Simulation Data Analysis

1. Stability Parameters Information of the Model Vessel

The basic information of the model vessel (including various lengths of the vessel, draught, breadth, etc.) and 18 kinds of cargo loading situations are derived from the information of the first model vessel in the literature [1].

According to the GZ curve and the relationship between GM and T_θ as shown in Equation (1), the required stability parameter information can be obtained as shown in Table 1.

$$GM = (2.01cB / T_{\varphi_0})^2 \quad (1)$$

Where.

c refers to dimensionless rolling period coefficient.

Table 1

The information of stability parameters

Scenario Number [Criteria]	Compliance With the Stability Reg	GM (m) [1.08]	GZ_{30deg} (m) [0.20]	$Angle_{maxGZ}$ (deg) [15.00]	Area0-30 (m•rad) [0.055]	φ_0 (deg) [11.25]	T_θ (s) [9,24.43]
1	X	0.100	0.44	36.50	0.10	14.95	67.13
2	X	0.200	0.49	37.00	0.11	13.71	47.46
3	X	0.400	0.59	38.00	0.14	11.45	33.56
4	X	0.600	0.69	38.50	0.17	9.58	27.40
5	X	0.781	0.78	39.00	0.19	8.23	24.02
6	X	0.800	0.79	39.00	0.19	8.10	23.73
7	X	1.000	0.89	40.00	0.22	6.95	21.23
8	O	1.200	0.99	40.50	0.25	6.51	19.38
9	O	1.381	1.05	42.00	0.26	6.40	18.26
10	O	1.418	1.07	42.20	0.27	6.20	18.02
11	O	1.884	1.33	42.50	0.34	4.50	15.46
12	O	1.905	1.24	45.70	0.32	5.40	15.79
13	O	1.919	1.35	42.50	0.34	4.50	15.32
14	O	2.362	1.53	45.60	0.39	4.00	14.00
15	O	2.408	1.44	47.70	0.37	4.60	14.18
16	O	2.519	1.47	48.30	0.38	4.50	13.91
17	O	2.829	1.72	47.90	0.44	3.60	12.91
18	O	2.931	1.76	48.30	0.46	3.50	12.72

/(x):Incompliant with Specified Stability Criteria, (O):Compliant with Specified Stability Criteria

2. Calculation and Assessment on the Ship Stability

The stability parameter index (VI_{ai}) and the moored vessel stability index (VI_{VSA}) are calculated, the stability performance of each loading condition has been evaluated, and the moment provided by the AMS are calculated, as shown in Table 2.

Table 2

VI_{VSA}, M_{m-e} and stability rating grade of the model vessel

Scenario Number	VI_{ai}						VI_{VISA}	Rating Grade	M_{m-e} (N-m)
	GM	GZ_{30deg}	$Angle_{\max GZ}$	$Area_{0\text{-}30}$	φ_0	T_θ			
1	0.05	0.65	0.92	0.62	0.01	0.18	0.33	I	1,971,463
2	0.09	0.68	0.93	0.64	0.17	0.26	0.39	I	3,575,640
3	0.19	0.75	0.95	0.72	0.47	0.36	0.50	I	5,835,909
4	0.28	0.81	0.96	0.79	0.68	0.45	0.59	II	7,150,430
5	0.36	0.87	0.97	0.85	0.82	0.54	0.66	II	7,818,346
6	0.37	0.87	0.97	0.85	0.83	0.57	0.68	II	7,862,363
7	0.46	0.94	0.99	0.92	0.95	0.82	0.80	II	8,217,424
8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	III	9,124,595
9	1.25	1.17	1.75	1.11	1.05	2.19	1.50	IV	\
10	1.30	1.22	1.85	1.22	1.15	2.17	1.55	IV	\
11	1.95	1.94	2.00	2.00	2.00	2.01	1.98	IV	\
12	1.98	1.69	2.08	1.78	1.55	2.03	1.89	IV	\
13	2.00	2.00	2.00	2.00	2.00	2.00	2.00	V	\
14	2.23	2.13	2.07	2.15	2.11	1.55	2.00	V	\
15	2.25	2.07	2.12	2.09	1.95	1.61	1.99	IV	\
16	2.31	2.09	2.14	2.12	2.00	1.52	2.00	V	\
17	2.47	2.27	2.13	2.29	2.20	1.18	2.02	V	\
18	2.53	2.30	2.14	2.35	2.22	1.12	2.04	V	\

: Stability rating level is lower than "General Safety" and the automated mooring system is necessary to respond.

As shown in Table 2, scenarios No.1-7 fail to comply with the prescribed standards listed in Table 1. Therefore, the moored vessel stability index should be less than 1. For scenarios No.8-18, they all meet the prescribed standards. The stability index should be larger or equal to 1. In Table 4, it is confirmed that the calculated moored vessel stability index (VI_{VSA}) adequately evaluated whether scenarios comply with the prescribed standards.

As shown in Table 2, at least half of the stability parameters fail to meet the specified standards in each scenario of No.1-3. Therefore, the corresponding stability index (VI_{VSA}) should be less than 0.5 in theory. The actual calculation result is between 0.33 and 0.50, which is consistent with the theory. Each stability performance of scenarios No.1-3 is rated as "Severe Risk". In scenarios No.4-7, less than half of the parameters fail to meet the specified standards, the corresponding stability index should be greater than 0.5 and less than 1 in theory. The actual calculation result is in the range of 0.59-0.8, which is consistent with the theory. The relevant stability capability is rated as "Danger". All stability parameters meet the specified standards in each scenario of No.8-18. Therefore, the corresponding stability index should be larger than or equal to 1 in theory. The actual calculation result is in range of 1-2.04, which is in concordance with the theory. In scenario No.8, the vessel's stability capability is rated as "Minimum Safety". The vessel's stability performance is rated as "General Safety" in scenarios No.9-13. In scenarios No.14-18, the vessel's stability performance is rated as "Fairly Safety". Overall, it was confirmed the model vessel stability evaluation was with an accuracy of 100% in the 18 cargo loading situations, and the effectiveness of the proposed guidelines.

3. Response of the AMS

Based on the value and the stability rating level of each scenario obtained in the previous section, it can be known that the stability rating level of scenarios No.1-8 is less than "General Safety", and the AMS needs to respond. The stability information of the vessel after the response are shown in Table 3 and Table 4

After the response of the automated mooring system, the approximate value of GM can be calculated by Eq. (2), which helps to reduce the time consumption in the process of re-measuring the GM value on the physical level, and to facilitate the rapid construction of GZ curve and the information process of stability parameters.

$$GM_{new} = 2GM - \frac{M_{m-e}B}{(2M_{m-e} + \Delta B)\tan(\varphi_0 - \varphi_1)} \quad (2)$$

Table 3

The information of the model vessel's stability parameters after the response

Scenario Number [Criteria]	Compliance With the Stability Reg	GM (m) [1.08]	GZ_{30deg} (m) [0.20]	$Angle_{maxGZ}$ (deg) [15.00]	Area0-30 (m•rad) [0.055]	φ_0 (deg) [11.25]	T_θ (s) [9,24.43]
1	X	0.150	0.47	36.75	0.10	1.00	54.81
2	X	0.299	0.53	37.50	0.13	1.00	38.82
3	X	0.599	0.69	38.50	0.17	1.00	27.43
4	X	0.900	0.84	39.50	0.20	1.00	22.38
5	O	1.171	0.96	40.30	0.24	1.00	19.62
6	O	1.200	0.99	40.50	0.25	1.00	19.38
7	O	1.500	1.11	41.30	0.28	1.00	17.33
8	O	1.801	1.29	42.00	0.32	1.00	15.82

/(x):Incompliant with Specified Stability Criteria, (O):Compliant with Specified Stability Criteria

Table 6

VI_{VSA} and stability rating level of the model vessel after the response

Scenario Number	VI_{ai} GM	GZ_{30deg}	$Angle_{max\,GZ}$	$Area_{0-30}$	φ_0	T_θ	VI_{VSA}	Rating level
1	0.07	0.67	0.93	0.62	2.78	0.22	0.70	I → II
2	0.14	0.70	0.94	0.69	2.78	0.31	0.75	I → II
3	0.28	0.81	0.96	0.79	2.78	0.45	0.85	I → II
4	0.42	0.90	0.98	0.87	2.78	0.70	0.97	II ↑
5	0.88	0.98	1.00	0.97	2.78	0.98	1.18	II → III
6	1.00	1.00	1.00	1.00	2.78	1.00	1.22	II → III
7	1.42	1.33	1.40	1.33	2.78	1.68	1.63	II → IV
8	1.84	1.83	1.75	1.78	2.78	1.17	1.77	III → IV

: Stability rating level is lower than “General Safety” and the automated mooring system is necessary to respond.

In each scenario of No.1-8, the stability performance of the model vessel had been improved after the response of the AMS, as shown in Table 6. It was confirmed that the effectiveness of the response of the AMS. Subjected to the distribution of the center of gravity of the cargo on the vessel. In scenarios No.1-6, although the vessel was assisted by the AMS to improve its stability, which still failed to achieve "General Safety". Especially in scenarios No.1-4, after the AMS’s responses, there were still some stability parameters failed to meet the specified standards, which was attributed to the extremely unsatisfactory cargo loading distribution on the vessel. At this time, the relative ship staff should adjust the cargo loading distribution, taking such measures as adjusting the cargo position or adding / discharging ballast water. Meanwhile, in the period of loading or unloading, reasonable loading or unloading strategy should be adopted to avoid aggravating the stability loss caused by uneven distribution of goods.

References

[1] IM Nam-Kyun,CHOE Hun. A quantitative methodology for evaluating the ship stability using the index for marine ship intact stability assessment model[J]. International Journal of Naval Architecture and Ocean Engineering,2021,13.

Scenario Number	VI_{ai} GM	GZ_{30deg}	$Angle_{\max GZ}$	$Area_{0\text{-}30}$	φ_0	T_θ	VI_{VISA}	Rating level	M_{m-e} (N-m)
1	0.05	0.65	0.92	0.62	0.01	0.18	0.33	I	1,971,463
2	0.09	0.68	0.93	0.64	0.17	0.26	0.39	I	3,575,640
3	0.19	0.75	0.95	0.72	0.47	0.36	0.50	I	5,835,909
4	0.28	0.81	0.96	0.79	0.68	0.45	0.59	II	7,150,430
5	0.36	0.87	0.97	0.85	0.82	0.54	0.66	II	7,818,346
6	0.37	0.87	0.97	0.85	0.83	0.57	0.68	II	7,862,363
7	0.46	0.94	0.99	0.92	0.95	0.82	0.80	II	8,217,424
8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	III	9,124,595
9	1.25	1.17	1.75	1.11	1.05	2.19	1.50	IV	\
10	1.30	1.22	1.85	1.22	1.15	2.17	1.55	IV	\
11	1.95	1.94	2.00	2.00	2.00	2.01	1.98	IV	\
12	1.98	1.69	2.08	1.78	1.55	2.03	1.89	IV	\
13	2.00	2.00	2.00	2.00	2.00	2.00	2.00	V	\
14	2.23	2.13	2.07	2.15	2.11	1.55	2.00	V	\
15	2.25	2.07	2.12	2.09	1.95	1.61	1.99	IV	\
16	2.31	2.09	2.14	2.12	2.00	1.52	2.00	V	\
17	2.47	2.27	2.13	2.29	2.20	1.18	2.02	V	\
18	2.53	2.30	2.14	2.35	2.22	1.12	2.04	V	\

: Stability rating level is lower than "General Safety" and the automated mooring system is necessary to respond.

Scenario Number	VI_{ai} GM	GZ_{30deg}	$Angle_{\max GZ}$	$Area_{0\text{-}30}$	φ_0	T_θ	VI_{VISA}	Rating level
1	0.07	0.67	0.93	0.62	2.78	0.22	0.70	I → II
2	0.14	0.70	0.94	0.69	2.78	0.31	0.75	I → II
3	0.28	0.81	0.96	0.79	2.78	0.45	0.85	I → II
4	0.42	0.90	0.98	0.87	2.78	0.70	0.97	II ↑
5	0.88	0.98	1.00	0.97	2.78	0.98	1.18	II → III
6	1.00	1.00	1.00	1.00	2.78	1.00	1.22	II → III
7	1.42	1.33	1.40	1.33	2.78	1.68	1.63	II → IV
8	1.84	1.83	1.75	1.78	2.78	1.17	1.77	III → IV

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16	O	2.519	1.47	48.30	0.38	4.50	13.91
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4	X	0.900	0.84	39.50	0.20	1.00	22.38
5	O	1.171	0.96	40.30	0.24	1.00	19.62
6	O	1.200	0.99	40.50	0.25	1.00	19.38
7	O	1.500	1.11	41.30	0.28	1.00	17.33
8	O	1.801	1.29	42.00	0.32	1.00	15.82

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