Annexes to comment document from JAPAN to SDC 6 (agenda 5)

ANNEX 1

DETAILED DESCRIPTION OF CRITICAL WAVE METHOD AS DIRECT STABILITY ASSESSMENT FOR BROACHING FAILURE MODE

1. This document describes procedures for critical wave method as one of extrapolation procedures of the direct stability assessment to be used for the broaching stability failure.

2. The critical wave method is a combination of the probabilistic evaluation of “no-rare” process and the deterministic evaluation of the “rare” process. The “no-rare” process can be regarded as the process of initial condition of the “rare” process. As described in annex 1 to document SDC 6/5, the "non-rare" procedure is evaluation or estimation of probability of encounter of a single large wave that is characterized by exceedance of values of parameters while initial conditions belong to a specified range and the "rare" procedure is the determination of the parameters of single wave and initial conditions that lead to stability failure.

3. For broaching associated with surf-riding, we may assume that broaching is a single wave event. This is because surf-riding can be regarded as a single wave event. As well established in nonlinear dynamics, surf-riding in regular following waves has two different types: one type occurs under any initial state of surge displacement and velocity if the wave and operational conditions satisfy a critical condition and the other does under the limited initial state of surge displacement and velocity. The latter means that, if a ship is initially placed on a stable surf-riding state for example, a ship keeps the surf-riding for ever. Because of a two-dimensional nature of the phase plane of dynamics, a self-propelled ship cannot enter the initial state for the latter surf-riding without additional forcing other than assumed waves. Therefore, if a ship keeps a specified propeller revolution with the initial propeller revolution is lower than the specified one, the ship cannot experience of the latter type of surf-riding so that the initial condition dependence of surf-riding in regular waves can be excluded. In case of irregular waves, possibility of the former type of surf-riding may exist but is negligibly small because of existing numerical investigations. Further investigations also confirmed that evaluation of broaching probability can be satisfactorily evaluated. Thus, we may ignore the effect of initial conditions. This approach is already adopted in the level 2 vulnerability criteria for surf-riding as shown in annex 3 to document SDC 6/5.

4. Firstly, the combinations of wavelength and the wave steepness leading to the first-type surf-riding in regular following waves should be determined by using the Melnikov analysis, which is adopted in the level 2 vulnerability criteria, or its equivalent, under the specified nominal Froude number and the autopilot course from the wave direction.

5. Secondly, the numerical simulation based on a surge-sway-yaw-roll coupled model with static heave, pitch and an autopilot or equivalent in regular stern quartering waves should be executed for various wavelength to ship length ratio and various wave steepness inside the region of the first-type surf-riding. Here the initial conditions of the ship motions should be set to be a periodic state under a small Froude number such as 0.1 and a small autopilot course from the wave direction such as 0 degrees. The proportional gain for the auto pilot should be set as a practical but reasonably large value, such as 3, the differential gain should be the minimum for avoiding a directionally unstable phenomenon in calm water. The integral gain, the nonlinear elements and the band pass filter of the autopilot may be excluded.

6. If the instant that both the yaw angle and yaw angular velocity increases over time despite the maximum opposite application of rudder deflection exists, it can be identified as a broaching event. Further, if the roll angle exceeds 40 degrees during this wave encounter, this combination of the wavelength and the wave steepness should be regarded as a stability failure condition due to broaching in regular waves.

7. Thirdly, the joint probability density function of wavelength and wave height in stationary irregular waves with the significant wave height and the mean wave period is integrated inside the stability failure condition due to broaching in regular waves. The obtained value indicates the conditional probability of the stability failure due to broaching in stationary irregular waves when the ship meets a zero-crossing wave for the specified significant wave height and the mean wave period under the specified nominal Froude number and the autopilot course. The probability density function and the numerical integration method to be used here can be found in paragraphs 3.3.2 and 3.3.4 in annex 3 to of document SDC 6/5.

8. Repeating the above procedures for various significant wave height and the mean wave period and integrating the product of the above obtained conditional probability and the joint probability density function of the significant wave height and the mean wave period, the year-averaged conditional probability of the stability failure due to broaching when the ship meets a zero-crossing wave under the specified nominal Froude number and the autopilot course. The joint probability density function of the significant wave height and the mean wave period and the numerical integration method to be used here can be found in paragraphs 3.3.3 and 3.3.4 in annex 3 to of document SDC 6/5.

9. Repeating the above procedures for various autopilot courses and integrating the product of the above obtained conditional probability and the probability density function of the autopilot courses, the year-averaged conditional probability of the stability failure due to broaching when the ship meets a zero-crossing wave under the specified nominal Froude number.

10. For the specified nominal Froude number, the probability of stability failure occurrence per ship year, P, can be calculated as follows:

$$P = 1 - (1 - p)^{365 \times 24 \times 3600 / T_{we}} \tag{1}$$

where p and T_{we} are the year-averaged conditional probability of the stability failure due to broaching when the ship meets a zero-crossing wave under the specified nominal Froude number and the mean encounter period under the specified nominal Froude number, respectively.

11. If the probability of stability failure occurrence per ship year, P, is larger than the standard specified in paragraph 5.4.2.2 in annex 1 to document SDC 6/5, the ship operating with the nominal Froude number is judged as unsafe with respect to broaching.

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Annexes to comment document from JAPAN to SDC 6 (agenda 5)

ANNEX 2

APPLICATION EXAMPLES OF DIRECT STABILITY ASSESSMENT FOR BROACHING FAILURE MODE

BACKGROUND

1. SDC 4 instructed the intersessional correspondence group to collect application examples of direct stability assessment, including the comparison of results with levels 1 and 2. Responding to this requirement, Japan executed direct assessment for broaching failure using a sample ship, i.e. the ONR flare topside vessel and its results as the application example are included in the annex 18 to the document SDC 5/INF.3. It indicates that the probability of broaching failure evaluated by the direct stability assessment is smaller than that of surf-riding obtained by the level 2 vulnerability criteria. Thus, the relationship between the vulnerability criteria and direct stability assessment is consistent. In this example of application of direct stability assessment, however, the specified failure mode was the occurrence of broaching associated with surf-riding. The draft direct stability criteria guidelines proposed by the correspondence group established at SDC 5 define the stability failures as the roll angle exceeding 40 degrees. Therefore, Japan re-executed the calculations of direct stability assessment using the roll angle due to broaching associated with surf-riding as the definition of stability failure and reports the outcomes as application examples requested by the document SDC 6/5.

SUBJEXT SHIP USED

2. The subject ship used here is the ONR flare topside vessel as shown in Fig. 1. Since the ship length is 154 m and the service Froude number is 0.4, this ship shall be regarded vulnerable to broaching in the level 1 vulnerability criteria. The details of this vessel is open for the correspondence group members under the permission of US office of Naval Research and the vessel are known to be vulnerable to broaching danger.

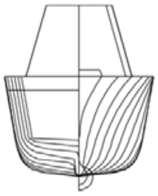

Fig. 1. Body plan of the ONR flare topside vessel.

USED PREDICTION TOOL

3. The used prediction tool enables us to calculate broaching probability when a ship meets a wave in the North Atlantic, is a combination of a surge-sway-yaw-roll simulation model with a proportional autopilot in regular waves and a stochastic wave theory. Firstly, the simulation model estimates the deterministic broaching zone for a subject ship as a function of wave steepness and wavelength for the given propeller revolution and the autopilot course from the wave direction. Secondly, the broaching probabilities in stationary sea states specified with the significant wave height, mean wave period and wave spectrum shape are calculated by integrating the probability density function of the local wave height and the wavelength within the deterministic broaching zone. Finally, the annual broaching probability in a specified water area can be obtained by integrating the product of the broaching probabilities in stationary sea states and the occurrence probability of the sea states.

4. The simulation model used here is based on a nonlinear manoeuvring model with the wave-induced forces and moments under the low encounter frequency assumption. The manoeuvring forces and moments, including resistance and propeller thrust, in calm water are estimated with circular motion captive model tests. The roll damping coefficient is estimated with the roll decay tests of the geometrically scaled ship model. The wave-induced forces and moments

in stern quartering waves are calculated with a linear slender body theory under the low encounter frequency assumption as the sum of the Froude-Krylov components and hydrodynamic lift due to wave particle velocity, and corrected with captive model tests or computational fluid dynamics of viscos flow. The interactions between the manoeuvring forces and waves are ignored under the assumption that the wave steepness and the ship motion normalised with the forward velocity is not so large. The stochastic wave theory used here was proposed by Longuet-Higgins using a wave envelop theory as used in the level 2 vulnerability criteria.

5. Broaching is defined as a phenomenon that ship cannot keep her straight course regardless the maximum opposite steering efforts. Based on this definition, the following judging criterion is used here:

When the rudder deflection angle reaches its starboard limit, both the ship yaw angular velocity and acceleration have the signs for port;
When the rudder deflection angle reaches its port limit, both the ship yaw angular velocity and acceleration have the signs for starboard.

It is noteworthy here that this criterion does not include any quantitative value for course deviation from the autopilot course.

6. The details of the used method are described in the following open-access paper.

https://link.springer.com/content/pdf/10.1007%2Fs00773-015-0364-8.pdf

7. The paper also presents a comparison between the broaching probability calculated with the above method and that measured in model experiments in irregular waves, which is based on the ITTC recommended procedure 7.5-02-07-04 for intact stability model tests. Examples of the comparisons are shown in Figs. 2-3. These results indicate that the used prediction procedure can be applied to the direct stability assessment of the ONR flare topside vessel.

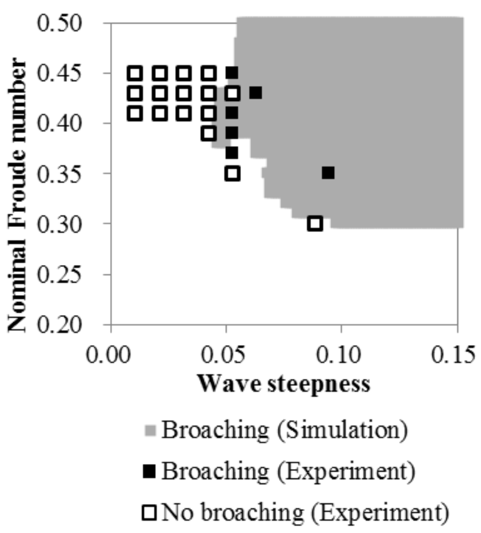

Fig. 2 Comparison of the experiment and simulation in broaching region for the ONR flare topside vessel in regular waves. Here, the wavelength to ship length ratio is 1.25. The autopilot course is 15 degrees from the wave direction.

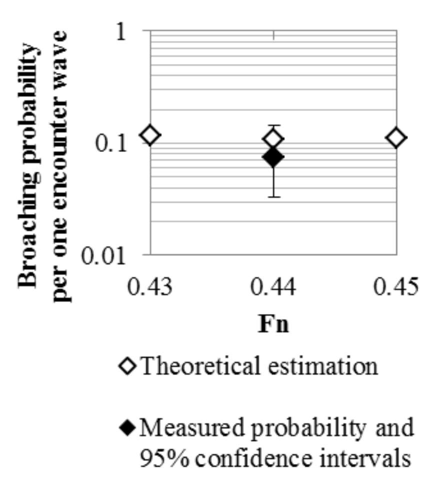

Fig. 3 Comparison of the experiment and simulation in broaching probability for the ONR flare topside vessel in long-crested irregular waves. Here, the significant wave height and mean wave period are 9.65 m and 11.11 s, respectively. The autopilot course is 15 degrees from the wave direction.

8. In addition, an example of comparison in time series between the model experiment and numerical simulation is shown in Fig. 4. Here, two broaching instances occurred, approximately 67 s and 97 s into the experiments. The simulation reproduces these two broaching and predicts roll angle due to broaching slightly conservatively.

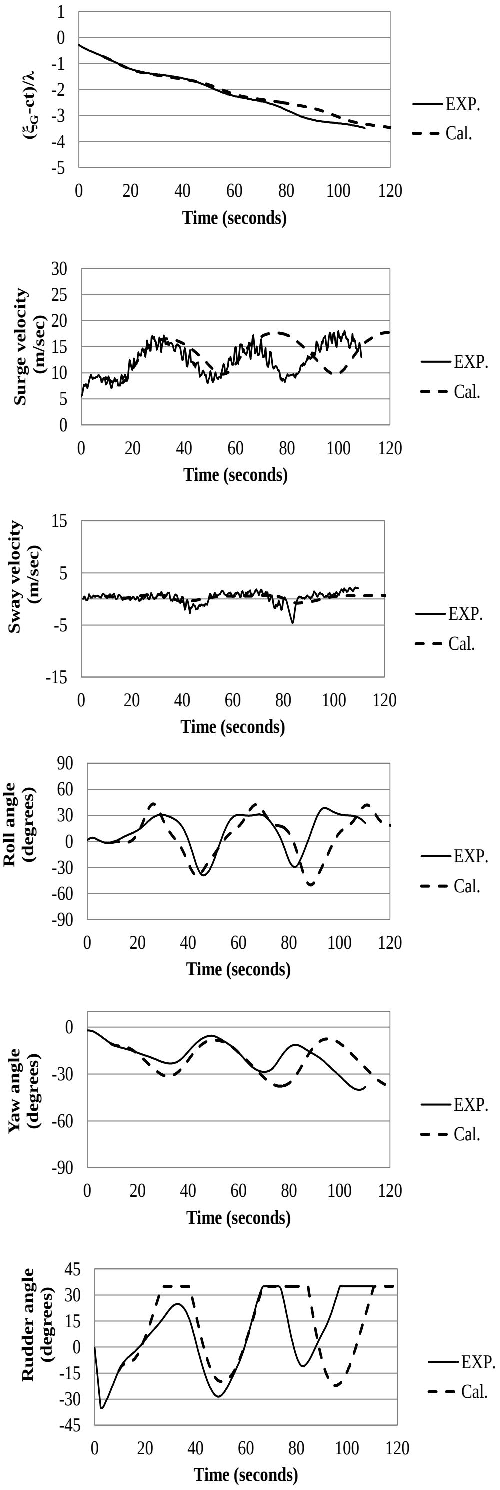

Fig. 4 A comparison between the model experiment and the numerical calculation.

RESULTS AND DISCUSSION

9. By using the above prediction procedure, the probabilities of roll exceeding 40 degrees due to broaching associated with surf-riding for stationary sea states as the function of the significant wave height, Hs, and the mean wave period, T_{01} for the different autopilot courses from the wave direction under the nominal Froude number of 0.4 are shown in Tables 1-6. The spectrum shape is based on the ITTC recommendation (1974) and the wave scatter diagram is the IACS No.

34. The Froude number corresponds to her service speed, is 0.4. The rudder gain for the autopilot is 3.

10. The calculations executed here also include the probabilities for different nominal Froude numbers. The effect of the autopilot course is shown in Fig. 4. It shows that broaching danger exists in the autopilot course ranging from 10 to 30 degrees. If we assume the uniform course distribution, the broaching probability in the North Atlantic is 0.000202. This is the conditional probability of the roll angle exceeding 40 degrees due to broaching associated with surf-riding when the ship meets a zero-crossing wave. As a result, the probability of such failure for one year in the North Atlantic is close to 1. Thus, this assessment concludes that this ship is judged as dangerous for broaching if she is operated without any operational care. Since this ship is judged as vulnerable to broaching failure in the vulnerability level 1 and 2 criteria, this result can be regarded as consistent. The operational guidance can be developed with Tables 1-6 if we specify the acceptable danger probability for each stationary sea state. Figs. 4 and 5 indicates that reducing the nominal forward speed and increasing the threshold of roll angle are effective for decreasing the failure probability of broaching.

Annexes to comment document from JAPAN to SDC 6 (agenda 5)

Table 1 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 3.75 degrees with the nominal Froude number of 0.4.

Total probability	χ=-3.75	T01(sec)																	
3.74E-07			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		10.5							0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
		11.5							0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
		12.5							0.0000	0.0001	0.0001	0.0002	0.0001	0.0001	0.0002	0.0002	0.0003	0.0002	0.0001	
		13.5								0.0001	0.0003	0.0003	0.0003	0.0002	0.0003	0.0004	0.0005	0.0004	0.0003	
		14.5								0.0002	0.0004	0.0005	0.0005	0.0004	0.0005	0.0006	0.0007	0.0006		
		15.5									0.0006	0.0008	0.0007	0.0006	0.0007	0.0009	0.0009	0.0008		
		16.5										0.0010	0.0010	0.0009	0.0010	0.0011	0.0012			

Table 2 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 7.5 degrees with the nominal Froude number of 0.4.

Total probability	χ=-7.5	T01(sec)																	
5.27524E-05			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0000	0.0000	0.0000	0.0001	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0000	0.0000	0.0002	0.0006	0.0010	0.0009	0.0005	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0000	0.0002	0.0007	0.0017	0.0026	0.0024	0.0015	0.0006	0.0002	0.0000	0.0000	0.0000	0.0000
		10.5							0.0005	0.0017	0.0037	0.0052	0.0049	0.0031	0.0015	0.0005	0.0001	0.0000	0.0000	0.0000
		11.5							0.0011	0.0032	0.0065	0.0088	0.0082	0.0055	0.0028	0.0011	0.0004	0.0001	0.0000	0.0000
		12.5							0.0020	0.0052	0.0098	0.0129	0.0120	0.0084	0.0046	0.0021	0.0008	0.0003	0.0001	
		13.5								0.0077	0.0135	0.0173	0.0162	0.0117	0.0068	0.0033	0.0014	0.0006	0.0002	
		14.5								0.0102	0.0172	0.0215	0.0204	0.0152	0.0093	0.0049	0.0024	0.0011		
		15.5									0.0207	0.0255	0.0244	0.0187	0.0119	0.0068	0.0036	0.0018		
		16.5										0.0289	0.0279	0.0220	0.0147	0.0089	0.0051			

Table 3 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 11.25 degrees with the nominal Froude number of 0.4.

Total probability	χ=-11.25°	T01(sec)																	
0.00068756			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0000	0.0001	0.0003	0.0009	0.0015	0.0014	0.0007	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0001	0.0004	0.0015	0.0038	0.0059	0.0057	0.0036	0.0016	0.0005	0.0001	0.0000	0.0000	0.0000
		8.5						0.0003	0.0014	0.0046	0.0100	0.0146	0.0147	0.0105	0.0055	0.0021	0.0006	0.0001	0.0000	0.0000
		9.5						0.0009	0.0035	0.0098	0.0197	0.0277	0.0284	0.0219	0.0131	0.0060	0.0021	0.0006	0.0001	0.0000
		10.5							0.0069	0.0173	0.0322	0.0440	0.0455	0.0371	0.0244	0.0129	0.0055	0.0018	0.0005	0.0001
		11.5							0.0115	0.0264	0.0464	0.0619	0.0645	0.0545	0.0384	0.0226	0.0110	0.0043	0.0014	0.0004
		12.5							0.0170	0.0365	0.0612	0.0801	0.0838	0.0728	0.0540	0.0344	0.0186	0.0084	0.0032	
		13.5								0.0467	0.0756	0.0975	0.1024	0.0909	0.0701	0.0475	0.0279	0.0141	0.0060	
		14.5								0.0565	0.0888	0.1133	0.1196	0.1079	0.0859	0.0610	0.0384	0.0210		
		15.5									0.1004	0.1271	0.1347	0.1234	0.1008	0.0744	0.0493	0.0290		
		16.5										0.1385	0.1477	0.1372	0.1144	0.0871	0.0603			

Annexes to comment document from JAPAN to SDC 6 (agenda 5)

Table 4 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 15 degrees with the nominal Froude number of 0.4.

Total probability	χ=-15°	T01(sec)																		
0.002355788			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0001	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0002	0.0010	0.0022	0.0027	0.0018	0.0007	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0003	0.0014	0.0045	0.0088	0.0108	0.0085	0.0044	0.0016	0.0004	0.0001	0.0000	0.0000	0.0000
		7.5						0.0012	0.0045	0.0118	0.0213	0.0261	0.0225	0.0139	0.0063	0.0021	0.0005	0.0001	0.0000	0.0000
		8.5						0.0031	0.0098	0.0227	0.0385	0.0474	0.0432	0.0301	0.0162	0.0068	0.0022	0.0006	0.0001	0.0000
		9.5						0.0062	0.0168	0.0360	0.0586	0.0722	0.0686	0.0517	0.0314	0.0155	0.0061	0.0020	0.0005	0.0001
		10.5							0.0252	0.0507	0.0800	0.0983	0.0959	0.0764	0.0506	0.0280	0.0129	0.0049	0.0016	0.0004
		11.5							0.0343	0.0658	0.1011	0.1239	0.1232	0.1021	0.0719	0.0434	0.0224	0.0099	0.0037	0.0012
		12.5							0.0436	0.0804	0.1210	0.1477	0.1488	0.1269	0.0937	0.0604	0.0340	0.0167	0.0071	
		13.5								0.0939	0.1388	0.1689	0.1718	0.1498	0.1145	0.0777	0.0468	0.0250	0.0119	
		14.5								0.1060	0.1541	0.1870	0.1917	0.1701	0.1336	0.0943	0.0599	0.0343		
		15.5									0.1666	0.2017	0.2082	0.1874	0.1506	0.1097	0.0728	0.0440		
		16.5										0.2129	0.2213	0.2019	0.1653	0.1236	0.0849			

Table 5 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 18.75 degrees with the nominal Froude number of 0.4.

Total probability	χ=-18.75°	T01(sec)																		
0.003325687			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0001	0.0003	0.0007	0.0007	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0001	0.0008	0.0025	0.0048	0.0053	0.0035	0.0014	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000
		6.5					0.0001	0.0008	0.0033	0.0088	0.0154	0.0175	0.0133	0.0070	0.0025	0.0006	0.0001	0.0000	0.0000	0.0000
		7.5						0.0026	0.0084	0.0196	0.0323	0.0374	0.0311	0.0190	0.0087	0.0030	0.0008	0.0002	0.0000	0.0000
		8.5						0.0057	0.0159	0.0339	0.0535	0.0624	0.0548	0.0371	0.0197	0.0083	0.0028	0.0008	0.0002	0.0000
		9.5						0.0100	0.0252	0.0502	0.0768	0.0895	0.0812	0.0588	0.0346	0.0168	0.0068	0.0023	0.0007	0.0002
		10.5							0.0355	0.0673	0.1001	0.1162	0.1078	0.0818	0.0518	0.0278	0.0128	0.0051	0.0018	0.0005
		11.5							0.0463	0.0840	0.1220	0.1412	0.1329	0.1042	0.0696	0.0402	0.0204	0.0091	0.0037	0.0013
		12.5							0.0568	0.0994	0.1416	0.1634	0.1556	0.1252	0.0870	0.0531	0.0290	0.0143	0.0064	
		13.5								0.1129	0.1582	0.1824	0.1755	0.1441	0.1033	0.0660	0.0381	0.0201	0.0098	
		14.5								0.1241	0.1715	0.1978	0.1923	0.1608	0.1183	0.0782	0.0473	0.0264		
		15.5									0.1817	0.2096	0.2058	0.1749	0.1317	0.0897	0.0562	0.0329		
		16.5										0.2181	0.2161	0.1866	0.1434	0.1002	0.0648			

Table 6 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 22.5 degrees with the nominal Froude number of 0.4.

Total probability	χ=-22.5°	T01(sec)																		
0.002643946			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0001	0.0002	0.0005	0.0004	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0001	0.0006	0.0020	0.0036	0.0037	0.0023	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0001	0.0007	0.0027	0.0072	0.0122	0.0132	0.0095	0.0046	0.0015	0.0004	0.0001	0.0000	0.0000	0.0000
		7.5						0.0022	0.0073	0.0172	0.0275	0.0302	0.0236	0.0135	0.0057	0.0018	0.0004	0.0001	0.0000	0.0000
		8.5						0.0050	0.0146	0.0313	0.0477	0.0524	0.0431	0.0272	0.0135	0.0053	0.0016	0.0004	0.0001	0.0000
		9.5						0.0093	0.0240	0.0475	0.0696	0.0764	0.0650	0.0441	0.0243	0.0111	0.0042	0.0013	0.0003	0.0001
		10.5							0.0345	0.0637	0.0903	0.0992	0.0867	0.0620	0.0370	0.0188	0.0082	0.0031	0.0010	0.0003
		11.5							0.0446	0.0782	0.1081	0.1190	0.1066	0.0795	0.0504	0.0277	0.0134	0.0057	0.0022	0.0007
		12.5							0.0537	0.0901	0.1222	0.1353	0.1240	0.0958	0.0637	0.0372	0.0194	0.0092	0.0039	
		13.5								0.0991	0.1328	0.1480	0.1385	0.1104	0.0764	0.0469	0.0260	0.0132	0.0062	
		14.5								0.1055	0.1403	0.1576	0.1503	0.1231	0.0882	0.0563	0.0327	0.0177		
		15.5									0.1451	0.1642	0.1594	0.1338	0.0987	0.0653	0.0395	0.0223		
		16.5										0.1684	0.1660	0.1424	0.1079	0.0736	0.0461			

Annexes to comment document from JAPAN to SDC 6 (agenda 5)

Table 7 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 26.25 degrees with the nominal Froude number of 0.4.

Total probability	χ=-26.25°	T01(sec)																		
0.000298595			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0000	0.0001	0.0003	0.0008	0.0009	0.0005	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0001	0.0005	0.0016	0.0029	0.0031	0.0021	0.0009	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000
		8.5						0.0004	0.0017	0.0043	0.0069	0.0071	0.0051	0.0026	0.0010	0.0003	0.0001	0.0000	0.0000	0.0000
		9.5						0.0011	0.0037	0.0082	0.0120	0.0126	0.0096	0.0054	0.0023	0.0008	0.0002	0.0001	0.0000	0.0000
		10.5							0.0064	0.0126	0.0178	0.0189	0.0153	0.0095	0.0046	0.0017	0.0006	0.0002	0.0000	0.0000
		11.5							0.0093	0.0169	0.0236	0.0258	0.0221	0.0148	0.0078	0.0033	0.0012	0.0004	0.0001	0.0000
		12.5							0.0120	0.0210	0.0292	0.0329	0.0296	0.0211	0.0120	0.0055	0.0022	0.0007	0.0002	
		13.5								0.0248	0.0347	0.0401	0.0376	0.0282	0.0171	0.0085	0.0036	0.0013	0.0005	
		14.5								0.0283	0.0400	0.0472	0.0455	0.0356	0.0228	0.0122	0.0055	0.0022		
		15.5									0.0448	0.0537	0.0531	0.0429	0.0288	0.0163	0.0079	0.0034		
		16.5										0.0596	0.0599	0.0499	0.0348	0.0207	0.0107			

Table 8 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 30 degrees with the nominal Froude number of 0.4

Total probability	χ=-30°	T01(sec)																		
1.76797E-05			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0000	0.0000	0.0000	0.0001	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0000	0.0001	0.0002	0.0004	0.0007	0.0007	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
		10.5							0.0002	0.0005	0.0011	0.0018	0.0019	0.0012	0.0005	0.0001	0.0000	0.0000	0.0000	0.0000
		11.5							0.0004	0.0011	0.0025	0.0039	0.0039	0.0026	0.0012	0.0004	0.0001	0.0000	0.0000	0.0000
		12.5							0.0008	0.0021	0.0045	0.0067	0.0068	0.0047	0.0023	0.0008	0.0002	0.0000	0.0000	
		13.5								0.0036	0.0072	0.0103	0.0104	0.0075	0.0040	0.0016	0.0005	0.0001	0.0000	
		14.5								0.0054	0.0103	0.0143	0.0144	0.0108	0.0061	0.0027	0.0010	0.0003		
		15.5									0.0136	0.0184	0.0186	0.0143	0.0086	0.0041	0.0016	0.0005		
		16.5										0.0225	0.0227	0.0179	0.0112	0.0058	0.0025			

Table 9 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 33.75 degrees with the nominal Froude number of 0.4

Total probability	χ=-33.75°	T01(sec)																		
0.000151044			1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	Hw(m)	0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0001	0.0004	0.0005	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0001	0.0005	0.0012	0.0017	0.0011	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0011	0.0024	0.0032	0.0024	0.0011	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0018	0.0036	0.0046	0.0038	0.0021	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0025	0.0045	0.0056	0.0050	0.0033	0.0016	0.0006	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		10.5							0.0050	0.0063	0.0061	0.0046	0.0027	0.0012	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000
		11.5							0.0054	0.0068	0.0071	0.0060	0.0041	0.0021	0.0008	0.0003	0.0001	0.0000	0.0000	0.0000
		12.5							0.0055	0.0072	0.0081	0.0076	0.0057	0.0033	0.0015	0.0005	0.0002	0.0000	0.0000	
		13.5								0.0076	0.0092	0.0094	0.0075	0.0047	0.0023	0.0009	0.0003	0.0001	0.0000	
		14.5								0.0082	0.0105	0.0113	0.0095	0.0062	0.0033	0.0014	0.0005	0.0002		
		15.5									0.0118	0.0132	0.0115	0.0079	0.0044	0.0021	0.0008	0.0003		
		16.5										0.0150	0.0135	0.0096	0.0056	0.0028	0.0012			

Annexes to comment document from JAPAN to SDC 6 (agenda 5)

Table 10 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 37.5 degrees with the nominal Froude number of 0.4

Total probability	χ=-37.5	T01(sec)																		
0.000330052	Hw(m)		1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
		0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0000	0.0001	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0000	0.0003	0.0011	0.0013	0.0006	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0003	0.0015	0.0036	0.0042	0.0024	0.0007	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0035	0.0072	0.0083	0.0055	0.0022	0.0005	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0059	0.0110	0.0125	0.0090	0.0043	0.0014	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0083	0.0140	0.0159	0.0122	0.0067	0.0027	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		10.5							0.0160	0.0181	0.0147	0.0090	0.0042	0.0015	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000
		11.5							0.0170	0.0192	0.0165	0.0110	0.0059	0.0025	0.0009	0.0002	0.0001	0.0000	0.0000	0.0000
		12.5							0.0172	0.0195	0.0175	0.0127	0.0075	0.0036	0.0014	0.0005	0.0001	0.0000	0.0000	
		13.5								0.0193	0.0181	0.0141	0.0090	0.0047	0.0021	0.0008	0.0003	0.0001	0.0000	
		14.5								0.0188	0.0184	0.0151	0.0104	0.0059	0.0029	0.0012	0.0005	0.0002		
		15.5									0.0184	0.0159	0.0116	0.0071	0.0037	0.0017	0.0007	0.0003		
		16.5										0.0165	0.0126	0.0081	0.0045	0.0022	0.0010			

Table 11 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 41.25 degrees with the nominal Froude number of 0.4

Total probability	χ=-41.25	T01(sec)																		
0.000467787	Hw(m)		1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
		0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0001	0.0004	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0002	0.0009	0.0023	0.0023	0.0009	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0008	0.0032	0.0066	0.0066	0.0033	0.0009	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0067	0.0122	0.0124	0.0073	0.0026	0.0006	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0105	0.0174	0.0179	0.0118	0.0052	0.0016	0.0004	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
		9.5						0.0137	0.0212	0.0221	0.0158	0.0081	0.0030	0.0009	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000
		10.5							0.0234	0.0247	0.0189	0.0108	0.0048	0.0017	0.0005	0.0005	0.0000	0.0000	0.0000	0.0000
		11.5							0.0241	0.0257	0.0208	0.0130	0.0065	0.0027	0.0009	0.0009	0.0001	0.0000	0.0000	0.0000
		12.5							0.0238	0.0256	0.0216	0.0146	0.0081	0.0037	0.0015	0.0015	0.0002	0.0000	0.0000	
		13.5								0.0247	0.0217	0.0157	0.0094	0.0048	0.0021	0.0021	0.0003	0.0001	0.0000	
		14.5								0.0234	0.0212	0.0161	0.0104	0.0058	0.0028	0.0028	0.0005	0.0002		
		15.5									0.0203	0.0162	0.0111	0.0066	0.0035	0.0035	0.0007	0.0003		
		16.5										0.0159	0.0115	0.0073	0.0041	0.0041	0.0010			

Table 12 Probabilities of roll angle exceeding 40 degrees due to broaching in stationary sea states with the autopilot course of 45 degrees with the nominal Froude number of 0.4

Total probability	χ=-45	T01(sec)																		
0.000599954	Hw(m)		1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
		0.5			0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000						
		1.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			
		2.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
		3.5				0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		4.5					0.0000	0.0004	0.0008	0.0006	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		5.5					0.0005	0.0023	0.0044	0.0034	0.0011	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		6.5					0.0019	0.0064	0.0111	0.0092	0.0039	0.0009	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		7.5						0.0119	0.0189	0.0167	0.0086	0.0027	0.0006	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
		8.5						0.0171	0.0257	0.0238	0.0140	0.0055	0.0016	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
		9.5						0.0211	0.0303	0.0291	0.0190	0.0088	0.0031	0.0008	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
		10.5							0.0327	0.0322	0.0228	0.0120	0.0049	0.0016	0.0005	0.0001	0.0000	0.0000	0.0000	0.0000
		11.5							0.0331	0.0333	0.0253	0.0148	0.0069	0.0027	0.0009	0.0003	0.0001	0.0000	0.0000	0.0000
		12.5							0.0323	0.0330	0.0264	0.0168	0.0088	0.0038	0.0015	0.0005	0.0002	0.0000	0.0000	
		13.5								0.0318	0.0266	0.0181	0.0103	0.0050	0.0021	0.0008	0.0003	0.0001	0.0000	
		14.5								0.0300	0.0260	0.0188	0.0115	0.0061	0.0029	0.0012	0.0005	0.0002		
		15.5									0.0249	0.0189	0.0124	0.0071	0.0036	0.0017	0.0007	0.0003		
		16.5										0.0186	0.0128	0.0079	0.0043	0.0022	0.0010			

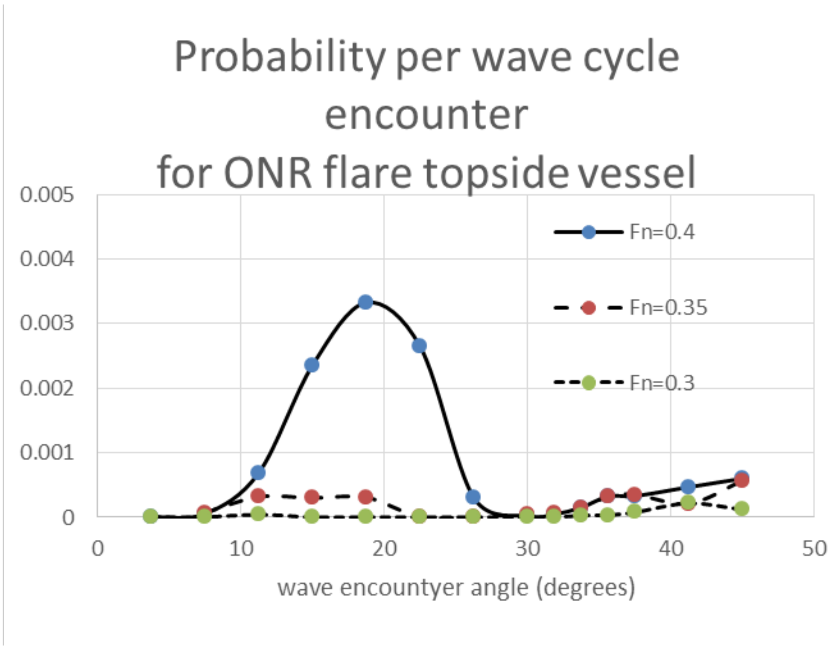

Fig. 4 Probabilities of roll angle exceeding 40 degrees due to broaching associated with surf-riding as functions of heading angle for the ONR flare topside vessel in the North Atlantic.

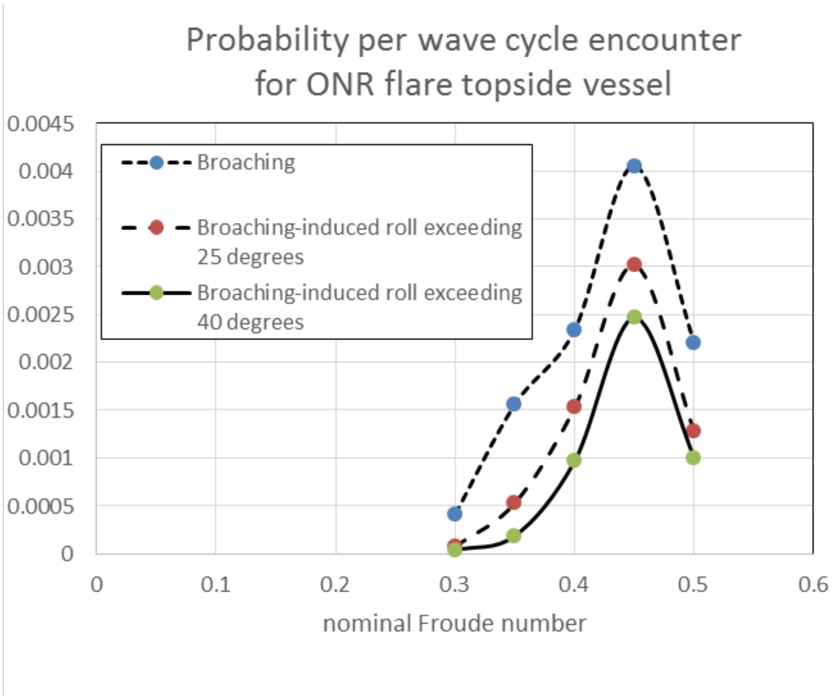

Fig. 5 Comparison of probabilities relating to broaching associated with surf-riding as functions of the nominal Froude number for the ONR flare topside vessel in the North Atlantic.

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ANNEX 3

DETAILED DESCRIPTION OF A NON-PROBABILISTIC METHOD AS DIRECT STABILITY ASSESSMENT FOR PARAMETRIC ROLLING FAILURE MODE

1. This document describes procedures for a maximum roll amplitude method as one of non-probabilistic assessment procedures of the direct stability assessment to be used for the parametric rolling stability failure.

2. The maximum roll amplitude method can be defined as a method for evaluating the stability failure probability by integrating the probability density of the maximum roll amplitude under the specified time duration above the threshold, which is specified in paragraph in annex 1 to document SDC 6/5.

3. The probability density of the maximum roll amplitude is estimated by numerical time domain simulation and then fitted the simulation results with a certain formula.

4. The numerical simulation should be executed for all possible stationary sea states spanned by the significant wave height and mean wave period with the specified Froude number and the wave heading for the specified time duration. Using the same wave spectrum and different random phases for the sampled frequencies, many different realisations should be repeated. For each numerical run, the maximum roll amplitude should be determined. Then the obtained set of the maximum roll amplitude should be fitted with a formula for the probability density function.

5. If the total stability failure occurs within the specified time duration, the ratio of the number of numerical runs resulting in total stability failures to the total numerical runs could be regarded as a simple estimates of the stability failure probability as an alternative to the probability defined in paragraph 2.

6. Integrating the product of the stability failure probability as a function of the significant wave height and mean wave period and the joint probability function of the significant wave height and mean wave period, the stability failure probability for the specified time duration can be calculated for the specified Froude number and wave heading.

7. Finally, for the specified nominal Froude number and wave number, the probability of stability failure occurrence per ship year, *P*, can be calculated as follows:

$$P = 1 - (1 - p)^{365 \times 24 \times 3600 / T_{duration}} \quad (1)$$

where p and $T_{duration}$ are the year-averaged conditional probability of the stability failure due to parametric rolling for the specified time duration under the specified nominal Froude number and the specified time duration, respectively.

11. If the probability of stability failure occurrence per ship year, *P*, is larger than the standard specified in paragraph 5.4.2.2 in annex 1 to document SDC 6/5, the ship operating with the nominal Froude number is judged as unsafe with respect to parametric rolling.

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ANNEX 4

APPLICATION EXAMPLES OF DIRECT STABILITY ASSESSMENT FOR PARAMETRIC ROLLING FAILURE MODE

Background

1. SDC 4 instructed the intersessional correspondence group to collect application examples of direct stability assessment, including the comparison of results with levels 1 and 2. Responding to this requirement, Japan executed direct assessment for parametric rolling failure using a sample ship, i.e. the C11 class post Panamax containership and its results as the application example are included in the document SDC 5/INF.7. It indicates that the probability of parametric rolling failure evaluated by the direct stability assessment is smaller than that of parametric rolling obtained by the level 2 vulnerability criteria. Thus, the relationship between the vulnerability criteria and direct stability assessment is consistent. In this example of application of direct stability assessment, however, the calculated failure probability was the probability of dangerous sea state for parametric rolling. The draft direct stability criteria guidelines proposed by the correspondence group established at SDC 5 require to calculate the probability of the roll angle exceeding 40 degrees for one year. Therefore, Japan executed the probability of the roll angle exceeding 40 degrees for one year.

SUBJECT SHIP

2. Japan attempted to execute direct stability assessment for parametric rolling failure mode using a sample ship, i.e. the ITTC provided C11 class container ship. Its principal particulars are shown in Table 1.

Table 1 Principal particular of the C11 class container ship

Length between perpendiculars : L_{PP}	262.0 m
Breadth : B	40.0 m
Depth : D	24.45 m
Mean draught : d	11.5 m
Metacentric height : GM	1.965 m
Natural roll period : T_{ϕ}	25.1 s
Block coefficient : C_b	0.56

The level 1 criterion judges this ship as vulnerable to parametric rolling failure because $\delta GM/GM$ is 1.045, which is larger than the standard of 0.3561. Here the simplified method is used for GM calculation in waves. The level 2 criterion also judges it as vulnerable because the C1 and C2 are 0.4368 and 0.07283, respectively, which are larger than the standard of 0.06. Here the C2 is calculated with the averaging method using seven ship speeds.

USED PREDICTION TOOL

3. The used prediction tool enables us to calculate the roll angle due to parametric rolling in irregular longitudinal waves. It is a numerical simulation code in time domain based on a heave-roll-pitch simulation model. A nonlinear Froude-Krylov force, which is a major component of parametric roll excitation in waves, is calculated for the instantaneous submerged hull in each time step. Dynamic components, i.e. radiation and diffraction forces, are calculated by a strip theory for the mean under-water hull changing with instantaneous heel angle. Two-dimensional hydrodynamic forces are calculated by solving a boundary integral equation for the flow velocity potential with the linear water and hull surface conditions. The radiation force is calculated at the encounter frequency of the ship to incident waves for the heave and pitch motions, whilst that for the roll motion is calculated at half the encounter frequency by assuming a condition of the principal parametric rolling.

4. In numerical simulations, a ship motion is obtained by the time integration of differential equations of ship motions with the fourth order Runge-Kutta method. Linear and

quadratic roll damping coefficients are used, which are determined from roll decay model tests. The irregular waves are modelled as the sum of many regular waves whose amplitude is determined with a wave energy spectrum and random phases. The wave energy spectrum used here is the ITTC recommended unlimited fetch spectrum (1974) and the significant wave height and the mean wave period are obtained by the wave scattering diagram for the North Atlantic. The wave frequency in the wave spectrum is divided by using energy equilibrium division method for avoiding self-repetition of wave profiles.

5. For validating the numerical simulation code, the numerical results are compared with the partly captive model experiments in the towing tank of Osaka University for the ITTC-provided C11 class container ship, which is based on the ITTC recommended procedure 7.5-02-07-04 for intact stability model tests. An example of the comparison is shown in Fig. 1. The average of the maximum roll angle estimated with numerical simulation well agrees with the experiment, as the 95 % confidence intervals of the simulation and those of the experiment are overlapped. These results indicate that the used numerical simulation code can be used for direct stability assessment for parametric rolling in irregular longitudinal waves.

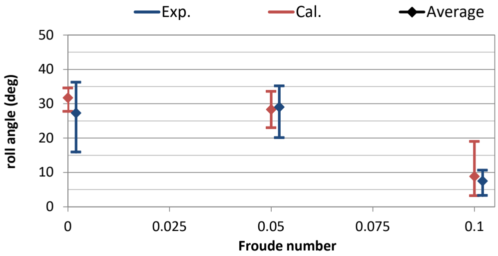

Fig. 1 Average of the maximum roll angle of parametric rolling for the C11 class container ship with respect to Froude number in irregular head waves with the significant wave height of 7.82 m and the mean wave period of 9.99 s.

RESULTS AND DISCUSSION

6. By using the above numerical simulation code, the mean and variance of the maximum roll angles among five realizations in irregular following waves for each sea state. As shown in Fig. 2, the maximum roll angle can be approximated as a Gaussian process. Thus, the probability of roll angle exceeding 40 degrees for the duration of 30 minutes can be evaluated as the function of the significant wave height, *Hs*, and the mean zero-crossing wave period, T, for the C11 class container ship as shown in Table 2. The Froude numbers corresponds to its worst speeds for parametric rolling, are 0.0 and 0.1088. Using Table 2 and the wave scattering diagram of IACS No. 34, the probability of roll angle exceeding 40 degrees for one year are calculated. The obtained values are 0.190455 for the Froude number of 0.0 and 0.099952 for 0.1198. Thus, this ship can be regarded as unsafe to parametric rolling failure from this result.

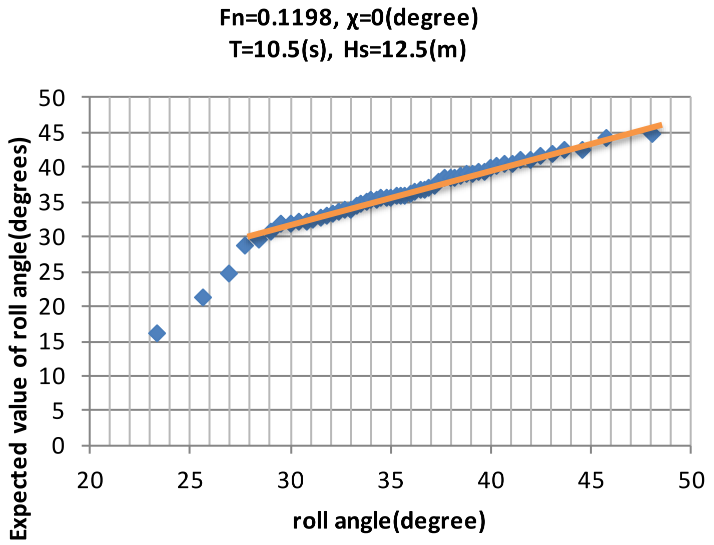

Fig. 2 A verification plot of Gauss fitting of the maximum roll angles.

Table 2 Probabilities of the maximum roll angles exceeding 40 degrees due to parametric rolling for one year among five realizations for stationary sea states as the function of the significant wave height, H_s, and the mean wave period, *T*, for the C11 class container ship with the nominal Froude number of 0.0.

		T(s)															
		3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
Hs(m)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3.5	0	0	0	0	5.18E-26	2.92E-64	5.64E-28	4.17E-27	8.71E-33	0	3.07E-68	0	0	0	0	0
	4.5	0	0	0	0	3.89E-33	1.65E-16	1.51E-14	2.71E-21	1.18E-33	1.25E-53	2.02E-51	3.57E-88	0	0	0	0
	5.5	0	0	0	0	3.19E-15	4.81E-19	1.82E-10	5.2E-12	4.43E-23	4.82E-26	5.04E-27	6.94E-47	3.95E-18	0	0	0
	6.5	0	0	0	4.3E-266	8.32E-15	6.96E-09	7.13E-09	2.28E-10	1.03E-12	6.6E-18	5.07E-18	3.43E-22	3.74E-29	8.2E-28	0	0
	7.5	0	0	0	3.14E-43	8.34E-11	1.39E-09	1.85E-08	1.87E-08	1.61E-07	6.52E-12	3.77E-10	9.39E-16	9.7E-13	5.55E-26	2.36E-16	0
	8.5	0	0	0	4.05E-17	7.9E-09	3.58E-07	3.35E-07	6.04E-09	6.65E-07	3.89E-12	9.44E-11	1.22E-16	8.82E-15	1.25E-17	1.71E-12	5.95E-16
	9.5	0	0	0	1.84E-07	4.91E-14	1.81E-08	1.64E-07	8.65E-09	2.06E-09	1.4E-12	6.02E-09	1.28E-11	2.7E-16	1.89E-15	1.47E-11	4.11E-14
	10.5	0	0	0	0	1.66E-08	1.31E-08	6.78E-10	7.58E-08	4.07E-11	1.67E-12	4.52E-09	3.6E-11	2.38E-11	2.85E-11	4.91E-16	2.86E-15
	11.5	0	0	0	0	3.97E-09	1.46E-08	1.03E-10	4.55E-08	6.65E-11	2.29E-09	1.83E-09	6.65E-11	1.06E-10	1.34E-11	8.26E-12	1.41E-11
	12.5	0	0	0	0	2.37E-07	3.37E-07	8.88E-11	7.93E-09	1.03E-09	7.17E-12	2.53E-12	6.3E-09	2.1E-09	5.08E-11	3.34E-08	0
	13.5	0	0	0	0	0	3.02E-07	1.83E-08	2.76E-10	1.92E-11	3.99E-11	2.07E-06	7.68E-08	2.34E-07	6.67E-08	3.34E-08	0
	14.5	0	0	0	0	0	1.34E-07	3.2E-08	3.3E-08	6E-07	1.2E-06	8.72E-07	4.68E-07	2E-07	6.67E-08	0	0
	15.5	0	0	0	0	0	0	1.68E-07	1.58E-07	6E-07	2.37E-07	3.35E-07	2.01E-07	1E-07	1.33E-07	0	0
	16.5	0	0	0	0	0	0	0	1.33E-07	2.14E-07	1.34E-07	2.01E-07	1E-07	1.67E-07	0	0	0

Table 3 Probabilities of the maximum roll angles exceeding 40 degrees due to parametric rolling for one year among five realizations for stationary sea states as the function of the significant wave height, *Hs*, and the mean wave period, *T*, for the C11 class container ship with the nominal Froude number of 0.1198.

		T(s)															
		3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3.5	0	0	0	0	1.61E-35	0	0	0	0	0	0	0	0	0	0	0
	4.5	0	0	0	1.61E-54	3.92E-08	4.61E-22	5.43E-12	1.3E-131	0	0	3.2E-143	0	0	0	0	0
	5.5	0	0	0	4.15E-19	6.39E-08	4.89E-09	6.49E-08	1.4E-14	4.13E-54	2.44E-48	1.32E-43	0	0	0	0	0
	6.5	0	0	0	2.09E-19	4.84E-07	8.02E-06	1.03E-05	4.65E-08	2.29E-13	7.34E-08	1.42E-23	4.38E-72	0	0	0	0
Hs(m)	7.5	0	0	0	2.14E-15	8.46E-07	1.74E-05	8.28E-05	1.47E-06	2.15E-06	2.71E-09	2.21E-08	1.11E-25	3.95E-84	0	0	0
	8.5	0	0	0	4.75E-10	4.24E-07	1.72E-05	6.62E-05	9.46E-06	2.03E-05	1.1E-07	3.75E-06	1.32E-31	6.01E-20	0	6.38E-18	1.85E-16
	9.5	0	0	0	1.47E-07	4.15E-07	1.23E-05	7.34E-05	3.98E-05	9.5E-06	1.66E-06	2.9E-06	8.44E-12	1.33E-09	1.99E-18	1.07E-13	1.04E-13
	10.5	0	0	0	0	3.11E-07	1.38E-05	3.46E-05	2.11E-05	1.23E-05	3.13E-06	2.07E-07	1.31E-07	2.6E-08	3.16E-10	1.67E-11	3.05E-09
	11.5	0	0	0	0	3.23E-07	4.24E-06	1.58E-05	1.71E-05	4.96E-06	5.59E-06	5.18E-06	2.25E-08	3.51E-08	2.44E-11	6.49E-11	1.43E-08
	12.5	0	0	0	0	2.95E-07	2.06E-06	7.29E-06	6.55E-06	2.82E-06	4.11E-06	2.81E-06	7.46E-10	2.11E-09	1.21E-10	8.95E-11	0
	13.5	0	0	0	0	0	8.71E-07	2.62E-06	2.93E-06	9.69E-08	2.78E-06	1.28E-06	2.46E-09	1.6E-09	1.25E-09	7.49E-10	0
	14.5	0	0	0	0	0	3.48E-07	7.72E-07	6.17E-07	1.02E-06	2.74E-06	1.17E-06	2.45E-07	2.67E-11	3.33E-08	0	0
	15.5	0	0	0	0	0	0	3.74E-07	2.35E-07	7.41E-07	9.74E-07	4.83E-07	2.34E-09	6.72E-08	6.67E-08	0	0
	16.5	0	0	0	0	0	0	0	1.44E-07	2.19E-07	4.09E-07	1.68E-07	1.02E-07	2.35E-07	0	0	0

Annexes to comment document from JAPAN to SDC 6 (agenda 5)
