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ORIGINAL ARTICLE

Stability assessment of anchor handling vessels during operations

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Abstract To ensure safety in anchor handling operations, maintaining anchor handling vessel stability is recognized as a critical and complex task. The vessel's stability depends primarily on the vessel's design and operational parameters, which are expressed by the vessel's dynamic rolling angle, static heeling angle, and capsizing angle. The vessel's stability during anchor handling operations (AHOs) is possible to attain by means of maintaining the vessel's heading in line with the mooring line direction. However, lessons learned from past accidents show that normal and abnormal events and gross errors can lead to capsizing. The occurrence of a large deviation between the vessel heading and the mooring line direction due to abnormal events is considered to be an accidental limiting condition. In this study, two stability criteria are established: (1) the critical static heeling angle criterion and (2) the critical rolling angle criterion. The first criterion is useful in the design phase for assessing the vessel's allowable static heeling angle for a well-defined operational sea state. The second criterion is useful for assessing the vessel's stability in the analysis and planning phase of the operation. A case study is conducted on the Bourbon Dolphin (BD) accident for assessing the stability in a capsizing scenario. The predicted results show that the BD can maintain stability under normal conditions but not under an accidental condition during anchor deployment. While assessing a vessel's intact stability, it is essential to account for the effect of normal uncertainty and variability on the operational parameters; this aspect is investigated in this paper through a sensitivity study.

Keywords Capsizing · Stability · Anchor handling vessel · Mooring load · Criterion · Static heeling angle · Critical rolling angle · Safety · Operation

1 Introduction

1.1 Background

Traditionally, anchor deployment, anchor recovery, and rig moving tasks are characterized as anchor handling operations (AHOs); these operations are conducted with the help of specially designed vessels called anchor handling vessels (AHVs). AHVs have been used in three modes of operation, namely, freely floating mode (while working as a supply vessel for transporting cargo between a supply base and rig), towing mode (while working as a tug during rig move operations), and AHOs mode (anchor deployment and recovery). The main failure modes of AHVs are instability (capsizing) and structural failure. The AHOs are complex operations that consist of AHVs, rig, equipment, and other hardware. Moreover, these operations require good weather conditions for a certain amount of time to execute an operation with a reasonable safety margin. During AHOs, the AHVs are subject to severe environmental loads and higher operational loads (due to the overturning moment coming from the mooring line), which substantially increases the chance of a vessel capsizing. The risk of a vessel capsizing is not possible to eliminate. However, the risk can be reduced by planning the operation based on an analysis of the vessel's stability and defining the operational limits in the operating manual with a

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sufficient safety margin. Furthermore, it is possible to mitigate this risk by continuously estimating the vessel's stability margin and implementing suitable risk mitigation strategies during the execution phase of the operation. However, the existing stability criteria do not cover the AHV's stability when it is subject to a mooring load during the AHO. Therefore, it is essential to develop for this operational phase a stability criterion that accounts for the effects of the major operational parameters.

1.2 Motivation and objective

The current paper focuses mainly on the vessel's transverse stability, which is a major safety requirement of the AHV during AHOs. The vessel's stability during AHOs depends on the operational parameters, which include the loading condition, the magnitude of the mooring load, the angle between the vertical axis and the mooring line, the angle of attack (the angle between the mooring line and the vessel's centreline), the control forces (exerted by the thruster and rudders in the transverse directions), and the environmental loads. Typically, during AHOs, a significant variation occurs in the aforementioned parameters. Hence, the vessel's stability characteristics considerably vary during the operation. In critical scenarios, the combination of these parameters can lead to the capsizing scenario.

Furthermore, experience has shown that the majority of the errors manifest themselves during the execution phase of the operation, although many of these could have root causes founded in the design and/or planning phases. Therefore, a greater attention should be paid to minimizing the errors at the design stage itself. The design should account for all hazards and human errors that are likely to arise during the different phases of an operation. Using safe design approaches, these hazards and human errors should be eliminated as far as practicable. Therefore, it is important to ensure that the chosen AHV fulfils the stability requirement while recognizing the possible variation in the operational parameters. Hence, it is essential to assess the effect of the variation of these parameters on the vessel's stability.

Thus far, there have been no effective and standard requirements or guidelines related to the vessel's stability while deploying or recovering anchors during AHOs. The existing supply vessel requirements cover only the vessel's stability during ocean moves (freely floating mode). In the aftermath of the tragic Bourbon dolphin vessel accident, the [1] IMO Sub-committee on Ship Design and Construction meeting (MSC 88/23/2) decided to establish a new international standard for the safe design and operation of tugs and AHVs, for inclusion in part B of the 2008 IS Code. The committee agreed to include criteria for AHOs in their meeting at MSC 95 (June 2015). During the discussion at SDC 3 [2], the working group agreed the amendments and further stated that these amendments should enter into force on 1 January 2020. However, the proposed amendments did not consider the wind and the current force effect on the vessel's static heeling angle and the vessel's dynamic rolling angle. To address these drawbacks, in this study, a precise method is developed that includes suitable criteria for determining the vessel's stability during AHOs. The vessel's stability limit, basically, is a function of the dynamic rolling angle and static heeling angle, which is further influenced by the operational parameters. Considering these two angles, two safety criteria are proposed for assessing the vessel's stability. In this paper, these criteria are referred to as the critical static heeling angle and critical rolling angle.

This study addresses stability criteria for AHVs during the AHOs by considering the influence of the operational parameters. Furthermore, methods for reducing human errors in the design and operation phases are identified. Using the proposed criteria, the reasons that are related to the Bourbon Dolphin accident are investigated. Furthermore, through a sensitivity study, the effect of the important operational parameters on the vessel's stability is investigated, and this investigation is necessary for aiding in decision-making for achieving safety by means of implementing safety measures during the design and planning phases of the operation.

1.3 Organization of this paper

This paper is organized into six sections. Section 2 describes AHOs and the current practices that are associated with it. Section 3 provides a literature review of the existing stability criteria. Section 4 presents the proposed methodology of Ultimate Limit State (ULS) criteria for stability assessment of an AHV during AHOs. The stability assessment procedure is described in Sect. 5. Section 6 includes analysis of the Bourbon Dolphin vessel's stability during its accident scenario, and furthermore, the operational parameters that influence the vessel's stability are investigated through a parametric study. Section 7 provides a discussion about the risk mitigation strategies used along with the proposed criteria and further discussion of the limitations of the proposed criteria. Finally, Sect. 8 provides conclusions and suggestions for future work on this problem.

2 Anchor handling operations

2.1 Technical and physical features

A typical AHO and the sequence of steps are described in the operational manuals, e.g., Vryhof Anchors [3], dedicated books, e.g., Gibson [4]; Hancox [5]; Maudsley [6]; Ritchie [7] and a paper by Gunnu et al. [8], among others. In general, the AHO requirements depend on the characteristics of the site-specific parameters, such as subsea assets (e.g., subsea structures, pipelines, risers, umbilical, and corals) and floating or fixed structures nearby the deployment or recovery location. These parameters vary from one operation to another, and the variation, in turn, causes each operation to be different from the others. Moreover, these operations come under categorizations of weather-restricted marine operations that have a limited duration and are executed during a specific season of a year. The weather window of these operations is highly dependent on the operational and safety requirements. In general, these operations are either temporarily stopped when the operational parameters exceed the operational limits or they will be started only when it is guaranteed that acceptable weather conditions will persist until the operation is completed.

An ideal situation during AHO is that the mooring line is perfectly in line with the vessel's centreline. This alignment means that the transverse overturning moment due to the tension induced by the mooring line will be zero. However, to achieve this alignment (ideal path) during AHOs is very demanding and challenging. Furthermore, deep-water AHOs require AHVs that have high bollard pull, brake horsepower, and winch capacity. Because of these features, the AHVs are subject to higher operational loads during the AHOs.

2.2 Accident experiences

In general, AHOs are designed, planned, and executed to comply with a given acceptable risk level with respect to the ultimate failure consequences (e.g., in terms of fatalities or loss of human life, pollution and loss of assets). Major accident scenarios for the vessel and its crew during AHOs are identified, namely collision, fire, and capsizing. The stability assessment during the freely floating mode is the same as for supply vessels. In this mode, both intact and damage stability are of concern. The stability assessment during the towing mode is the same as the tug while used for towing. In the AHO mode, it is anticipated that traffic control ensures that vessel collisions are rare. Therefore, in view of the traditional stability criteria, it is essential to study the vessel's stability in an intact condition but considering a mooring load effect. In general, the vessel's stability during AHO is more critical than the freely floating mode due to the effect of the mooring line. Therefore, the focus of this study is the vessel's stability assessment, while the vessel is subjected to a mooring load and other influence factors during AHOs.

The study on the Bourbon Dolphin [1] vessel accident is used to understand the influential factors and sequences of the events related to the AHV capsizing event during AHOs. Vessel capsizing occurs primarily when the restoring moment is less than an induced overturning moment. Figure 1 illustrates how accidental actions and events escalated into the Bourbon Dolphin vessel accident. Furthermore, Fig. 1 shows that the key sequences of the events related to this accident are the vessel drift-off (with respect to the desired mooring line track), a large angle of attack, a large overturning moment, a large initial heeling angle (or static heeling angle), and capsizing. The vessel's drift motion and angle of attack depend on the vessel's positioning capability [9] and the vessel behaviour on the horizontal plane [10]. Moreover, the drift motion depends on the implementation of the correct ship handling techniques at a correct time, which depends on the skills of the vessel's master.

2.3 Uncertainties and human errors

Along with higher operational loads as mentioned in Sect. 2.1, there might be a deviation from the ideal path due to normal uncertainties and gross errors that lead to a large overturning moment, which in turn could lead to capsizing. Furthermore, even though no mistakes or errors occur, deviations with respect to the planned operation could still occur. Deviations due to both normal and abnormal events can cause a large static heeling angle, even for a small magnitude of mooring load, which in turn increases the risk of capsizing. This context can be observed from the Bourbon Dolphin capsizing investigation report [1] and from the previous research articles [8, 11]. Furthermore, the accident investigation report reveals that along with operational errors, a series of technical and physical errors (in the design of the vessel and its equipment, operational analysis and planning, and operational execution) were the main reasons for the progression of events from vessel drift-off, large static heeling angle to vessel capsizing.

2.3.1 *Classification of uncertainties*

Moan [12] classified the causes of structural failures into three categories, namely, (1) too small safety factors to account for the normal uncertainty and variability (inherent) related to the resistance and load, (2) abnormal resistance or accidental actions, both intended and unintended, due to (induced by or caused by) human errors [13, 14] and omissions during the life cycle, and (3) unknown phenomena. During AHOs, the AHV performance is influenced by various uncertainties that are caused by inherent physical randomness, for example, due to the variability of

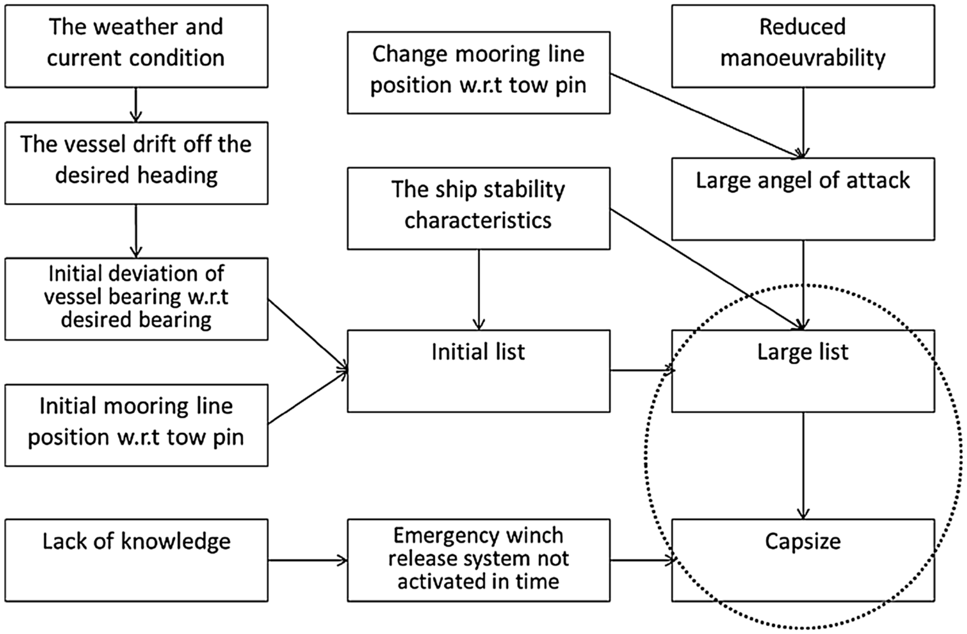


Fig. 1 Influencing parameters on capsizing of an AHV during the operation phase

environmental parameters and uncertainties in the weather forecast, and the existing models used for estimating their performance (e.g., stability, horizontal motions), or other factors. In some cases, there are random normal uncertainties, such as analytical procedures that arise from sources that cannot be corrected, avoided, or identified. However, normal random uncertainties can be understood and modelled using the laws of probability and basic statistics. The magnitude of normal uncertainties can be calculated mathematically. The operational uncertainties that are related to human decisions or actions are possible to reduce by means of appropriate planning, with a sufficient safety margin, on-board condition monitoring systems and decision support systems, and other approaches.

2.3.2 Abnormal events and human errors

In addition to normal uncertainties, certain abnormal events might occur, namely, accidental conditions such as mechanical, hydraulic, or structural failure of a vessel's equipment (critical to AHO—such as tow pins and shark jaw), and gross errors (human errors) such as error-induced accidental decisions and actions, poor vessel handling skills, mishandling tow pins, or spurious activation of tow pins. The basic root causes of the gross errors can be a combination of severe circumstances and/or physiological limitations [15] and the incapacity to address an unusual environment. Typically, different personnel are involved in the operation, and it becomes very difficult to predict the probability of the above-mentioned occurrence of gross errors in the operation. Hence, often, these errors are not visible [16] unless the operation is exposed to a hazardous scenario, and they are difficult or impossible to predict.

Experiences from accidents show that gross errors during an operation are the dominate causes. In the Bourbon Dolphin accident, the vessel's master was not able to prevent the capsizing event partly because of normal uncertainties and partly because of abnormal uncertainties and gross errors [1, 8]. The accident investigation report reveals that a series of operational errors was the main reasons for initiating the first event (the vessel drift-off) and the progress of events until the capsizing event. The restoring and overturning moment of the vessel depends on the vessel's initial loading condition, the vessel heading relative to the environment and the vessel's speed. The vessel's loading condition varies from operation to operation, and the mooring load magnitude for a given operation varies continuously. Furthermore, these variations are subject to the uncertainty that is associated with the operator skills in vessel handling and other factors. Due to the random nature of the ocean waves, the vessel's dynamic roll motion is a random process and is subjected to the control of their extremes by the operators. Furthermore, the initially planned strategy might not be strictly followed in an actual operation, owning to human "error" or exceptional situations.

2.4 Risk management with respect to stability

2.4.1 General

The normal uncertainties and errors mentioned above influence the vessel's capacity (restoring moment) and loads (over turning moment) significantly. An assessment of these uncertainties is very important to estimate the risk of instability at the design phase as well as in the operation phase, to aid in the decision-making. The gross errors are possible to prevent or are reduced [13, 14] through understanding their influence on the situation and by making the correct decisions and actions at the correct time throughout the operation, from the analysis and planning phase to the execution phase. This decision-making process is possible to improve by crew training [13] and situational awareness.

Safe AHOs can be achieved by means of assuring the vessel's stability by fulfilling the design criteria. However, this strategy is not always applicable or economical. Alternatively, additional safety measures can be adopted in the execution phase of the operation. In principle, the safety margin used in ULS design criteria does not reflect gross errors. Therefore, the risk of a vessel capsizing due to a gross error is the most difficult to manage, because it is not feasible to remove by increased safety coefficients or margins. However, the risk can be reduced by reducing the probability of gross errors in an operation, through proper verification and quality assurance of important aspects in the design, planning, and execution phases of the operation [13]. Furthermore, the operational errors can be reduced by defining proper operational limitations, and providing decision support system, training of the crew, and other relevant actions are all put in place to avoid or reduce gross errors [13]. However, a large deviation between the vessel heading and the mooring line direction can occur during an operation due to the normal uncertainty and variability in the operational conditions, or any accidental actions or gross errors (human errors) followed by severe weather (wind, current and waves), and the tension of the mooring line can lead to a capsizing event. Therefore, the large deviation between the vessel heading and the mooring line direction along with variations of other parameters need to be considered in the Accidental Limit State (ALS) criteria.

In summary, the aforementioned uncertainties and errors associated with the operational parameters' influence on the vessel's stability must be considered in the design phase, the analysis and planning phase, and the execution phase of the operation. The decisions that are related to the vessel's stability at different phases, such as the vessel's design, operational analysis and planning, and operational execution phase for reducing uncertainties and errors are shown in Fig. 2 and can be explained as follows:

2.4.2 *Vessel's design phase*

AHVs are designed to fulfil many requirements, which include large transverse stability characteristics, large internal cargo capacity, large deck area, the ability to tow rigs, lifting and positioning rig anchors, and the services of emergency response and rescue operations. Moreover, these vessels can undertake cargo runs and supply duties between onshore bases and offshore drilling sites. The stability of the vessel during AHO depends on design parameters such as the vessel shape, mass distribution, the general arrangement of the vessel, the number of tow pins, the positions of the tow pins, and the transom shape and size of the stern roller. An overdesigned stability can result in stiff-motioned vessels that are uncomfortable. At the same time, an under-designed transverse stability can result in poor performance of the stability and, perhaps, the entire loss of the vessel by capsizing. The consequence of overdesigned and under-designed stability should be considered in the design phase. In addition, the vessel should be designed to resist failure from accidental conditions, such as human error. While designing the vessel, the designer should define the vessel's stability limits by considering the operational parameters such as the mooring load, the transverse component of the thruster force, and the weather. This information is helpful for the operators in the decision-making process while selecting the vessel based on the operational demands [17]. Moreover, this information is helpful for the master for avoiding catastrophic failures such as capsizing or having a large static heeling angle.

2.4.3 *Analysis to plan operations*

The second aspect is the analysis to plan operation. This phase occurs well ahead of the actual deployment or recovery operation. During this phase, the analyses are conducted by considering the operational and statutory requirements. As per the statutory requirements, the offshore operators must assess the operational safety before commencing the AHO. In this assessment, the analysis must show that the hazards that have the potential to develop into a serious accident have been identified, the associated risks are below a tolerable limit, and if not, the risks have been reduced as low as a reasonably practicable (ALARP) level. The operational requirements such as the vessel's position capability and stability are assessed. The vessel position capability is assessed by analysing how much thrust is required to keep the AHV in the desired heading and position under a specified weather conditions. Similarly, the sensitivity of the vessel's stability margin is to be assessed for the appropriate range of operational parameters. These analysis results can be used for selecting proper vessels in the planning phase.

For preventing large drift-off, angle of attack, and static heeling angle events, the vessel should have sufficient propulsion and thruster capacity (or capability). This aspect should be accounted for in the analysis and planning phase

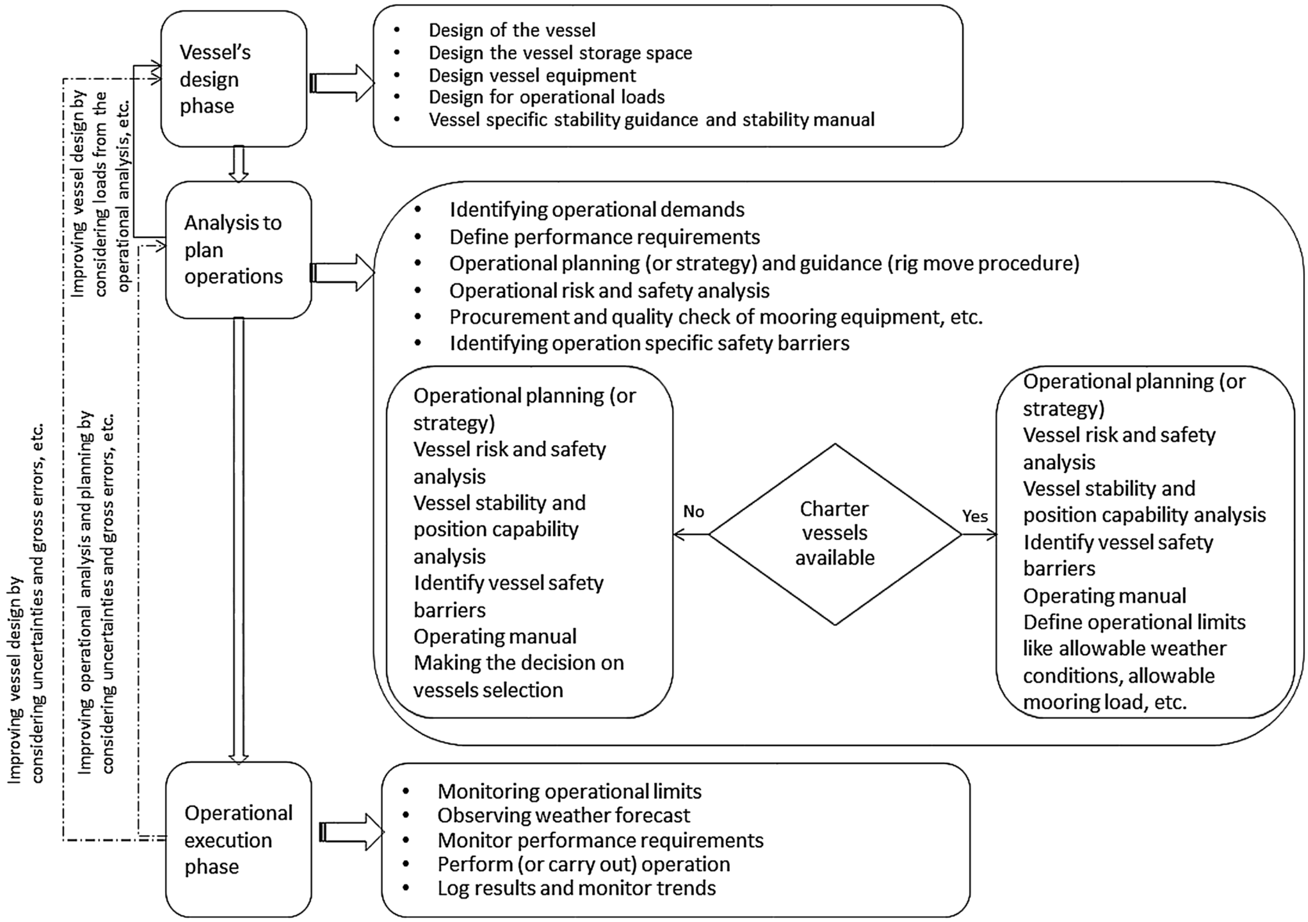


Fig. 2 Design, analysis to operation, and execution phase interactions in AHOs

before finalizing the vessel selection. However, the vessels that satisfy the stability and position capability requirements for all of the ranges of operational parameters are rarely available. In practice, these requirements are achieved by performing the operation within the defined operational parameters' limits. These operational limits are defined by considering the available vessels and the estimated operational and environmental loads in the operation analysis. Furthermore, while defining these operational limits, margins should be built for accommodating normal uncertainties and variability, as well as abnormal action and human errors. Moreover, the results of the operational analysis should be reflected in the operating manual that serves as a basis for decision-making during the execution phase of the operation.

2.4.4 Operational execution phase

During the execution of the operation, the decisions are made by considering the operating limits, weather forecast, estimated duration of the operation, and other factors. The key personnel involved in the decision-making process are a marine warranty surveyor, an offshore manager and the vessel's master. The vessel's stability depends on the vessel's design and its equipment, the operating environment, and the vessel handling skills. The qualified bridge crew is essential for executing efficient vessel handling skills, which further depend on the quality of situational awareness and decision-making. These skills are possible to improve with the help of a suitable condition monitoring/decision support system and training, or both.

3 Literature review of stability criteria

It is important to study an AHV's stability to avoid accidents such as the Bourbon Dolphin [1] and Stevns Power [18] in future operations, because the consequences of such events are catastrophic (loss of the ship, the crew, and reputation in public). The stability of the vessel depends on the initial equilibrium position due to the heeling moment and the restoring moment of the vessel. The heeling moment depends on the operational parameters, which were mentioned in Sect. 1. The restoring moment depends primarily on the vessel's draft at the operational loading condition and the wetted geometry at this draft. The stability of the vessel during an operation can be improved by reducing the exerted overturning moment. The reduction can be achieved by limiting the operational parameters' effects on the overturning moment.

Various stability criteria have been proposed for freely floating vessels in recent decades. Most of these criteria have focused on the static stability of the vessel in sailing conditions [19–24]. Similarly, in the offshore sector, stability of floating platforms was addressed in terms of standards [25–31] in the research literature [32, 33]. Depending on the condition of the vessel, stability is defined as either intact or damaged stability. Moreover, stability is classified into static and dynamic stability. Static stability presents the ability of a vessel to return to the upright position based on the static heeling angle. Dynamic stability is related to the amount of work that is expended to bring the vessel back to its upright position. Administrations, statuary bodies, and classification societies enforce intact and damage stability criteria on vessels. Earlier, the focus of these statutory bodies was on the static stability. The dynamic behaviour of the vessel under severe weather conditions was not considered. Later, the focus moved toward dynamic stability. Here, the dynamic rolling angle of the vessel in waves was accounted for. The basis for this criterion is model tests, simulation, and empirical observations.

A wide range of stability regulations and guidelines are issued for vessels in a free mode, i.e., without a mooring line. The load induced by the mooring line is typical for AHVs but not for other conventional vessels. Intact stability criteria for all types of conventional vessels are specified by IMO [28]. This code covers the essential features such as general precautions against capsizing by the criteria for the metacentric height (GM) and righting lever (GZ); weather criterion; effect of free surfaces and icing; and watertight integrity. The vessel-specific rules that are associated with offshore supply vessels are covered by the Guidelines for the design and construction of offshore supply vessels [34]. There are no special rules for AHVs that account for the mooring load influence on the vessel's stability during AHOs. Limited efforts have been devoted to the AHV's stability during operation (while subject to mooring loads). The stability of AHVs is related to the tug stability, because these vessels are affected by high-tension mooring and towing lines that are oblique to the vessel's longitudinal axis. During towing, a towline will exert a heeling moment on the tug; if the heeling moment is higher than the restoring moment, tug capsizing occurs. This phenomenon is called "girting", which can develop rapidly. Hence, tugs should be designed with sufficient stability to survive such events. Because the towline in most cases will act horizontally or upward, a vertical component of the towline force is often disregarded in assessing the tug's stability. To evaluate the tug stability, the stability criteria proposed in the IACS Recommendation No. 24 [35, 36] are widely used. The tug stability criteria provide sufficient stability to prevent a capsizing scenario due to girting, while the towline exerts maximum tension (board pull) perpendicular to the vessel's centreline. There are some very important differences between a conventional tug being "girted" and the "girting" of an AHV. In the towing, the small vertical (upward) component is often disregarded, while on AHVs, the mooring line forces act downward on the stern region of the vessel. This force acts similar to a hanging load that changes the draft, trim, and transverse centre of gravity of the ship and, at the same time, increases the AHV list. In combination with the propulsion and thruster forces, this combination could have a detrimental effect on the ship's stability. Fishing vessels with fishing gear such as trawls are in a similar mode of behaviour as that of AHVs during operation. Mantari et al. [37] studied the effect of the heeling moment caused by fishing gear, wind, and waves on the vessel's stability. Even though both fishing vessels and tugs have a mode of heeling that is similar, the AHV requires particular consideration. Today, the AHVs stability is treated as that of a supply vessel under the existing rules. In the IMO [29] regulation, the "weather criterion" is applied to the freely floating modes but not for AHVs during operation. This criterion is inadequate for AHOs. Therefore, intact stability, i.e., the ability to capsize the vessel without damage, is considered in this study.

4 Methodology for the development of ULS criteria for stability assessment of AHVs during AHOs

To achieve safe operations, the limit states used for assessing the vessel's stability in the design and analysis phase should be redundant and robust. Typically, for a freely floating mode, the vessel's stability must be examined under the design criteria formulated in terms of two limit states, namely the ULS and ALS. Traditionally, for the freely floating mode, the vessel's stability during the damage condition is considered in the ALS test, which is damage stability. While assessing the AHV's stability during AHOs in the ALS test, it can be reasonable to assess the effect of the large deviation between the vessel heading and the mooring line direction and the variations that are related to the operational parameters on the vessel's stability instead of the traditional damage stability.

The ULS ensures that the vessel has adequate restoring capacity to prevent the overturning moment, while the vessel is operating on an ideal path (or small deviation with respect to the ideal path). Therefore, while conducting a ULS test on the vessel's stability in the design phase, and analysis and planning phase, the effect of tension (load) due to the mooring line should be accounted for. The ULS approach requires the application of a safety factor for reflecting the uncertainties that are associated with the overturning movements due to the applied loads, restoring moment, and design limit state under consideration, which occur despite the efforts that are made to avoid human errors (error-induced accidental decisions and actions) and abnormal events (see Sect. 2.3.2), which cannot be eliminated. Due to the above-mentioned events, during the AHOs, the vessel can deviate with respect to the desired heading, which leads to a large angle of attack; in turn, the vessel is subjected to a large overturning moment [11] that is induced by the mooring line. Therefore, while conducting ALS test of the vessel's stability in the design, and analysis and planning phases, the effect of human errors and abnormal events should be accounted for. For this reason, the introduction of ALS criteria should be considered. This limit state focuses on the survival of the vessel with respect to relevant actions during operations. The intention of ALS assessment is to ensure that the vessel will be able to tolerate specified accidental and abnormal events, and where an overturning moment occurs, subsequently maintain stability for a sufficient period under specified environmental and operational loads. Furthermore, an ALS analysis is helpful for identifying the procedures in stopping the escalation of these errors before they become accidental events.

As mentioned in Sect. 3, there is no appropriate criterion for assessing the AHV's stability during AHO. Existing criteria in IMO, Japanese, and UUSR standards are intended for conventional vessels. Typically, AHOs are not conducted in sea states with a significant wave height that exceeds 3.5 m and a mean wind velocity above 40 knots. The allowable operating sea state (wave steepness) for AHVs in AHOs is generally lower than the freely floating mode. However, in this paper, the aim is to establish the vessel's operational limits, which can be either lower or higher than the above-specified limits in terms of the sea state, current velocity, wind velocity, line tension, water depth, etc.

To ensure a vessel's stability during AHOs while subjected to operational parameters, two new safety criteria (or limit state formulations) are proposed in this section. To establish robust stability criteria, the traditional IMO "weather criterion" is modified by incorporating the effect of the mooring load. The established criteria are referred to as the critical rolling angle criterion and critical static heeling angle criterion in this work. The established criteria include the following parameters:

- Mean wind velocity and direction;
- standard deviation of the turbulent component of the wind velocity;
- current velocity and direction;
- significant wave height, peak period and wave direction;
- vessel's position, transverse velocity and heading;
- mooring line parameters and position of line with respect to the tow pins;
- thruster and propulsion force components in the transverse direction;
- vessel's operating loading conditions (excluding mooring load effects).

The influence of the above-mentioned parameters on the vessel's stability is considered in this study. As mentioned above, only intact stability criteria are considered herein. Furthermore, in the existing IMO [29] criteria, the rolling (rollback) angle is calculated by considering the worst possible wave steepness that the conventional vessel can be subjected to in their lifetime while transporting cargo (from one location to another location). However, AHOs are weather-restricted operations. Therefore, the vessel has never experienced the wave steepness assumed in IMO [29] during AHOs. For this reason, the IMO [29] criteria overestimate the vessel's rolling angle compared with the actual rolling angle in the operating sea state during AHOs. To address this issue, the assessment of the vessel's dynamic rolling angle in waves is proposed in this study.

4.1 Development of "critical rolling angle criterion"

Three approaches are widely used for evaluating a vessel's stability when considering operations in wave and wind conditions [38]. These are a semi-static safety criterion, dynamic stability following roll against the wind and dynamic stability from the vertical position. The drawback with the first approach is that the roll motion is not considered. This drawback is addressed in the other two approaches. In this study, the second approach, which is based on the energy balance method, is considered.

As mentioned above, this criterion is developed for AHVs based on the existing IMO [34] "Weather criterion". In the IMO criteria, the limiting angle (ϕ_2) is either the angle where significant openings are down flooded (ϕ_f), the vanishing angle (ϕ_v), i.e., an angle at which the righting moment or righting lever arm (GZ) is zero, or the angle of 50° (see Fig. 3), which can be assumed to be an explicit safety limit, whichever of the three is the lowest. These criteria are developed based on IMO's "weather criterion", which was developed based on the energy balance method [29, 39]. The IMO's "Weather criterion" approach considers all of the relevant factors that have influence (such as the maximum wave steepness, wind gust factor, wind speed, and dynamic rolling angle at natural frequency) on the vessel's stability. Therefore, the safety margin is not included in the IMO's "Weather criterion". Furthermore, during AHOs, the capsizing phenomenon due to an excessive (accidental or due to mooring load) overturning moment is more hazardous than a slow flooding. Therefore, the limiting angle (ϕ_2) is considered to be a second intercept point between the righting lever arm and the heeling lever arm.

In this section, a critical rolling angle criterion is proposed. This critical rolling angle is useful for preventing a capsizing event during AHOs. Human decisions and actions during an AHO are not explicitly accounted for in this study. However, the results of these actions or decisions are implicitly accounted for in the form of the angle of attack and the transverse thrust force, among other factors. The procedure for this criterion is shown in Fig. 4 and can be explained as follows:

- Initial loading condition of the vessel at the start of the operation is considered. For this loading condition, the vessel's equilibrium position and static stability are established by considering only the effect of gravity and buoyancy.
- The total heeling moment and heeling lever arm (h_{H}) induced by the mooring load, current load, wind load (gust wind effect included), and thruster force are calculated. The static angle of equilibrium (ϕ_0) due to this total heeling lever arm is computed (gust wind effect included). This static angle varies by varying the operational parameters.
- The angle beyond which the vessel capsizing due to the heeling lever arm is computed (the second intercept of the heeling lever arm with the righting lever arm curve). This angle is called the limiting angle or capsize angle (ϕ_2 or ϕ_{c}). Area "*b*" between the first intercept and the limiting angle is computed.
- Identification of the angle (ϕ_1) at which area "*a*" exceeds area "*b*"; if the angle of rolling exceeds this limit (due to the subject sea states), the vessel does not have a large enough righting moment to come back to the windward side from the leeward side. This angle is referred as the critical rolling angle $\phi_{\mathrm{cr\_roll}}$ in waves.
- For a given set of operational parameters, a unique set of static angle of equilibrium (ϕ_0), capsize angle (ϕ_c) and critical rolling angle $\phi_{\mathrm{cr\_roll}}$ exists. By varying the ranges of the operational parameters, these angles vary significantly. A complex relationship exists between these angles.
- The vessel is safe as long as the vessel's rolling angle $\phi_{\mathrm{dy\_roll}}$ in an operating sea state is within the limits of the vessel's critical rolling angle $\phi_{\mathrm{cr\_roll}}$ for a subjected total overturning moment due to the operating parameters (excluding waves).
- With the help of this criterion, for the given operating parameters (or the vessel's static heeling angle), the allowable operating sea states (combination of H_{S} and T_{P}) can be derived.

4.2 Development of the vessel's "critical static heeling angle criterion"

As previously mentioned, it is essential to define the operational limit state of AHVs for assessing the stability during the AHOs. To address this limit state, the vessel's critical static heeling angle criterion is developed. The vessel's static heeling angle can be easy to understand and monitor by the operators during AHOs. If the vessel's static heeling angle tends to exceed the critical limit during the

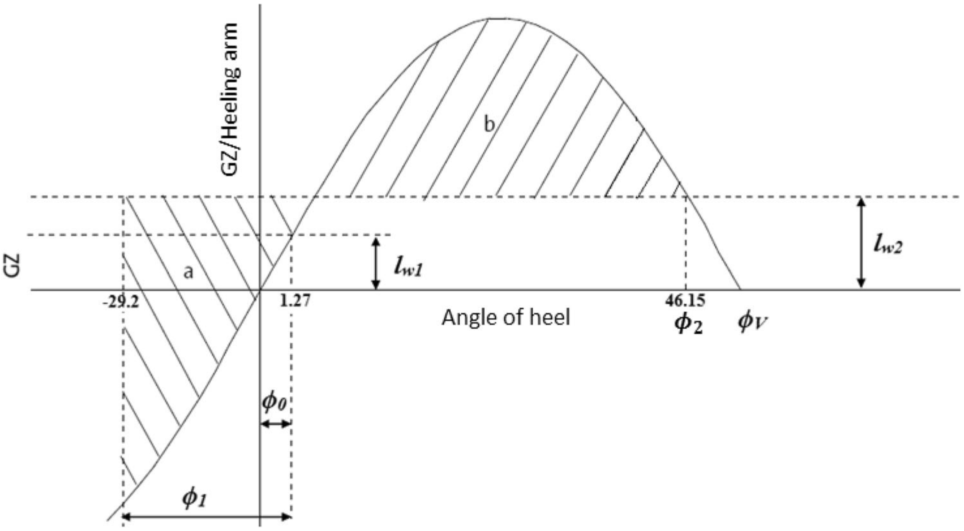


Fig. 3 Severe wind and rolling criteria (the values indicated in the figure refer to the Bourbon Dolphin accident)

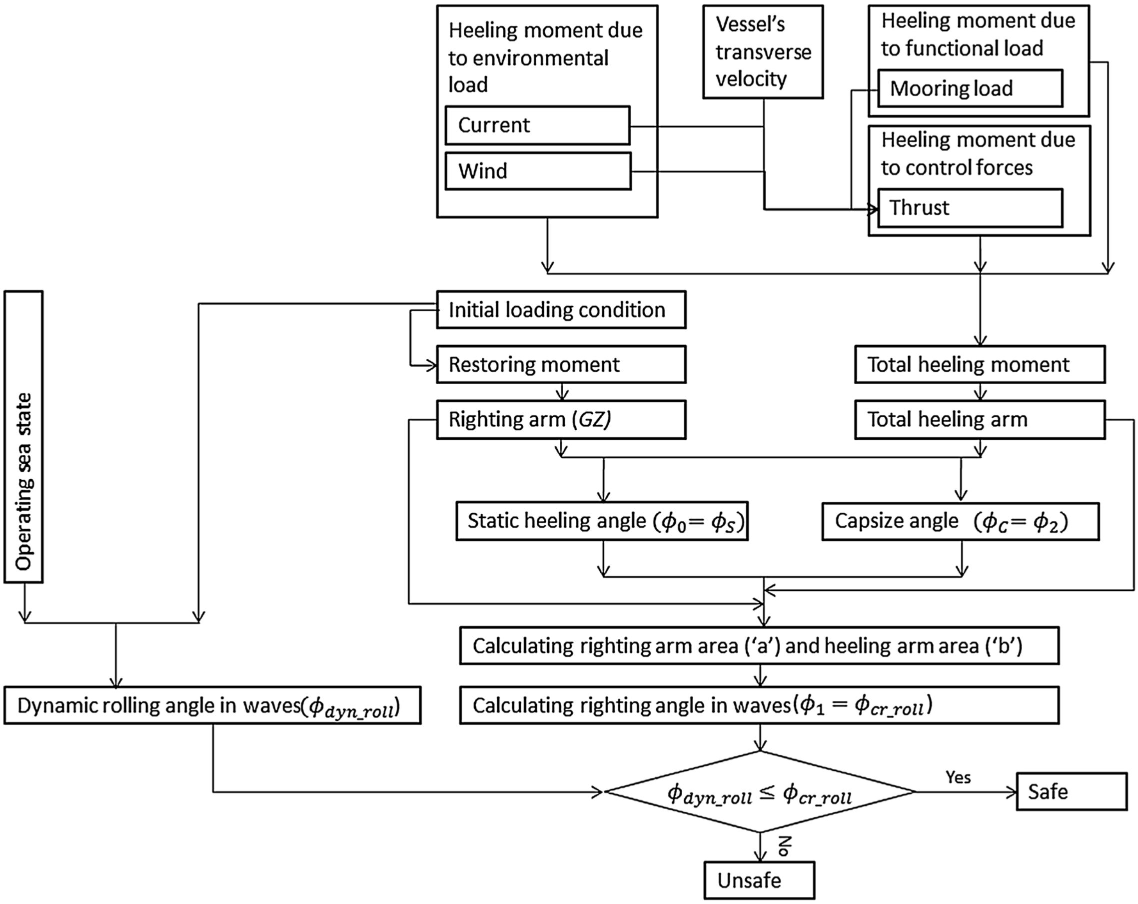


Fig. 4 Procedure of calculating the critical rolling angle criteria. External load and thrust are in equilibrium. The variation in the vessel's static heeling angle effect on the dynamic rolling angle in not considered

AHOs, it can be brought back to be within the safety limit by executing an effective recovery action (such as changing the vessel heading, transverse thrust, etc.) by the vessel's master. To perform an effective recovery action, these operations require a sufficient time window (defined as the time from the normal condition of the vessel until it reaches its critical static heeling angle). In the present study, the time window is not considered. The analysis procedure for calculating the vessel's critical static heeling angle criterion includes the following sequence of steps:

- The vessel operating sea state must be determined;
- The vessel's maximum dynamic rolling angle $\phi_{dy\_roll\_max}$ for the possible operating sea states (combination of H_S and T_P) must be calculated;
- For a given maximum rolling angle $\phi_{dy\_roll\_max}$ in waves (calculated for the above operating sea states) and an operating loading condition, the vessel's critical static heeling angle $\phi_{cr\_initial\_heeling}$ is estimated (see Sect. 6.3);
- The vessel is safe as long as the actual vessel's static heeling angle $\phi_{actual\_initial\_heeling}$ subjected to the operational parameters is within the limits of the vessel's critical static heeling angle $\phi_{cr\_initial\_heeling}$ for the possible operating sea states;
- With the help of this criterion, for a given set of operating sea states (or vessel dynamic rolling angles), the allowable operating parameters (excluding the sea states) can be derived.

4.3 Vessel's "allowable static heeling angle criterion" and "allowable rolling angle criterion"

To define the allowable static heeling angle criterion and allowable rolling angle criterion, it is essential to consider the effect of the uncertainties as mentioned in Sect. 2.3. The assumed uncertainties that are associated with the restoring moment and overturning moments in the limit state function have a direct and important influence on the calculated probability of capsizing. To account for these uncertainties, the allowable criteria should be defined with a certain safety margin (or safety factor). Different authorities can judge the safety margins differently. The safety factor in the criterion should ensure a sufficient safety margin while accounting for the uncertainties in the calculation. On the other hand, the criterion must not be too conservative, because this circumstance would increase the costs. In this study, the heeling lever arm is obtained from the results of a computer simulation program. Therefore, the heeling lever arm might need to be corrected by a safety factor to cover the uncertainties that result from the assumptions on which the simulation model was based.

The allowable rolling angle can be obtained after introducing the safety factor to this critical rolling angle. If we know the critical rolling angle, then we can assess the allowable rolling angle by considering the safety factor. The relation between the critical rolling angle and the allowable rolling angle can be defined as

$$\phi_{\text{all\_roll}} = \frac{\phi_{\text{cr\_roll}}}{\gamma_{\text{roll}}} \tag{1}$$

where $\phi_{\text{all\_roll}}$ is the allowable roll angle, $\phi_{\text{cr\_roll}}$ is the critical roll angle, and γ_{roll} is the safety factor.

Similarly, the relation between the critical static heeling angle and the allowable static heeling angle can be defined as

$$\phi_{\text{all\_static\_heeling}} = \frac{\phi_{\text{cr\_static\_heeling}}}{\gamma_{\text{static\_heeling}}} \tag{2}$$

where $\phi_{\text{all\_static\_heeling}}$ is the allowable roll angle, $\phi_{\text{cr\_static\_heeling}}$ is the critical roll angle, and $\gamma_{\text{static\_heeling}}$ is the safety factor.

Typically, these safety factors are derived by considering the target reliability. However, a particular challenge with this problem is to combine the stability and probabilistic analyses. As an example, Sarchin and Goldberg [40] included safety requirements in terms of an area ratio with a safety factor of 1.4 in their stability and buoyancy criteria for the freely floating mode. In this study, the safety factor is not considered. Future studies and calculations are necessary to obtain a suitable safety factor.

4.4 Assessment of the vessel's dynamic rolling angle in waves

The current stability criteria [41–45] use a constant rolling angle. The rolling angle in these criteria is developed by considering the worst possible wave steepness (sea state) that the conventional vessels could experience in their lifetime in the free-floating mode during transportation. However, AHOs are conducted in lower sea states (the present practice is 3.5 m significant). Hence, the rolling angle computations based on the Japanese and IMO criteria are not relevant for AHVs during AHOs, which requires an improvement for assessing the vessel's dynamic stability in random waves. On the other hand, USSR [46] proposed a method for the rolling angle calculation for a vessel in irregular waves. In this approach, the maximum amplitude of 50 rolling periods [45] is estimated. Similarly, the significant roll response [47] and extreme roll response (as described in Eq. 29) are practical for predicting the vessel's rolling angle in irregular waves. An extreme roll response is important to consider for a catastrophic scenario such as capsizing. Therefore, an extreme roll response based on direct calculation is more rational to consider for the calculation of a dynamic rolling angle. This approach is considered in this study. For conducting a safe operation, the rolling angle in an actual sea state should be within the limits of the critical rolling angle. During AHOs, the operational parameters influence the vessel's draft, static heel angle, and other factors. These influences on the vessel's dynamic rolling angle are not considered in this study.

The response spectrum $S_R(\omega)$ for the rolling angle to windward is obtained by

$$S_R(\omega) = S_E(\omega)|\text{RAO}(\omega)|^2 \tag{3}$$

where $S_R(\omega)$ is the response spectrum, $S_E(\omega)$ is the wave spectrum, and $\text{RAO}(\omega)$ is the response amplitude operator.

The significant roll amplitude (mean value of 1/3 of the highest roll amplitude) is calculated as follows:

$$\phi_s = 2\sqrt{m_0} \tag{4}$$

where m_0 is the zero spectral moment

$$m_0 = \int_0^\infty S_R(\omega) \cdot \mathrm{d}\omega. \tag{5}$$

The maximum response that corresponds to the 90% percentile in the extreme value distribution is (short-term response) as follows:

$$\phi_{\max} = \phi_s \cdot \sqrt{-0.5\ln(1-p^{\frac{1}{N}})} = 2.12\phi_s = 4.24\sqrt{m_0} \tag{6}$$

where N is a number of waves (1080 in a 3-h storm), p is the fractal level, and $(1-p)$ is the probability of exceedance.

5 Analysis to demonstrate compliance with the stability criteria

The first step toward assessing the vessel's stability is to decide upon the operation variables that are relevant in contributing to the restoring moment (or righting moment) and overturning moment (or heeling moment). The relationship between the operation variables and the restoring and overturning moments is established in this section.

5.1 Righting the lever arm

The vessel's righting moment depends on the vessel's shape and loading condition. The parameters that are related to the loading condition for a specified vessel are a function of the following:

$$L = f(\mathrm{CG}, \Delta) \tag{7}$$

where CG is the position of the centre of gravity, and Δ is the displacement. The vessel draft, heel, and trim for the specified loading condition is determined based on the hydrostatic values. It is important to track the equilibrium position of the vessel in calm water by balancing the load and buoyancy for a specified mass model (weight and centre of gravity). Possible deck immersion and changes in the water plane area, the centre of flotation, buoyancy, and deck opening positions should be accounted for. The main aim is to find the shape of a righting lever arm curve (GZ curve), static heeling angle, and capsizing angle of the vessel at which the vessel's stability is lost. Many software tools are available for computing and establishing the vessel's static stability curve. In the current study, the software tool HydroD of the DNV GL SESAM [48] package is used. Figure 5 presents the GZ curve with respect to the heeling angle (produced using the tool HydroD).

5.2 Heeling lever arm calculation

In this section, the factors that influence the vessel's heeling moment are discussed. These factors are the mooring load, chain attachment point, thruster force, current force, and wind force, as illustrated in Fig. 6.

5.2.1 Heeling moment due to the transverse component of the wind force

The heeling moment due to the wind is defined as

$$M_\mathrm{W} = f(v_\mathrm{W}, \psi, \psi_\mathrm{W}, A_\mathrm{AP}, v, Z_\mathrm{A}, \mathrm{CG}, C_\mathrm{D,air}) \tag{8}$$

where M_W is the wind heeling moment, v_w is the wind velocity, ψ is the vessel heading, ψ_w is the wind heading, A_AP is the projected area of the vessel above the water line, CG is the vessel's centre of gravity, Z_A is the distance between the centre of the projected area above the water line and CG, v is vessel's sway (lateral) velocity, and $C_\mathrm{D,air}$ is vessel's transverse drag coefficient in air, as shown in Fig. 7. The variables A_AP, Z_A and $C_\mathrm{D,air}$ vary with respect to the vessel heeling angle, which is not considered in this study. The heeling moment due to wind is considered to be constant for all of the heeling angles, which is calculated for the upright condition.

$$F_\mathrm{MW} = \frac{1}{2} \cdot \rho_\mathrm{air} \cdot A_\mathrm{AP} \cdot v_\mathrm{R,W}^2 \cdot C_\mathrm{D,air} \tag{9}$$

$$M_\mathrm{MW} = F_\mathrm{MW} \cdot Z_\mathrm{A} \tag{10}$$

where F_MW is the mean wind load, $v_\mathrm{R,W}$ is the relative lateral velocity between the vessel and the wind, air is the air density (1.239 kg/m^3), and M_MW is the heeling moment due to the mean wind.

The force and moment due to the gust wind are computed as

$$F_\mathrm{GW} = F_\mathrm{MW} \cdot 1.5 \tag{11}$$

$$M_\mathrm{GW} = M_\mathrm{MW} \cdot 1.5 \tag{12}$$

where F_GW is the gust load, and M_GW is the heeling moment due to the gust wind.

5.3 Heeling moment due to the mooring load ($F_{ML,XYZ}$)

A severe heeling moment can occur due to the mooring load when the mooring line is at an angle with respect to the vessel's heading. The vertical ($F_\mathrm{ML,Z}$)) and horizontal ($F_\mathrm{ML,Y}$) components of the mooring load cause the vessel to heel. The maximum possible offset of the vertical component from the centreline for the specified vessel is decided by the vessel transom shape (vessel aft end shape). The heeling moment due to the mooring load is defined as

$$M_\mathrm{ML} = f(F_\mathrm{ML,XYZ}, \alpha, \beta, Z_\mathrm{TP}, Y_\mathrm{SR}, \mathrm{CG}) \tag{13}$$

where M_ML is the heeling moment due to the mooring load, $F_\mathrm{ML,XYZ}$ is the magnitude of the mooring load, α is the angle between the mooring load and the vertical axis, β is the angle between the mooring line and the vessel centreline, Z_TP is the distance between the deck and CG, and Y_SR is the distance between the centreline and the mooring line position along transverse direction. The variables Z_TP and Y_SR depend on the position of the line with respect to the tow pins and transom design. Moreover, Z_TP and Y_SR depend on the heeling angle. The angle β depends on the vessel's position and heading with respect to the rig's fairlead. The angle α depends on the line length and characteristics, the vessel's position and heading with respect to the rig's fairlead, the line departure angle at the rig, the vessel speed and bollard pull, and the vessel bearing with respect to the wave, wind, and current directions. The method for calculating M_ML was described by Nilsson [49]. The effect of the heeling angle and mooring line position with respect to the tow pins and transom design is considered in this study:

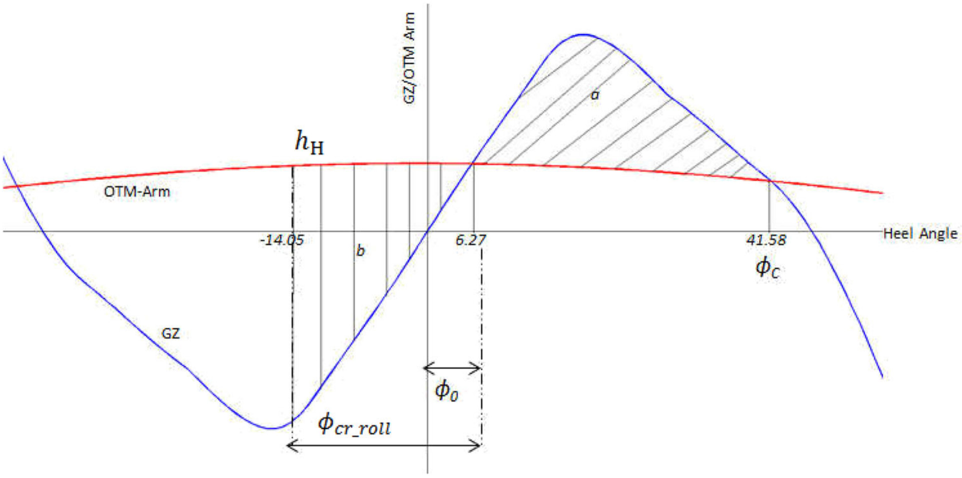
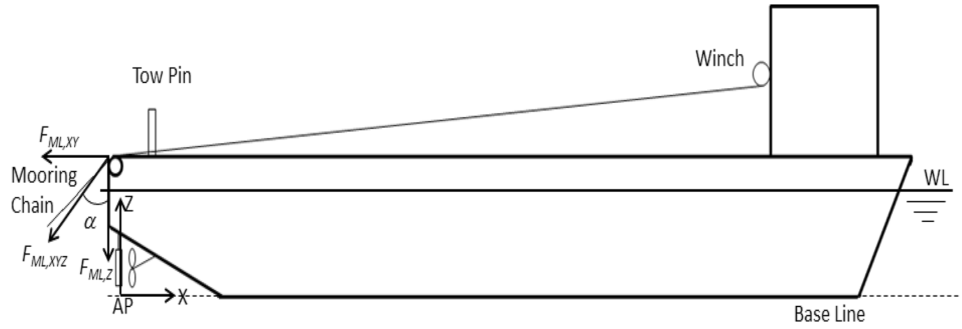
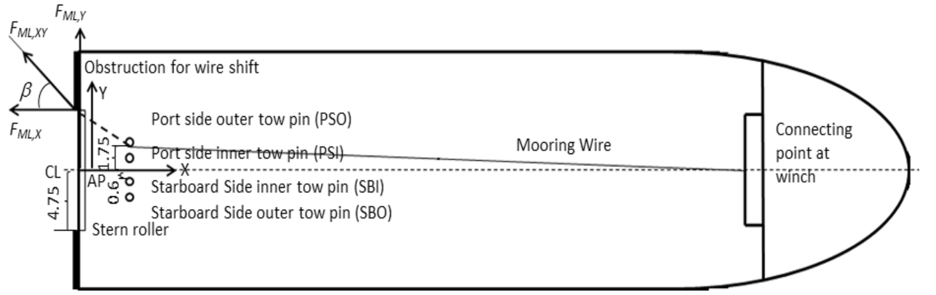


Fig. 5 Example of heeling lever arm (in *red*) and righting lever arm (in *blue*) for Bourbon Dolphin. The numerical values in the figure are for the BD vessel for a mooring load of 100 tons, a 38° angle between the mooring load and vertical axis, a 48° angle of attack, a mooring line that is passing through the port side outer and inner tow pins, 35-knot wind coming from the port, 3-knot current coming from the starboard side, and vessel drifting in the sway direction at 1 knot

Fig. 6 **a** Side view. **b** Plan view. The figures are not in scale. Example AHV: Bourbon Dolphin vessel and its coordinate and force system



(a) Side view.



(b) Plan view. The figures are not in scale.[a]

$$Z_{\mathrm{TP}} = z_{\mathrm{DECK}} \cos(\theta_{\mathrm{YZ}}) - y_{\mathrm{TP}} \sin(\theta_{\mathrm{YZ}}) \tag{14}$$

$$Y_{\mathrm{SR}} = y_{\mathrm{SR}} \cos(\theta_{\mathrm{YZ}}) + z_{\mathrm{DECK}} \sin(\theta_{\mathrm{YZ}}) \tag{15}$$

where z_{DECK} is the vertical distance between the centre of gravity and the deck, y_{TP} is the distance between the tow pin and vessel centreline (which depends on the line position with respect to the tow pins), y_{SR} is the distance between the vessel centreline and the mooring loading touch point at the transom (the maximum value is limited by the vessel transom shape), and θ_{YZ} is the vessel's heeling angle.

The heeling moment due to the mooring load is calculated as

$$M_{\mathrm{ML}} = F_{\mathrm{ML,Y}} \cdot Z_{\mathrm{TP}} + F_{\mathrm{ML,Z}} \cdot Y_{\mathrm{SR}} \tag{16}$$

where $\mathrm{F}_{\mathrm{ML,Y}}$ and $\mathrm{F}_{\mathrm{ML,Z}}$ are calculated by the following formulas:

$$F_{\mathrm{ML,Z}} = F_{\mathrm{ML,XYZ}} \cdot \sin(\alpha) \cdot \cos(\beta) \tag{17}$$

$$F_{\mathrm{ML,Y}} = F_{\mathrm{ML,XYZ}} \cdot \sin(\alpha) \cdot \sin(\beta). \tag{18}$$

5.3.1 Heeling moment due to the transverse component of the current force

The heeling moment due to current is defined as

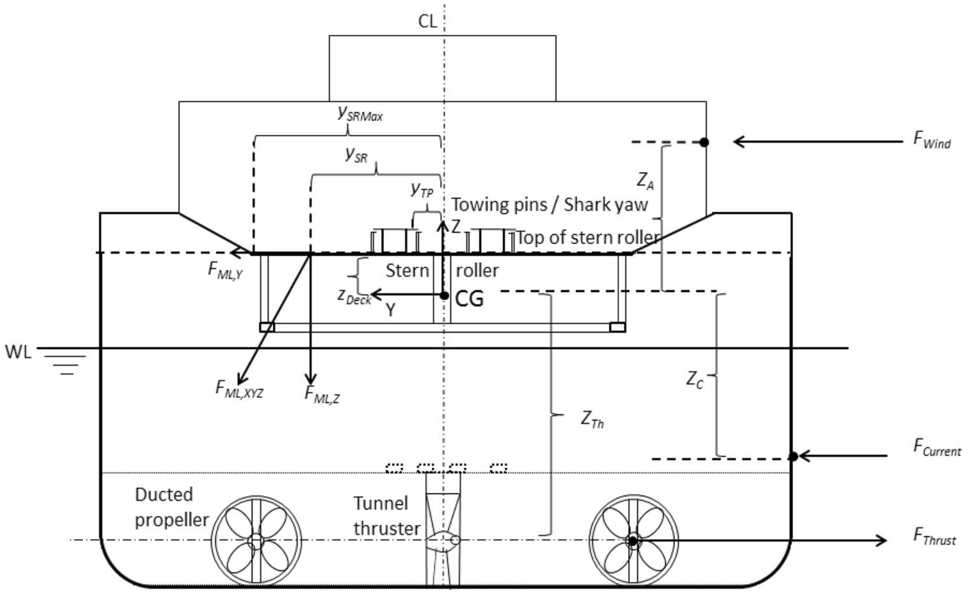


Fig. 7 Transom of the AHV vessel (BD vessel) seen from aft. The forces and lever arms are shown

$$M_C = f(v_C, \psi, \psi_C, A_{UP}, v, Z_C, \mathrm{CG}, C_{D,\mathrm{water}}) \tag{19}$$

where M_C is the heeling moment due to the current, v_C is the current velocity, ψ is the vessel heading, ψ_C is the current heading, A_{UP} is an underwater projected area, v is vessel sway velocity, Z_C is the distance between the centroid of the underwater projected area and the vessel CG, and $C_{D,\mathrm{water}}$ is the vessel's transverse drag coefficient in water (see Fig. 7). The variables A_{UP}, Z_C and $C_{D,\mathrm{water}}$ vary with respect to the vessel heeling angle, and this variation is not considered in this study. The heeling moment due to the current is considered to be constant for all heeling angles:

$$F_C = \frac{1}{2} \cdot \rho_{\mathrm{water}} \cdot A_{UP} \cdot v_{R,C}^2 \cdot C_{D,\mathrm{water}} \tag{20}$$

$$M_C = F_C.Z_C \tag{21}$$

where $v_{R,C}$ is the relative lateral velocity between the vessel and the current, and F_C is the current force.

5.3.2 *Heeling moment due to the transverse component of the thrust force*

The heeling moment due to the thruster is defined as

$$M_{Th} = f(M_{Th}, Z_{Th}). \tag{22}$$

The resultant thruster moment is defined as

$$M_{Th} = F_{Th} \cdot Z_{Th} \tag{23}$$

where M_{Th} is the heeling moment due to the transverse thrust component,F_{Th} is the vessel's transverse thrust force, and Z_{Th} (see Fig. 7) is the distance between the centre of the thruster and the vessel CC.

However, to calculate M_{Th}, it is essential to calculate the total thrust force, which is defined as

$$F_{Th} = f(v, F_C, F_{GW}, F_{ML,Y}) \tag{24}$$

where v is the vessel sway velocity (see Fig. 8), F_C is the current force, F_{GW} is the gust wind force, and $F_{ML,Y}$ is the mooring force component in the transverse direction.

The F_{Th} is calculated by considering the equilibrium between the external force and thruster force. The resultant total F_{Th} is defined as

$$F_{Th} = F_C + F_{GW} + F_{ML,Y}. \tag{25}$$

5.3.3 *Heeling lever arm*

The total heeling moment M_T due to the current, wind, thruster and mooring load is calculated as

$$M_T = M_{ML} + M_C + M_{GW} + M_{Th}.$$

Moreover, the vessel is subject to the heeling moment due to the rudder and propulsion forces. The influences of these parameters are not considered in this study. The M_T is scaled to the heeling lever arm by the following expression:

$$h_H = \frac{M_T}{1000 \cdot g \cdot \Delta} \tag{26}$$

where h_H is total heeling lever arm, g is the acceleration of gravity, and Δ is the vessel displacement in tons. An example of the heeling lever arm (red line) is illustrated in Fig. 5.

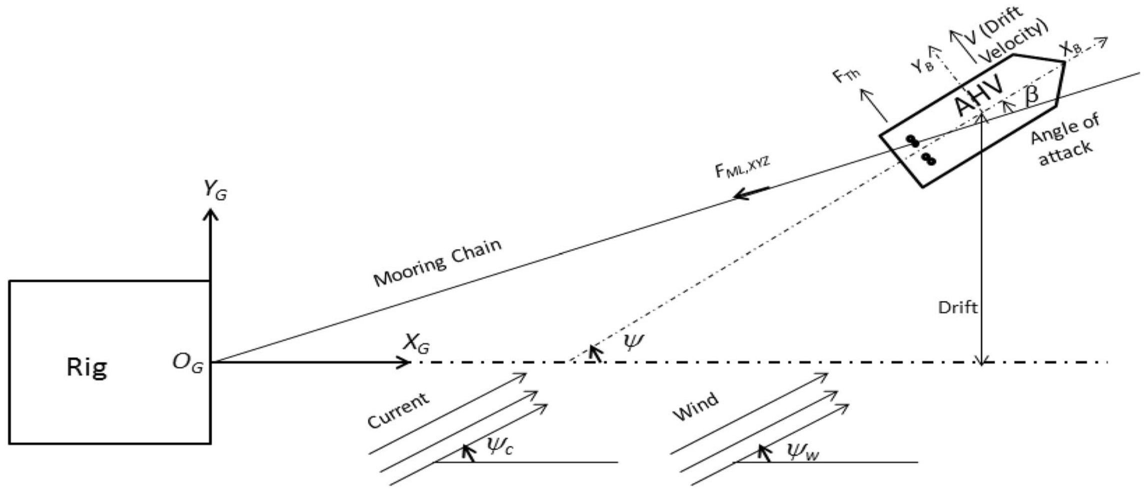


Fig. 8 Coordinate systems in AHO

Table 1 Principle particulars of the example AHV

Parameter	Value
Overall length	LOA = 75.20 m
Length between particulars	LBP = 64.91 m
Breadth	$B = 17.00$ m
Draft (mean)	$T = 6.50$ m
Displacement	$\Delta = 5332$ tons
Depth	$D = 8.00$ m
Bollard pull capacity	180 tons
Winch capacity	400 tons
Nearby down flooding points	Port side: (0.3, 7.56, 8.86) m Starboard side: (0.3, −7.56, 8.86) m

5.4 Assessment of the vessel's static heeling angle

The angle at which the first intercept between the righting lever arm and heeling lever arm occurs is called the static heeling angle. As described in Sect. 4.1, due to the influence of the operational parameters, the vessel is subjected to the heeling lever arm h_H, the righting lever arm GZ, and the static heeling angle ϕ_0, as shown in Fig. 5.

6 Case study

The Bourbon Dolphin vessel is considered as a case study for a vessel stability assessment. The vessel's stability depends on the heeling and righting moments. The principal particulars of the Bourbon Dolphin vessel are listed in Table 1. Load condition 2.1 (condition without roll reduction tank) from the Bourbon Dolphin accident report [1] is considered as the initial loading condition. For the purpose of simplification, the free surface correction is considered to be a constant. The rolling natural period of the vessel is computed using Shipx [50] software, and its value is 15.1 s (as shown in Table 2). The static stability characteristics that are associated with the initial loading condition are shown in Table 2. In this section, the vessel's stability during an accident scenario is assessed, and the effects of the operational parameters on the vessel's stability are studied based on the methods described in Sects. 4 and 5.

6.1 Vessel stability assessment during the Bourbon Dolphin vessel accident situation

A case study is conducted to show the effect of the mooring load on the AHV stability during AHOs. During AHOs, the vessel is subject to a mooring load, which is in the range of 30 tons to the maximum bollard pull (approximately 200 tons). The environmental loads together with the mooring load can lead to a capsizing scenario. Hence, miscalculations and misjudgements that are related to the vessel's stability could lead to fatal situations. Therefore, a proper criterion is required for assessing the stability. In this section, the Bourbon Dolphin vessel accident has been analysed using the criteria proposed in Sects. 4 and 5.

6.1.1 Event background

6.1.1.1 Normal condition as per rig move procedure In the analysis phase, the allowable environmental conditions for safe operations were assessed by considering that the wind, wave and current acts from the same direction. Table 3 presents the allowable environmental conditions defined in the rig move procedure. When the angle of attack is large, even a small magnitude of the mooring load can create a high transverse overturning moment. These

Table 2 Vessel stability characteristics without accounting for the mooring loads

Parameter	Value
Displacement	4540.100 tons
Centre of gravity	(32.03, 0, 6.9) m
Draft at amid ship	5.74 m
Initial trim	0.11° (forward)
Metacentre	1.05 m
Initial heel	0°
Projected XZ area above waterline	653.28 m2
Centre projected XZ area above WL	6.16 m
Projected XZ area below waterline	390.42 m^2
Centre projected XZ area below Z	−2.83 m
Down flooding angle	22.75°
Vanishing angle	48.12°
Maximum righting lever arm (GZ_{Max})	0.29 m
Angle at maximum GZ occurs	19°
Block coefficient	0.68
Natural rolling period	15.1 s

moments makes the AHV more vulnerable from a stability point of view. In the analysis phase, it was implicitly assumed that the mooring line is positioned in line with the AHV heading (or the centreline of the vessel), which leads to a zero angle of attack. In a real-time application, this alignment can only occur by implementing efficient vessel handling skills. Based on the above assumptions, the allowable operating parameters were estimated as listed in Table 4. During the hazard and operability study, the maximum tension was estimated to be 200 tons, which is documented in the rig move procedure.

6.1.1.2 Accident condition During the accident on 12th April 2007, the Bourbon Dolphin vessel had run out all of the chain (approximately 1820 m length, of which 900 m was 84-mm chain size and 920 m was 76-mm chain size) for the last anchor (no. 2) before it capsized. In this situation, the vertical angle α (the angle between the mooring line and the vertical plane) was 38°. Before the BD accident, the following actions were conducted by the vessel's master: applying a transverse thrust force towards the port side, lowering the starboard inner tow pin, and changing the vessel heading towards the port side. More details can be found in Lyng et al. [1]. The environmental and operational parameters for an accident scenario are listed in Tables 3 and 4. The accident report states that the tension on the winch before the starboard side inner tow pin depressed was approximately 295 tons, but it increased suddenly to 330 tons just before the vessel rolled over.

Table 3 Environmental parameters

	Notation	Normal condition	Accident scenario	Units
Wave	H_s	2.2	3.5	m
	T_p	8.5	7	s
	ψ_w	270	270	Degrees
Wind	V_w	10	18	m/s
	ψ_w	270	270	Degrees
Current	V_c	1	1.5	m/s
	ψ_c	270	270	Degrees

6.1.2 Comparison of normal and accident conditions from the perspective of stability

The stability assessment is conducted for both the normal and accident conditions with the help of the proposed stability criteria. The vessel's static heeling angle, capsizing angle, and critical rolling angle are presented in Table 5. Figure 9 shows the static stability curves for both conditions. During the accident condition, the vessel is subject to an overturning moment due to the $F_{ML,XYZ}$ and angle β. As a result, the higher overturning moment acting on the vessel increases the static heeling angle and reduces the capsizing angle as well as the critical rolling angle. The Jonswap wave spectrum is considered for assessing dynamic rolling angle in the operating sea state. The results show that the Bourbon Dolphin vessel satisfies the stability criteria under normal conditions, but not in the accidental condition. For a normal condition (see Table 4), it can be concluded that a suitable factor of safety should be considered to obtain the allowable rolling angle from the critical rolling angle. For an accidental condition (see Table 4), the vessel's significant response (Eq. 4) is 6°, and its extreme wave response (Eq. 6) is 12.7°. From this study, it can be concluded that the extreme wave response can be used for the vessel's dynamic rolling angle computation. Furthermore, it can be noted from the Table 5 that the vessel does not satisfy the safety criteria even when considering the allowable rolling angle to be the same as the critical rolling angle (no safety margin). Therefore, a large magnitude of $F_{ML,XYZ}$ and angle β is found to be the critical parameters to contributing to capsizing during the accident.

6.2 Sensitivity analysis

The vessel's stability depends on the mooring parameters, the mooring line position with respect to the tow pins, the environmental parameters, and the thruster force in the transverse direction, as described in Sect. 4. Hence, it is vital to assess clearly the influence of these parameters on the stability. The static heeling angle, capsizing angle, and

Table 4 Operational parameters

	Notation	Normal condition	Accident scenario	Unit
Mooring line parameters (see Fig. 6)	$F_{\mathrm{ML,XYZ}}$	200	200	Tonnes
	α	38	38	Degrees
	β	0	−60	Degrees
Line position between tow pins (see Fig. 6)	T_{P1}	SBI	PSO	
	T_{P2}	SBO	SBO	
Thrust force in the transverse direction	$T_{\mathrm{H,Y}}$	213	507	kN

Table 5 Vessel static heeling angle, capsizing angle, and critical rolling angle for normal and accident conditions

	Normal	Accident	Units
Static heeling angle	−1.7 (port)	12.3 (starboard)	Degrees
Capsizing angle	46.3	31.5	Degrees
Critical rolling angle	30.2	10.7	Degrees
Dynamic rolling angle	8.0	12.7	Degrees
Safety limit	Satisfied	Not satisfied	
Capsizing	Does not occur	Occurs	

critical rolling angle are computed for the different operational parameters discussed in Sect. 1. Moreover, in this study, the influence of the vessel's transom shape (see Fig. 7) is accounted for. In this section, the vessel's heading (ψ) is considered to be zero degree which implies that the wind direction (ψ_{W}) is the same as the relative heading between the vessel and the wind. Similarly, the current direction (ψ_{C}) is the same as the relative heading between the vessel and the current. The sensitivity study had been performed by considering wide variation in the operational parameters. Table 6 presents the selected variation of the operational parameters.

6.2.1 *Mooring parameter influence*

The first parametric study that relates to the mooring line investigates the effects of angles α and β on the vessel's static heeling angle, critical rolling angle and capsizing angle, while considering that all of the other influencing parameters remain constant (see Fig. 10). Figure 10 shows that for a given small angle of β, the effect of angle α on the vessel's static heeling and critical rolling angles is insignificant. However, the effect is marginally significant for higher angles of β. Figure 10 further shows that for increased β values, the vessel is subject to a larger static heeling angle and smaller capsizing angle, which, in turn, yields a smaller critical rolling angle. Hence, the effect of the β values on the vessel's stability is significant irrespective of the α values.

The second parametric study related to the mooring line investigates the effect of the mooring line position with respect to the tow-pin configuration (see Fig. 6) and angle β on the vessel's static heeling angle, critical rolling angle, and capsizing angle, while considering that all of the other influencing parameters remain constant (see Fig. 11). Figure 11 shows that when the direction of the mooring line is toward the port side (β <0) and the line is positioned between PSO-PSI/PSO-SBI/PSO-SBO (see Table 6), the

Fig. 9 Vessel righting lever arm and heeling lever arm comparison for the BD vessel in normal and accidental conditions

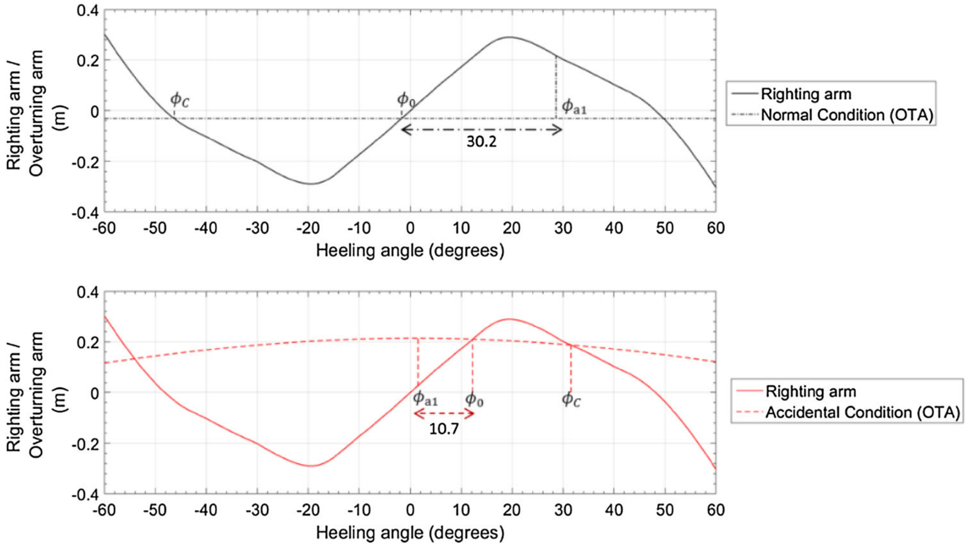


Table 6 Ranges of the influencing parameters for simulation purposes

Parameter	Data range
Mooring load ($F_{\mathrm{ML,XYZ}}$)	75–180 tons
Angle between mooring line and vertical axis (α)	20° to 60°
Angle of attack (β)	−90° to 90°
Wind velocity (v_{W})	0 to 40 knots
Wind direction (ψ_{W})	90° and 270°
Current velocity (v_{C})	0 to 4 knots
Current direction (ψ_{C})	90 and 270°
Line position with respect to tow pins (Tow-pin configuration)	PSO-PSI, PSO-SBI, PSO-SBO, PSI-SBI, PSI-SBO and SBI-SBO
Sway velocity (v)	−4 to 4 knots
Sea state	H_{S} and T_{P} combination[a]

PSO port side outer tow-pin, *PSI* port side inner tow-pin, *SBO* starboard side outer tow-pin, *SBI* starboard side inner tow-pin

[a] The sea states (combination of H_{S} and T_{P}) should be used for assessing the vessel's maximum dynamic rolling angle in normal operational conditions. However, this study focusses primarily on assessing the vessel's static heeling angle and critical rolling angle. Therefore, a parametric study related to the operating sea states was not conducted

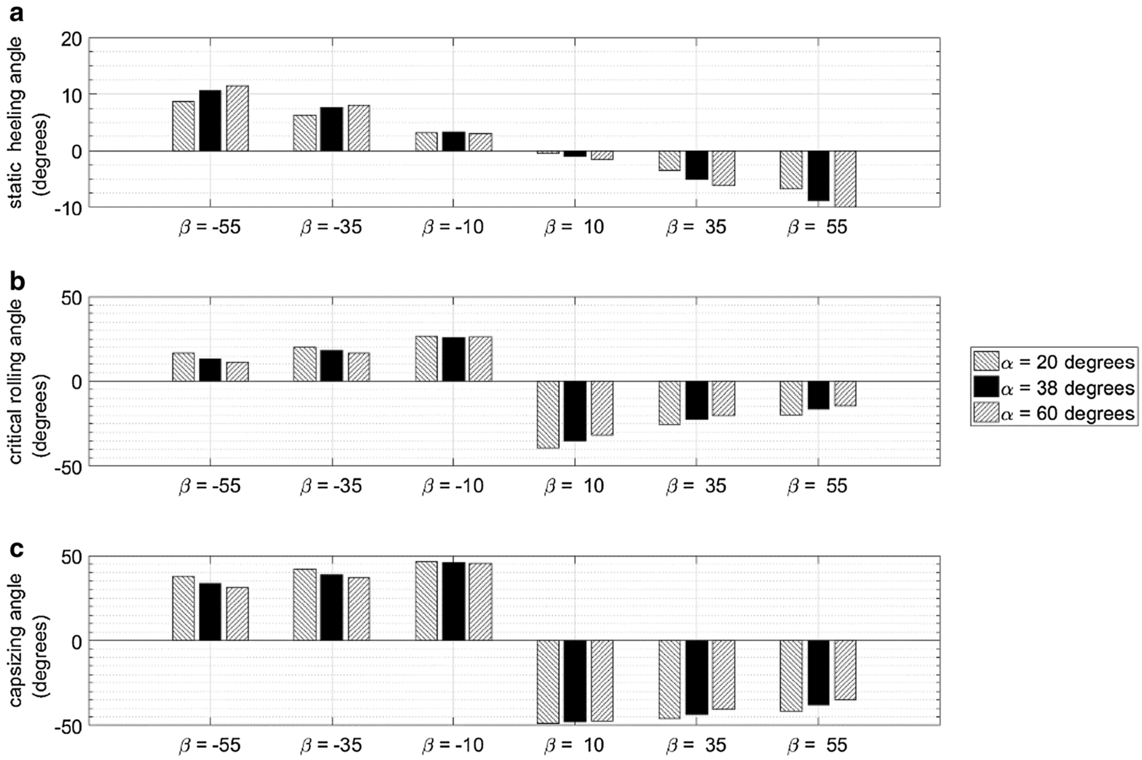


Fig. 10 **a** Static heeling angle, **b** critical rolling angle in waves, **c** capsizing angle for various β and α for $F_{\mathrm{ML,XYZ}} = 100$ tons, $v_{\mathrm{W}} = 0$ knots, $\psi_{\mathrm{W}} = 90°$, $v_{\mathrm{C}} = 0$ knots, $\psi_{\mathrm{C}} = 90°$, line position (PSO-PSI) and $v = 0$ knots

vessel's static heeling angle and the critical rolling angle remain the same. Similarly, the effect is the same when the line is positioned between PSI-SBI/PSI-SBO (see Table 6). Hence, the position of the line with respect to the tow pin plays a critical role in the stability. The reason is that the vertical component of the mooring load is constant at a specified angle α, which does not depend significantly on the angle β. The variation in the overturning moment due to the vertical component of the mooring load depends on the lever. The lever depends on the angle β until the line reaches the obstruction at the transom. Whenever the line reaches the obstruction at the transom, the lever associated

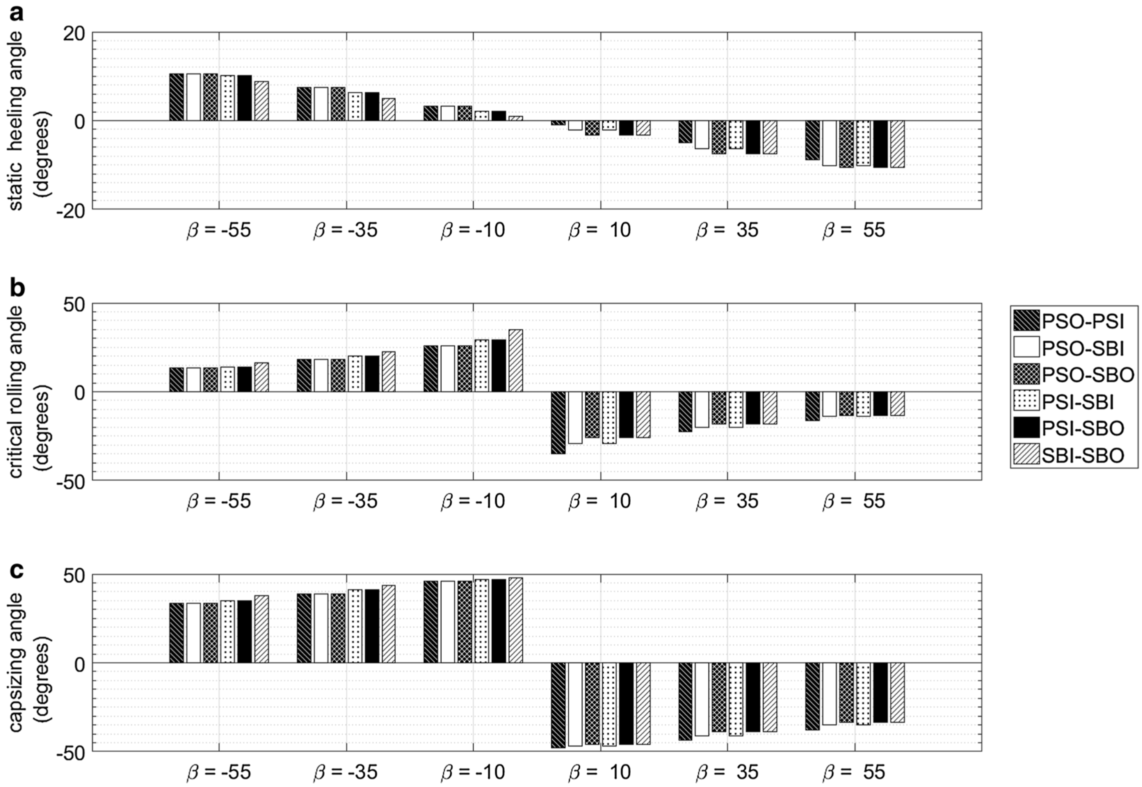


Fig. 11 **a** Static heeling angle, **b** critical rolling angle in waves, **c** capsizing angle for various β and line position for $F_{\mathrm{ML,XYZ}} = 100$ tons, $\alpha = 38°$, $v_{\mathrm{W}} = 0$ knots, $\psi_{\mathrm{W}} = 90°$, $v_{\mathrm{C}} = 0$ knots, $\psi_{\mathrm{C}} = 90°$, and $v = 0$ knots

with the vertical component of the mooring load is constant that leads to a constant heeling moment. However, there is a small difference in the overturning moment due to the variation in the transverse component of the mooring load, which comes from the variation in the angle β. This relationship leads to a smaller variation in the static heeling angle for a larger β. Therefore, approximately, the overturning moment induced from the vertical and transverse components of the mooring load is same. However, for a small angle β, there is a significant difference in the heeling moment that is induced from the vertical component of the mooring load. When the direction of the mooring line is toward the port side ($\beta < 0$), from a stability perspective, it is wise to position the line between the SBI-SBO tow pins. Similarly, when the direction of the mooring line is toward the starboard side ($\beta > 0$), it is wise to position the line between the PSO-PSI tow pins.

The third parametric study related to the mooring line investigates the effect of the line position with respect to the tow-pin configuration (see Fig. 6) and angle α on the vessel's static heeling angle, critical rolling angle, and capsizing angle, while considering that all the other influencing parameters remain constant (see Fig. 12). Figure 12a shows that for a chosen tow-pin configuration (PSO-PSI), the vessel's static heeling angle increases from 8.4° to 10.6° for a given angle α, which ranges from 20° to 60° Similarly, Fig. 12b shows that the critical rolling angle in the waves reduces from 17° to 12.9°. The effect of angle α on the critical rolling angle is significant, whereas the effect of α on the static heeling angle is marginally insignificant.

6.2.2 *Effects of the wind and current*

This parametric study examines the influence of the wind and current on the vessel's static heeling angle, critical rolling angle, and capsizing angle, while considering that all the other influencing parameters remain constant (see Fig. 13). For a specified current velocity ($v_{\mathrm{C}} = 3$ knots) and variable wind velocity of -40 knots ($\psi_{\mathrm{W}} = 270°$, wind direction from port side) to 40 knots ($\psi_{W} = 90°$, wind direction from starboard side), the vessel static heeling angle varies from 6° to 17.2°, and the critical rolling angle varies from 20.8° to 2.4°. Similarly, for a specified wind velocity ($v_{\mathrm{W}} = 40$ knots) and variable current velocity of -3 knots ($\psi_{\mathrm{C}} = 270°$, current direction from port side) to 3 knots (at $\psi_{\mathrm{C}} = 90°$, current direction from starboard side), the vessel static heeling angle varies from 13.9° to 17.2° and the critical rolling angle varies from 7.5° to 2.4°. For a combined situation, when the wind

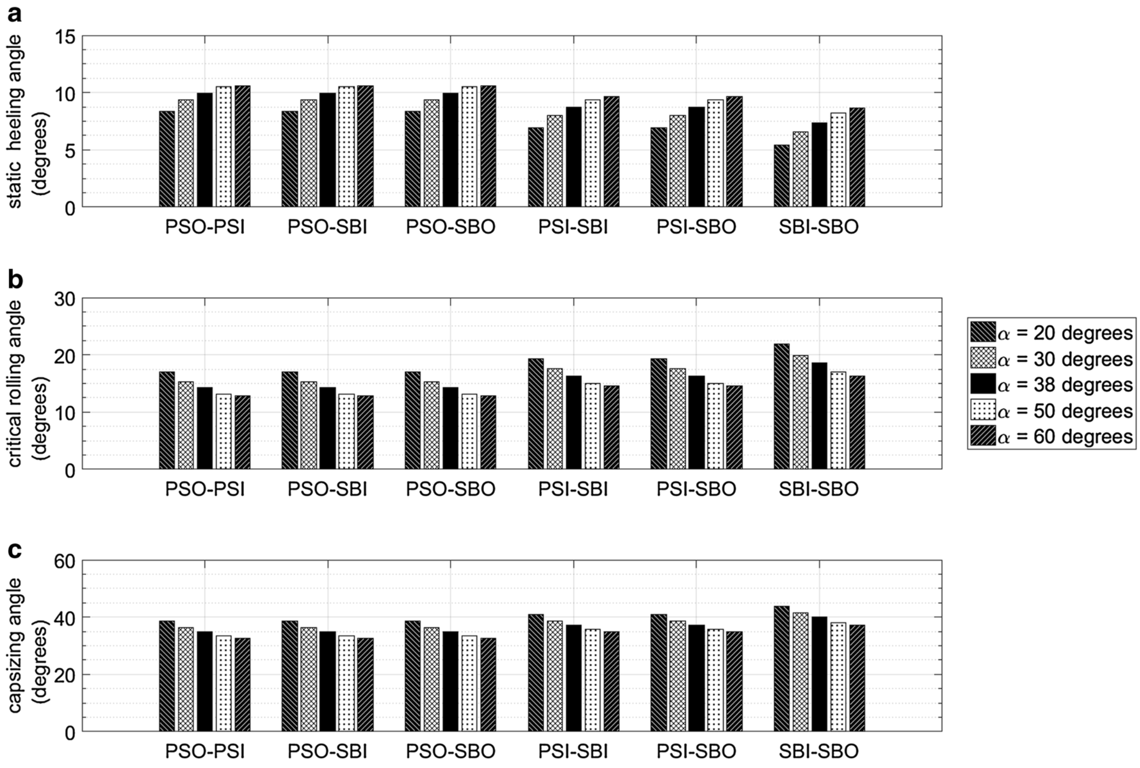


Fig. 12 **a** Static heeling angle, **b** critical rolling angle in the waves, **c** capsizing angle for a set of α for $F_{ML,XYZ} = 100$ tons, $\beta = -48°$, $v_W = 0$ knots, $\psi_W = 90°$, $v_C = 0$ knots, $\psi_C = 90°$, and $v = 0$ knots

is coming from the port side, the mooring load direction is towards the port side, and the current direction is towards the starboard side. The vessel requires a large thrust force to keep the vessel in a stationary (drift velocity is zero) position. In this situation, the direction of the heeling moment induced from the thruster is in the same direction as the heeling moment induced by the mooring load. As a result, the vessel is subjected to a large heeling moment. This circumstance further leads to a large static heeling angle and a lower critical rolling angle in the waves.

6.2.3 Effect of the vessel's sway velocity

This parametric study examines the effect of the vessel's drift velocity and direction (velocity in the sway direction) for fixed wind and current velocities, variable wind and current directions on the vessel's static heeling angle, critical rolling angle, and capsizing angle, while considering that all of the other influencing parameters remain constant (see Fig. 14). For a current with a velocity $v_C = 3$ knots from the starboard side, and the mean wind with a velocity $v_W = 35$ knots from the starboard side and the vessel drift with a velocity of $v = -3$ knots towards the starboard side, the vessel capsize without any waves. The reason is that the direction of the resulting heeling moment induced from the current, wind, and thruster acts in the same direction as the heeling moment induced from the mooring load. In contrast to the above, when the wind and current act opposite to the horizontal component of the mooring load ($F_{ML,Y}$), i.e., the wind direction and current direction are 270° (coming from port) and the vessel drifts with $v = 3$ knots (towards port side), the vessel will have a small static heeling angle and more critical rolling angles in the waves. The reason is that the direction of the resultant overturning moment induced from the current, wind, and thruster acts in the opposite direction to the overturning moment induced from the mooring load. Hence, the total resultant overturning moment is lower.

6.2.4 Magnitude of the mooring load influence

The effect of the mooring load on the stability is investigated for a variable wind and current directions and variable angle β while considering that all of the other influencing parameters remain constant (see Fig. 15). Table 7 shows that when $\beta = -48°$ (mooring line direction toward the port side) and ψ_W and ψ_C are from the starboard side ($\psi_W = \psi_C = 90$), the vessel is subject to a large static heeling angle. Similar to this situation, when $\beta = 48°$ (mooring line toward the starboard side) and ψ_W and ψ_C are from the port side ($\psi_W = \psi_C = 270$), the vessel is subject to a large static heeling angle. In fact, both

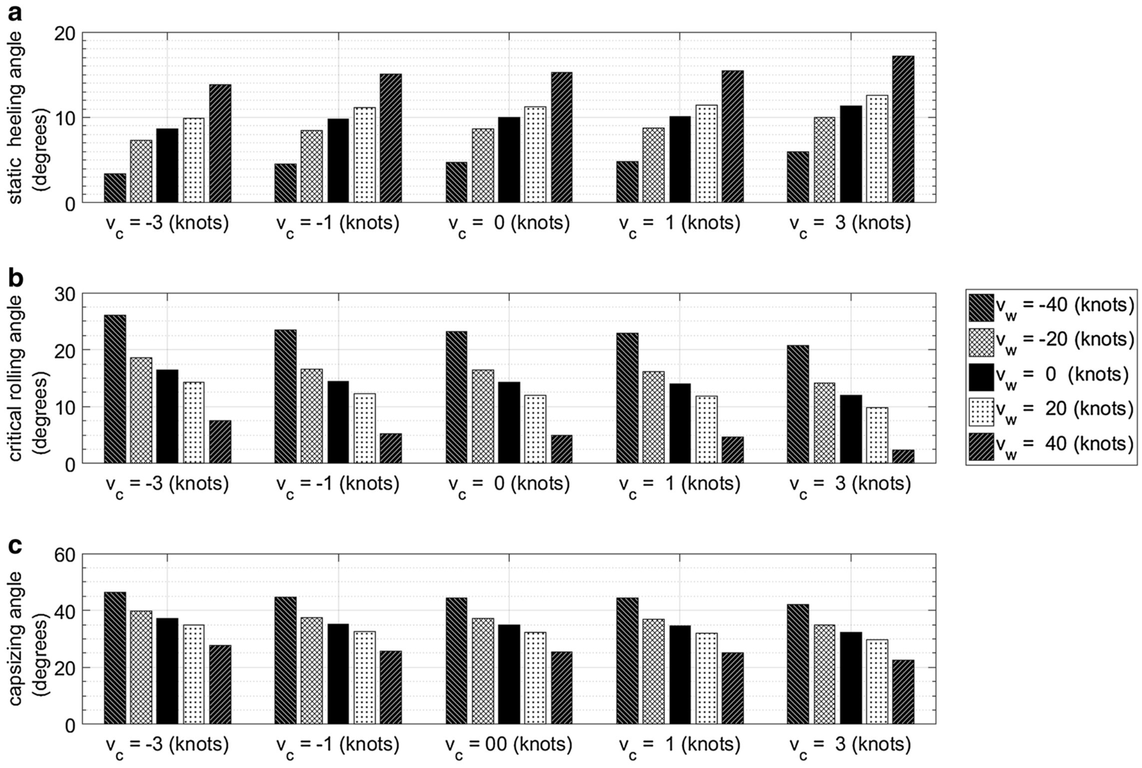


Fig. 13 **a** Static heeling angle, **b** critical rolling angle in the waves, **c** capsizing angle for $F_{\mathrm{ML,XYZ}} = 100$ tons, $\alpha = 38$, $\beta = -48°$, tow-pin configuration (PSO-PSI), and $v = 0$ knots

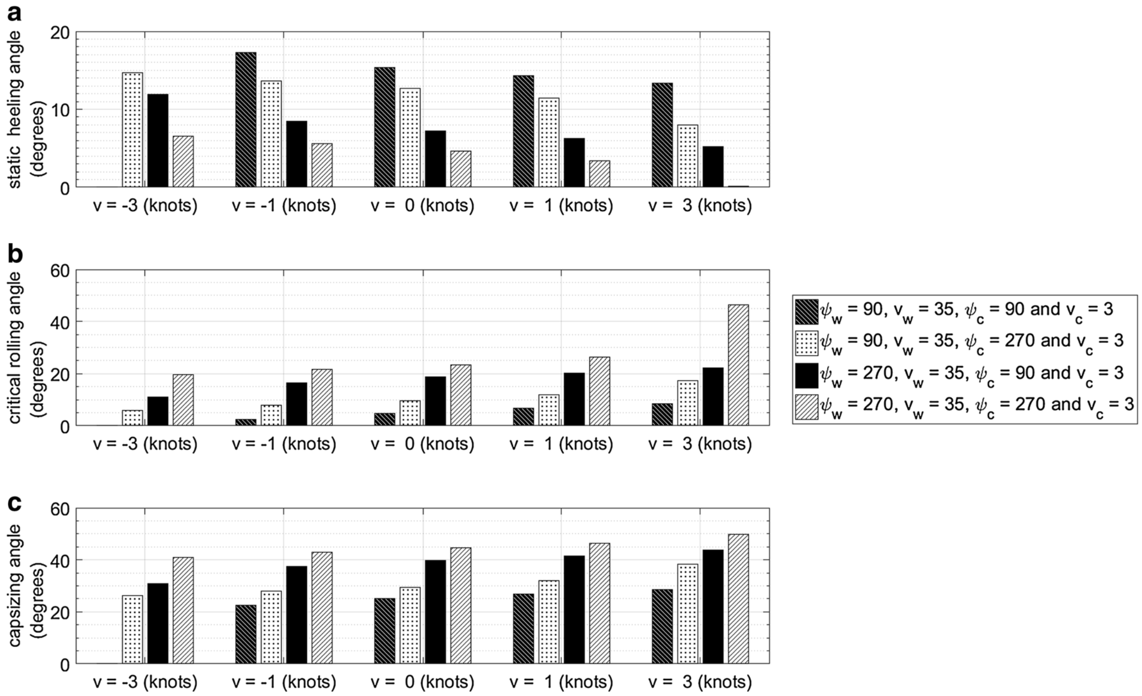


Fig. 14 **a** Static heeling angle, **b** critical rolling angle in the waves, **c** capsizing angle for $F_{\mathrm{ML,XYZ}} = 100$ tons, $\alpha = 38°$, $\beta = -48°$, $v_{\mathrm{W}} = 35$ knots, and $v_{\mathrm{C}} = 3$ knots and tow-pin configuration (PSO-PSI)

cases are symmetric, wherein the only difference is the tow-pin configuration. In the second situation, if the mooring line is positioned between SBI and SBO (see Table 6), and then, the magnitudes of the static heeling angle are the same as those from the first situation, while the mooring line is positioned between PSO and PSI. For specified angles β, ψ_W, and ψ_C, it can be noted from Fig. 15 that the increased mooring load causes an increase in the vessel's static heeling angle. Moreover, Table 7 shows that capsizing can occur only for a combination of the mooring load and wind and current forces (without considering the influence of waves).

6.3 AHV vessel's rolling angle assessment in the waves during the operation

Due to the vessel's motion and stability limitations, AHOs in industrial practice is not conducted beyond a significant wave height of 3.5 m. The vessel's rolling angle is calculated based on the vessel's response in irregular waves, which is more practical. For a significant wave height of 3.5 m, the vessel's extreme wave response (Eq. 6) is estimated to be 12.7°. The vessel's critical rolling angle is a function of the vessel's static heeling angle and capsizing angle, which depends on the heeling moment that is induced from the operating parameters and the righting moment due to the vessel's geometry, as described in Sect. 5. Systematic analyses have been performed for a selected set of operational parameters to assess the stability. For the selected set of parameters, a set of static heeling angle, capsizing angle and critical rolling angle exists. However, due to the variations in the heeling moment (variations in the operational parameters), the static heeling angle and capsizing angle of the vessel vary. These variations lead to a variation in the critical rolling angle. By considering the selected variations in the operational parameters (as shown in Table 6), the relationship between the vessel's static heeling angle and capsizing angle and between the maximum critical rolling angle and static heeling angle are established, which are shown in Fig. 16a, b, respectively.

Thus, the vessel can be safer during the operation as long as the rolling angle in the operating sea state is within the limits of the critical rolling angle. In this study, the vessel's rolling angle is predicted for a significant wave height of 3.5 m. Following the same procedure, the vessel's rolling angle can be predicted for higher or lower significant wave heights (sea states). When the vessel operates in higher sea states, the vessel's actual rolling angle increases. A similar safety margin is possible to achieve by reducing the vessel's critical static heeling angle. Similarly, when the vessel operates in a lower sea state, the vessel's actual rolling angle decreases. Hence, the vessel is safe to be operated for higher static heeling angles.

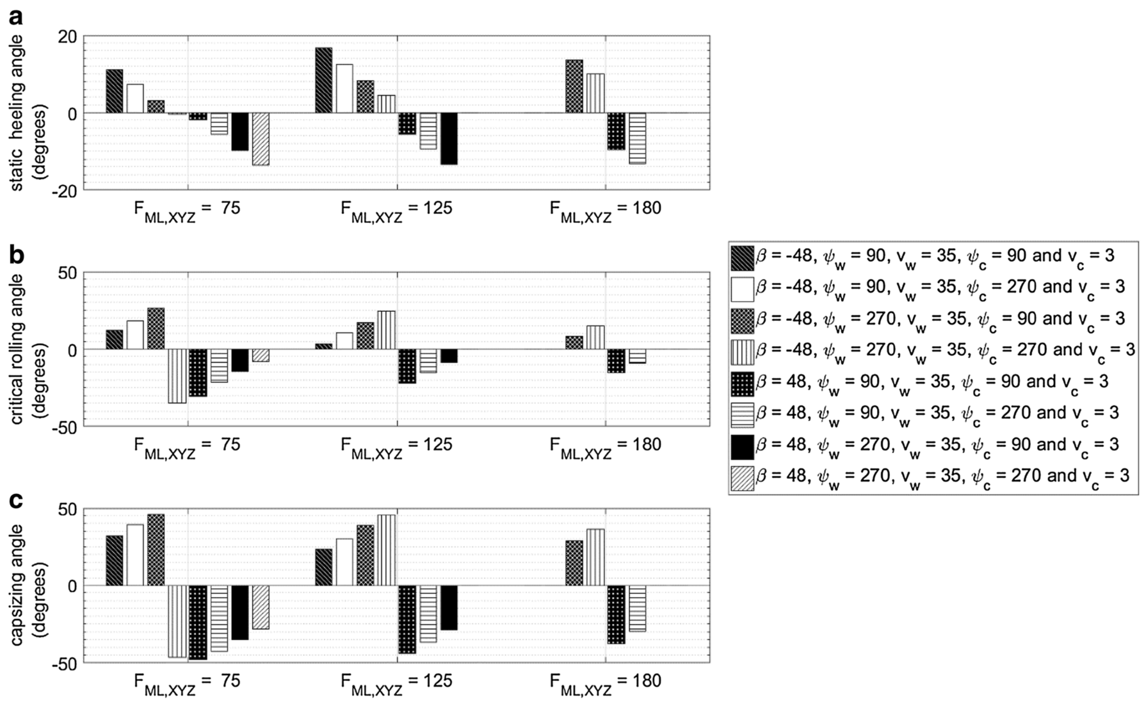


Fig. 15 **a** Static heeling angle, **b** critical rolling angle in the waves, **c** capsizing angle for $\alpha = 38°$, $\beta = 35$ knots, $v_W = 35$ knots, $v_C = 2$ knots, and tow-pin configuration (PSO-PSI)

Table 7 Vessel static heeling angle, capsizing angle, and critical rolling angle

$v_W = 35$, $v_C = 3$, $v = 2$ knots→angles				Static heeling	Capsizing	Critical rolling
$F_{ML,XYZ} = 75$	$\beta = -48$	$\psi_W = 90$	$\psi_C = 90$	11.16	32.134	12.13
			$\psi_C = 270$	7.2677	39.104	18.421
		$\psi_W = 270$	$\psi_C = 90$	3.1318	46.096	26.546
			$\psi_C = 270$	−0.4658	−46.407	−34.988
	$\beta = 48$	$\psi_W = 90$	$\psi_C = 90$	−1.9508	−47.611	−30.657
			$\psi_C = 270$	−5.5745	−42.547	−21.326
		$\psi_W = 270$	$\psi_C = 90$	−9.7787	−34.976	−14.421
			$\psi_C = 270$	−13.579	−28.028	−8.0066
$F_{ML,XYZ} = 180$	$\beta = -48$	$\psi_W = 90$	$\psi_C = 90$	C*	C*	C*
			$\psi_C = 270$	C*	C*	C*
		$\psi_W = 270$	$\psi_C = 90$	13.657	28.642	8.169
			$\psi_C = 270$	9.8994	36.468	14.83
	$\beta = 48$	$\psi_W = 90$	$\psi_C = 90$	−9.5872	−37.633	−15.487
			$\psi_C = 270$	−13.256	−29.676	−9.0525
		$\psi_W = 270$	$\psi_C = 90$	C*	C*	C*
			$\psi_C = 270$	C*	C*	C*

C* stand for capsizing

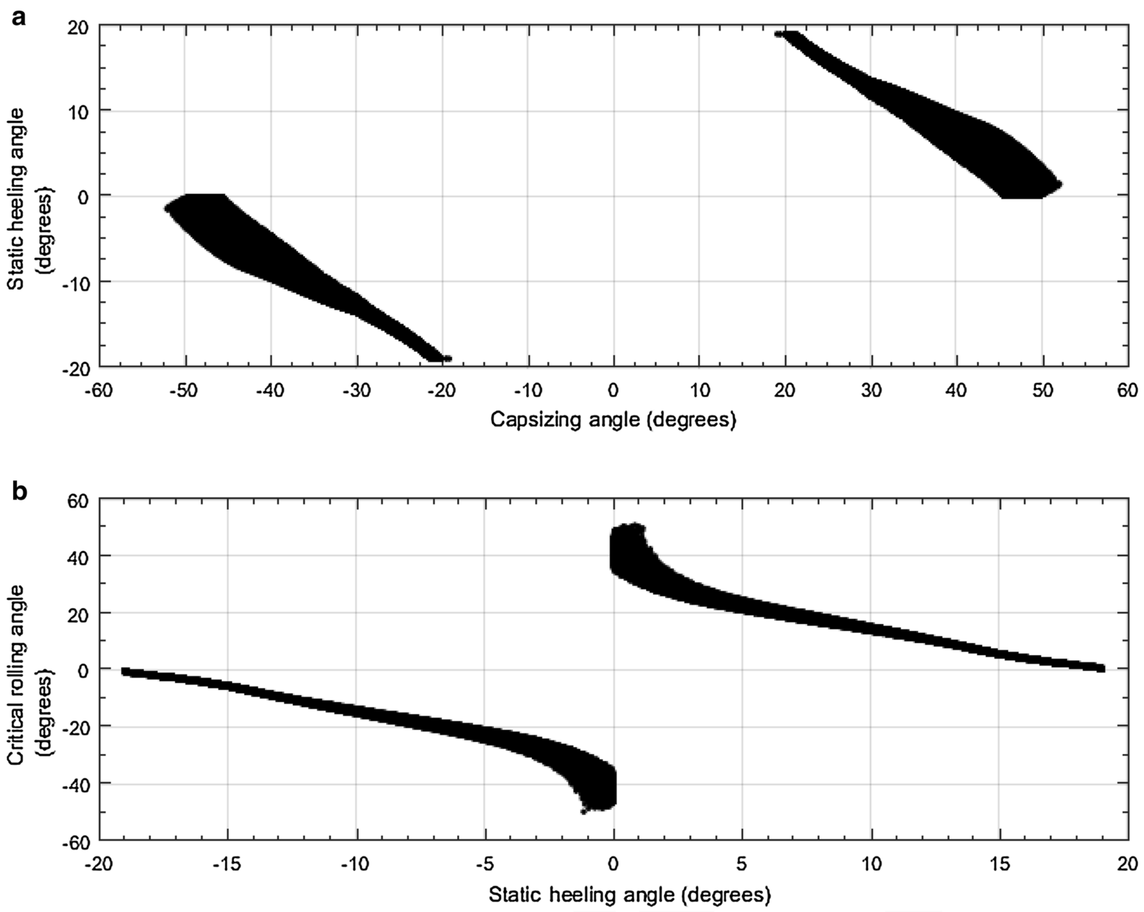


Fig. 16 **a** Relationship between the vessel's capsizing angle and the static heeling angle. **b** Relationship between the critical rolling angle in the waves and the static heeling angle

7 Discussion

AHOs are conducted in a demanding ocean environment that has significant hazards. Therefore, the safety of the people, environment, and assets are the main concern. In principle, safety can be defined as the absence of accidents or failures. Hence, an understanding about the safety or risk can be gained from the detailed investigations of catastrophic accidents, such as the Bourbon Dolphin [1] and Stevns Power [18]. The safety of AHOs can be achieved with adequate design and analysis, operational criteria, operational planning, and execution of the operation, as well as other factors.

For AHVs in a free-floating mode, both intact and damage stability criteria are applicable. In the AHOs mode, the mooring line exerts forces on the AHV and does not significantly affect the stability when the operation is executed within the ideal path (a perfectly aligned heading and mooring line). However, to achieve this ideal path is very demanding. The efficiency of the ship handling depends on the master's skill, knowledge, and experience. Furthermore, it depends on the vessel's manoeuvring capability (position and heading). For preventing large drift-off, angle of attack, and static heeling angle events, the vessel should have sufficient propulsion and thruster capacity (or capability) and stability. These factors should be accounted for in the analysis and planning phase before finalizing the vessel selection.

In principle, the operational design and analysis, as well as the planning, should be accomplished to withstand the vessel's stability for a small variation in operational parameters. An appropriate stability criterion can ensure robustness or capsizing tolerance, i.e., it ensures that small changes in the operational parameters do not escalate into a disproportionate consequence; however, a progressive failure could still lead to delays in the operation or a vessel capsizing. However, in the present practice, there are no proper criteria for assessing the vessel's stability. Furthermore, the practice in the industry is due to accidental events when the stability progresses beyond the threshold (safety margin) level; in these cases, the anchor handling winch's emergency release system should be activated, and if not, a capsizing event might occur. Therefore, suitable criteria are required for assessing the vessel's stability threshold by accounting for all of the operational parameters that are proposed in this paper during the AHOs. The proposed criteria provide the ship with sufficient stability to withstand variations in the operational parameters and unexpected mooring line deviations with respect to the desired direction, as well as sufficient time to implement emergency or corrective measures when necessary.

During AHOs, the capsizing event might occur due to normal uncertainties, accidental actions, and gross errors, as mentioned in Sect. 2.3. In other words, the capsizing can occur due to too small safety factors (no safety margin), which account for the normal uncertainty and variability in the overturning (heeling) moment and restoring moment with respect to the stability criteria. Therefore, while conducting Ultimate Limit State (ULS) checks on the vessel's intact stability, the effect of the overturning moment induced by extreme environmental and operational loads such as mooring loads should be accounted for.

Furthermore, to explain accident event sequences, it is necessary to understand them in view of the human and organizational factors of influence. These accidental events can commonly be traced back to errors in the design, planning, or execution of the operation. Furthermore, the earlier accident investigations show that the accidental actions are significant contributors. In some cases, the accidents have been caused by a lack of knowledge of the operation at large by the vessel master, i.e., an unknown phenomenon (or unknown vessel situation and control strategies) rather than the lack or erroneous use of the available knowledge. Such accidental scenarios are expected to be primarily determined in the design and analysis phase, as well as the planning phase, by risk assessment through accounting for the relevant influences of the operational parameters. In general, the escalation of accidental actions to the large vessel static heeling angle would normally occur progressively and slowly. However, once it reaches the large static heeling angle, the vessel can capsize due to the external influence of the waves. To limit the risk of this undesirable event, it is necessary to avoid errors by those who perform the work in the first place. Furthermore, it is crucial to conduct quality assurance and control from the design to the execution phase of the operation. Additional safety measures (or barriers) should be established while designing and planning the operation, to avoid a capsizing scenario due to an unfavourable condition of the vessel. This goal is possible to attain by means of either defining a margin of safety or changing the vessel heading, the transverse thrust, or the magnitude of the mooring line tension.

Due to the above-mentioned accidental actions and gross errors, if the vessel's path deviates from the ideal path, the mooring line is subjected to the angle of attack β (the angle between the mooring line and the vessel's centreline) with respect to the vessel, which, in turn, can cause a capsizing event to occur. The results from Sect. 6.1 reveal that during the accidental situation, the Bourbon Dolphin vessel was subjected to large β and mooring load. As a result, the vessel was subjected to a large static heeling angle, and it capsized. Therefore, the large β is dangerous from a stability point of view. Depending on the likelihood of such a condition, it might be necessary to consider the contribution of abnormal actions and gross errors on the overturning moment induced by the mooring line in an ALS, which is analogous to the ALS criterion for strength and (damage) stability [12].

In principle, the safety margin defined in ULS does not reflect gross errors. Therefore, it is essential to prevent the gross errors that are associated with AHOs from the analysis and planning phase to the execution phase of the operation. The present study is helpful for making the correct decisions and actions at the correct time by means of understanding the vessel's stability and its margin. Furthermore, the key findings from this study are useful for improving the crew's training and its situational awareness.

8 Conclusions

The existing weather criteria are applicable for the stability of conventional cargo vessels while transporting cargo from one location to another. The weather criteria do not have any provision for including the effect of the mooring load on the vessel's stability. These criteria are not suitable for anchor handling vessels (AHV) while operating in anchor handling operations (AHOs).

In this paper, the stability criteria are developed for the AHVs during AHOs in terms of the critical rolling angle criterion and critical static heeling angle criterion. These stability criteria are established by considering the effect of the mooring load, current, wind and waves, and control forces. These criteria can be used in identifying a basis for design operational criteria and planning operational procedures in terms of allowable weather, mooring parameters, and thruster forces. Furthermore, these criteria can also serve to aid the vessel's masters in decision-making to achieving the vessel's safety during different phases of the operation.

Currently, there is no criterion for monitoring the vessel's stability during an operation. In this paper, the critical static heeling angle criterion has been proposed, which is useful to understand or/and monitor the vessel's stability during the execution phase of the operation. Moreover, it is useful for developing control strategies for the safe execution of operations and for preventing capsizing scenarios. With the help of these results, it is possible to identify critical scenarios. Identification of these scenarios is useful for preparing operating guidance and simulator training.

A parametric study is conducted for assessing a vessel's critical static heeling angle and critical rolling angle. Based on the results of the parametric analysis, the following conclusions can be made:

- It is possible to prevent an AHV capsizing scenario during AHOs either by means of the vessel operating within the acceptable safety limits or by applying adequate vessel handling techniques.
- For a specified mooring load, the influence of the angle between the mooring load and the vertical axis (α) on the vessel's stability is predicted to be insignificant for small angles of attack (β).
- For the angle of attack $\beta < 0$ (the mooring line tension is toward the port side), the vessel's critical static heeling angle and critical rolling angle depend only on the towpin position on the port side.
- The effect of the line position with respect to the tow pin is significant for a small angle of attack β.
- If the mean mooring line tension is toward the port side ($\beta < 0$), it is safe to position the mooring line between the starboard inner tow pin and outer tow pin. Similarly, when the mooring line tension is towards the starboard side ($\beta > 0$), it is safe to position the mooring line between the port side outer tow pin and inner tow pin.
- In a situation when the mean mooring line tension is toward the port side ($\beta < 0$) and the wind is coming from the starboard side and the current is coming from the port side, the vessel is subject to a large static heeling angle and a less critical rolling angle.
- In a situation when the mooring line tension is toward the port side ($\beta < 0$), the wind and current comes from the starboard side and control forces are applied to the control drift-off, and then, the vessel is subject to a higher heeling moment. A higher heeling moment causes the vessel to be highly vulnerable with respect to stability. On the other hand, if the wind and current are coming from the port side and an action is taken to control the vessel's drift-off, then the vessel has good stability characteristics due to having a lower heeling moment.
- For an increased mooring load, the vessel's static heeling angle increases significantly. Higher mooring loads along with other parameters can lead the vessel into a capsizing scenario without any waves.

The proposed ultimate limit state (ULS) check should account for the effect of the mooring line tension, environmental loads, and other operational loads on the vessel's stability, while the vessel is operating along an ideal path. However, during the AHOs, all the operational and vessel's parameters (related to the loading condition) are subjected to normal uncertainty and variability. Therefore, a probability of capsizing can exist for all ships. As a result, further research into this subject is required to come to a satisfactory stability criterion that provides a safety margin against capsizing. A better measure of safety, even in a realistic sense, is likely to be obtained from a probabilistic approach (reliability-based approach) by accounting for these uncertainties. Hence, future work for these operations must be conducted by considering probability-based safety criteria for obtaining an improved prediction of the risk level. In addition to normal uncertainties and variability during AHOs, the gross errors due to the accidental actions can occur, which can contribute a large angle of attack, and in turn, a vessel can be subjected to large overturning moment. The safety margin defined in ULS does not reflect gross errors. Therefore, in the design and analysis phase and in the planning phase, in addition to the ULS check, an Accidental Limit State (ALS) check should be conducted on the vessel's stability. Furthermore, the proposed criteria should be validated with an experimental analysis or very advanced time domain simulations.

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