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Numerical Investigation of Hydrodynamic Responses of a Moored Liquefied Natural Gas Ship under Multimodal Waves

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Abstract: Ocean waves typically consist of wind, sea, and swell trains. Conventionally, the treatment of multimodal waves has been to conceptualize them as a unified wave system and employ a single set of aggregate wave parameters for the representation of their collective characteristics. Nevertheless, a better understanding of multimodal waves is important when analyzing the interactions between waves and moored vessels, considering the pronounced sensitivity of a ship's responses to wave periods and directions. Many spectral partitioning methodologies have been proposed to discern and segregate multimodal waves into two or more distinct wave systems, providing fundamental information for investigating moored ship responses to multimodal waves. Utilizing the wave spectra data acquired from a specific water region in South America, a comprehensive numerical study was undertaken by employing the specialized ocean engineering software ORCAFLEX 11.2e. The primary objective of this investigation is to analyze the dynamic response of a moored liquefied natural gas (LNG) vessel in ballast conditions subjected to waves defined by distinct wave identification methods (i.e., overall method and spectral partition method). Furthermore, the waves are categorized into two groups: beam waves and head waves. Results show that beam waves induce a substantial ship response, whereas head waves pose a comparatively lower risk to maritime vessels. Furthermore, the conventional overall wave approach tends to neglect the roll motion generated by multimodal waves when they propagate as head waves. Nevertheless, when the wave direction aligns with beam waves, the overall wave approach tends to produce the roll motion. These findings indicate the importance of considering multimodal waves in quay layout and mooring configuration design.

Keywords: multimodal waves; LNG ship; berthing; moored vessel motions; ORCAFLEX



Citation: Lu, N.; Xu, T.; Xia, L.; Dong, G. Numerical Investigation of Hydrodynamic Responses of a Moored Liquefied Natural Gas Ship under Multimodal Waves. *Water* **2023**, *15*, 3804. <https://doi.org/10.3390/w15213804>

Academic Editor: Mariano Buccino

Received: 13 September 2023

Revised: 24 October 2023

Accepted: 25 October 2023

Published: 31 October 2023



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1. Introduction

Oceanic waves frequently encompass multiple wave systems, typically characterized by the presence of wind, sea, and swell trains, each exhibiting distinct directions and/or periods [1]. Wind waves, herein referred to as waves generated by local winds, remain continually influenced by prevailing wind forces. Swells denote waves that persist after the diminishing or alteration of local wind dynamics or that propagate from distant maritime regions [2,3]. Strong wind on the sea surface can cause waves to grow significantly, reaching heights of several meters and damaging vessels and marine structures. Swells with long wavelengths exert a significant impact on nearshore structures and port operations. It is imperative to recognize that wind waves and short/long swell trains exhibit disparate characteristics concerning their growth, dissipation, propagation dynamics, and consequential effects on engineering. Consequently, they require differentiated treatment in ocean research and applications [4].

Historically, only one single set of integral wave parameters, including but not limited to significant wave height, peak period, and mean wave direction, has been widely employed for the purpose of data simplification [5], often without due regard for the intricacies of wave origins [6]. These parameters exhibit limitations in their ability to capture the complexities inherent to maritime environments characterized by the coexistence of wind, sea, and swell systems, as observed, for instance, along the southeastern Pacific coast [7]. These parameters offer only a cursory overview of prevailing wave conditions, failing to describe the multimodal wave systems.

To enhance the accuracy of multimodal wave descriptions, 2D schemes of the wave spectral partitioning method have been proposed following the watershed algorithm developed by Hasselmann, Bruning, Hasselmann, and Heimbach [2]. This technique detects the wave system in both frequency and direction domains, ensuring that each individual wave system can be represented. Various utilized cases can be referred to prove that 2D schemes of wave spectral partitioning method do have a greater advantage for wave condition identifications. For example, Kerbiriou et al. [8] examined the influence of various sea-state description methods on wave energy production and found that the 2D wave spectral partitioning method yields a better assessment of the instantaneous device response than the unimodal method. Similarly, Portilla-Yandún et al. [9] evaluated the performance of the wave model WW3 in the eastern equatorial Pacific using both multimodal and unimodal methods. The results showed that the multimodal method can objectively identify and quantify the source of modeling errors, whereas the unimodal method distorted the real situation.

The response of moored vessels suffering from an external force (e.g., wind, current, wave) needs to be previously modeled to avoid severe accidents (e.g., breakage of mooring ropes). Zou and Bowers [10] developed a mathematical model to simulate the ships moored against a quay wall in the harbor. Ma et al. [11] utilized a numerical method to investigate the effect of wave groupness on a moored ship. A physical model test was conducted by Rosa-Santos et al. [12] to assess the influence between fenders and pre-tensions on ship movement. Zheng et al. [13] adopted the transient hydrodynamic characteristics of moored ships under seismic-induced harbor oscillations investigated by a hybrid Boussinesq-panel model where the free-surface oscillations are modeled by a fully nonlinear Boussinesq wave model and are further used to drive the ship motions. Among the moored ships, LNG vessels face more complicated sea conditions due to their open-sea operation platforms' lack of protection by breakwaters; moreover, the liquid gas that LNG ships carry is much more dangerous, so ensuring the safety of the moored LNG ship deserves attention. Many factors that may influence moored LNG ships have been widely studied, such as the non-linearity of the mooring stiffness [14], berth length [15], and mooring configurations [16]. Above all, the main influential parameters to ship movement are wave actions [17]. Sun et al. [18] took a physical model experiment with different wave directions to investigate the mooring tension of the moored LNG ship. Wang et al. [19] took a numerical simulation of the hydrodynamic analysis software Aqwa 19.2 to study the response of the LNG under the combined effect of wind, wave, and current. Ji and Wichers [20] comprehensively investigated the dynamic response of an LNG ship moored at a jetty subject to different wave conditions, for example, swells, wind-sea mixed swells, or only one of them alone. van der Molen et al. [21] systematically constructed a numerical model based on a real port geometry at Withnell Bay, Australia, to study the response characteristics of an LNG vessel under swell trains. A physical experiment has also been undertaken by Shi et al. [22] to study the dynamic effects of a moored LNG vessel excited by long-period waves. Shi [23] studied the difference of the response characteristic of moored LNG ship between bimodal spectral waves and wind waves.

However, in the aspect of wave modeling, most of the former research studies simply considered only one set of wave parameters to treat the measured wave data, which ignores the significance of wave identifications. In our present work, we try to bridge this gap

by applying the novel wave spectral partitioning method to more precisely describe the measured waves.

In this paper, we design a numerical simulation to investigate the response of a moored 177,000 m³ LNG ship subject to multimodal waves represented by two distinct wave analysis methods. For simplification, the LNG ship is in ballast condition, so liquid sloshing is not taken into account for the current study. To better examine the ship's sensitivity to wave direction, both head waves and beam waves were considered to make up the incident wave. The separation of wave systems is achieved through 2D spectral partitioning methods in this paper due to its good capacity to yield a precise and refined representation of the real wave system (detecting wave systems in both the frequency and directional domains), referring to SPM subsequently. Similarly, for making comparison data, the traditional wave representation method (referring to OVERALL) was also employed.

The subsequent sections are structured as follows: Section 2 introduces the numerical configuration, encompassing the mooring layout and wave conditions. Section 3 examines the responses of a moored LNG vessel when subjected to distinct representative wave scenarios. Finally, Section 4 encapsulates the concluding remarks of this study.

2. Numerical Setup

2.1. Wave Identification

The desired wave spectra employed in this study were measured on the western coast of Peru with a Nortek acoustic wave and current (AWAC) sensor [24]. The AWAC recorded direction-resolved surface elevation at a rate of 64 min per 2 h with a sampling frequency of 4 Hz. Field observations were conducted during the period spanning from 19 July to 10 October 2018. The geographic coordinates for the measurement site are depicted in Figure 1.

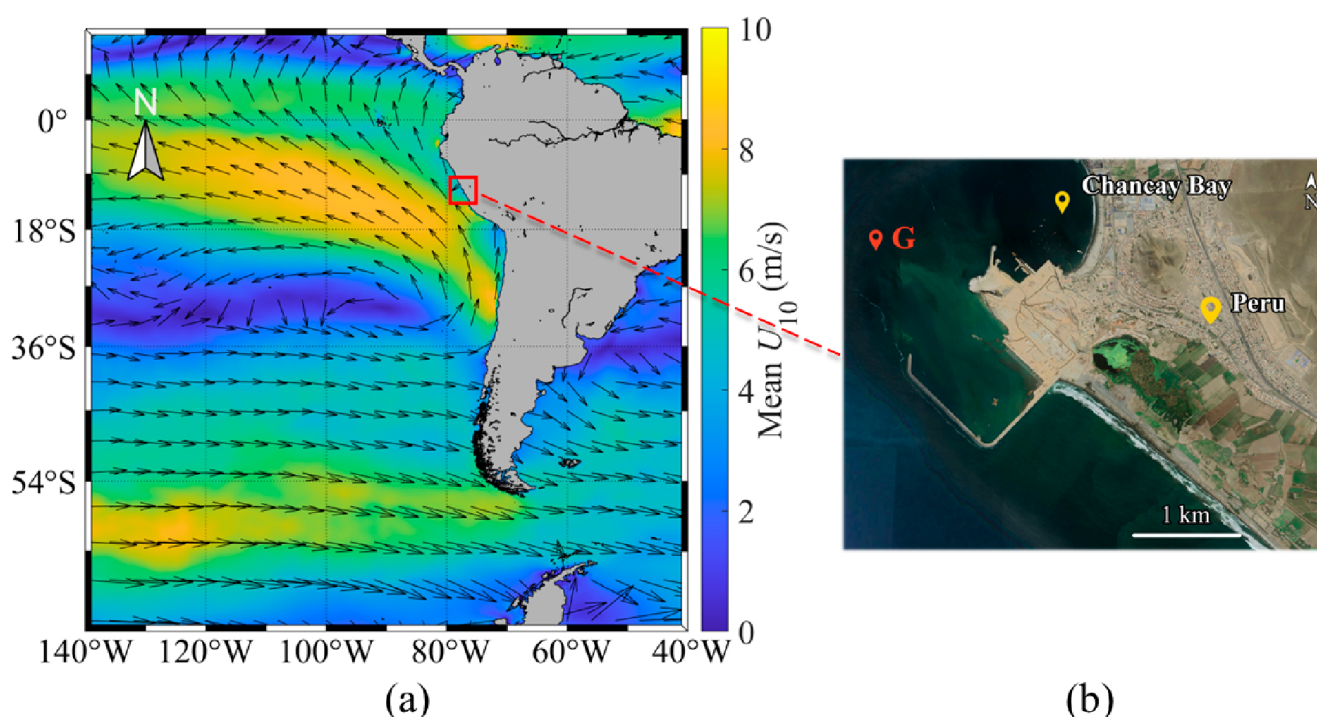


Figure 1. (a) Location of the sea area studied, (b) wave sensor deployed.

An open-source watershed algorithm, accessible at the following repository link, data will be made available on reasonable request. (<https://github.com/gvoulgaris0/WavePart/tree/v1.1>, accessed at 14 April 2022), was employed to partition the two-dimensional wave spectrum. Building upon the conceptual framework proposed by Hasselmann et al. [2], this algorithm conceptualizes the wave spectrum as an inverted

catchment area and subsequently leverages the steepest ascent methodology originally formulated by Hanson and Phillips [25] to cluster grid points that correspond to a shared local peak, thereby establishing a partition.

Two distinct sets of measured wave spectra were chosen for analysis, each subjected to different methodologies: the traditional wave characterization method (henceforth referred to as OVERALL) and the spectral partitioning method (hereafter abbreviated as SPM). The OVERALL approach simplifies the representation of the entire wave spectra by utilizing a single set of integral parameters (significant wave height H_s , peak wave period T_p , and mean wave direction D_m). Conversely, the SPM method segregates the measured wave spectra into two categories: long swell wave spectra and short swell wave spectra, thus acknowledging the presence of two distinct swell trains characterized by distinct integral parameters. Figure 2 shows the measured wave spectral data processed by SPM. Two different colors are used to characterize the wave system in frequency and direction domains, separating the wave system into two wave modes (blue represents wave mode 1 and green represents wave mode 2). The description above the figure represents the wave parameters both in use of SPM and OVERALL (long swell and short swell are the result of SPM, and overall is the result of OVERALL).

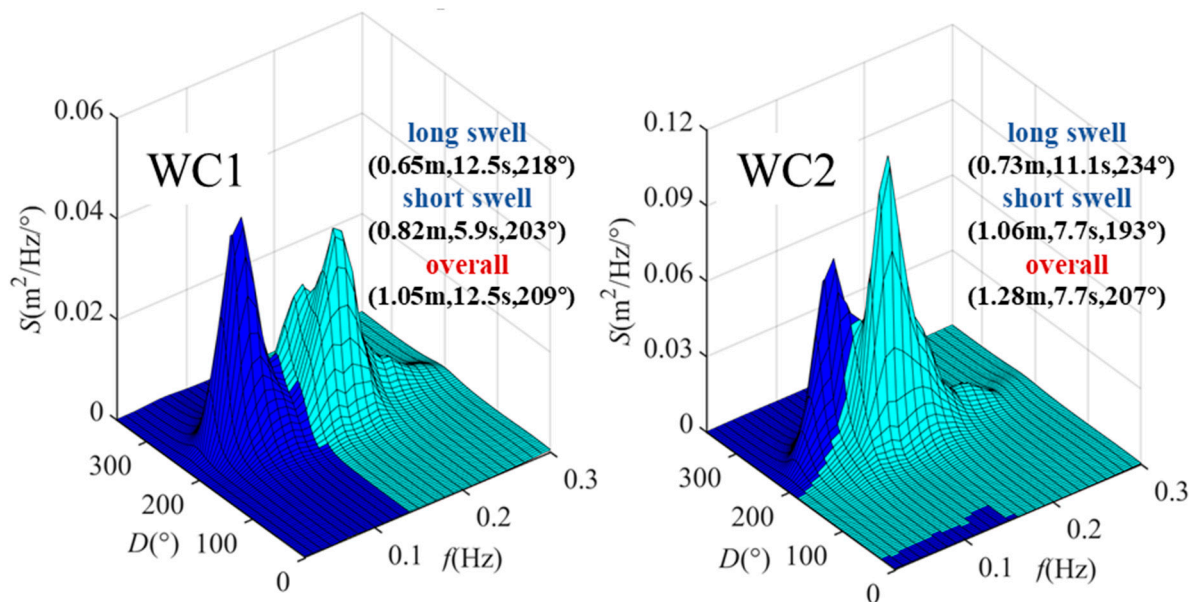


Figure 2. Typical bimodal spectra and the bulk wave parameters (significant wave height H_s , peak period T_p , and mean wave direction D_m) described by two methods. Note that WC denotes wave case).

The specific wave parameters pertaining to the OVERALL and SPM methods can be found in Figure 2 for further elucidation.

The n th-order and bulk parameters used in this study are defined as follows:

$$m_n = \int_0^\infty \int_{-\pi}^\pi f^n E(f, \theta) df d\theta \quad (1)$$

$$H_s = 4.0\sqrt{m_0} \quad (2)$$

$$\theta_m = \frac{180}{\pi} \arctan \left[\frac{\int \sin \theta E(f, \theta) df d\theta}{\int \cos \theta E(f, \theta) df d\theta} \right] \quad (3)$$

$$T_{m02} = \sqrt{\frac{m_0}{m_2}} \quad (4)$$

where m_n , H_S , θ_m , and T_{m02} denote the n th-order moment of the wave spectra, significant wave height, mean wave direction, and second-order moment wave period, respectively.

2.2. Vessel Type and Mooring Configures Information

The present investigation employs a prototype simulation, wherein an LNG vessel with a volumetric capacity of 177,000 m³ serves as the subject of numerical analysis. The vessel exhibits specific geometric characteristics, with a draft of 11.8 m, an overall length of 291.965 m, and a beam measurement of 45.854 m. Detailed information is provided in Table 1.

Table 1. Characteristics of the LNG carrier adopted in this work.

Parameters	Unit	Value
Displacement	tons	115,257
Draft	m	11.8
Overall length	m	291.965
Beam	m	45.854
Depth	m	28
Rxx	m	11.6786
Ryy	m	72.9912
Rzz	m	72.9912

The berth configuration adheres to a butterfly-shaped design, incorporating an elevation of 6.5 m while accounting for a designated design water level of 2.5 m. The schematic representation of the berth layout is depicted in Figure 3. The terminal infrastructure encompasses several key components, including a workspace platform, four fenders, eight bitts, and a total of eighteen mooring lines. These mooring lines are distributed as follows: three stern lines, four aft breast lines, four breast lines, four fore breast lines, and three bow lines. The mooring points at ship are listed in Table 2.

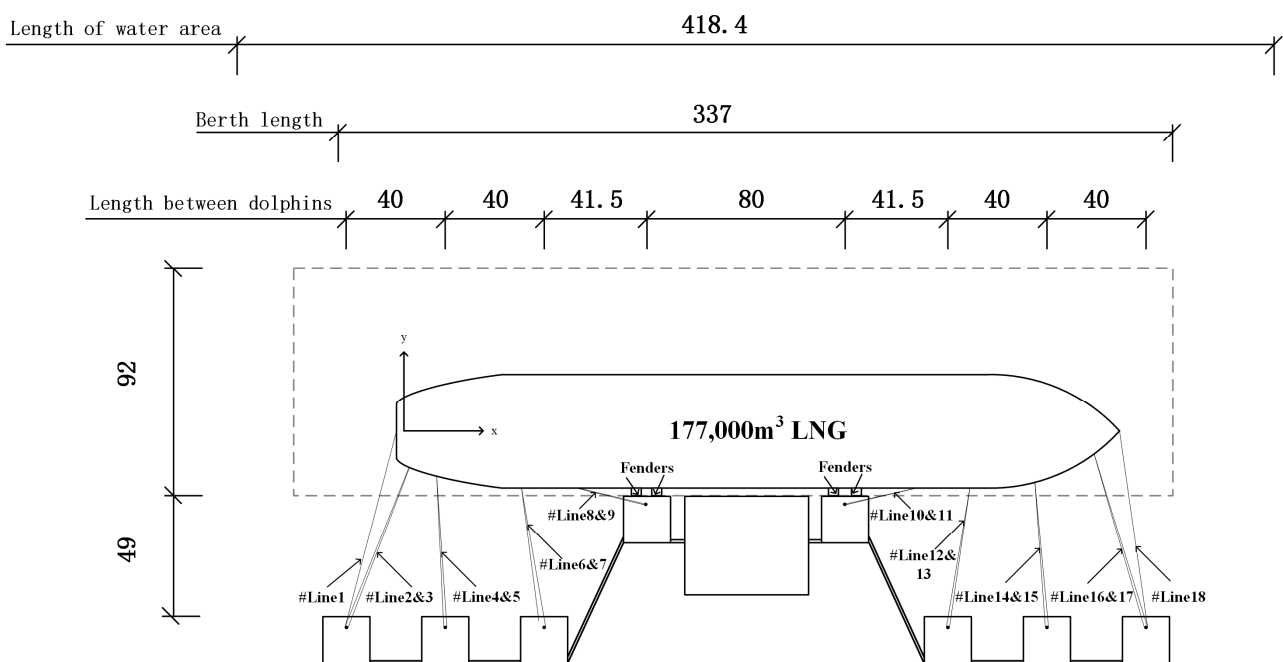
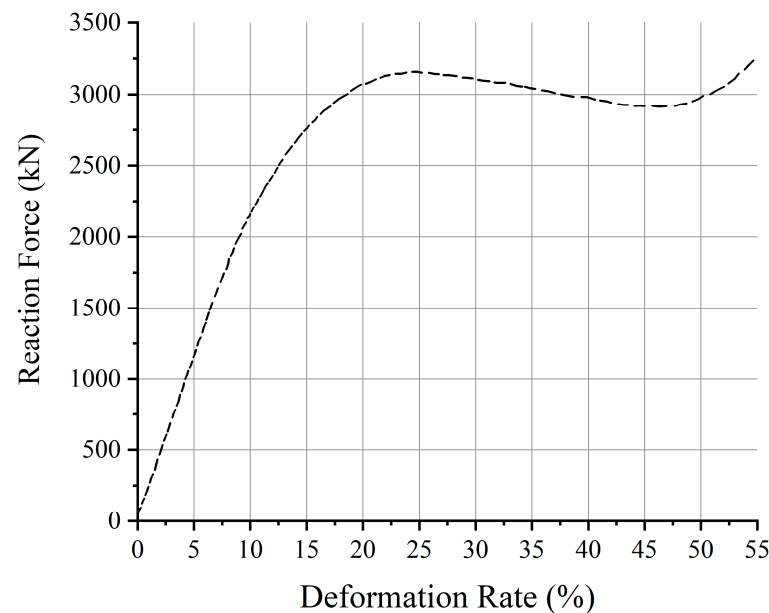


Figure 3. Sketch of the open sea terminal layout. The length unit is in meters.

Table 2. Position of the mooring point on the ship and length of each line.

Line	X (m)	Y (m)	Z (m)	Length (m)
1	−4.5	0	16.2	71.43
2 and 3	−3.0	−18.6	16.2	56.01
4 and 5	11	−21.45	16.2	51.83
6 and 7	54	−22.9	16.2	50.32
8 and 9	86.28	−22.9	16.2	16.74
10 and 11	196.28	−22.9	16.2	18.93
12 and 13	225	−22.8	16.2	50.31
14 and 15	261	−17.3	16.2	54.93
16 and 17	278	−9.7	16.2	64.26
18	287.42	0	16.2	70.86

Nylon ropes with 75 diameters are adopted as the constituent material for fabricating the mooring lines with a unit mass of 3.6 kg/m. Each individual mooring line is subjected to a pre-tension of 100 kN. Furthermore, the mooring system is augmented by the inclusion of SCK2500H standard reaction fenders, which exhibit a noteworthy capacity to generate a 3283 kN reaction force when subjected to a deformation rate of 52.5%. The graphical representation of the force–deformation relationship for this specific fender can be observed in Figure 4.

**Figure 4.** Reaction force–deformation rate curve of fender.

Two ocean engineering models, AQWA and ORCAFLEX, are utilized in this study for numerical simulations. AQWA, recognized globally for its authoritative capabilities, serves as a formidable tool for the computation of hydrodynamic data pertaining to diverse floating structures. Within the scope of this research, AQWA is harnessed specifically to perform frequency domain analyses, entailing the calculation of hydrodynamic coefficients such as added mass, radiation damping, and the vessel's response amplitude operator (RAO). The schematic representation of the vessel's computational grid is elucidated in Figure 5. Subsequently, to make use of the interface of ORCAFLEX to receive AQWA's data, an LNG ship model can be easily constructed. The ensuing phase encompasses the establishment of the mooring system within the ORCAFLEX framework and the subsequent

execution of a simulation. A visual depiction of the mooring system model is presented in Figure 6 for reference and clarity. The hydrodynamic data of the LNG ship are shown in Figures 7 and 8, which are referred to added mass and radiation damping respectively.

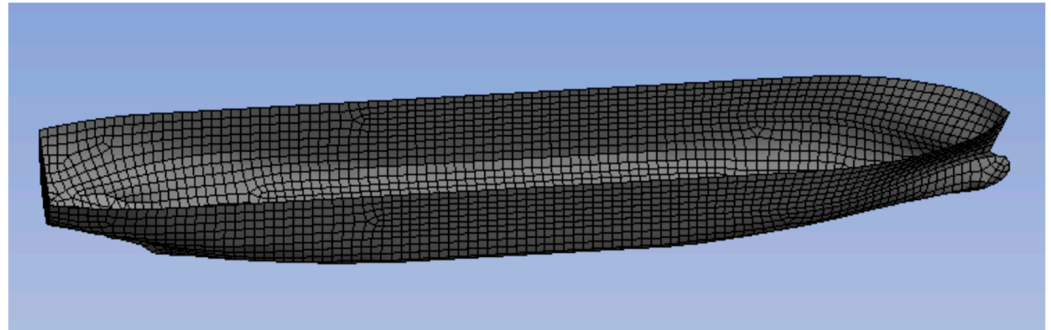


Figure 5. Grid of LNG for AQWA calculation.

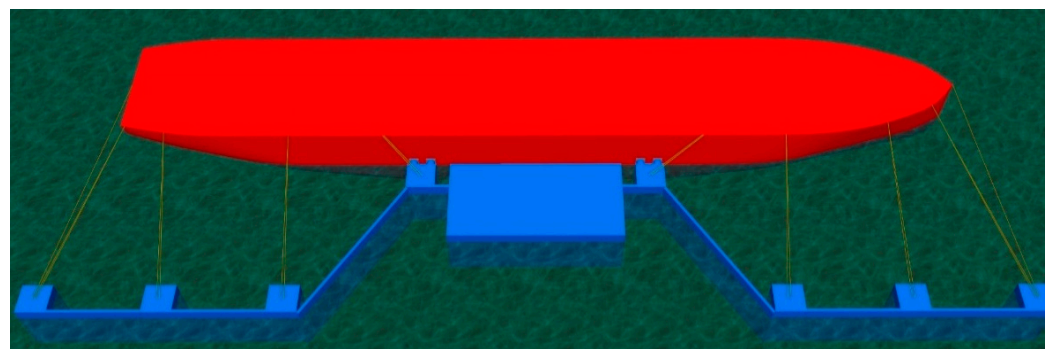


Figure 6. Mooring system in OCRAFLX.

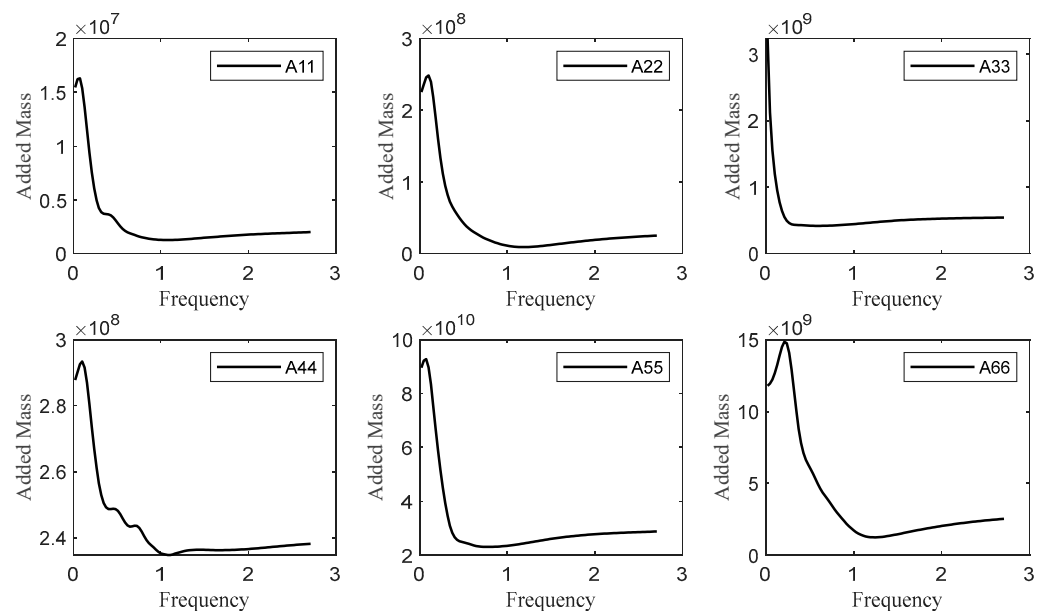


Figure 7. Added mass of LNG vessel calculated by AQWA.

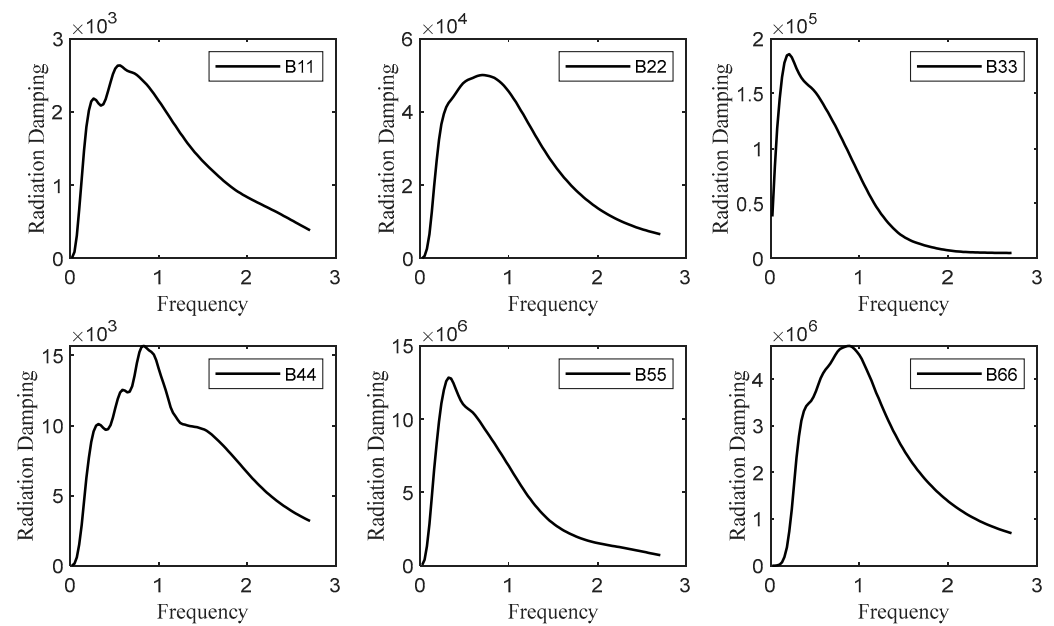


Figure 8. Radiation damping of LNG vessel calculated by AQWA.

2.3. Computational Cases

JONSWAP spectra are adopted in ORCAFLEX to model the incident irregular waves. The function is given as follows:

$$S(f) = \frac{\alpha g^2}{16\pi^4} f^{-5} \exp \left[-\frac{5}{4} \left(\frac{f}{f_p} \right)^{-4} \right] \gamma^b \quad (5)$$

where

$$b = \exp \left[-\frac{1}{2\sigma^2} \left(\frac{f}{f_p} - 1 \right)^2 \right] \quad (6)$$

$$\sigma = \begin{cases} \sigma_1 & \text{for } f \leq f_p \\ \sigma_2 & \text{for } f > f_p \end{cases} \quad (7)$$

where α represents the spectral energy parameter, automatically calculated by ORCAFLEX; g is the acceleration due to gravity; f_p is the spectral peak frequency; γ is the peak enhancement factor; σ_1 and σ_2 are spectral width parameters, only apply to the JONSWAP spectrum, and are fixed at the standard values of $\sigma_1 = 0.07$ and $\sigma_2 = 0.09$.

In the context of this simulation, the user-defined input parameters are H_s , T_p , and γ . The values of the first two parameters, H_s and T_p , are directly derived from the corresponding values found in WC1 and WC2 (as depicted in Figure 2). On the other hand, γ is established through a fitting process based on the measured wave spectra, wherein when T_p exceeds 8 s, γ assumes a value of 1.3, while when T_p is less than 8 s, γ is assigned a value of 3.3.

To comprehensively assess the influence of wave direction on vessel response, a deliberate configuration was adopted wherein the primary wave direction is established as either perpendicular to the vessel's beam or directed head-on. The specifics of this wave configuration are visually presented in Figures 9 and 10, corresponding to the WC1 and WC2 cases, respectively. For instance, in the WC1 cases, the OVERALL method encompasses an overarching methodology to characterize the sea state; the waves are incident upon the LNG vessel from two distinct directions: beam waves and head waves, thus constituting two distinct scenarios within the WC1 under OVERALL. Consequently, this research encompasses a total of eight distinct simulation scenarios, each designed to investigate various wave conditions and their effects on vessel response.

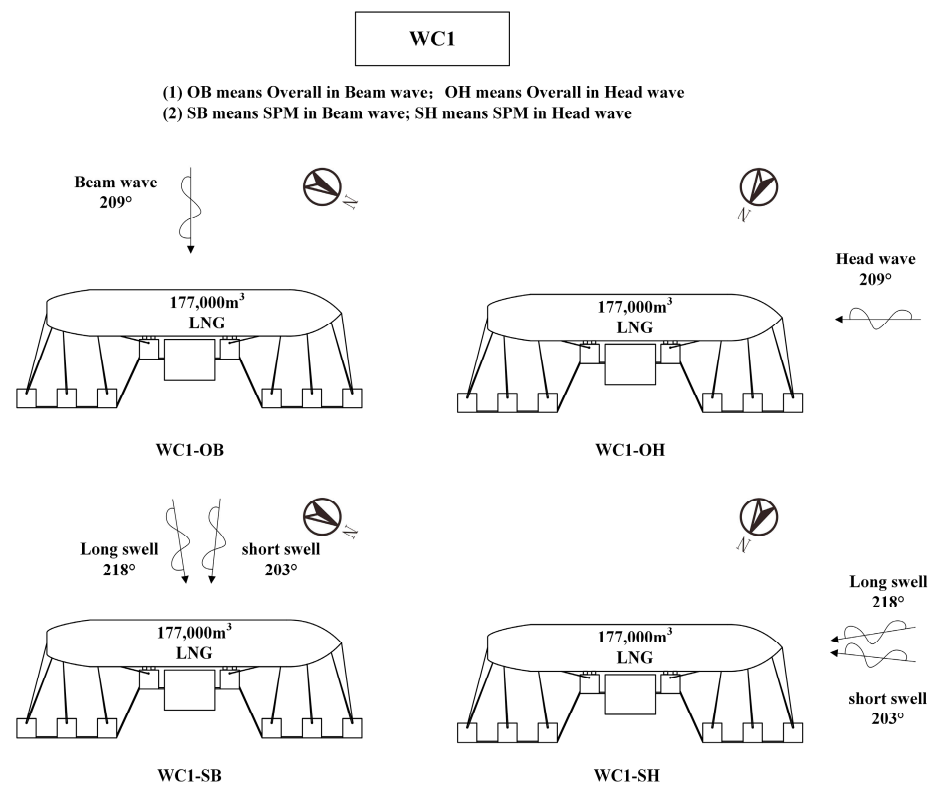


Figure 9. Wave set of WC1 (OB means OVERALL method in beam wave, OH means OVERALL in head wave, SB means SPM method in beam wave, and SH means SPM method in head wave).

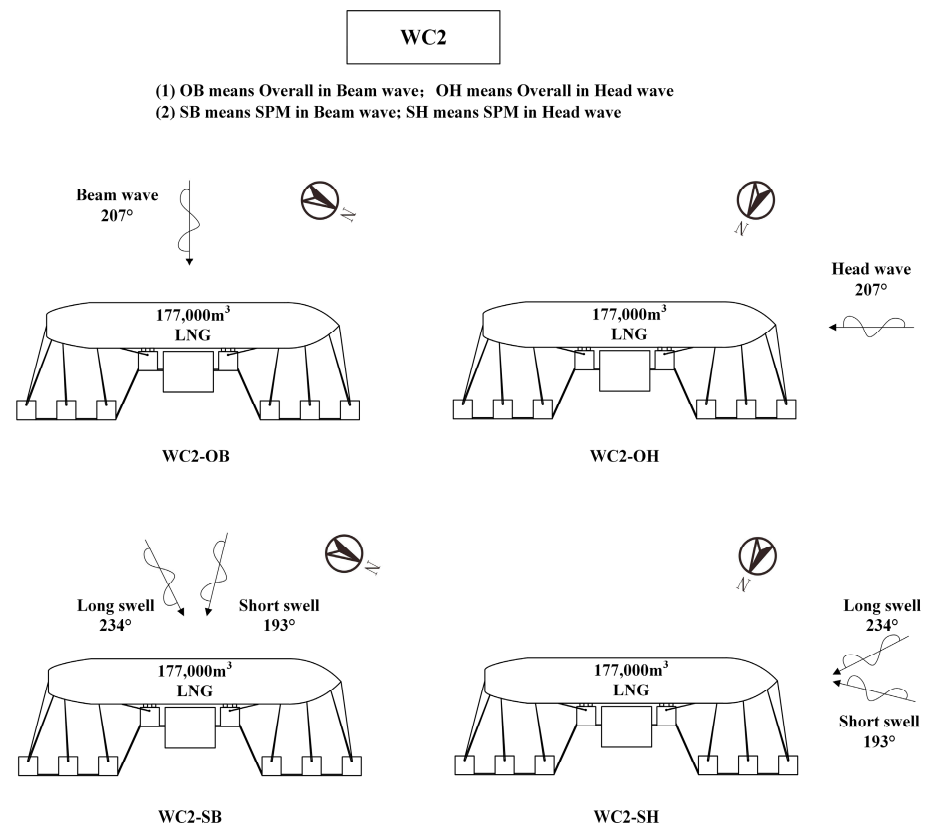


Figure 10. Wave set of WC2 (OB means OVERALL method in beam wave, OH means OVERALL in head wave, SB means SPM method in beam wave, and SH means SPM method in head wave).

3. Results and Discussion

This section presents the findings derived from the analysis of the eight distinct cases under examination. Note that when assessing the degrees of freedom (DOFs) encompassing surge, heave, pitch, roll, and yaw, the statistical data pertaining to their respective motions is computed as the cumulative sum of the maximum absolute values observed on both sides. This methodology is implemented by employing an “up-cross-zero” approach to the data. However, in the context of sway motion, the analysis solely considers the maximum absolute value at which two sides are compared. Allowable vessel movements during operation are reported in Table 3, which is useful in results discussion.

Table 3. Allowable vessel movements during operation [26].

Vessel Type	Limitation of Movement					
	Surge (m)	Sway (m)	Heave (m)	Pitch (°)	Roll (°)	Yaw (°)
LNG	2.0	2.0	—	2.0	2.0	2.0

Note that the allowable amount of movement in the table is the sum of amplitude values in two directions of surge, pitch, roll, and yaw motion. For sway motion, the movement toward the berth wall is much less than that away from the wall due to the action of the fenders; as a result, the statistic value is conventionally defined as the maximum amplitude of one side. For open docks, the loading and unloading arms are usually equipped to allow the maximum longitudinal movement of the ship to reach 5.0 m.

3.1. Discussion of the Results When OVERALL Is Used

Figure 11 provides a depiction of the LNG vessel’s response when subjected to incident waves characterized by the OVERALL method. The observed trends in the motion response can be summarized as follows.

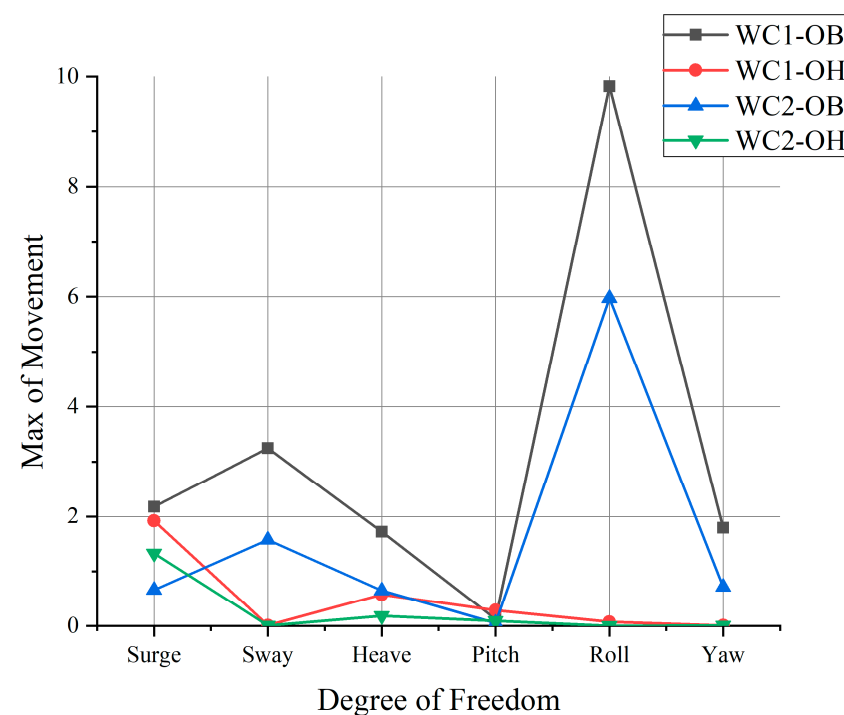


Figure 11. Comparison of six DOF movements in beam waves and head waves when OVERALL method is used (OB means OVERALL method in beam waves, OH means OVERALL method in head waves).

When the main wave direction is set to beam wave, the maximum amplitude of motion is predominantly observed in the roll motion, and the minimum of that is noted as pitch motion. However, when the main wave direction switches to the head wave, the maximum motion amplitude manifests in the surge motion, while the sway, pitch, roll, and yaw motions register nearly negligible amplitudes. Considering these observations, it can be inferred that beam waves tend to induce substantial vessel movements, rendering them more hazardous in comparison to head waves. Consequently, heightened attention is warranted when encountering beam waves to mitigate the potential disturbance. It is evident that roll motion caused by head waves is minimal in OVERALL; conversely, in beam waves, which exert a substantial influence on roll motion, the roll motion surpasses the stipulated regulatory limitation of 2 m in both WC1 and 2.

Figure 12 shows the response standard deviation of all OVERALL cases. The trend and distribution of these are quite similar to the statistics of movement results. The most significant values are of sway and roll motions for beam wave cases, as these two movements can easily be driven by beam wave and keep the large amplitude of movement over the simulation time. On the other side, much fewer values are presented in head wave cases, especially of roll motion. This can be attributed to the fact that the head wave is parallel to the ship's length direction and crosses the ship's center of mass; as a result, only surge motion can be easily excited.

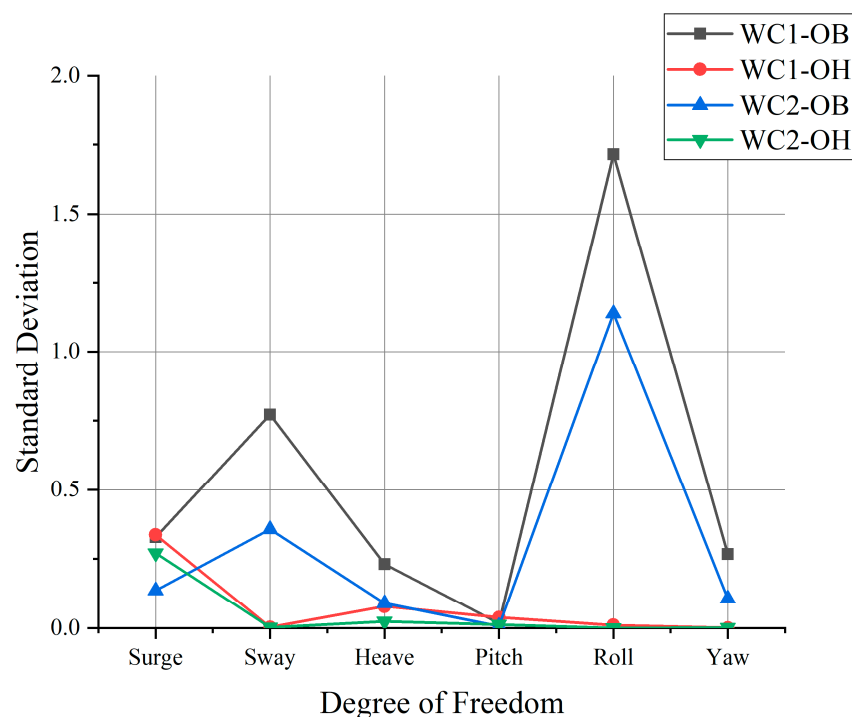


Figure 12. The response standard deviation of all OVERALL cases for six degrees of freedom.

Moreover, despite in OVERALL head wave conditions, the pitch motion remains relatively small, as depicted in Table 4. Because pitch motion is strongly relevant to wave length and ship length, when the wave length is much less than the ship length, the pitch motion would not be significantly excited, even if in head waves [27].

Table 4. Ratio of wave length to ship Length.

Wave Cases	Wave Length (m)	Ship Length (m)	Ratio
WC1	145.34	291.965	0.50
WC2	78.88	291.965	0.27

3.2. Discussion of the Results When SPM Is Used

Figure 13 portrays the outcomes derived from the analysis of the LNG vessel's response when subjected to incident waves characterized using the spectral partitioning method (SPM). The overarching trends in the vessel's response to motion can be succinctly encapsulated as follows:

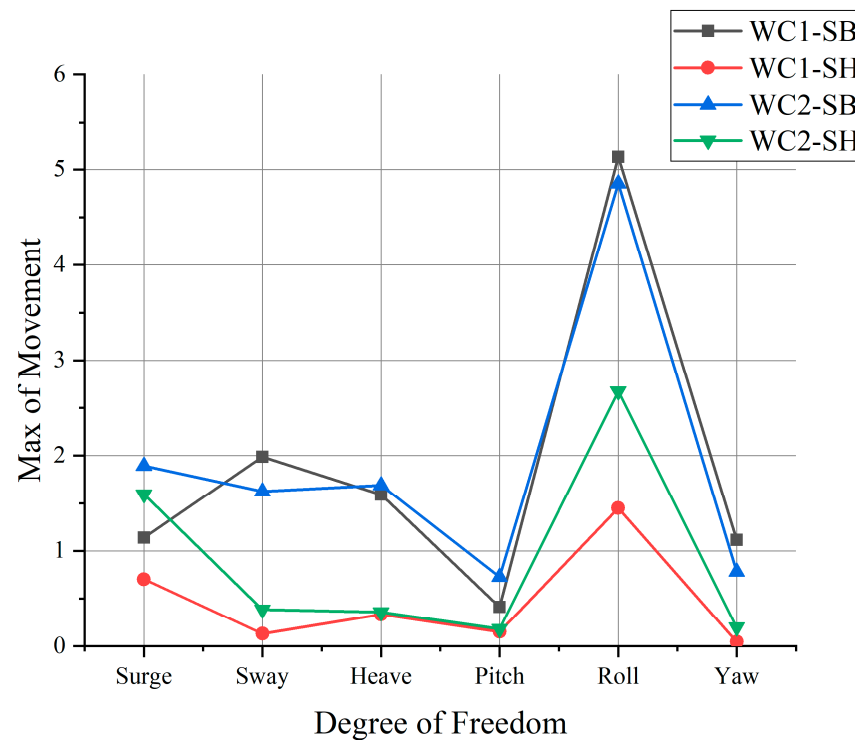


Figure 13. Comparison of 6 DOF movements in beam waves and head waves when SPM method is used (SB means SPM method in beam wave and SH means SPM method in head wave).

In comparison to the OVERALL method, the most noteworthy change is that even faced with head waves, which cause a slight roll motion in OVERALL cases, a higher magnitude of roll motion is still engendered here. This phenomenon is more evident in the WC2-SH case, where the roll motion exceeds prescribed limits. The distinction between WC1-SB and WC2-SB is less pronounced under the SPM method; the motions across all six degrees of freedom (DOFs represented in the following) tend to exhibit remarkable similarity.

Only subtle differences emerge in terms of motion trends between the six DOFs. In WC2-SB, the surge motion surpasses the sway motion; the situation is converse in WC1-SB, in which the surge motion is comparatively less pronounced than the sway motion. This finding aligns with the trend observed in the OVERALL cases.

Figure 14 is the response standard deviation of all SPM cases. The distribution is quite the same as in OVERALL cases, in which the sway and roll motions of beam wave cases can result in a larger number of standard deviations. What makes the difference is that the head wave cases also lead to an increased value of roll motion compared with OVERALL cases because the energy of incident waves is distributed multi-directionally, so even head waves can also drive significant roll motion, and subsequently, the standard deviation also increases.

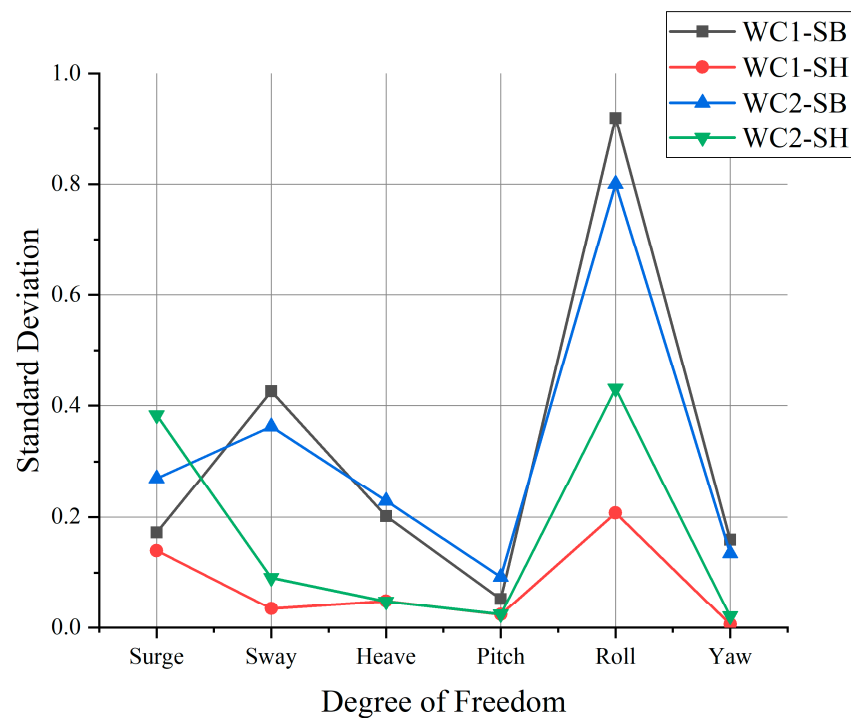


Figure 14. The response standard deviation of all SPM cases for six degrees of freedom.

3.3. Discussion of the Results Compared with OVERALL and SPM

Figure 15 shows the result of the maximum movement in WC1 between OVERALL and SPM, where the main wave direction is set to beam wave. The implementation of the OVERALL method leads to a significant increase in roll motion. Despite how, in the SPM method, the roll motion decreases two times compared with OVERALL, it also surpasses the stipulated limit of 2 m. Different from the large changes in roll motion, heave and yaw motion do not vary too much between different methods. In the case of the OVERALL method, the surge motion slightly exceeds the prescribed limitation, while the sway motion surpasses the limit of up to 1 m. Among the motion of six DOFs, most of them remained within the stipulated limits except roll motion in SPM cases, but three DOFs, surge, sway, and roll motion, exceeded the limitation in OVERALL. Considering the SPM method is much closer to the real sea state, it indicates that if OVERALL is employed to estimate the wave condition, unnecessary upgradation of the mooring configurations should be considered to meet the regulations.

Figure 16 illustrates the outcomes obtained for WC1 when subjected to head waves. Evident differences can be observed in the roll motion between the OVERALL and SPM methods. Specifically, the roll movement recorded under the SPM methodology reaches 1.448° , whereas the OVERALL method yields a considerably lower value of only 0.0737° —a difference of nearly 20-fold. This discrepancy underscores the sensitivity of roll motion to wave directions; when head waves act in isolation, they may not induce pronounced roll motion. However, any changes in wave direction can substantially amplify roll motion. Furthermore, it is noteworthy that the head wave direction under the OVERALL method coincides entirely with the surge motion direction. Consequently, the OVERALL method generates greater surge movement compared to the SPM approach. The other motion parameters exhibit a relatively consistent pattern.

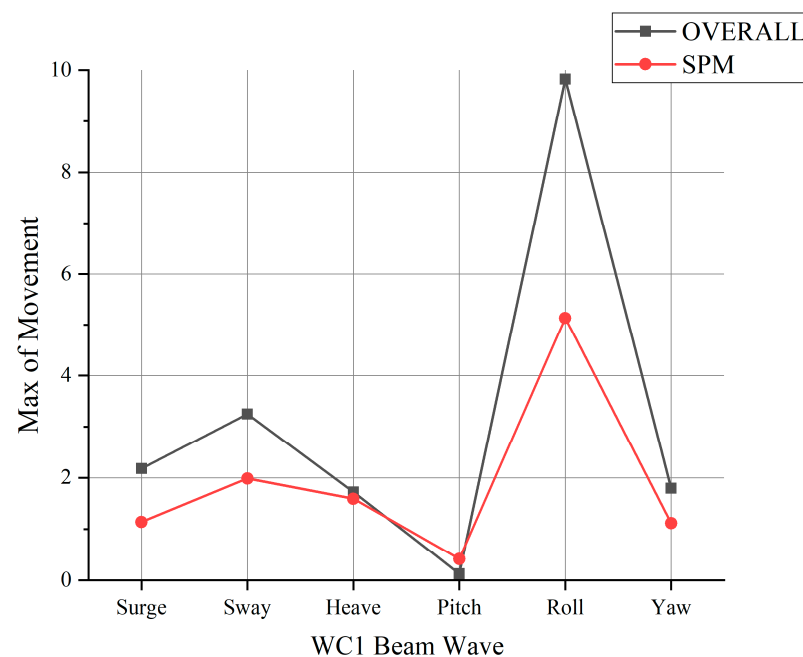


Figure 15. Maximum movement of six degrees of freedom for WC1 applying beam wave. The unit of the surge, sway, and heave is m; the unit of pitch, roll, and yaw is $^{\circ}$.

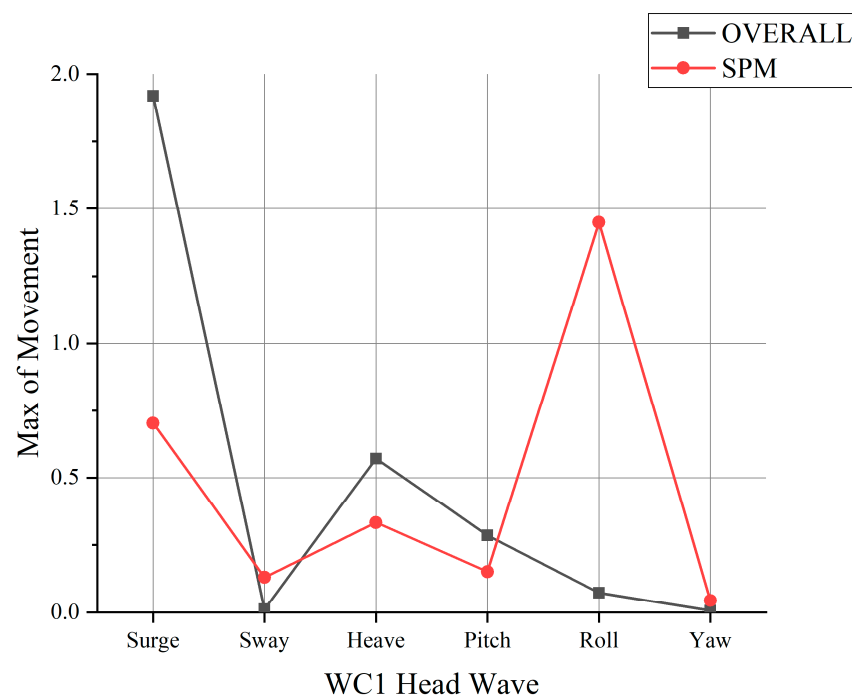


Figure 16. Maximum movement of six degrees of freedom for WC1 applying head wave. The unit of the surge, sway, and heave is m; the unit of pitch, roll, and yaw is $^{\circ}$.

The marked increase in roll movement, as observed in Figure 16, warrants close attention, particularly given the widespread utilization of the OVERALL method in practical applications. Notably, the SPM method is considered to provide a more accurate representation of real sea states. Consequently, these findings imply that vessels may experience greater roll movement than anticipated when relying on the OVERALL method for ocean wave predictions, potentially increasing the risk of serious accidents.

Figure 17 illustrates the outcomes of WC2 under beam wave conditions. There is a marginal alteration in the movement of all DOFs, with sway and yaw motions exhibiting

minimal changes. A notable similarity is observed in the trend of roll motion compared to 0, indicating again that the OVERALL method shows a higher magnitude of movement.

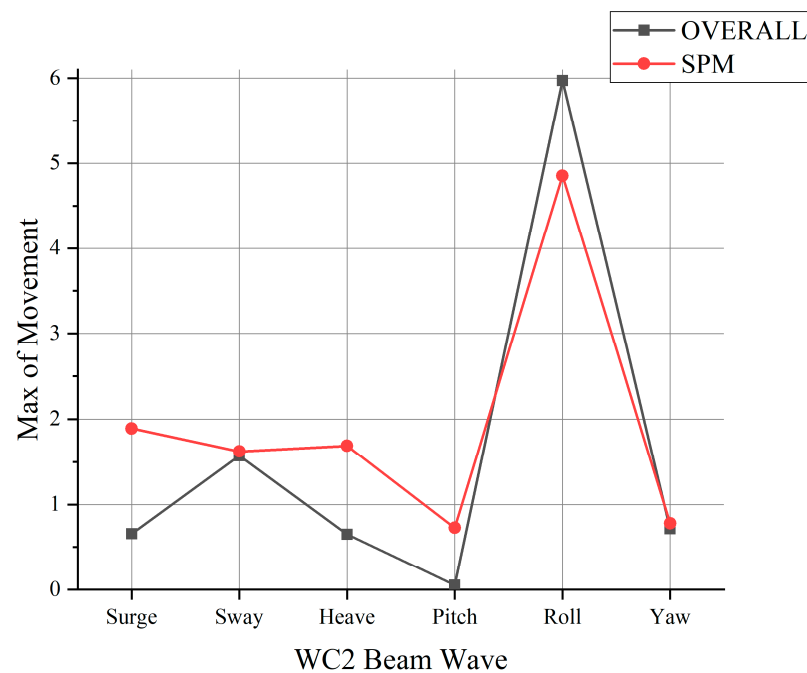


Figure 17. Maximum movement of six degrees of freedom for WC2 applying beam wave. The unit of the surge, sway, and heave is m; the unit of pitch, roll, and yaw is $^{\circ}$.

Figure 18 presents the results for WC2, where the wave direction is configured as head waves. The trends observed here closely align with those identified in WC1 under head wave conditions. It is discernible that only roll movement experiences a substantial increase, consistent with earlier observations and more pronounced than depicted in Figure 11.

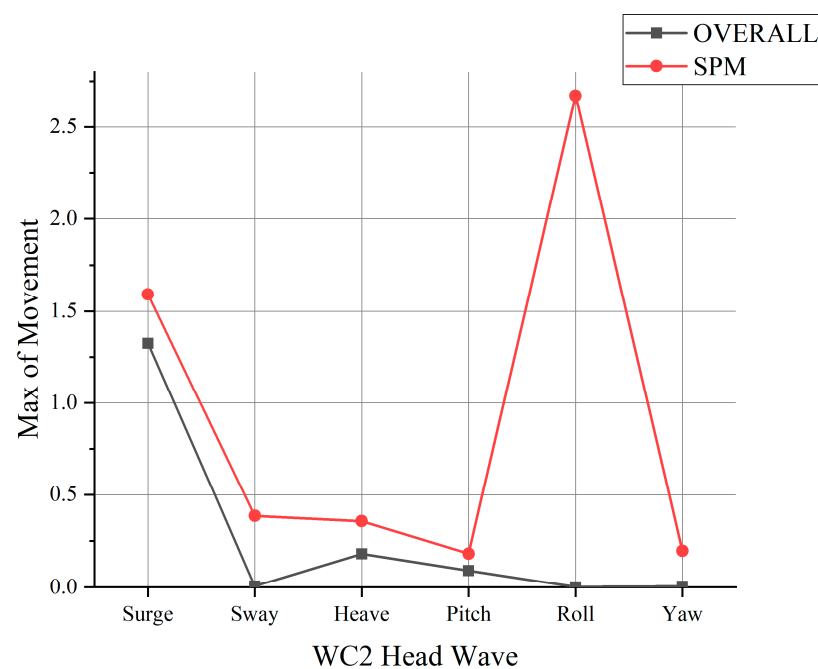


Figure 18. Maximum movement of six degrees of freedom for WC2 applying head wave. The unit of the surge, sway, and heave is m; The unit of pitch, roll, and yaw is $^{\circ}$.

4. Conclusions

This research aims to investigate the effects of different multimodal wave representation methods on ship response. To facilitate this analysis, a 177,000 m³ liquefied natural gas (LNG) vessel serves as the basis for constructing the ship model and conducting hydrodynamic simulations. The wave data used for this study originate from a specific sea area in South America. Two distinct wave characterization methodologies, namely the OVERALL and SPM, are independently employed to define the incident waves. Three key conclusions can be deduced from this investigation:

- (1) Beam waves tend to induce more substantial vessel motion, particularly for roll motion. This heightened roll motion often exceeds regulatory limits. Conversely, head waves typically result in minimal vessel motion, with roll motion registering at approximately zero.
- (2) In the SPM method, even head waves would yield considerable roll motion.
- (3) Compared with the SPM method, OVERALL contributes to a higher magnitude of roll motion but underestimates the roll motion of head wave cases.

To extend this research, the influence of liquid sloshing can be considered in further study, as it is a significant phenomenon of LNG ships and certainly garners interest in examining its interaction with different multimodal wave identification methods.

Author Contributions: Conceptualization, G.D.; Methodology, N.L.; Validation, T.X.; Formal analysis, N.L. and G.D.; Investigation, T.X.; Resources, L.X.; Data curation, L.X. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (Grant No. 51979037), Dalian Science and Technology Bureau (2021RD03), and the Fundamental Research Funds for the Central Universities (Grant Nos. DUT22LAB101, DUT22RC(6)006).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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