Response Strategies of Automated Mooring System Using the Vessel Intact Stability Assessment Model

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***Abstract*—The main purposes of the response of the automated mooring system (AMS) are to fasten the vessel and actively improve the safety of the mooring process, avoiding the casualty accident. The intact stability of a vessel has a strong influence on the response strategy of the AMS. As the high stability is in favor of the vessels mooring, the response frequency will be significantly reduced. The vessel intact stability assessment (VISA) model was suggested to assist the AMS to develop the response strategy, which includes whether needs to respond and how much output moment needs to provide. The VISA model is composed of the stability index module and the stability performance evaluation module. The stability index module can quantify the ship stability. And then, the evaluation module proposed the assessment guidelines to evaluate the stability of the vessel. Finally, for a model vessel under 18 loading conditions, stability calculations, evaluations of the stability performance, and the analysis on the result of the response strategy were performed. It was confirmed that the assessment model could evaluate the stability performance efficiently by using the stability index, and the AMS can actively respond and help the vessel improve stability performance in terms of the suggested response strategy.**

***Index Terms*—Automated Mooring System, Ship Stability, Response Strategy, Stability Index, Stability Assessment**

I. Introduction

Advanced mooring methods using mooring robots have been widely used in ports [1]. The patent search has introduced mooring robots for the automated mooring [2]. Mooring robots are with an attractive attachment element to fasten the vessel. When a vessel is approaching the terminal, mooring robots are able to secure a vessel and subject it to large forces during a short time to counter significant dynamic environmental forces(interferences), which mainly come from the action of wind and waves. The AMS is consisted of multiple mooring robots. It is the vessel mooring system with active control.

With the consistent growth in the vessel tonnage and the development of intelligent vessels, traditional methods using mooring lines become more unsuited and time-consuming. Furthermore, the traditional mooring methods can not monitor and automatically adjust the tension of mooring lines, so the condition of mooring lines must be checked regularly by a human. It increases workload and there are operational hazards that cannot be ignored. The AMS have a number of advantages over conventional methods [3].

- The time spent mooring or detaching is reduced to less than one minute.
- Monitoring the mooring loads applied to and displacement of a vessel.
- Putting an end to casualties occurred.
- Realizing the coordinated work among the mooring robots to reduce the motion of the vessel drastically.

Hence, AMS can ensure the safety, reliability, and timeliness of the mooring process.

The devices of quick release mooring hooks are developed for detaching the vessel quickly. The quick release mooring hooks are regard as the starting point of automated mooring technology [4]. The current researches on AMS mainly focus on the working mechanism and the structure design of mooring robots. Hassan and Roya proposed a dynamic model of a single mooring robot and explored the interaction between the mooring robots and the vessel [5]. Mooring robots are required to achieve the independent force/position control [6]. According to the mooring principles, mooring robots can be divided into three types: vacuum chuck, magnetic and mechanical type.

The advantages of AMS are to quickly fasten and reduce the motion of the vessels [5], which make vessels moored efficiently.It is known that the vessel with high stability, that is, with the excellent performance(anti-interference ability) to resist external environmental forces(interferences). Generally, good ship stability is beneficial to the mooring. Therefore, the response strategy of the AMS has a close relationship with the

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ship stability.

Brown and Witz presented a method of evaluating the ship stability in real time employing rolling measurement [7]. Ariffin et al. developed a real-time evaluation system for Second-Generation Intact Stability Criteria (SGISC) employing the data acquired by Radar and Buoy [8]. Terada et al. proposed a system to evaluate metacentric height by measuring the natural frequency on the roll motion for containerships [9]. Deakin and Wolfson Unit proposed a stability index to express the vessel's stability performance by using two kinds of significant wave height [10]. Im and Choe suggested an index for marine vessel intact stability assessment model based on various International Maritime Organization (IMO) stability items [11].

Although there are many studies on the operational mechanism of single mooring robot or the ship stability, few researches on the AMS from the response strategy and the ship stability are produced. Hence, this paper proposed the VISA (Vessel Intact Stability Assessment) model, which provides the theory for AMS to make a response strategy in terms of the ship stability. The stability assessment model figures out an index that can express the vessel's intact stability quantitatively, called the Moored Vessel Stability Index. Then, the ship stability can be evaluated and the AMS can decide whether it needs to respond. The main contributions of this paper are as follows.

- For moored vessels, the stability index is suggested to quantify the vessels' stability.
- The stability index provides guidelines for assessing the ship stability to the AMS. Using the guidelines, the AMS can check the stability status of vessels intuitively.
- The response strategy of the AMS based on the ship stability is proposed, including response criterion, output forces/moments, etc.

To develop the VISA model, the mooring constraint conditions and IMO stability regulation both were reviewed. To verify the VISA model and the proposed response strategy of the AMS, the basic stability calculations and evaluations were performed for a model vessel with various cargo loading situations. It was proven that the suggested stability index can assess the ship stability adequately, and the suggested response strategy did contribute to improving the vessel's stability.

II. VISA MODEL

This chapter introduces the VISA model. Two modules: the moored vessel stability index calculation, stability performance evaluation are contained in the VISA model. In the calculation module, six stability parameters and several formulae are used to calculate the stability index. And then, the evaluation module proposes the stability assessment guidelines.

A. Stability parameters

Six stability parameters are considered to derive the stability index of the moored vessels, based on mooring constraint conditions and IMO stability parameter regulations. These stability parameters involved in the VISA model and the minimum criteria are shown in Table I, which are described as follows.

TABLE I
STABILITY PARAMETERS & MINIMUM CRITERIA FOR VISA MODEL

Stability Parameter	Criteria
GM	4%moulded breadth (B) m
T_θ	9 s
φ_0	15°
GZ_{30deg}	0.200 m
$Angle_{\max GZ}$	15° or 80% of the angle of deck edge immersion
$Area_{0-30deg}$	0.055 m·rad

- **GM** expresses the height between the center of gravity(G) and the transverse metacenter(M). The minimum expected value of GM is taken as 4% moulded breadth (B).
- $\boldsymbol{T_\theta}$ refers to the rolling period. The minimum expected value of T_θ is set as 9s.
- $\boldsymbol{\varphi_0}$ refers to the heeling angle of the vessel. The maximum expected value of φ_0 is 15° or 80% of the angle of deck edge immersion, whichever is less.
- **GZ** refers to the vertical distance from the center of gravity to the line of action of buoyancy, called lever of static stability.
- $\boldsymbol{GZ_{30deg}}$ refers to the lever of static stability when heeling angle is 30°. The minimum expected value of GZ_{30deg} is 0.200 m.
- $\boldsymbol{Angle_{\max GZ}}$ refers to the heeling angle when the GZ reaches the maximum value. The minimum expected of $Angle_{\max GZ}$ is taken as 15°.
- $\boldsymbol{Area_{0-30deg}}$ refers to the area of heeling angle from 0° to 30° under the GZ curve, which expresses the relationship between GZ and φ_0. The minimum expected value of $Area_{0-30deg}$ is 0.055m·rad.

B. Moored vessel stability index

The moored vessel stability index is calculated by Eqs. (1) and (2), in the VISA model. The six stability parameters ($a_i, i = 1, 2 \cdots 6$) obtained from the vessel are normalized into these stability parameters index (VI_{ai}) by employing the stability parameter index formula, Eq. (1).

AS shown in Eq. (1), according to the relationship between the value of the parameter and the ship stability, the normalization of the six stability parameters are divided into three pattern, as follows.

- First pattern: the higher the parameter value is, the better the ship stability plays, such as GM(a_1), $GZ_{30deg}(a_2)$, $Angle_{\max GZ}(a_3)$, and $Area_{0-30deg}(a_4)$.
- Second pattern: the lower the stability parameter value is, the greater the ship stability plays, such as φ_0 (a_5).
- Third pattern: the relationship between the parameter value and the ship stability is similar to a normal distribution, for T_θ (a_6).

$$\boldsymbol{First\,pattern}:$$
$$VI_{ai}=\begin{cases} k\times\frac{a_i}{a_{i-c}}\,(if\ 0\le|a_i|<|a_{i-c}|)\\ k+(1-k)\times\frac{a_i-a_{i-c}}{a_{i-S}-a_{i-c}}\,(if\ |a_{i-c}|\le|a_i|<|a_{i-S}|)\\ 1+\frac{a_i-a_{i-S}}{a_{i-F}-a_{i-S}}\,(if\ |a_{i-S}|\le|a_i|<|a_{i-F}|)\\ 2+\frac{a_i-a_{i-F}}{a_{i-F}}\,(if\ |a_{i-F}|\le|a_i|)\end{cases}$$
$$\boldsymbol{Second\,pattern}:$$
$$VI_{ai}=\begin{cases} k\times\frac{Angle_{coffe}-a_i}{Angle_{coffe}-a_{i-c}}\,(if\ \ |a_i|>|a_{i-c}|)\\ k+(1-k)\times\frac{a_i-a_{i-c}}{a_{i-S}-a_{i-c}}\,(if\ \ |a_{i-c}|\ge|a_i|>|a_{i-S}|)\\ 1+\frac{a_i-a_{i-S}}{a_{i-F}-a_{i-S}}\,(if\ |a_{i-S}|\ge|a_i|>|a_{i-F}|)\\ 2+\frac{a_{i-F}-a_i}{a_{i-F}}\,(if\ |a_{i-F}|\ge|a_i|)\end{cases}$$
$$\boldsymbol{Third\,pattern}:$$
$$VI_{ai}=\begin{cases} k\times\frac{a_i}{a_{i-c}}\,(if\ 0\le a_i<a_{i-c})\\ k+(1-k)\times\frac{a_i-a_{i-c}}{T_\theta-SL-a_{i-c}}\,(if\ \ a_{i-c}\le a_i<T_\theta-SL)\\ 1+\frac{T_\theta-SL-a_i}{T_\theta-SL-a_{i-F}}\,(if\,T_\theta-SL\le a_i<a_{i-F})\\ 2+\frac{a_i-a_{i-F}}{a_{i-F}}\,(if\ a_{i-F}\le a_i<T_{\theta-1})\\ 1+\frac{a_{i-S}-a_i}{a_{i-S}-T_{\theta-1}}\,(if\ T_{\theta-1}\le a_i<a_{i-S})\\ k+(1-k)\times\frac{T_{\theta-2}-a_i}{T_{\theta-2}-a_{i-S}}\,(if\ a_{i-S}\le a_i<T_{\theta-2})\\ k\times\frac{T_{\theta-2}}{a_i}\,(if\ T_{\theta-2}\le a_i)\end{cases} \tag{1}$$

In Eq. (1), k means the moored vessel stability index coefficient and is taken as 0.5. The value denotes 50% of the stability parameters meet the required minimum criteria. a_{i-c} denotes the minimum criterion of the stability parameter as listed in Table I. a_{i-S} means the value of the stability parameter, when all parameters meet the minimum criteria for the first time as the ship stability improves. a_{i-F} refers to the value of the stability parameter in the "standard full loading condition" according to the Code on Intact Stability for All Types of Ships (IS Code, 2008). $T_{\theta-1}$ is the rolling period when the value of GM is 5% B, $T_{\theta-2}$ is the rolling period when the value of GM is 4% B. $T_{\theta-SL}=2T_{\theta-1}-a_{i-F}$. $Angle_{coffe}$ refers to the maximum heeling angle coefficient, when the vessel is moored by employing the AMS. The value of $Angle_{coffe}$ is set as 15°. If a_{i-S} is larger than a_{i-F}, it is need to exchange the roles of a_{i-S} and a_{i-F} in Eq. (1). After obtained the value of each index (VI_{ai}), the stability index of the moored vessel (VI_{VISA}) can be calculated by Eq. (2).

$$\boldsymbol{VI_{VISA}}=\frac{(N-2)(VI_{a1}+VI_{a6})+2\sum_{i=2}^{N-1}VI_{ai}}{4(N-2)} \tag{2}$$

Equation (2) is determined as the normalization index of VI_{ai}. VI_{ai} refers to the normalization index of parameters calculated by Eq. (1), GM(VI_{a1}), T_θ(VI_{a6}). N is the number of stability parameters involved in the VISA model.

C. Stability performance evaluation

As shown in Table II, according to the stability index (VI_{VISA}), the ship stability assessment is divided into five grades, which mean the satisfaction with the minimum expected standards listed in Table I. If the stability index $VI_{VISA}<0.5$, it denotes that more than 50% of the stability parameter values fail to meet the specified criteria, and the stability performance is evaluated as "Severe Risk". $0.5\le VI_{VISA}<1$ means less than 50% of the stability parameters do not meet the specified standards, and the stability performance is assessed as "Danger". $VI_{VISA}\ge 1$ denotes that all stability parameters reach the required criteria, the stability performance is rated as "Safety". In addition, to ensure that the vessel is with enough stability capacity, according to experience [12], the margin of stability is set as 30%. Therefore, in the condition of $1\le VI_{VISA}<1.3$, the stability performance is rated as "Minimum Safety ". The stability is rated as "General Safety", in the condition of $1.3\le VI_{VISA}<2$. Finally, in the last condition of $VI_{VISA}\ge 2$, meaning the vessel stability performance is larger than or equal to the stability capacity under the "standard full loading condition" proposed by IS Code (2008), and the stability performance is rated as "Fairly Safety".

III. Response strategy of the AMS

According the result of ship stability assessment in the previous work, the AMS can take these five risk levels to judge the stability and safety of the moored vessel. When the assessment level of ship stability is lower than the "General Safety ", the response of the AMS occurs to improve ship stability actively. On the contrary, the AMS not does, as shown in Table II. In the worst case, when the stability performance of the vessel is still not good after the response, it is necessary for human intervention to help the vessel improve its stability performance.

Assumption 1: The moored vessel and the AMS communicate with each other based on Automatic Identification Systems (AIS) to realize the information transmission.

Assumption 2: The water area where the vessel is located is calm, i.e. the influence of external environmental forces(interferences) are not obvious.

The specific form of the AMS response is to reduce the center of gravity and the heeling angle of the vessel, to improve the stability of the vessel during the period of mooring. When the response is determined, according to the **Assumption 1** the AMS can calculate the moment output required using the information obtained from the vessel and Eqs. (3) - (6).

As shown in Fig. 1(a), M_I means the heeling moment caused by the uneven loading of cargo(P). Based on the **Assumption 2**, the heeling angle (φ_0) is caused by the uneven loading of cargo(P), when vessel is in static equilibrium, as shown in Fig. 1(b). At this time, the heeling moment and the stability moment are balanced, as shown in Eq. (3).

$$M_{I-\varphi_0}=M_{r-\varphi_0}=\Delta\cdot GM\cdot sin\varphi_0 \tag{3}$$

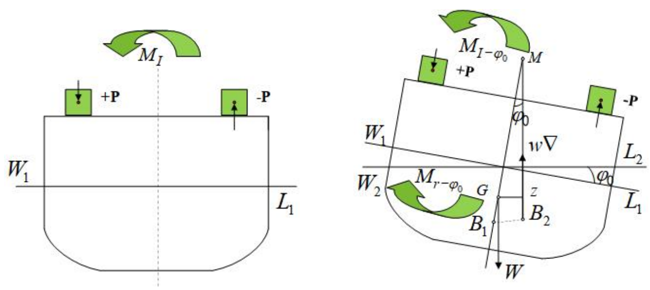
In Eq.(3), $M_{r-\varphi_0}$ means the stability moment formed by the Gravity(W) and the Buoyancy($w\nabla$) at heeling angle φ_0. w is the weight density of water, ∇ is the ship's drainage volume. $M_{I-\varphi_0}$ refers to the heeling moment at heeling angle φ_0. Δ refers to the displacement of the vessel.

As the heeling angle is zero degree, combined with Eq. (3).

$$M_I=M_{I-\varphi_0}/\cos\varphi_0 \tag{4}$$

TABLE II
GUIDELINES OF STABILITY ASSESSMENT AND RESPONSE STRATEGY OF THE AMS

VI_{VISA}	Compliance with the Specified Stability Reg.	Evaluation Grade	Response strategy of the AMS
0.0-0.5	Incompliant(More than 50% of the parameters)	Severe Risk (I)	Necessary to respond and help the vessel improve st
0.5-1.0	Incompliant (Less than 50% of the parameters)	Danger (II)	-ability performance, for stability rating I to III.
1.0-1.3	Compliant(With less than 30% margin)	Minimum Safety (III)	
1.3-2.0	Compliant(With more than 30% margin)	General Safety (IV)	no need to respond and just maintain ship stability
2.0↑	Compliant(Full Load Condition)	Fairly Safety (V)	for stability rating IV or V.



(a) Uneven loading of cargo (b) Static equilibrium

Fig. 1. Analysis on the force of the vessel under the condition of heeling

To decrease the heeling angle, reducing the φ_0 to φ_1. The vessel is in dynamic balance at the heeling angle of φ_1, as shown in Eq. (5).

$$\begin{aligned} & W_{m-e} + W_r - W_I = 0 \\ & W_r = \int_{\varphi_0}^{\varphi_1} \Delta GM \sin\varphi d\varphi \\ & W_I = \int_{\varphi_0}^{\varphi_1} M_I \cos\varphi d\varphi \\ & W_{m-e} = \int_{\varphi_0}^{\varphi_1} M_{m-e} d\varphi = M_{m-e} S \end{aligned} \tag{5}$$

In Eq. (5), W_r means the work done by stability moment, W_I is the work done by heeling moment, W_{m-e} refers to the work provided by the AMS. Make the value of S equal to the radian value of $(\varphi_1 - \varphi_0)$. The moment provided by the AMS (M_{m-e}) can be calculated, according to Eqs. (4) and (5), as shown in Eq. (6)

$$\boldsymbol{M_{m-e}} = \frac{\Delta GM(\cos\varphi_1 - \cos\varphi_0) + M_I(\sin\varphi_1 - \sin\varphi_0)}{S} \tag{6}$$

IV. SIMULATION ANALYSIS

In this chapter, To investigated the effectiveness of evaluation and the response strategy using the VISA model, 18 loading scenarios were implemented using a model vessel, which stemmed from the information of the first model vessel in the literature [11]. Each loading situation was analyzed based on the VISA model.

Assumption 3: The model vessel is seen as a rigid body.

A. Basic stability information of the model vessel

The relationship between GM and T_θ is shown in Eq. (7). According to the relation ship and the GZ curve, the required stability parameter can be calculated as shown in Table III. As the ship stability improves, in scenario No.8, all stability parameters meet the specified standards as listed in Table I for the first time. These value of the stability parameter were taken as a_{i-S} in Eq. (1). Scenario No.13 is the "full loading condition" according to IS Code (2008). These values of the stability parameters in this condition were taken as a_{i-F} in Eq. (1). a_{i-S} and a_{i-F} also can be obtained by consulting the Ship Manuals.

$$GM = 2.01cB/{T_{\varphi_0}}^2 \tag{7}$$

Where.

c refers to the dimensionless rolling period coefficient.

B. Calculation and Assessment on Ship Stability

This section calculates the stability parameter index (VI_{ai}) and the moored vessel stability index (VI_{VISA}) based on the stability parameters information obtained in the previous section, using Eqs. (1) and (2) (in this study N=6). According to the proposed assessment guidelines, the stability performance of each loading condition has been evaluated, as shown in Table IV.

As shown in Table III, scenarios No.1-7 fail to comply with the minimum expected standards listed in Table I. Therefore, the moored vessel stability index should be less than 1. Scenarios No.8-18 meet the prescribed standards, the stability index should be larger or equal to 1. In Table IV, it is confirmed that the calculated moored vessel stability index adequately evaluated whether scenarios comply with the prescribed standards.

As shown in Table IV, in scenarios No.1-3, the stability performance is rated as "Severe Risk", the actual calculation result of VI_{VISA} is between 0.33 and 0.50. In scenarios No.4-7, the stability capability is rated as "Danger", the calculation result is in the range of 0.59-0.8. In scenarios No.8-18, the calculation result is in range of 1-2.04. In scenario No.8, the stability capability is rated as "Minimum Safety". The stability performance is rated as "General Safety" in scenarios No.9-13. For scenarios No.14-18, the stability performance is rated as "Fairly Safety". As the actual calculation result of VI_{VISA} is consistent with the expectation listed in Tale II, it is confirmed the effectiveness of the proposed guidelines.

C. Response of the AMS

Based on the value and the stability rating grade of each scenario obtained in the previous section, it can be known

TABLE III
THE INFORMATION OF THE MODEL VESSEL'S 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

TABLE IV
VI_{VISA}, M_{m-e} AND STABILITY RATING LEVEL OF THE MODEL VESSEL

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.

that in scenarios No.1-8, the stability rating grade is less than "General Safety". Thus, the AMS needs to respond according to the suggested response strategy. For the response, how much moment the AMS provides can be calculated according to Eqs. (3) - (6).

In the actual calculation, the value of φ_1 is set as 1°,the basic information of the model vessel (including various lengths of the vessel, draught, breadth, etc.) are derived from the information of the first model vessel in the literature [11].

As shown in Table IV, the maximum value of M_{m-e} is 9,124,595 N·m. F_{m-e} refers to the force that the AMS needs to offer. According to the **Assumption 3**, it can be calculated by Eq. (8). For the scenario of the maximum M_{m-e}(No.8), the corresponding F_{m-e} is about 676 KN. Many existing AMSs can meet the required output F_{m-e}, such as these developed by Cavotec company [13].

$$F_{m-e} = \frac{2M_{m-e}}{B} \tag{8}$$

After the response of the AMS, the approximate value of GM can be calculated by Eq. (9), which is beneficial 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. The model vessel's stability information in scenarios No.1-8 after the response are shown in Table V.

$$GM_{new} = 2GM - \frac{M_{m-e}B}{(2M_{m-e} + \Delta B)\tan(\varphi_0 - \varphi_1)} \tag{9}$$

In scenarios No.1-8, the stability performance had been improved after the response of the AMS, as shown in Table VI. It was confirmed that the effectiveness of the response strategy 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, the vessel's stability still failed to achieve "General Safety". Especially in scenarios No.1-4, after the AMS's response, there were still some stability parameters failed to meet the minimum expected standards, which was attributed to the extremely unsatisfactory cargo loading distribution on the vessel. In view of this situation, the ship staff should adjust the cargo loading distribution, taking such measures as adjusting the cargo position or adding / discharging ballast water. In the period of loading or unloading, reasonable loading or

TABLE V
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 VI
VI_{VISA} AND STABILITY RATING LEVEL OF THE MODEL VESSEL AFTER THE RESPONSE

Scenario	VI_{ai}						VI_{VISA}	Rating level
Number	GM	GZ_{30deg}	$Angle_{max\,GZ}$	$Area_{0\text{-}30}$	φ_0	T_θ		
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.

unloading strategy should be adopted to avoid aggravating the stability loss caused by uneven distribution of goods.

V. CONCLUSION

The proposed VISA model can express the vessel's stability performance adequately according to the stability index, and provide the guidelines of the vessel's stability assessment. The staff and the AMS can judge and manage vessel's stability performance directly using the guidelines. Based on the result of stability assessment and the suggested calculation formula of the moment provided by the AMS, the proposed response strategy can help the vessel improve its stability performance actively.

It is worth noting that the damaged stability issues of the vessel are outside the scope of this research. Besides, in this research, the object of study considered was only 10,000-ton cargo vessels. Therefore, in future work, the stability index that is fit for more types of vessel should be developed, and the relevant response strategy of the AMS needs to be explored.

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REFERENCES

[1] "automated mooring official website," http://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring, accessed: 2020-12-5.

[2] P. J. Montgomery and B. J. Rossiter, "Mooring system with active control," Nov. 13 2007, uS Patent 7,293,519.

[3] J. de Bont, W. van der Molen, J. van der Lem, H. Ligteringen, D. Muhlestein, and M. Howie, "Calculations of the motions of a ship moored with moosmaster units," in *Port Infrastructure Seminar*. Delft University of Technology, 2010, pp. 1–20.

[4] "Quick Release Mooring Hooks official website," https://mampaey.com/berthing-mooring-overview/quick-release-mooring-hooks/, accessed: 2020-12-5.

[5] H. Sayyaadi and R. Rasa, "Dynamics modeling of the moormaster unit and investigate the interaction between the moored ship and the moormaster," *International Journal of Coastal and Offshore Engineering*, vol. 1, pp. 7–13, 2016.

[6] M. Madani and M. Moallem, "Hybrid position/force control of a flexible parallel manipulator," *Journal of the Franklin Institute*, vol. 348, no. 6, pp. 999–1012, 2011.

[7] D. Brown, "Estimation of vessel stability at sea using roll motion records," *Trans. RINA*, vol. 138, pp. 130–146, 1996.

[8] A. Ariffin, J. Laurens, and S. Mansor, "Real-time evaluation of second generation intact stability criteri," in *Smart Ship TechnologyAt: RINA Headquarters, London*, 2016, pp. 26–27.

[9] D. Terada, M. Tamashima, I. Nakao, and A. Matsuda, "Estimation of metacentric height using onboard monitoring roll data based on time series analysis," *Journal of Marine Science and Technology*, vol. 24, no. 1, pp. 285–296, 2019.

[10] B. Deakin, "Collating evidence for a universal method of stability assessment or guidance," *Trans RINA*, vol. 152, no. Part A2 2101, pp. A–85, 2010.

[11] I. Nam-Kyun and C. Hun, "A quantitative methodology for evaluating the ship stability using the index for marine ship intact stability assessment model," *International Journal of Naval Architecture and Ocean Engineering*, vol. 13, pp. 246–259, 2021.

[12] *Recommended Procedure and Guidelines - Predicting Powering Margins (7.5-02-03-01.5)*, 2nd ed., ITTC, 2017.

[13] "cavotec moormaster references," http://www.https://www.https://www.ca-votec.com/en/your-applications/ports-maritime/automated-mooring, accessed: 2021-6-1.