형 연안 어선의 서프라이딩/브로칭 조건에 대한 복원성을 파라메트릭 해석함으로써 유체동역학적 거동 상황에서 비손상 복원성을 평가할 수 있게 되었다.

• 주제어 : 소형 어선, 서프라이딩, 브로칭, 복원성 평가, 국제해사기구 2세대 비손상 복원성 규정

Abstract This study evaluates the stability of a 4.99-ton small coastal fishing boat using data interpreted according to the second-generation intact stability criteria of the International Maritime Organization (IMO). The focus is on the ship's behavior under surfriding/broaching conditions during sea navigation, ensuring compliance with international standards. The data processing procedures presented apply stricter criteria than the first-generation intact stability standards to assess the ship's intact stability in waves. However, if the vessel deviates from its standard condition, a separate intact stability assessment based on actual loading conditions is necessary. The surfriding/broaching data processing procedures utilized a program developed by the Shipbuilding and Ocean Equipment Research Center at Kunsan National University. The results were analyzed and compared in detail according to the conditions, parameters, and criteria used for the calculations. Additionally, the study presents the results of Level 1 and Level 2 assessments according to IMO regulations, providing a parametric analysis of the small coastal fishing boat's stability. This allows for the evaluation of intact stability in hydrodynamic motion scenarios.tract.

• Key Words : Small fishing boat, Surfriding, Broaching, Stability evaluation, IMO Second generation intact stability regulation

Received 16 June 2024, Accepted 27 June 2024

* **Corresponding Author** Moon, Byungyoung, Department of Shipbuilding and Ocean Engineering, Kunsan National University, 558 Daehak-ro, Gunsan-si 54150, Korea. E-mail: moonby20@hanmail.net

Ⅰ. Introduction

The International Maritime Organization (IMO) is actively developing second-generation intact stability criteria to address various stability failure modes, including pure loss of stability, parametric roll, surfriding/broaching, dead ship conditions, and excessive accelerations. These criteria aim to enhance the safety of ships navigating challenging wave conditions, ensuring a higher level of maritime safety [1-2].

The second-generation intact stability criteria are structured into two tiers of vulnerability assessments, utilizing both straightforward physical models and advanced numerical simulation methods for direct stability evaluation. Surfriding, a phenomenon where a ship is caught by a wave from the stern and forced to move with the wave's speed, introduces significant instability and can lead to uncontrollable turning, known as broaching. Broaching is particularly dangerous for high-speed vessels, such as destroyers and fishing ships, especially in following and stern-quartering waves.

During the 3rd session of the Sub-committee on Ship Design and Construction (SDC), the vulnerability criteria for surfriding/broaching at Levels 1 and 2 were established [1-2]. Surfriding is often seen as a precursor to broaching; thus, the likelihood of surfriding is used as a vulnerability criterion instead of broaching. The Level 1 criterion involves a straightforward assessment based on ship speed and length, while the Level 2 criterion incorporates a formula derived using the Melnikov method, stochastic wave theory, and wave statistics, with the calculated value compared against a safety threshold of 0.005.

An essential component of the Level 2 criterion involves estimating surfriding thresholds. Recent advancements include several approximate formulas based on Melnikov's method for predicting surfriding thresholds in following regular waves [3-7, 8-11]. Additionally, researchers [8-9] have proposed an analytical formula using a continuous piecewise linear approximation, offering greater transparency compared to Melnikov's method.

Transitioning to numerical simulations in irregular waves presents the challenge of identifying surfriding/broaching phenomena. Belenky et al. [5] proposed a method for detecting surfriding in irregular waves based on wave celerity. This method involves computing the point of maximum wave steepness on the downslope of the wave nearest to the ship, providing a robust framework for analyzing ship stability in irregular wave conditions [12].

Fig. 1 A snapshot of surfriding(upper)/broaching(lower) in the free running experiment [7].

This study focuses on evaluating the surfriding/broaching mode among states vulnerable to stability issues based on the most recent criteria of the second-generation intact stability. The International Maritime Organization's (IMO) second-generation intact stability criteria involve a structured assessment procedure using Level 1 and Level 2 formulas. If a vessel meets the standard Level 1 criteria, further evaluation steps are deemed unnecessary. However, if the Level 1 criteria are not satisfied, a more detailed Level 2 assessment is required. If the Level 2 evaluation also falls short, a Direct Stability Assessment (DSA), corresponding to Level 3, must be conducted. The DSA can be performed experimentally or through advanced simulations.

This paper presents a detailed hydrodynamic modelling and calculation procedure for a Level 2 assessment, following the latest draft defined by the IMO Sub-committee on Ship Design and Construction (SDC). This approach is employed in cases where Level 1 criteria are not met, necessitating a more rigorous evaluation. Specifically, the paper provides a comprehensive presentation and calculation of Level 2 criteria, focusing on dynamic stability against waves. The study utilizes the design data of a 4.99-ton fishing boat, with the calculations implemented through an in-house developed code. This detailed assessment ensures a robust evaluation of the fishing boat's stability, particularly in surfriding/broaching conditions, thereby contributing to enhanced maritime safety.

Ⅱ. Evaluation Procedures and Results

2.1 Level 1 Evaluation Procedure

The criteria for Level 1 vulnerability assessment are determined by a boat's length (LBP) and Froude number (Fn). If the following conditions in Equation (1) are met, the ship is considered not vulnerable to surfriding/broaching.

$$L_{BP} \geq 200m \ \text{or} \ Fn \leq 0.3$$
$$Fn = \frac{V}{\sqrt{gL_{BP}}} \qquad (1)$$

where, L_{BP} : Ship length (m)
V : Ship speed (m/s)
g : Gravity acceleration (m/s^2)

In Level 1 criteria, the Froude number guideline takes into account that surfriding is likely to occur when the ship's speed (V) meets the conditions outlined in Equation (2).

$$V(knot) \geq \frac{1.8\sqrt{L_{BP}}}{\cos(180-\alpha)} \qquad (2)$$

Here, α represents the angle of the wave incident on the bow. When α is 0 degree, it constitutes a head wave. Assuming α is 180 degrees (following wave), the Froude number, Fn is transformed according to Equation (3).

$$Fn \geq \frac{1.8 \times 0.5144}{\sqrt{g}} = 0.296 \approx 0.3 \qquad (3)$$

Equation (3) is considered the minimum threshold defining the ship's stability state transitioning into a surfriding condition.

2.2 Level 2 Evaluation Procedure

The Level 2 vulnerability assessment determines that the ship is not susceptible to surfriding/broaching if the following Equation (4) is satisfied.

$$C \leq R_{SR} \qquad (4)$$

where, $R_{SR} = 0.005$

$$C = \sum_{H_S}\sum_{T_Z}\left(W2(H_S,\ T_Z)\sum_{i=0}^{N_\lambda}\sum_{j=0}^{N_a} w_{ij} C2_{ij}\right)$$

$W2(H_S,\ T_Z)$: Weight factor of short-term sea state (Table 1)

$$w_{ij} = 4\frac{\sqrt{g}L^{5/2}T_{01}}{\pi\nu(H_s)} s_j^2 r_i^{3/2}\left(\frac{\sqrt{1+\nu^2}}{1+\sqrt{1+\nu^2}}\right)\Delta r \Delta s$$
$$\cdot \exp\left[-2\left(\frac{L \cdot r_i \cdot s_j}{H_s}\right)^2\left\{1+\frac{1}{\nu^2}\left(1-\sqrt{\frac{gT_{01}^2}{2\pi r_i L_{BP}}}\right)^2\right\}\right]$$

where, $\nu = 0.425$, $T_{01} = 1.086\,T_Z$

s_j : wave steepness

r_i :wavelength to boat length ratio

$$C2 = \sum_{i=0}^{N_\lambda} \sum_{j=0}^{N_a} w_{ij} C2_{ij}$$

$$C2_{ij} = \begin{cases} 1 & \text{if } Fn \geq Fn_{cr}(r_j, s_i) \\ 0 & \text{if } Fn \leq Fn_{cr}(r_j, s_i) \end{cases}$$

where, Fn : critical Froude number

Table 1. Wave scatter diagram

Tz(s) -> Hs(m)	5.5	7.5	9.5	11.5	13.5
0.5	866	634	37	1	0
1.5	986	7738	2376	161	5
2.5	198	6230	4860	645	34
3.5	35	3227	5099	1114	84
4.5	6	1354	3858	1275	131
5.5	1	498	2373	1126	151
6.5	0	167	1258	826	141
7.5	0	52	594	525	112
8.5	0	15	256	297	78
9.5	0	4	102	152	48

2.3 Level 2 Evaluation Procedure

In the case of this fishing boat, the length, L is less than 200m. Therefore, it is clear that it does not satisfy the criteria for vulnerability to surfriding/broaching.

Considering the evaluation criteria for surfriding/broaching, the Froude number, Fn for this boat has been computed and presented in Fig. 2. According to IMO second-generation intact stability criteria, it is apparent that this boat does not meet the vulnerability standards for surfriding/broaching when navigating at speeds exceeding approximately 6.35 knots (Fn=0.3).

2.4 Evaluation Results of Surfriding/Broaching Mode in Level 2 Vulnerability Criteria

In the context of the Level 2 vulnerability assessment, a comprehensive analysis was undertaken to calculate and assess the resistance values, specifically the total resistance (RT). This rigorous evaluation aligns with the stringent regulations stipulated by the International Maritime Organization (IMO), particularly concerning the potential failure modes of surfriding/broaching.

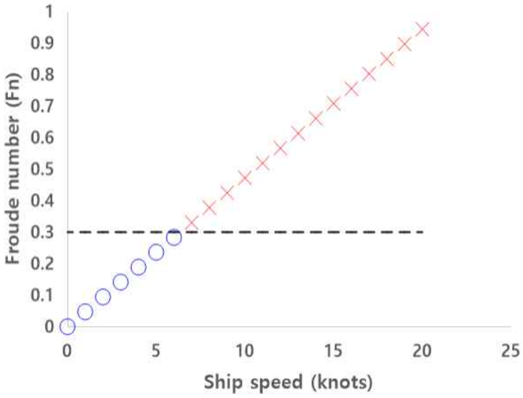

Fig. 2. The Froude number, Fn of a 4.99-ton fishing boat. Level 1 Vulnerability of boat length = 12.10m.

Table 2. Specification of a 4.99-ton fishing boat

Parameters (Unit)	Value	Remark
LBP (m)	12.10	Length between perpendiculars
Midship location (m)	0.0	Midship position at longitudinal-axis
Displacement (ton)	25.6	Displacement
D_prop (m)	0.96	Propeller diameter
Vs (knots)	15.0	Ship speed
W_P (-)	0.15	Approximate wake fraction
t_P (-)	0.15	Approximate thrust deduction factor
Number of propeller	1	Single-axle : 1, Twin-axle : 2

The determination of resistance values, encapsulated in the total resistance parameters, is a pivotal component in understanding the ship's response to hydrodynamic forces and environmental conditions. The findings and calculations, presented in a detailed and comprehensive manner in Fig. 3, contribute to a nuanced comprehension of the ship's performance characteristics and its compliance with the established safety standards outlined by the IMO.

Table 3. Sectional area variable of a 4.99-ton fishing boat

Sectional Area					
x (m)	Area (m^2)	d_x (m)	x (m)	Area (m^2)	d_x (m)
-6.450	1.783	0.429	0.000	2.387	1.002
-6.050	1.822	0.443	0.605	2.344	0.951
-5.445	1.892	0.465	1.210	2.295	0.899
-4.840	2.155	0.499	1.815	2.305	0.847
-4.235	2.387	0.548	2.420	2.203	0.795
-3.630	2.500	1.312	3.025	1.967	0.744
-3.025	2.560	1.261	3.630	1.635	0.692
-2.420	2.583	1.209	4.235	1.311	0.64
-1.815	2.567	1.157	4.840	0.892	0.589
-1.210	2.534	1.106	5.445	0.478	0.566
-0.605	2.447	1.054	6.050	0.256	0.545
			6.550	0.140	0.526

where,

x(m) : Sectional position at longitudinal-axis based on midship

Areas(m2) : Sectional area of submerged portion at each x position

d_x(m) : Local draught at each x position

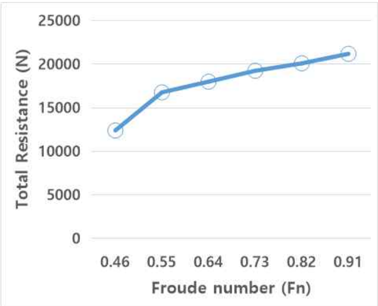

Fig. 3. The total resistance, R_T of a 4.99-ton fishing boat.

In conducting the Level 2 vulnerability assessment, a accurate computation of the propeller thrust coefficient for the current boat was undertaken and provided in Fig. 4. This assessment aligns with the stringent regulations outlined by the International Maritime Organization (IMO), particularly in the context of surfriding/broaching failure mode. The propeller thrust coefficient serves as a pivotal parameter in evaluating the boat's propulsion efficiency, a critical factor in determining its susceptibility to potential surfriding/broaching scenarios.

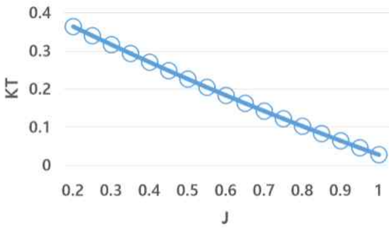

Fig. 4. The propeller thrust coefficient, KT against the propeller advanced ratio, J of a 4.99-ton fishing boat.

Utilizing the IMO's Level 2 calculation formula, the results for the coefficient (C) relative to Froude number (Fn) have been compiled and are visually represented in Fig. 5. The complicated analysis reveals that under the condition of Fn < 0.8617 (Vs < 18.25 knots), the vulnerability criteria are deemed satisfied. Conversely, when Fn ≥ 0.8617 (Vs ≥ 18.25 knots), the vulnerability criteria are not met. Given the boat's operational speed of 15.0 knots, it is discerned that the criteria for vulnerability are deemed satisfied.

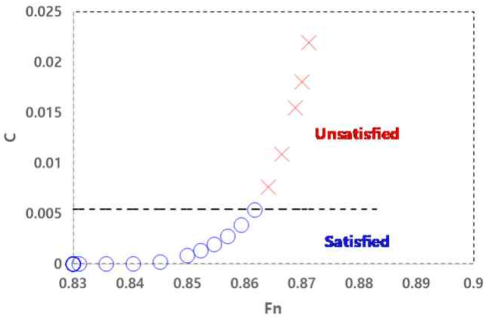

Fig. 5. The Level 2 calculation results for a 4.99-ton fishing boat.

Tables 4 and 5 present the results of this assessment, offering insights into the ship's susceptibility to these critical failure modes across various conditions. By aligning with IMO regulations, this evaluation contributes to a thorough understanding of the boat's operational characteristics, ensuring compliance with international safety standards and enhancing overall maritime safety during its operational life.

Table 4. The Level 1 vulnerability assessment results for a 4.99-ton fishing boat

Level 1 criteria	Principal dimension	Result
L ≥ 200m	L = 121.0m	Vulnerability
Vs ≤ 6.35 knots (Fn ≤ 0.3)	Vs = 15.0 knots Fn = 0.71 (> 0.3)	Vulnerability

Table 5. The Level 2 vulnerability assessment results for a 4.99-ton fishing boat

Level 2 assessment		Boat speed	Result
Vs < 18.25 knots (Fn < 0.8617)	Safe	15.0 knots (Fn = 0.71)	Safe
Vs ≥ 18.25 knots (Fn ≥ 0.8617)	Vulnerability		

Ⅲ. Conclusions

Implementing the elaborate regulatory framework delineated by the International Maritime Organization (IMO) for the restoration of capabilities, an exhaustive and detailed assessment was conducted to evaluate the surfriding /broaching vulnerability of the 4.99-ton fishing ship. This comprehensive examination spanned across both Level 1 and Level 2 evaluations, incorporating a multifaceted array of parameters aligned with the precise stipulations set forth by IMO second generation intact stability. The objective was to quantify the boat's resilience or to potential surfriding/broaching failure mode.

Within the Level 1 vulnerability assessment, a profound exploration was undertaken, centering around the boat's length and Froude number. These key parameters, recognized as fundamental in gauging a boat's susceptibility to surfriding/broaching phenomenon, were analyzed and cross-referenced. The intricate results, documented and presented in Table 4, incontrovertibly prove the boat's vulnerability to these failure mode under diverse operational conditions. This comprehensive interpretation underscores the significance of a holistic examination, one that takes into account not only the physical dimensions of the boat but also its nuanced hydrodynamic response to varying environmental conditions.

Transitioning to the Level 2 assessment, the investigation extended to more complicated parameters, such as the boat's resistance and thrust coefficients, attuned to the intricate standards stipulated by IMO regulations. This phase of the evaluation sought to delve into the nuanced hydrodynamics governing the boat's propulsion and resistance characteristics, pivotal elements in determining its vulnerability to surfriding/broaching mode. The outcomes of this analysis are methodically summarized in the exhaustive details presented in Table 5. These results provide a comprehensive on the boat's vulnerability, factoring in the intricacies of its operational speed and its consequential impact on surfriding/broaching mode.

In granular terms, the Level 2 findings bring to light a dynamic categorization: the boat is deemed vulnerable to surfriding /broaching mode when its operational speed surpasses the specified threshold of 18.25 knots. Conversely, the boat is considered secure from these modes when navigating below this stipulated speed. The actual cruising speed of the ship, gauged at 15.0 knots, aligns commendably with the Level 2 assessment criteria, offering a robust adherence to IMO standards and attesting conclusively to the boat's safety from potential surfriding/broaching phenomenon.

ACKNOWLEDGMENT

This research was supported by Korea Institute of Marine Science & Technology Promotion(KIMST) funded by the Ministry of Oceans and Fisheries, Korea(RS-2022-KS221546) and by the research fund of the Naval Academy Maritime Research Institute in 2024.

REFERENCES

[1] IMO SDC 7/INF.2; FINALIZATION OF SECOND GENERATION INTACT STABILITY CRITERIA Information collected by the Correspondence Group on Intact Stability (part A). International Maritime Organization: London, UK, 2019.

[2] IMO SDC 7/WP.6; FINALIZATION OF SECOND GENERATION INTACT STABILITY CRITERIA Report of the Drafting Group on Intact Stability. International Maritime Organization: London, UK, 2020.

[3] D. M. Ananiev, (1996). On Surf-Riding in Following Seas. Transaction of Krylov Society. 13. pp. 169-176.

[4] J. Artyszuk. (2003). Wave fraction and thrust deduction during ship astern Manoeuvres. WIT Trans. Built Environ. 68.

[5] V. Belenky. C. G. Bassler. K. J. Spyrou. (2011). Development of Second Generation Intact Stability Criteria (NSWCCD-50-TR-2011/065). Naval Surface Warfare Center Carderock Division, US Navy.

[6] S. Chouliaras, "Evaluation of IMO'S Second Generation Intact Stability Criteria," M.S. thesis, National Technical Univ., of Athens, Athens, Greece, 2014.

[7] M. Gu. J. Chu. Y. Han. J. Lu. "Study on Vulnerability Criteria for Surf-riding/Broaching with a Model Experiment," Proc. of the 16th International Ship Stability Workshop, 2017.

[8] A. Maki. N. Umeda. M. Renilson. (2014). Analytical methods to predict the surf-riding threshold and the wave-blocking threshold in astern seas. J. Mar. Sci. Technol., 19, pp. 415-424.

[9] A. Maki. N. Umeda. M. Renilson. (2014). Analytical methods to predict the surf-riding threshold and the wave-blocking threshold in astern seas. J. Mar. Sci. Technol. 19, pp. 415-424.

[10] W. Peters. V. Belenky. C. Bassler. K. J. Spyrou. N. Umeda. G. Bulian. B. Altmayer. "The Second Generation Intact Stability Criteria: An Overview of Development," IN Proc. of SNAME Annual Meeting and Expo-Society of Naval Architects and Marine Engineers, 2011.

[11] D. M. Shin. B. Y. Moon. J. Chung. (2021). Application of surf-riding and broaching mode based on IMO second-generation intact stability criteria for previous ships. Int. Journal of Naval Architecture and Ocean Eng. 13, pp. 545-553.

[12] K. J. Spyrou. V. Belenky. N. Themelis. K. Weems. "Conditions of Surfriding in an Irregular Seaway," in Proc. of 11th International Conference on Stability of Ships and Ocean Vehicles. 2012.

저자소개

강 용 덕 (Yong Duck Kang)

1998년 2월 : 부산대학교 조선해양공학과(공학사)
2003년 8월 : 부산대학교 조선해양공학과(공학석사)
2023년 7월~현재 : 해군사관학교 조선공학과
관심분야 : 난류유동 제어/추진기 효율 향상, 풍력발전시스템, 전기추진시스템

이 상 목 (Sang-Mok Lee)

2006년 2월 : 울산대학교 조선해양공학과(공학사)
2008년 2월 : 울산대학교 조선해양공학(공학석사)
2020년 7월~현재 : 국립군산대학교 산학협력단 연구교수
관심분야 : 친환경 선체, 친환경 연료추진, 선체 구조/피로강도, 해상풍력

김 대 현 (Dae-Hyeon Kim)

2006년 2월 : 한국해양대학교 조선해양공학과(공학사)
2008년 8월 : 한국해양대학교 해양시스템공학(공학석사)
2022년 4월~현재 : 국립군산대학교 산학협력단 책임연구원
관심분야 : 선박운동/계류, 해상풍력, 해양구조물, 선박복원성,

문 병 영 (Gil-Dong Hong)

1992년 2월 : 부산대학교 조선공학과(공학사)
1996년 2월 : 코베대학 시스템설계공학(공학석사)
2002년 2월 : 코베대학 시스템설계공학(공학박사)
2010년 ~현재 : 국립군산대학교 조선해양공학과 교수
관심분야 : 선박진동, 선박복원성, 선박설계, 선박추진