

Article

An Analysis of Working Sea States and Operational Ranges for the Gangway Equipped Offshore Wind Turbine Maintenance Vessels

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Abstract

During offshore wind turbine maintenance operations, maintenance vessels typically rely on transfer gangways to achieve safe transfer of personnel from the vessel to the wind turbine. With the development of offshore wind farms toward far sea areas, working sea state conditions have become increasingly complex. In recent years, the application of large-scale active wave compensation (AWC) transfer gangways has mitigated the adverse effects of ship motions on transfer operations to a certain extent, but the problem of limited motion ranges of each gangway joint has also emerged as a prominent issue. Under complex sea state conditions, if the station-keeping position of the maintenance vessel is improperly selected, joint limit violations may occur during the gangway compensation process, thereby posing safety risks. To address the above problems, this paper develops a novel geometric-envelope-based analytical method for operational sea states and ranges that explicitly accounts for gangway joint constraints and wave-induced vessel motions to meet the safety requirements of large-scale gangways. Subject to the motion constraints of gangway joints, to ensure that the initially selected station-keeping position of the vessel satisfies the requirements for safe gangway transfer, the feasible domain and motion range of the gangway base point under different sea states are obtained. By solving for the solutions where the motion range of the base point lies entirely within the feasible domain, feasible schemes for vessel station-keeping operations under different sea states are derived. The results show that the gangway can operate safely under sea states 3 and 4 but fails under sea state 5. The allowable height difference between the transfer point and the gangway base is $[-2.7\text{ m}, 8.7\text{ m}]$ for sea state 3 and $[1.8\text{ m}, 3.5\text{ m}]$ for sea state 4. The operational area on the horizontal plane presents a partial ring shape, and the ring width first increases and then decreases with increasing height difference. Finally, random numerical examples are designed to demonstrate the applicability and internal consistency of the proposed analytical method.

Keywords: offshore wind operation and maintenance; transfer gangway; ship motions; operational ranges; wave compensation



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1. Introduction

As the global energy structure transitions toward low-carbon and clean directions, offshore wind power, with its advantages of stable resource availability and large single-unit capacity, has become one of the important directions for renewable energy development [1,2]. In recent years, the installed capacity of offshore wind power in coastal areas of Europe and China has continued to grow, and wind farms are gradually expanding into mid-to-far sea areas, imposing higher requirements on operation and maintenance support capabilities [3]. During the entire life cycle of offshore wind turbines, personnel tower climbing inspections and equipment maintenance operations are frequent, and safe and efficient personnel transfer methods have become a key link in ensuring operation and maintenance efficiency and operational safety [4]. In parallel, with the advancement of digital and intelligent technologies, research on intelligent operation and maintenance systems for vessels has also gained increasing attention, aiming to enhance the safety and efficiency of shipboard operations through data-driven decision support [5].

In engineering practice, personnel transfer between maintenance vessels and offshore wind turbines is typically accomplished using transfer gangways (offshore access gangways). However, under the combined action of marine environmental loads such as wind, waves and currents, vessels exhibit significant six-degree-of-freedom (6-DOF) motion responses during operations, particularly heave, roll, and pitch motions, which directly affect the stability of the gangway end-point and the safety of personnel transfer [6,7]. To mitigate the adverse effects of ship motions on transfer operations, active wave compensation (AWC) transfer gangways have been gradually applied in recent years. Through multi-joint coordinated control, they maintain the gangway end-point relatively stable within a certain range, thereby effectively expanding the operational sea state range [8–11].

Most existing studies have focused on the kinematic modeling and control strategy optimization of transfer gangways or the analysis of motion response characteristics of vessel-gangway systems under specific sea states using frequency-domain and time-domain methods [12–14]. Some scholars have addressed the problem of contact-type transfer between gangways and target structures, proposed operational safety evaluation methods based on the fixed end-point condition, and provided corresponding environmental parameter limits or dynamic positioning (DP) accuracy requirements [15,16]. These studies provide important references for the design and control of transfer gangways. However, with the development of transfer gangways toward large-scale, long-arm, and contactless directions, their structural dimensions and mass have increased significantly, and the problem of limited motion ranges and compensation capabilities of each gangway joint has gradually become prominent [17]. Under higher sea state conditions, even if the gangway has excellent active compensation control performance, improper selection of the station-keeping position of the maintenance vessel may still lead to joint limit violations during the gangway compensation process, thereby causing operation interruptions and even safety risks [18]. Current research has predominantly focused on control strategy analysis during field operation processes, while there remains a scarcity of studies on the safety windows and optimal operational area ranges for maintenance vessels and transfer gangways under different operating conditions.

In recent years, increasing attention has been paid to the operational availability of offshore wind turbine maintenance systems, particularly for walk-to-work vessels and motion-compensated access technologies. The improvement of dynamic positioning (DP) systems has enhanced the station-keeping capability of maintenance vessels under complex marine environments, while probabilistic operability assessment methods have been increasingly adopted to evaluate offshore operational windows considering environmental uncertainties. Meanwhile, advanced active motion compensation technologies have

improved the adaptability of transfer gangways under various sea states. However, most existing studies still focus on the performance optimization of individual components, such as vessel positioning control or gangway motion compensation, and the integrated evaluation of vessel station-keeping position, gangway joint constraints, and operational feasibility remains insufficient. Therefore, a systematic method considering the coupled effects of vessel motions and gangway kinematic limitations is required to determine safe operational sea states and station-keeping ranges for maintenance vessels equipped with transfer gangways.

On this basis, this paper presents kinematic modeling of transfer gangways and analysis method for coupled motions of the gangways and maintenance vessels and then proposes a methodology for determining the initial station-keeping operational envelope of transfer gangways. Through the proposed analytical method, the feasible domain of the gangway base point in the transfer point coordinate system and the motion region of the gangway base point on the vessel under wave-induced motions are obtained. The suitable operational ranges for the studied gangway are discussed under still water and different sea states, and the rationality of the operational ranges is further illustrated through random numerical examples to demonstrate the applicability of the proposed analytical method., which provides a theoretical basis for the rational selection of vessel operational positions in practical offshore wind turbine maintenance transfer operations. In conclusion, for a given sea state, wave heading, transfer elevation, and vessel station-keeping position, the proposed geometric envelope and dynamic simulation method can reliably judge whether the joint displacement of the gangway exceeds its mechanical limit and further quantitatively delineate the safe operational area of the maintenance vessel, which is systematically verified through numerical cases in the subsequent sections.

2. Kinematic Model of Transfer Gangways and Coupling Method for the Gangway and Vessel

2.1. Kinematic Model of the Gangway

In the current study, the relative key parameters can be described as follows: (1) Vessel and gangway parameters: We added the main dimensions of the operation and maintenance vessel (length between perpendiculars 76.0 m, breadth 20.4 m, depth 8.0 m, operational draft 5.6 m, displacement 6479 t), and the full geometric and mass parameters of the gangway (joint range, D-H parameters, 60 t mass schemes, telescopic range 25 m). (2) Hydrodynamic model: We clarified that the simulation is based on 3D potential flow theory, solved by the AQWA-Line frequency domain module and AQWA-Drift time domain module, with linear free surface boundary conditions and inviscid, incompressible fluid assumptions. (3) Wave settings: We adopted the JONSWAP wave spectrum with a peak enhancement factor of 3.3; the significant wave height and peak period corresponding to each sea state are given in the original manuscript. (4) Simulation settings: The total simulation duration was 3600 s, and the time step was 0.1 s. (5) Mesh details: The hull wet surface was divided into about 4200 panel elements, with an average element size of about 1 m, which met the calculation accuracy requirements of potential flow theory.

To achieve high-precision motion control and safe operation of transfer gangways, this section constructs their kinematic model based on robotic manipulator kinematics theory, and verifies the model validity through workspace analysis [19,20]. Transfer gangways realize telescopic, pitching, and yawing motions through the coordination of joints and links, and their structural characteristics are highly similar to those of robotic manipulators. Therefore, they are equivalent to a prismatic-revolute-revolute (PRR)-type manipulator. During modeling, the gangway is treated as a rigid body, and flexible deformation is

ignored (whose deformation magnitude is far smaller than the gangway dimensions and thus has negligible influence).

The coordinate systems are established using the modified Denavit–Hartenberg (D-H) parameter method. The center of the gangway base is taken as the origin of the base coordinate system $\{0\}$, the connection points between the base and the fixed passage are taken as the origins of coordinate systems $\{1\}$ and $\{2\}$, and the end of the telescopic passage is taken as the origin of coordinate system $\{3\}$. All axes are defined in accordance with the modified D-H parameter method. The D-H parameter θ_1 denotes the rotation angle ($180^\circ \sim 360^\circ$), θ_2 denotes the pitch angle ($80^\circ \sim 115^\circ$), and d_3 denotes the telescopic displacement (15 m~25 m). Substituting these parameters into the modified D-H homogeneous transformation matrix formula yields the transformation matrices of each joint and the overall transformation matrix:

$${}^0_1R = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$${}^0_2R = \begin{bmatrix} \cos \theta_1 \cos \theta_2 & -\cos \theta_1 \sin \theta_2 & \sin \theta_1 \\ \sin \theta_1 \cos \theta_2 & -\sin \theta_1 \sin \theta_2 & -\cos \theta_1 \\ \sin \theta_2 & \cos \theta_2 & 0 \end{bmatrix} \quad (2)$$

$${}^0_3T = {}^0_1T \times {}^1_2T \times {}^2_3T = \begin{bmatrix} \cos \theta_1 \cos \theta_2 & \sin \theta_1 & \cos \theta_1 \sin \theta_2 & \cos \theta_1 \sin \theta_2 d_3 \\ \sin \theta_1 \cos \theta_2 & -\cos \theta_1 & \sin \theta_1 \sin \theta_2 & \sin \theta_1 \sin \theta_2 d_3 \\ \sin \theta_2 & 0 & -\cos \theta_2 & -\cos \theta_2 d_3 + L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Assuming the coordinates of the transfer point in the coordinate system are $(A, B, C)^T$, then the following system of equations can be obtained:

$$\begin{cases} \cos \theta_1 \cdot \sin \theta_2 \cdot d_3 = A \\ \sin \theta_1 \cdot \sin \theta_2 \cdot d_3 = B \\ -\cos \theta_2 \cdot d_3 + L_1 = C \end{cases} \quad (4)$$

By solving the above system of equations, the three joint variables θ_1 , θ_2 , and d_3 can be uniquely determined, providing a theoretical basis for the active control of the gangway.

2.2. Coupling Method for the Gangway and Vessel

The coupling effect between the gangway and the vessel can be described. The vessel undergoes six-degree-of-freedom (6-DOF) motion under wave action, which is transmitted to the gangway through its base and determines the gangway's compensation requirements [21]. The gravity and dynamic attitude changes of the gangway exert additional forces and moments on the vessel, altering its static equilibrium position and motion response.

By considering the restoring force of the dynamic positioning system and the additional load of the gangway, the coupled motion equations can be expressed as

$$\sum_{j=1}^6 \left[(m_{ij} + a_{ij}(\infty)) \ddot{v}_j(t) + \int_0^t R_{ij}(t - \tau) \dot{v}_j(\tau) d\tau \right] = F_i^{FK}(t) + F_i^{res}(t) + F_i^{dif}(t) + F_i^{dp}(t) + F_i^{gan}(t) \quad (5)$$

where $i = 1, 2, \dots, 6$. m_{ij} and $a_{ij}(\infty)$ represent the inertia mass of the vessel and the added mass at infinite frequency, respectively. The convolution integral term $\int_0^t R_{ij}(t - \tau) \dot{v}_j(\tau) d\tau$ represents the memory effect of the fluid, where R_{ij} is the retardation function accounting for the radiation damping and frequency-dependent added mass. On the right-hand side, $F_i^{FK}(t)$, $F_i^{dif}(t)$, $F_i^{dp}(t)$, and $F_i^{gan}(t)$ denote the combined Froude–Krylov and restoring

forces, the wave diffraction force, the additional restoring force provided by the dynamic positioning system for horizontal motions, and the force/moment exerted on the vessel due to the gravity of the gangway, respectively. This time-domain formulation follows the Cummins impulse response theory and is implemented through the AQWA-Drift module, in which the retardation functions and wave excitation forces are pre-computed by the AQWA-Line frequency-domain solver and then applied in the time-domain simulation.

The proportional and differential gains in Equation (5) were determined based on the principal characteristics of the maintenance vessel and general tuning principles of dynamic positioning systems. The initial gain values were selected considering the vessel's station-keeping requirements and motion response characteristics. Subsequently, the gains were adjusted through time-domain simulations to obtain reasonable positioning accuracy and avoid excessive control actions. Furthermore, a sensitivity analysis was performed to investigate the influence of gain variations on the calculated operational ranges.

The restoring force of the dynamic positioning system adopts the PD control model:

$$\begin{aligned} F_x &= -F_{x-mean} + C_x p_x + b_x \dot{p}_x \\ F_y &= -F_{y-mean} + C_y p_y + b_y \dot{p}_y \\ M_z &= -M_{z-mean} + C_\gamma \psi + b_\gamma \dot{\psi} \end{aligned} \quad (6)$$

where F_{x-mean} , F_{y-mean} , M_{z-mean} represent the average environmental forces (torques), which can be calculated using AQWA. p_x and p_y are the surge and sway displacements of the vessel, and ψ is the yaw angle. C_x , C_y , C_γ are the proportional gains related to displacement. b_x , b_y , b_γ are the derivative gains related to velocity. The proportional and derivative gains for this maintenance vessel are $C_x = C_y = 1 \times 10^6$, $C_\gamma = 1 \times 10^7$, $b_x = b_y = b_\gamma = 1 \times 10^5$. The additional load $F^{gan}(t)$ of the gangway on the vessel is determined by the gravity and center of gravity position of the gangway. Assuming the gangway mass is uniformly distributed and the center of gravity is located at the center of its length, the position of the center of gravity can be calculated through the attitude parameters (θ_1 , θ_2 , d_3) of the gangway [22]. Therefore, there is a mutual coupling between the three control amounts of the gangway and the six degrees of freedom of the vessel.

The coupling analysis subroutine was written in Fortran language, compiled into a dynamic link library (DLL) file, and called through the user-defined load interface of AQWA. During the simulation, AQWA calculates the motion response of the vessel under the action of waves and the gangway load from the previous time step. Then, the vessel motion response was transmitted to the coupling subroutine to calculate the compensation amount of each joint of the gangway. Next, the additional forces and moments of the gangway on the vessel were calculated according to the gangway attitude and returned to AQWA. Finally, the next time step was entered, and the above process was repeated. This method realizes real-time coupled simulation of vessel motion and gangway compensation, which can accurately reflect the interaction between the two.

3. Feasible Region of the Gangway Base Point Under Still Water

According to the kinematic model of transfer gangways, a 3D scatter plot of the transfer gangway workspace can be obtained. This scatter plot represents a set of spatial points that the end-point of the gangway can reach in the gangway base coordinate system. The space occupied by these scatter points is related to the working capabilities of the gangway's pitching, yawing, and telescopic joints.

The gangway end-point coordinate system is defined with the gangway end-point as its origin, whose axes are parallel to but opposite in direction to those of the gangway base point coordinate system. The feasible region of the gangway base point, constrained by the joint variables, is plotted as a 3D scatter plot in the end-point coordinate system (hereinafter

referred to as the gangway base point 3D scatter plot), as illustrated in Figures 1 and 2 below. In this plot, the gangway base point is rigidly fixed to the maintenance vessel, and the axes of the vessel body-fixed coordinate system remain parallel to those of the gangway base point coordinate system at all times.

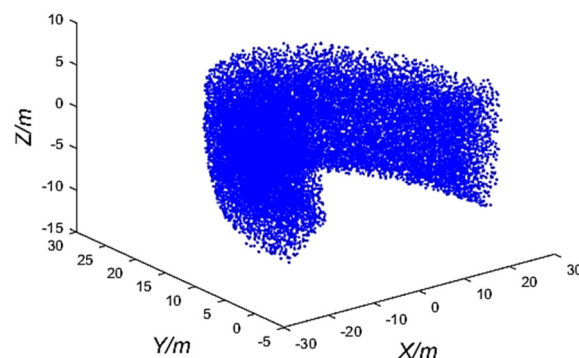


Figure 1. A three-dimensional scatter diagram of the base point of the gangway in the coordinate system of the gangway end point.

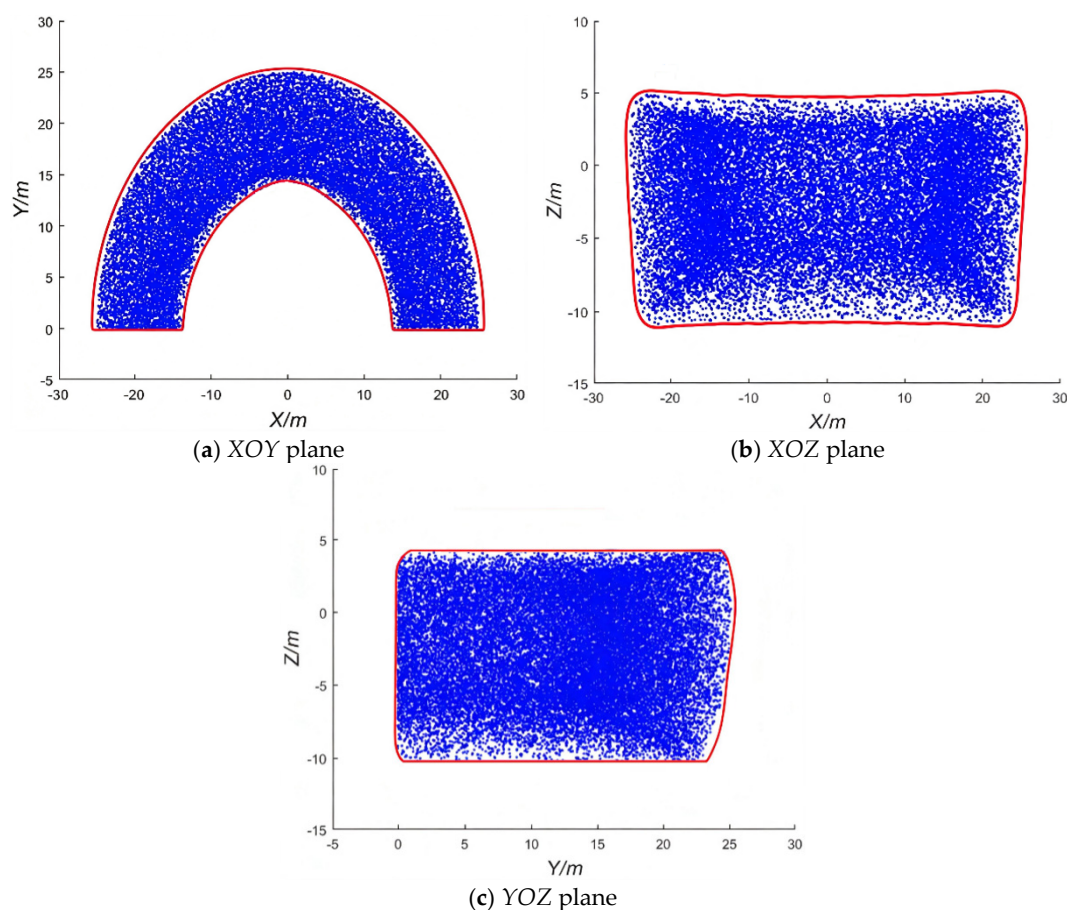


Figure 2. Projections of the gangway base point 3D scatter plot onto typical planes.

To better understand and visualize the spatial extent occupied by the gangway base point, the gangway yaw angles are fixed at 180° , 270° , and 360° , and the cross-sectional views of the gangway base point space at $x = 0$ and $y = 0$ are obtained, as shown in Figures 3 and 4.

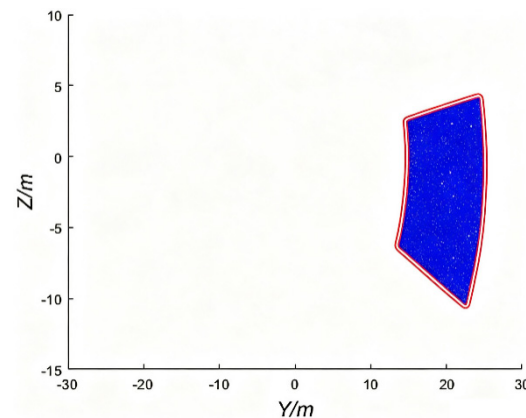


Figure 3. The cross-section of the base point space of the gangway at $x = 0$.

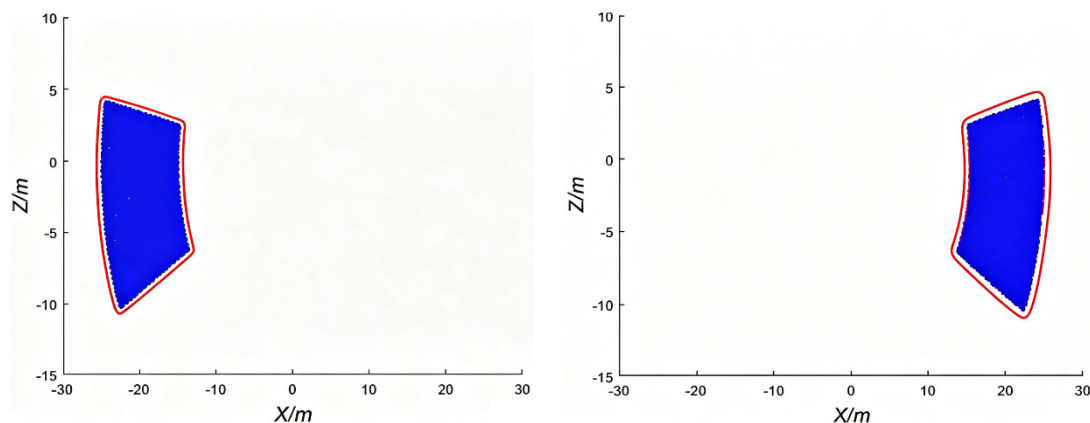


Figure 4. The cross-section of the base point space of the gangway at $y = 0$.

It can be observed that the cross-sectional view at $y = 0$ is symmetric about the $x = 0$ plane and identical in shape to Figure 3. Combined with the motion joints of the gangway, it can be concluded that the upper and lower boundaries in the cross-sectional view correspond to the pitch angle range of the gangway, while the left and right boundaries correspond to its telescopic displacement range. The entire gangway base point space is formed by rotating the cross-sectional profile shown in the figure around $x = 0, y = 0$ (i.e., the z -axis), and the rotation angle is limited by the yaw joint variables of the transfer gangway. Accordingly, the gangway base point feasible region can be geometrically represented as an annular spherical shell between two concentric spheres centered at $(0, 0, -5)$ with radii of 15 m and 25 m, respectively. Taking the half-space where $y \geq 0$ of this shell and truncating its upper and lower extremities by two coaxial cones with apex at $(0, 0, -5)$ and apex angles of 160° and 130° gives the complete spatial extent of the gangway base point.

From the foregoing analysis, it is evident that the spatial extent represented by these scatter points is governed by the gangway joint variables and can be formulated as the following system of equations.

$$\begin{cases} y \geq 0 \\ 225 \leq x^2 + y^2 + (z + 5)^2 \leq 625 \\ -\tan 25^\circ \leq (z + 5) / \sqrt{x^2 + y^2} \leq \tan 10^\circ \end{cases} \quad (7)$$

The gangway base point spatial region simulated by this system of equations is presented in Figure 5 below. A comparison reveals that it is fully consistent with Figures 1 and 2. It is therefore established that the aforementioned system of equations forms the constraint equations governing the gangway base point spatial region.

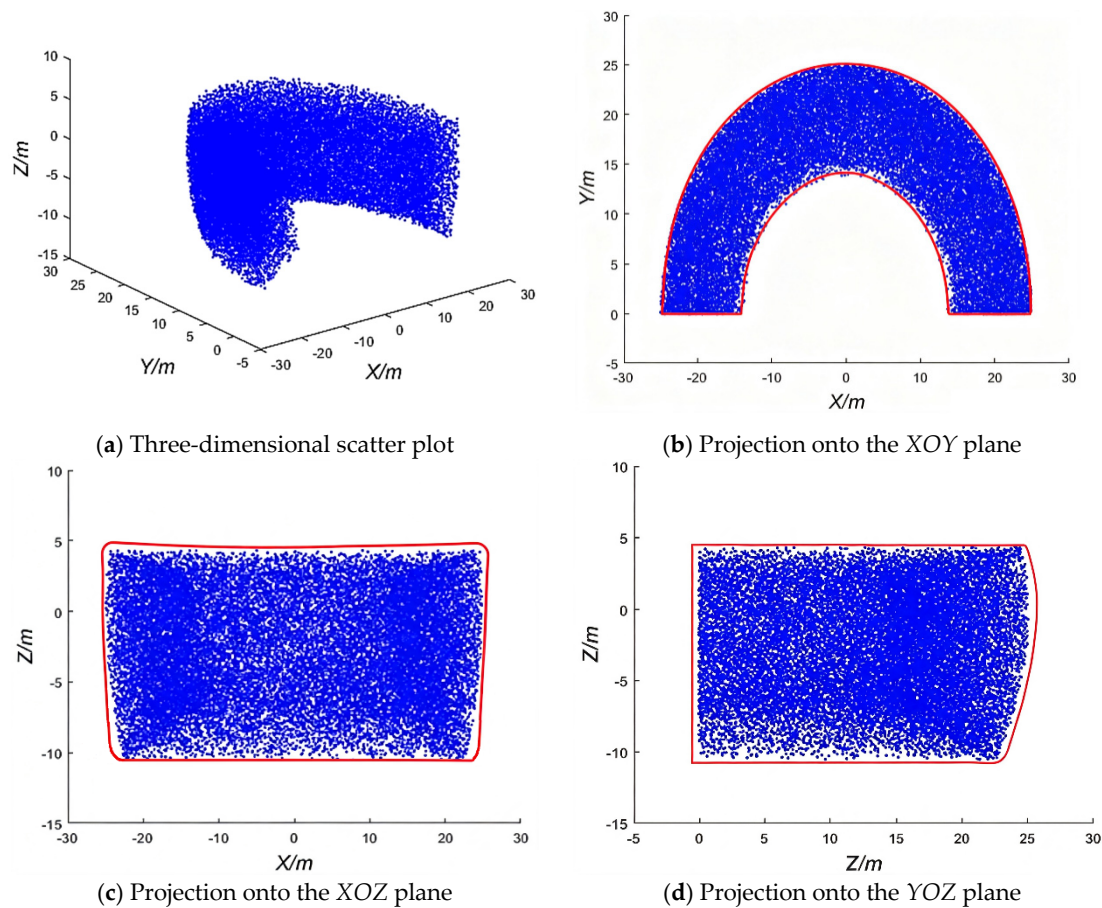


Figure 5. The scatter plot based on constraint equation.

The transfer gangway is mounted on the vessel, so the position of the gangway base point coordinate system relative to the transfer point coordinate system changes as the vessel rotates around the transfer point. Accordingly, to obtain the 3D scatter plot of the gangway base point in the gangway end-point coordinate system under actual operating conditions, full-range rotation of the gangway base point frame about the transfer point must be taken into account. When the transfer point is set as the coordinate origin (0, 0, 0), the resulting spatial region of the gangway base point is illustrated in the Figures 6 and 7 below.

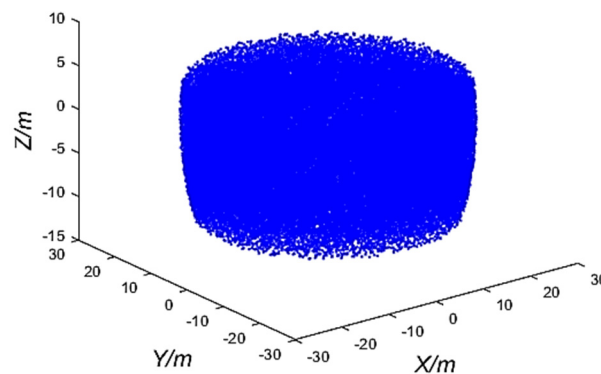


Figure 6. A three-dimensional scatter plot of the gangway base point when the transfer point is the origin.

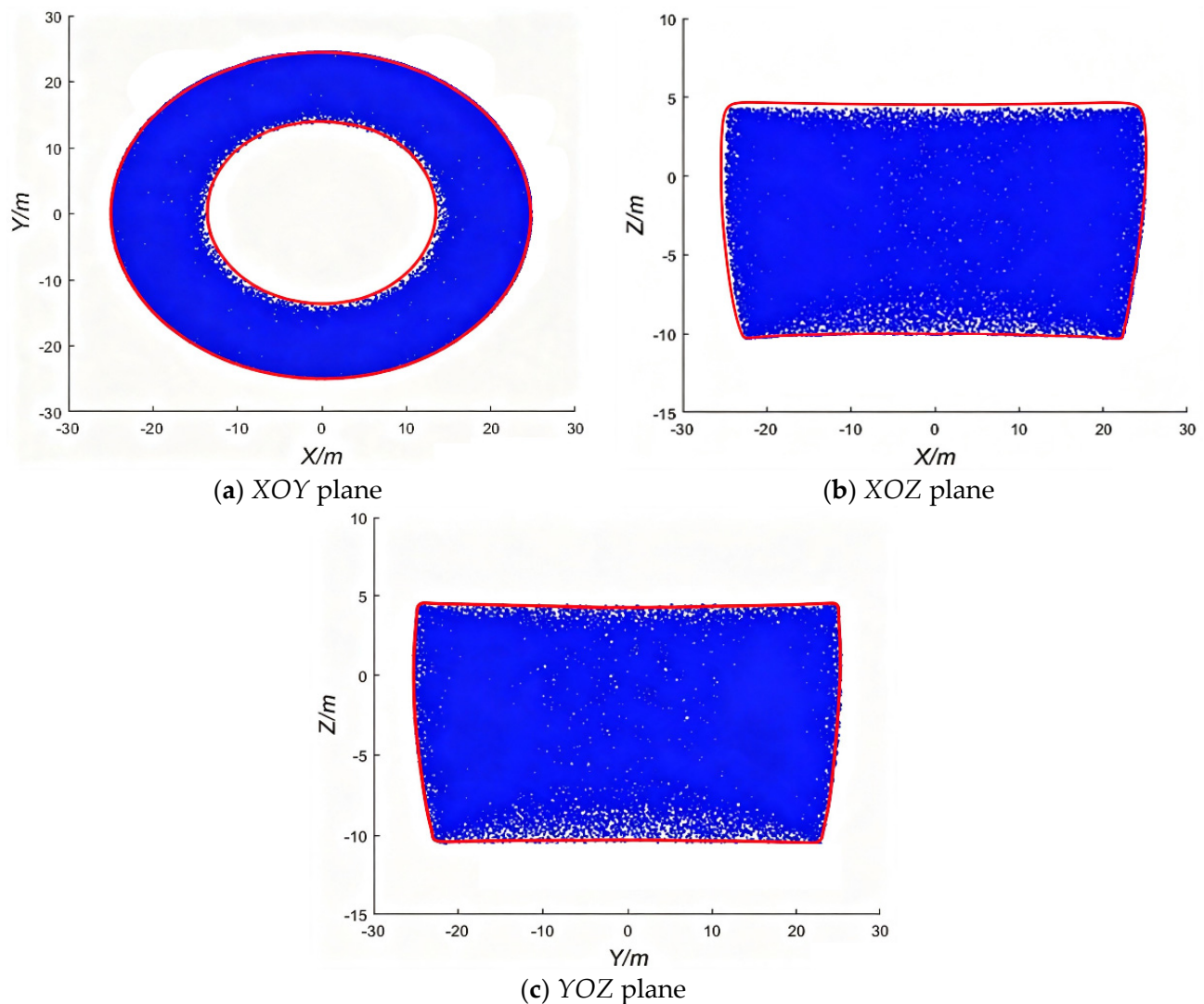


Figure 7. Projections of gangway base point scatter plot onto typical planes with transfer point as origin.

This paper investigated personnel transfer operations for offshore wind turbine maintenance. Wind turbines are cylindrical structures, and the transfer point was simplified as a point at a certain height on the outer surface of the cylinder. Due to the cylindrical geometry, the outermost boarding positions on both sides corresponded to the gangway frame being tangent to the cylinder on either side. Taking the transfer point as the coordinate origin (0, 0, 0) and accounting for the tangency constraint with the cylinder, only the half region where $y \geq 0$ in Figure 6 was adopted. Since the spatial domain of the gangway base point exhibited identical cross-sectional profiles at all radial distances, the final scatter plot of the gangway base point with the transfer point as the origin was obtained. This plot matches Figures 1 and 2, and the derived equations serve as the constraint equations for the gangway base point spatial region.

Judging from the final equations and scatter plots of the gangway base point spatial region under still water, the gangway base point space was restricted in the vertical z -direction, with a range of $[-10.57, 4.34]$. Thus, even for transfer operations in still water using the gangway studied in this paper, the gangway cannot operate if the transfer point is more than 10.57 m higher than the gangway base point or more than 4.34 m lower than the gangway base point.

4. Feasible Region and Motion Domain of the Gangway Base Point Under Wave Conditions

Restricted by the joint variables of the gangway, the operable sea states are inherently limited. Before determining the sea states within which the gangway can operate safely, it is necessary to simulate the vessel motion responses under various sea conditions [23,24].

Furthermore, several simplifying assumptions have been made. (1) Rigid gangway assumption: This study focused on the kinematic feasibility analysis at the rigid body level. Referring to the design specification of large offshore gangways, the maximum full-load deflection was less than 1/1000 of the span. For the 25 m maximum length gangway in this paper, the maximum deformation was about 25 mm, which was far smaller than the meter-level wave compensation amplitude, so the rigid assumption had engineering rationality. (2) Center of gravity assumption: The telescopic gangway was of uniform truss structure, and the center of gravity at the midpoint of the length was a reasonable simplification. The influence of non-uniform mass distribution will be discussed in the follow-up refined analysis. (3) Neglected yaw and pitch rotation: Under DP control, the yaw and pitch amplitudes of the vessel were much smaller than the roll amplitude (less than 1/5 of the roll amplitude in the calculation example), which had little influence on the attitude of the gangway base point, so it could be ignored in the preliminary analysis.

According to Lee's annual sea state statistics for the North Atlantic and North Pacific Oceans, the ranges and mean values of significant wave heights corresponding to each sea state are listed in Table 1. For the simulations in this section, to ensure that the motion envelope of each sea state was fully covered, the upper bound of significant wave height for each sea state was selected as the representative significant wave height of that sea state.

In this chapter, the simulations covered sea states 3 to 5 and full wave directions from 0° to 360°, with an interval of 30° between adjacent wave directions as listed in Table 1. Three wave seeds were calculated for each wave direction. This seed number setting was adopted consistently throughout the present framework, and the obtained identification of feasible sea states was based on the simulation results under this configuration. The consistency of the conclusions is further supported by the random validation cases in Section 5.3. Among the six-degree-of-freedom motion responses, the translational displacements of the gangway base point along the x , y , and z axes affected its motion space, while the rotational motions about the x , y and z axes exerted influences on the feasible region of the gangway base point.

Table 1. Annual sea state statistics in the north Atlantic and north Pacific.

Sea State	Significant Wave Height (m)	
	Range	Mean
3	0.50~1.25	0.88
4	1.25~2.50	1.88
5	2.50~4.00	3.25

4.1. Motion Domain of Gangway Base Point Under Wave Conditions

Affected by wave loads, the coordinate position of the gangway base point within its initial coordinate frame varied continuously over time. The coordinates of the gangway base point corresponding to different wave directions and wave seeds under each sea state were plotted in a unified coordinate system to generate the full-wave-direction diagram for that sea state. The full-wave-direction diagram of the gangway base point under sea state 3 is presented in the Figure 8 below.

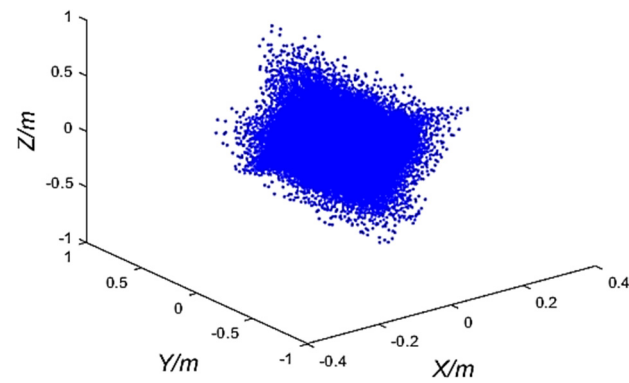


Figure 8. Full-wave-direction map of level 3 sea conditions.

It can be observed in Figure 9 that significant heave motion occurs near $x = 0$, which corresponds to the wave direction of 90° , as shown in Figure 10 below.

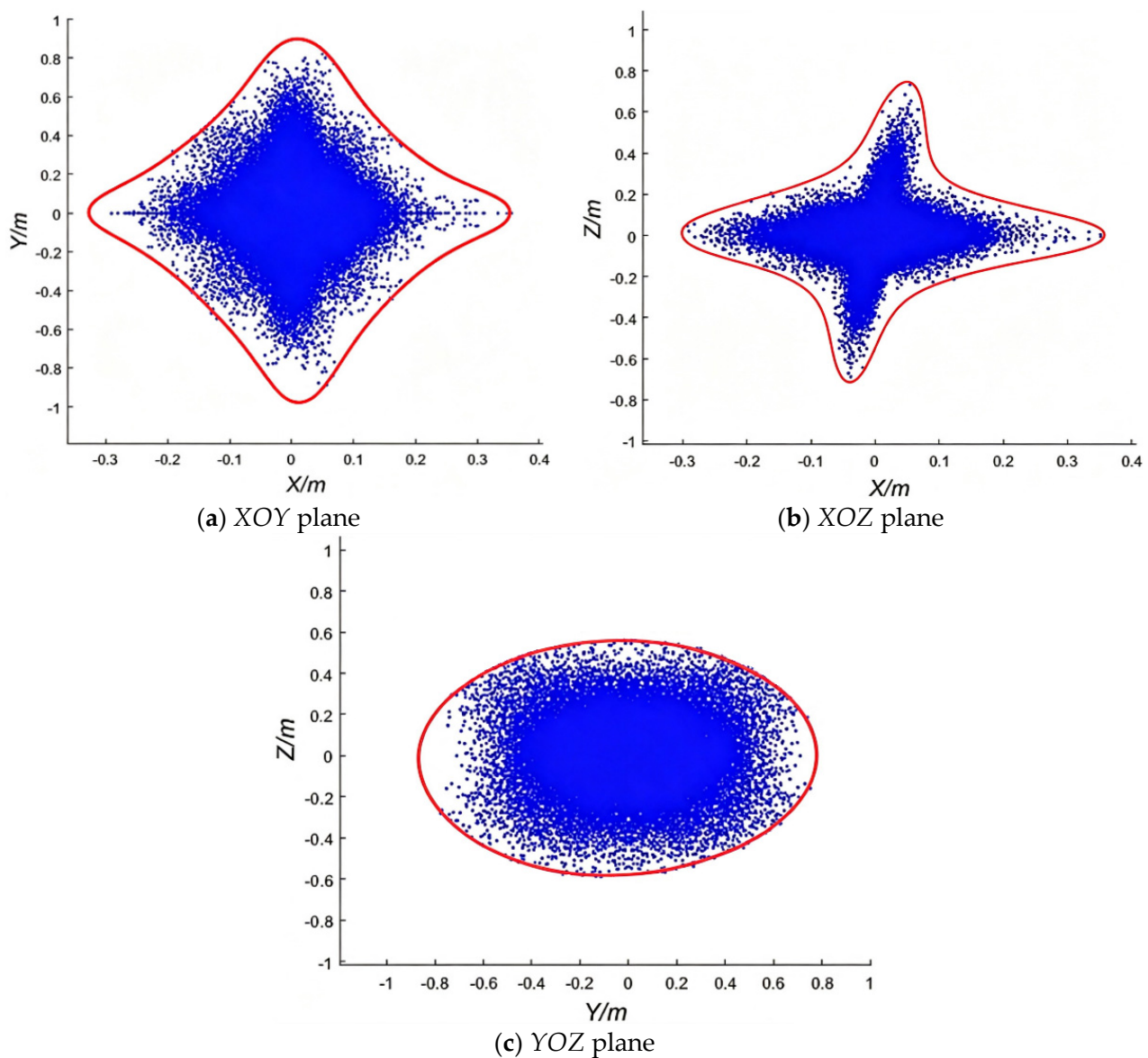


Figure 9. Projection of level 3 sea state full-wave-direction map on the classic plane.

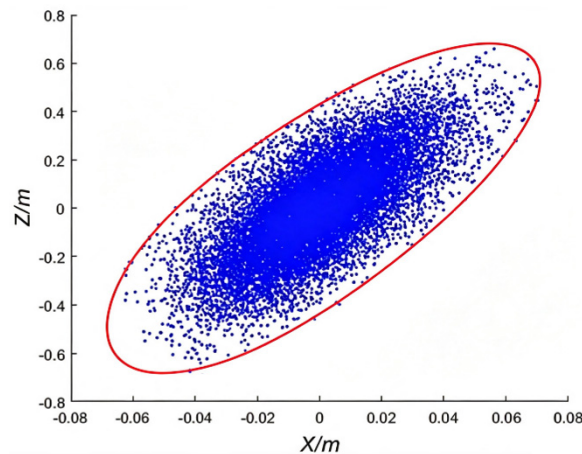


Figure 10. A projection of the 90° wave scatter map of level 3 sea state in the XOZ direction.

The reasons for the distribution of scatter points under sea state 3 and 90° wave direction shown in the above figure are analyzed as follows:

- (1) At the wave direction of 90°, the peak value of the vessel's heave RAO reached 0.9, which was close to the peak wave spectrum value of 1.12, as illustrated in Figure 11. Resonance occurred in the heave direction of the hull at this time, resulting in a substantial heave motion response.
- (2) Due to the asymmetric hull lines at the bow and stern, waves generated surge forces on the vessel, as shown in Figure 12 below.

In summary, large-amplitude heave accompanied by slight surge appeared under sea state 3 with 90° wave direction.

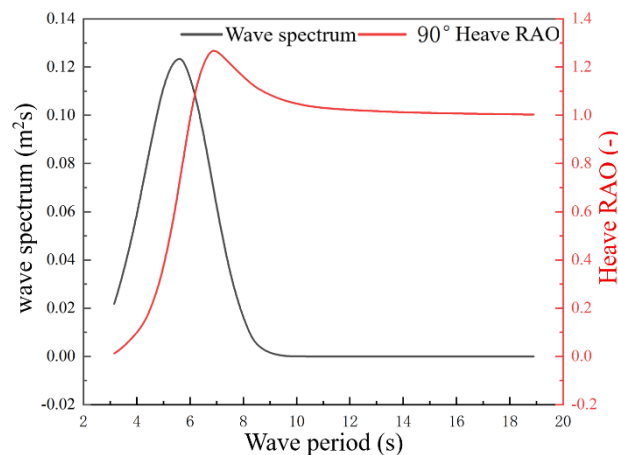


Figure 11. Heave RAO (90°) and wave spectrum for level 3 sea conditions.

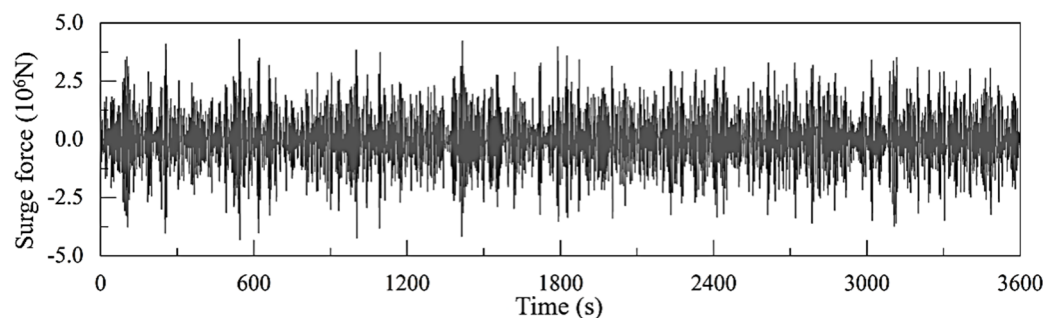


Figure 12. Longitudinal diffraction force under level 3 sea state at 90° wave direction.

Full-wave-direction diagrams for sea states 4 and 5 obtained using the above method are shown in the Figures 13 and 14 below.

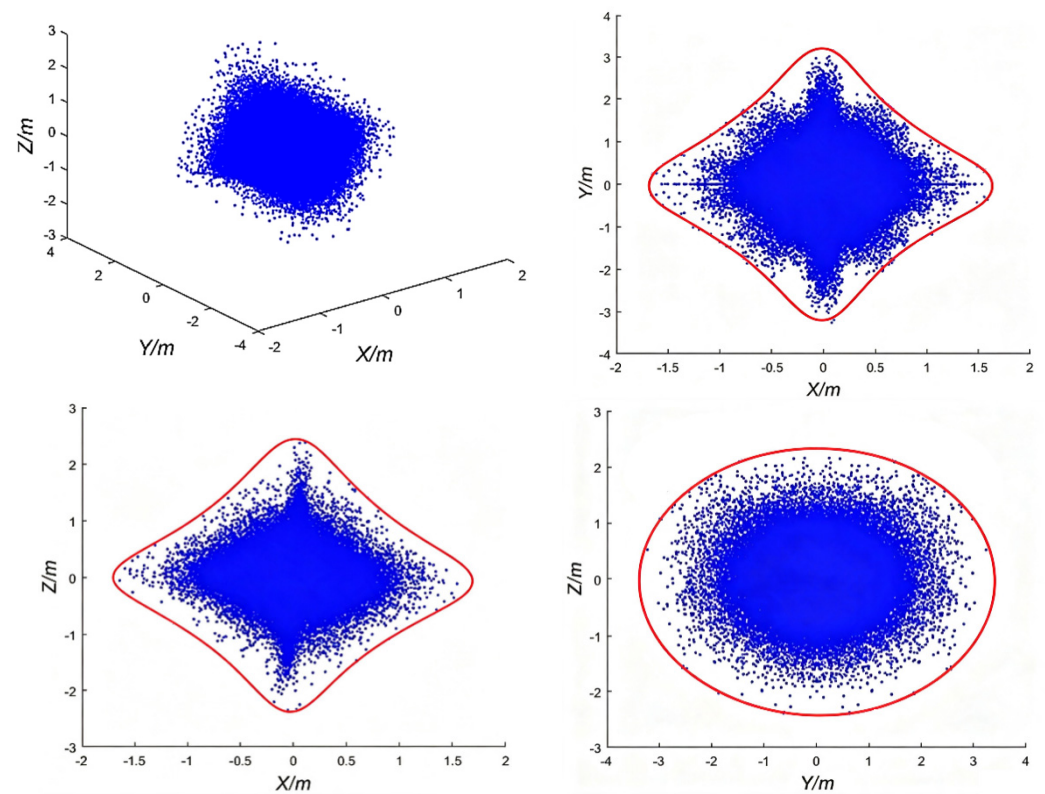


Figure 13. Full-wave-direction map of level 4 sea state and projection map on coordinate plane.

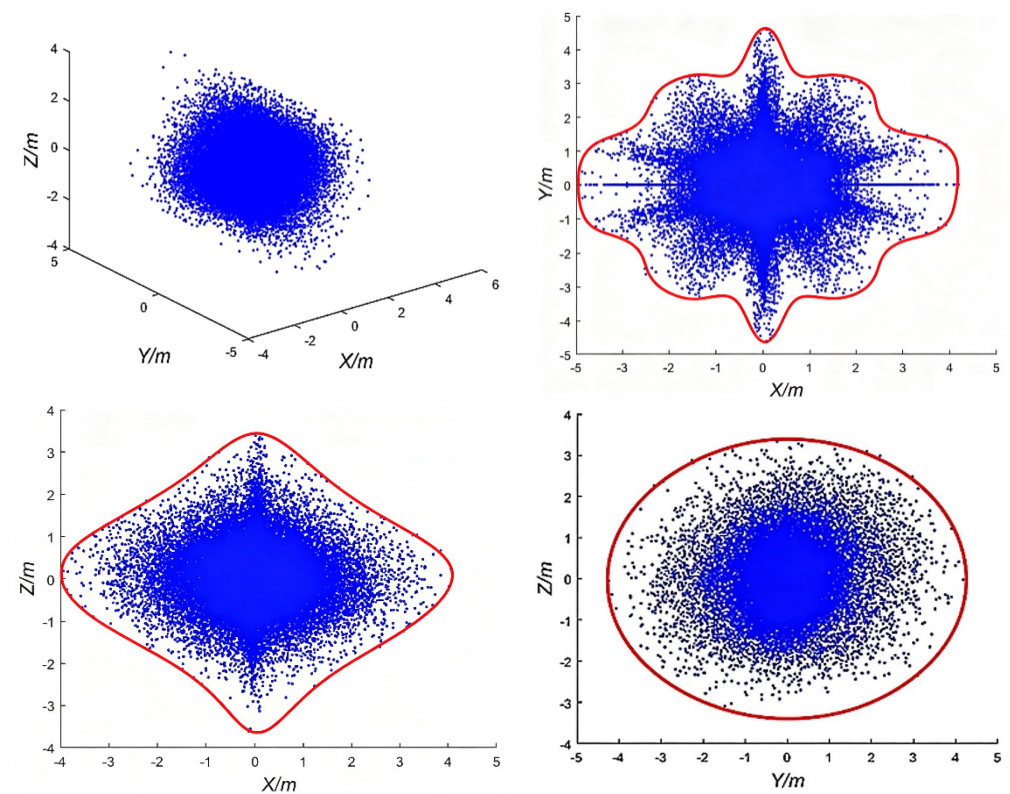


Figure 14. Full-wave-direction map of level 5 sea state and projection map on coordinate plane.

It can be observed from the full-wave-direction diagrams under sea states 3 to 5 that the scatter plots projected onto each coordinate plane exhibited a pattern of dense concentration in the central region and sparse distribution at the edges. Among the six-degree-of-freedom motion responses, the angular motions (roll, pitch, and yaw) exhibited distinct characteristics under different wave headings. The roll motion was most significantly affected by wave excitation, particularly under beam sea conditions (wave heading around 90°), where the roll RAO peak approached the wave spectrum peak and induced resonance. The pitch motion showed stronger response under oblique wave headings, while the yaw motion remained relatively small due to the DP system constraint. These angular motion characteristics directly influenced the required compensation of the gangway joints, as the pitch angle of the gangway was strongly correlated with the vessel roll response, and the gangway rotation was correlated with the vessel pitch response. To facilitate subsequent calculations, the minimum ellipsoid enclosing all scatter points was adopted to represent the motion domain for each sea state. The scatter points were generated using the Monte Carlo method with 30,000 samples for each sea state, following the procedure described in the kinematic workspace analysis. The ellipsoid parameters a , b , and c were obtained by fitting the minimum-volume ellipsoid that enclosed all sampled motion response points. A 10% margin was then added to these parameters to account for sampling variability and unmodeled factors, which is a conventional practice in preliminary marine operability assessments. The values of a , b , and c corresponding to each sea state are listed in Table 2, and the ellipsoid equation is given as follows.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad (8)$$

Table 2. Value of a , b , and c under sea conditions of levels 3~5.

Sea State	a	b	c
3	0.49	1.24	1.03
4	1.91	4.20	3.17
5	4.90	8.93	4.61

The minimum bounding ellipsoid was adopted to represent the vessel motion envelope because the simulated motion responses were distributed in a three-dimensional space and involved coupled variations among surge, sway, and heave motions. Compared with independent limits of each motion component, the ellipsoidal envelope can describe the spatial correlation of vessel motions and provide a conservative boundary for evaluating whether the gangway base point remains within the allowable region.

It should be noted that the fitted ellipsoid in this study was used as a deterministic operational envelope rather than a statistical confidence boundary. The safety margin was introduced to account for modeling uncertainties and environmental variations. To evaluate the influence of the margin selection, sensitivity analyses with 5%, 10%, and 15% margins were performed. The results demonstrated that the 10% margin provided a reasonable compromise between operational safety and available working space.

4.2. Feasible Region of the Gangway Base Point Under Wave Action

The influence of rotations of the gangway base point about the x -, y -, and z -axes of its coordinate system on the suitable fixed-point operation area of the vessel was mainly reflected in the feasible region of the gangway base point. With the application of dynamic positioning, the rotation amplitude of the gangway base point about the z -axis was small, which was negligible compared with the 180° to 360° motion range of the slewing joint of

the transfer gangway. Secondly, the rotation amplitude of the gangway base point about the y -axis was also small and could be neglected. However, its rotation angle about the x -axis was relatively large, which exerted a direct influence on the range of the pitch joint within the feasible region of the gangway base point. For the vessel, the rotation angle about the x -axis of the gangway base point was equal to the roll angle. Thus, the roll angle of the vessel was analyzed in the following section.

The calculated extreme values of the roll angle under sea states 3 to 5 across all wave directions and wave seeds are presented in Table 3. It can be noted that the extreme values of roll angle varied considerably across sea states 3, 4, and 5, which shown in Figures 15–17. A comparison of the wave spectrum and roll RAO at the 90° wave heading under sea states 3 to 5 revealed that as the sea state level increased, the peaks of the wave spectrum and the roll RAO gradually converged. As a result, the roll angle grew rapidly with the rise of sea state grade.

Table 3. Maximum values of roll angles for sea conditions of levels 3–5.

Sea State	Extreme Values of Absolute Roll Angle ($^\circ$)
3	0.76
4	6.06
5	18.97

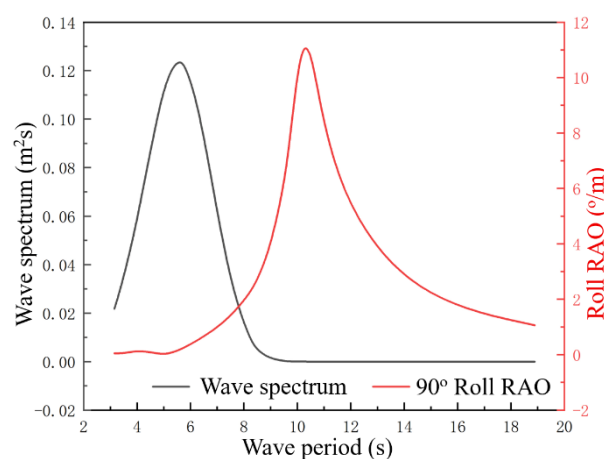


Figure 15. Wave spectra and rolling RAO in a 90° wave direction for level 3 sea conditions.

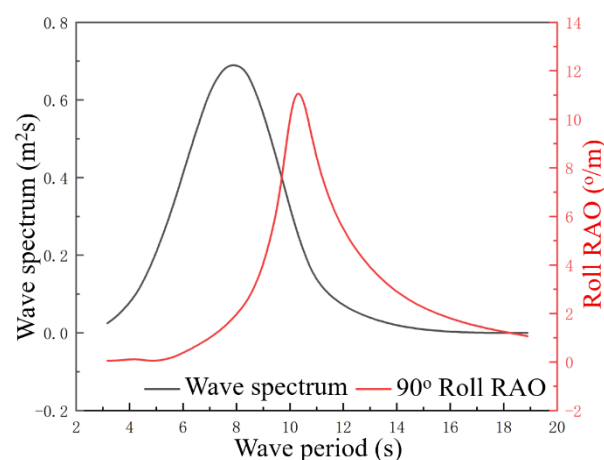


Figure 16. Wave spectra and rolling RAO at 90° wave direction for level 4 sea conditions.

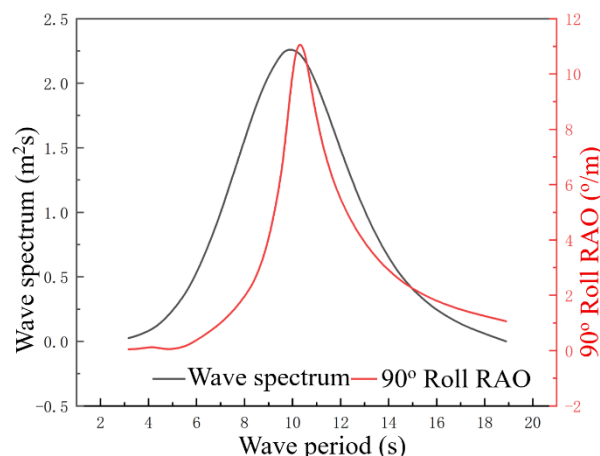


Figure 17. Wave spectrum and rolling RAO of 90° wave direction for level 5 sea state.

Under the influence of the roll angle, the upper angle limit of the gangway base point feasible region shall be subtracted by the absolute value of the extreme roll angle, while the lower angle limit shall be added with the maximum value among the roll angle extremes. The revised upper and lower limits of the gangway base point feasible region were finally obtained, as shown in Table 4.

Table 4. Upper and lower limits of feasible range angles for base points under sea conditions of levels 3–5.

Sea State	Upper Angle Limit of the Feasible Region (°)	Lower Angle Limit of the Feasible Region (°)
3	9.24	−24.24
4	3.94	−18.94
5	−8.97	−6.03

It can be observed that under sea state 5, the upper angle limit of the feasible region (−8.97°) fell below the lower angle limit (−6.03°), which indicates that the feasible interval completely collapsed and the pitch capacity of the gangway could not meet the wave compensation requirements for sea state 5. For sea states 3 and 4, the feasible regions of the gangway base point are presented in Figures 18 and 19.

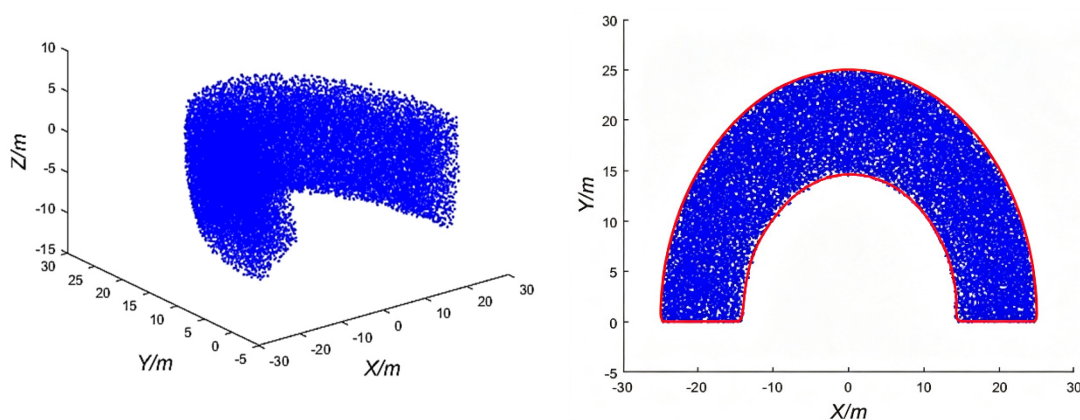


Figure 18. Cont.

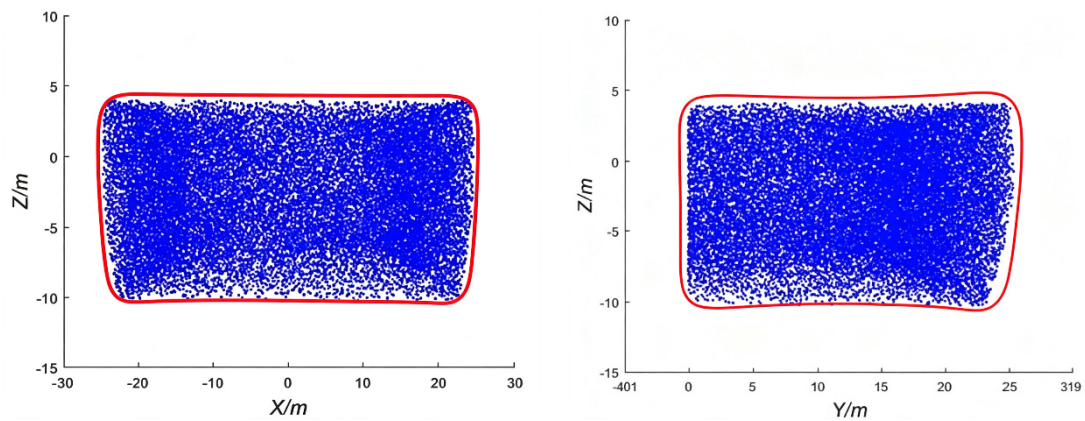


Figure 18. Scatter plot and projection of feasible range of gangway base point under level 3 sea conditions.

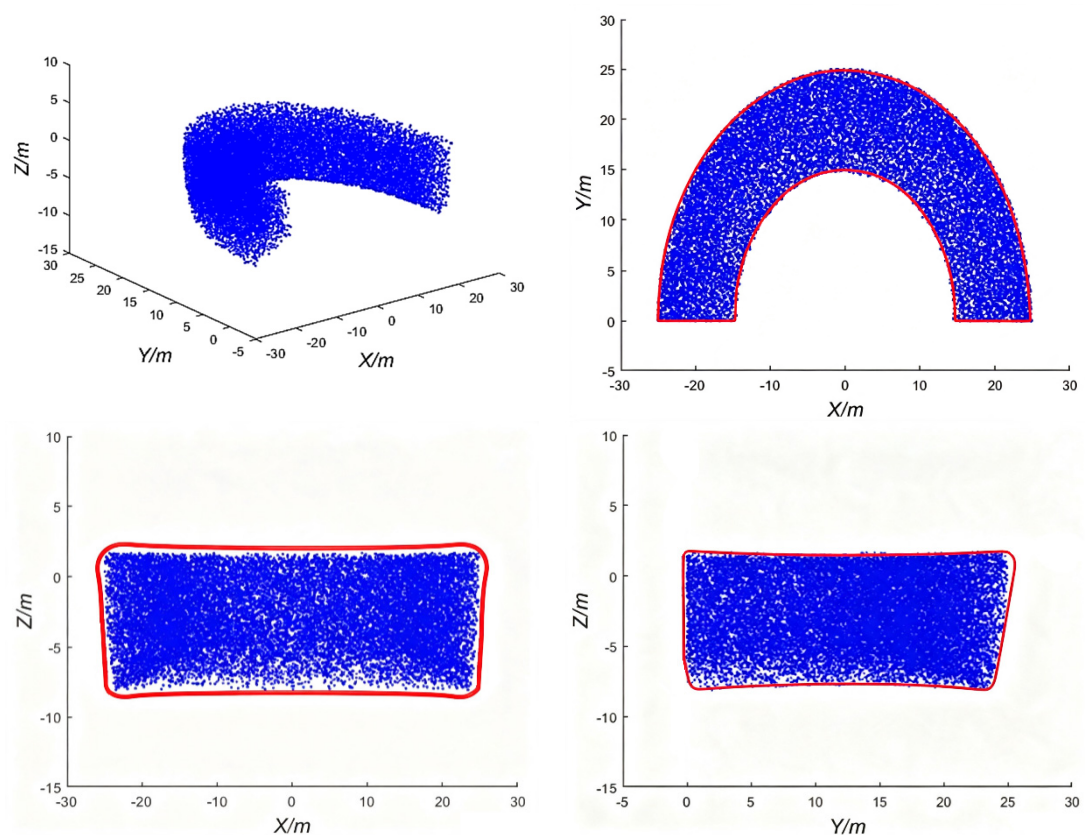


Figure 19. Scatter plot and projection of feasible region of gangway base point under level 4 sea conditions.

The constraint equations for the feasible region of the gangway base point under sea states 3 and 4 are presented in Equations (9) and (10), respectively.

$$\begin{cases} y \geq 0 \\ 225 \leq x^2 + y^2 + (z + 5)^2 \leq 625 \\ -\tan 24.24^\circ \leq (z + 5) / \sqrt{x^2 + y^2} \leq \tan 9.24^\circ \end{cases} \quad (9)$$

$$\begin{cases} y \geq 0 \\ 225 \leq x^2 + y^2 + (z + 5)^2 \leq 625 \\ -\tan 18.94^\circ \leq (z + 5) / \sqrt{x^2 + y^2} \leq \tan 3.94^\circ \end{cases} \quad (10)$$

5. Analysis on Suitable Fixed-Point Operation Area

5.1. Suitable Fixed-Point Operation Areas Under Different Sea States

By embedding the ellipsoids calculated for sea states 3 and 4 into the corresponding feasible regions of the gangway base point for each sea state, the suitable berthing areas for the vessel under different sea states can be determined. The specific implementation method was as follows: With scatter points in the workspace of the gangway base point taken as the ellipsoid centers, the Monte Carlo method was used to sample points on the ellipsoid surface in combination with the ellipsoid equation so as to simulate the extreme motion response of the vessel under sea conditions. If all sampled points on the ellipsoid surface fall within the feasible region of the gangway base point, the center of the ellipsoid is deemed a suitable fixed-point operation position for the vessel.

To generate points on the ellipsoid surface, the following method was adopted in this paper. Random points of the x -coordinate were sampled within the interval $(-a, a)$. For each x value, a new elliptical cross-section was obtained, meaning that the value ranged of y and z vary accordingly. For each given x , the value range of y was solved, and random y values were sampled within this range. Finally, the z -coordinate was derived from the ellipsoid equation, yielding two values z_1 and z_2 corresponding to the positive and negative square roots. It should be noted that pure Monte Carlo random sampling has low point density at the ellipsoid boundary, especially at the ends of the principal axes. To compensate for this, deterministic boundary points on the elliptical sections of the three coordinate planes ($x = 0$, $y = 0$, and $z = 0$ sections) were additionally supplemented on the basis of the random samples. This combined strategy ensured both the integrity of the ellipsoid surface representation and the statistical representativeness of the sampled points.

The points on the ellipsoid surface simulated by this method are illustrated in the Figure 20 below.

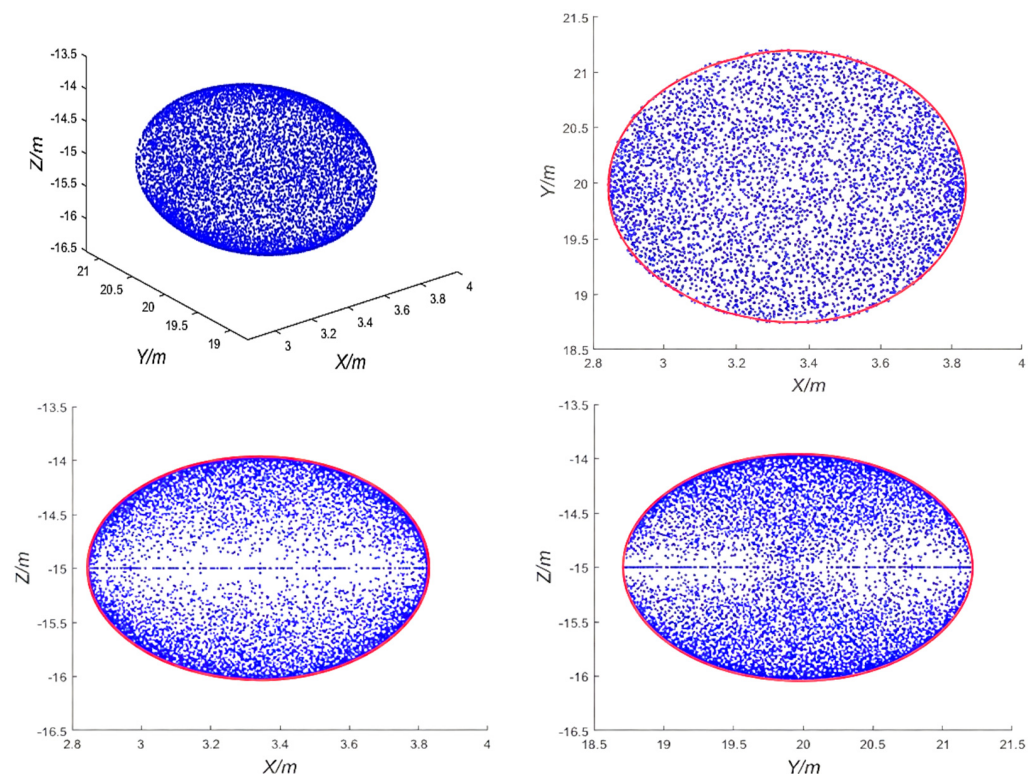


Figure 20. Ellipsoid and its three-sided projection obtained from Monte Carlo points.

It should be noted that Monte Carlo sampling alone is insufficient to accurately simulate the ellipsoid surface. As Monte Carlo sampling operates on open intervals, boundary points such as $(x = a, y = 0)$ or $(x = 0, y = a)$ cannot be sampled. Very few points satisfy the equation $x^2/a^2 + y^2/b^2 = 1$, meaning the points on the ellipse at $z = 0$ are not well represented. The final simulated ellipsoid surface is presented in Figure 20, which are in good agreement with the corresponding values in Table 2.

During actual operation, the x -axis of the ship's body-fixed coordinate system was perpendicular to the line connecting the transfer point and the origin of this coordinate system. That is to say, the port side of the vessel faced directly towards the transfer point. In this configuration, the slewing joint of the gangway retained sufficient margin in both clockwise and counterclockwise directions. Taking wind, wave, and current loads from different directions into account, this fixed-point operation position is relatively appropriate.

Owing to a certain angular deviation between the coordinate axes of the ship's body-fixed coordinate system and the transfer point coordinate system, it is necessary to perform coordinate transformation on the coordinate values on the ellipsoid surface defined in the ship's body-fixed coordinate system to derive their corresponding coordinates in the transfer point coordinate system. The final fixed-point operation range for the transfer vessel under sea state 3 is presented in the Figure 21 below.

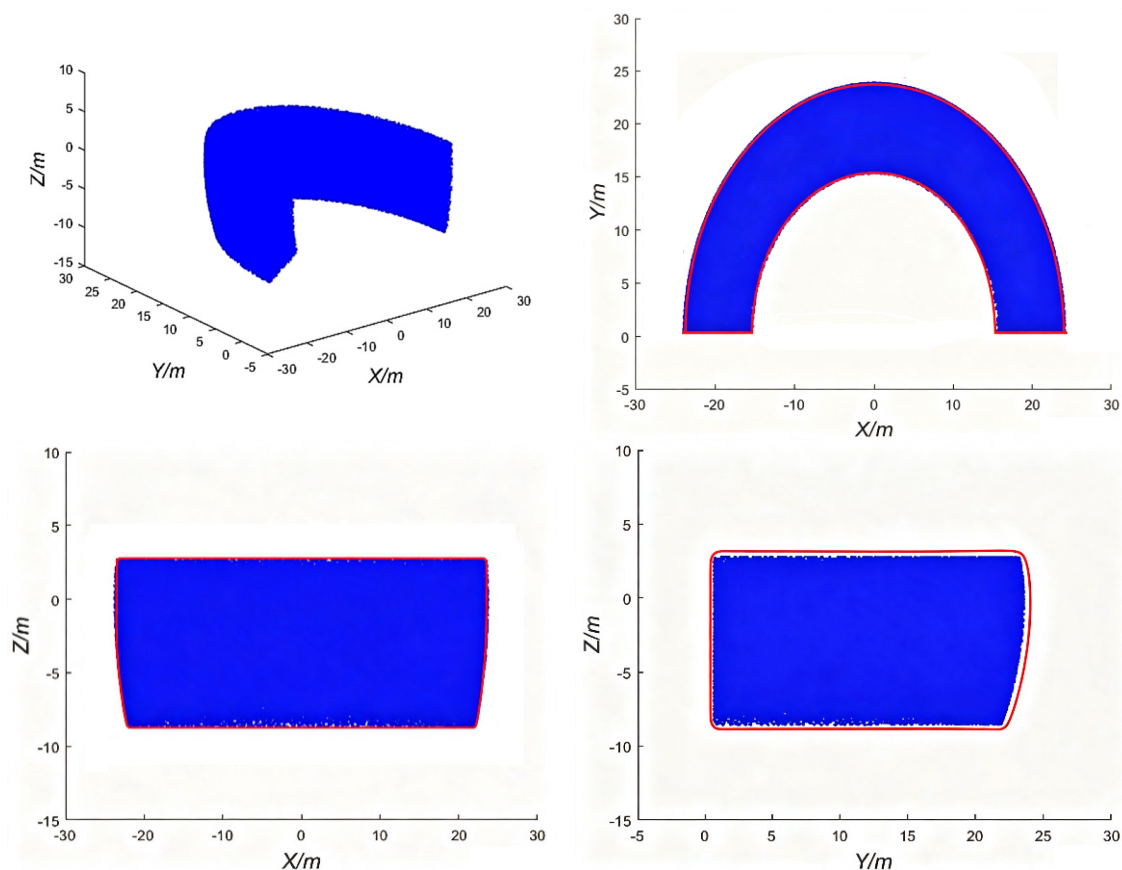


Figure 21. Suitable fixed-point operation space and projection views of transfer vessel under sea state 3.

The z -axis value range of this fixed-point operation interval is $[-8.7, 2.7]$. That is to say, the height of the transfer point shall not be 8.7 m higher than the gangway base point, nor shall it be 2.7 m lower than the gangway base point. The suitable fixed-point operation range for the transfer vessel under sea state 4 is presented in the Figure 22 below.

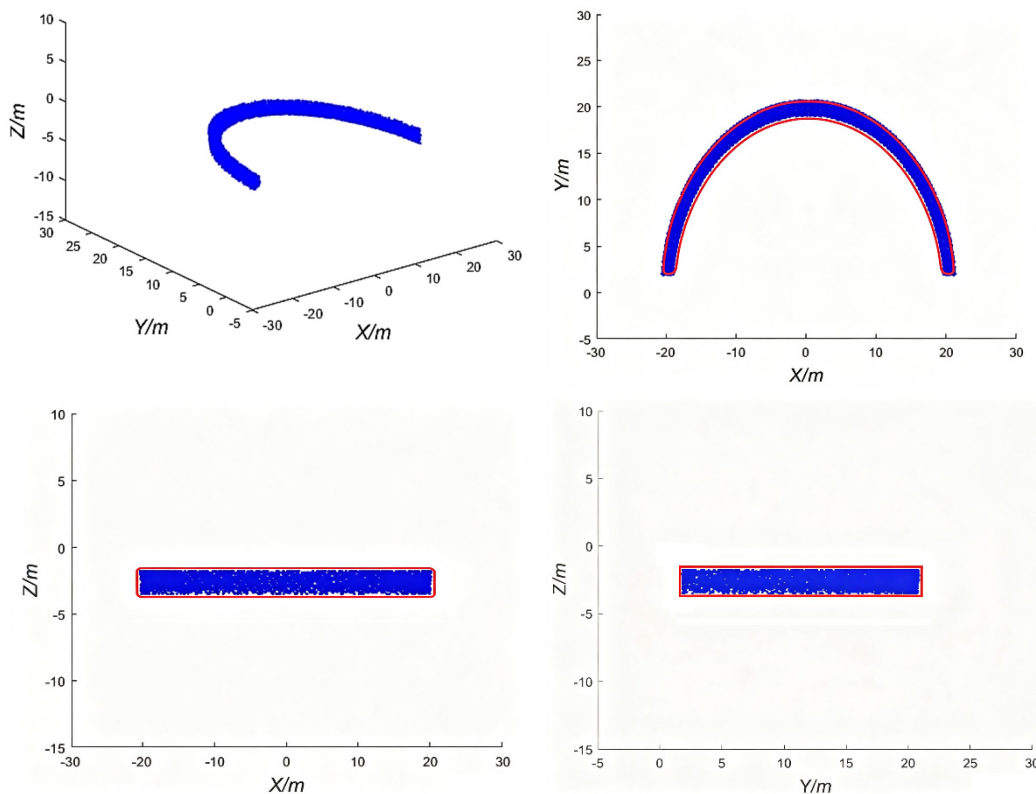


Figure 22. Suitable fixed-point operation space and projection for transferring ships under level 4 sea conditions.

In this case, the z -axis range of the fixed-point operation interval is $[-3.5, -1.8]$; that is to say, the height of the transfer point can only be 1.8 m to 3.5 m above the gangway base point. Based on the criterion that the motion range of the gangway base point must lie entirely within the feasible domain, the feasible station-keeping positions for the vessel are those where all sampled ellipsoid surface points fall within the feasible region. Furthermore, it is clearly observed from the suitable fixed-point operation intervals of the transfer vessel under sea states 3 and 4 that as the sea state level increases, the space of the suitable fixed-point operation area gradually shrinks until operation becomes infeasible.

5.2. Suitable Fixed-Point Operation Areas at Different Transfer Point Heights

For a single transfer mission, the height coordinate of the gangway base point in the geodetic coordinate system remains fixed under calm water conditions, and the height of the transfer point in the same coordinate system is also constant. The height difference between the two is therefore fixed. Accordingly, in practical engineering applications, once the height coordinates of the transfer point and the vessel's gangway base point are confirmed, only the height difference between them needs to be determined. By assigning a given z value and applying the method presented in the previous section, the suitable berthing areas of the vessel at different transfer point heights can be derived when the coordinate origin is set at the transfer point located on the outer side of the wind turbine tower.

In previous calculations, the transfer point was set as the coordinate origin, and variations in the height difference between the two points reflect differences in the height of the gangway base point. For a given operation and maintenance vessel, the height of its gangway base point remains constant. Accordingly, the gangway base point was adopted as the coordinate origin herein: the z value was positive when the transfer point lay above the gangway base point, and negative when it lay below.

Under sea state 3, multiple height difference values were selected at regular intervals from the z range of the fixed-point operation interval. The suitable fixed-point operation areas versus different z values are plotted in Figure 23.

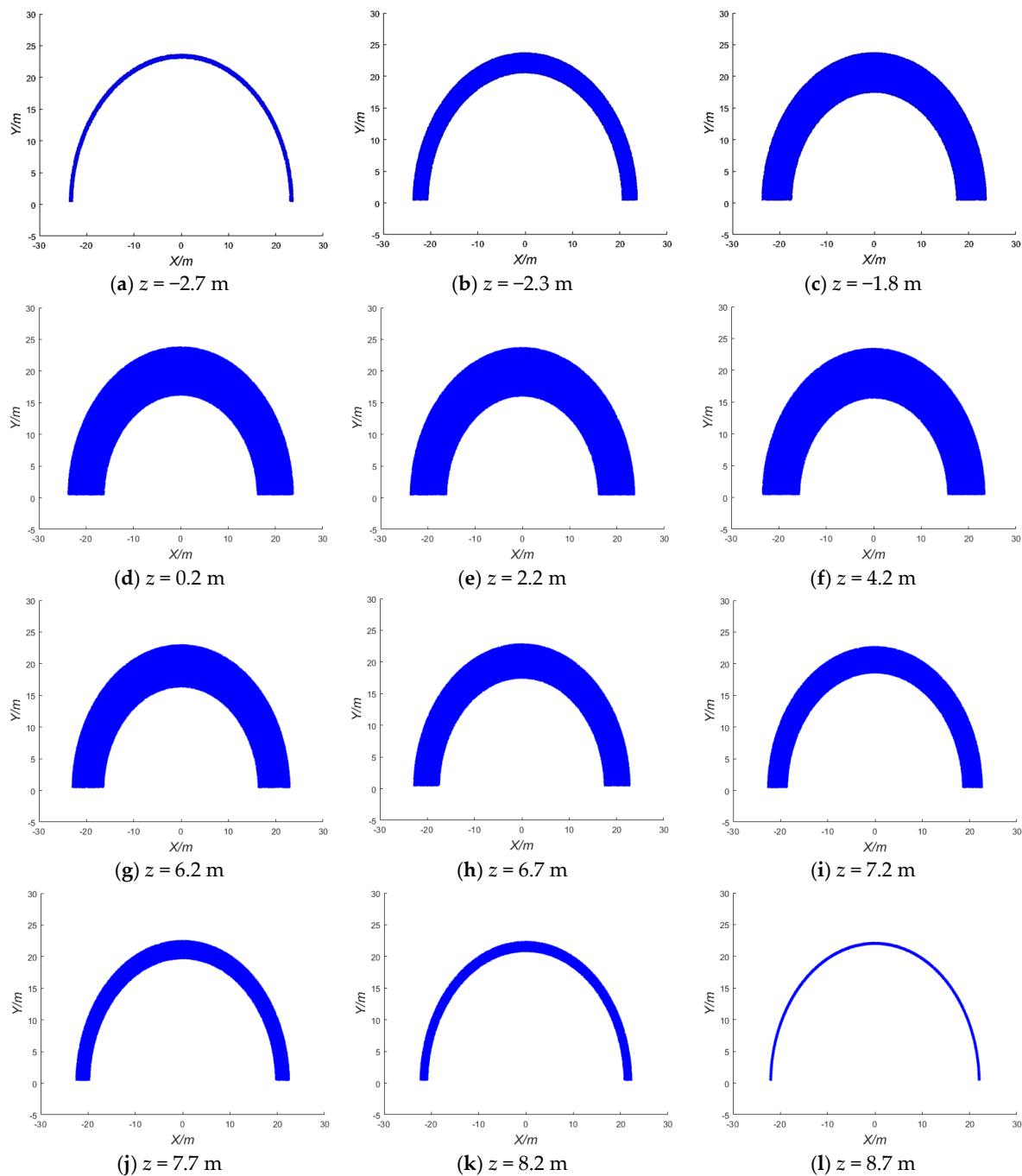


Figure 23. Suitable fixed-point operation areas corresponding to different z under level 3 sea conditions.

It can be observed that all suitable fixed-point operation areas at different transfer point heights are portions of an annulus, each with its corresponding radius range and annulus width. Under sea state 3, the variation trends of the maximum and minimum annulus radii as well as the annulus width corresponding to different height differences are presented in Figures 24 and 25.

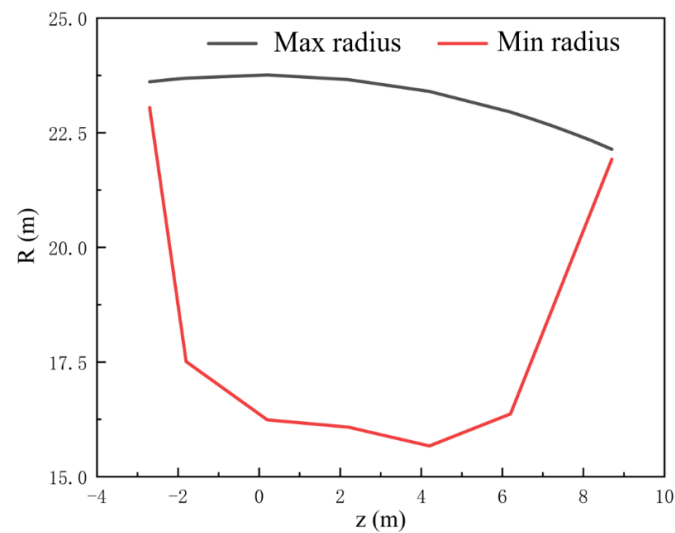


Figure 24. Maximum and minimum radius of suitable operating area under different z conditions under level 3 sea conditions.

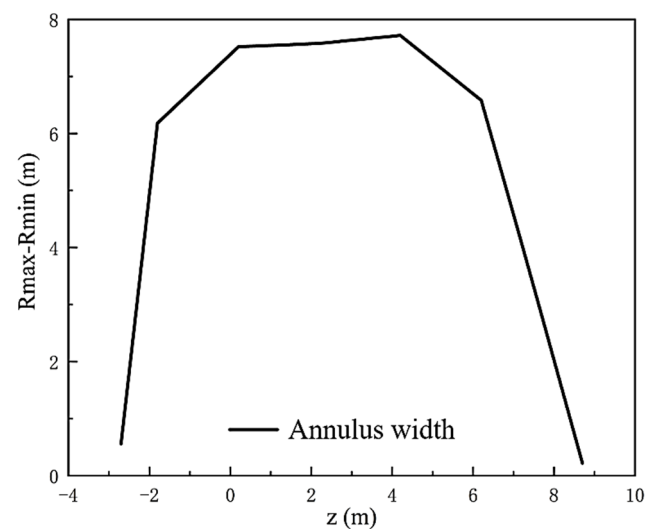


Figure 25. Circle width of suitable operation area for different z under level 3 sea conditions.

Correspondingly, the suitable berthing areas of the vessel corresponding to different height differences under sea state 4 can also be obtained using the same method, as presented in the Figure 26 below.

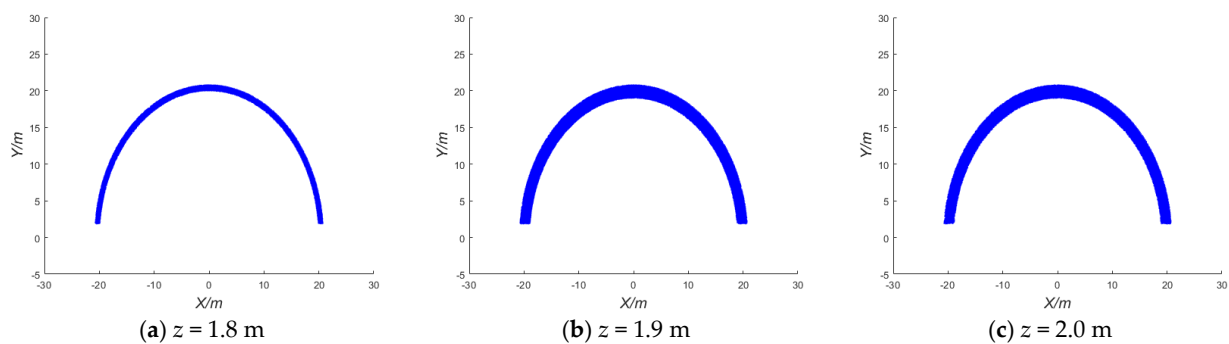


Figure 26. Cont.

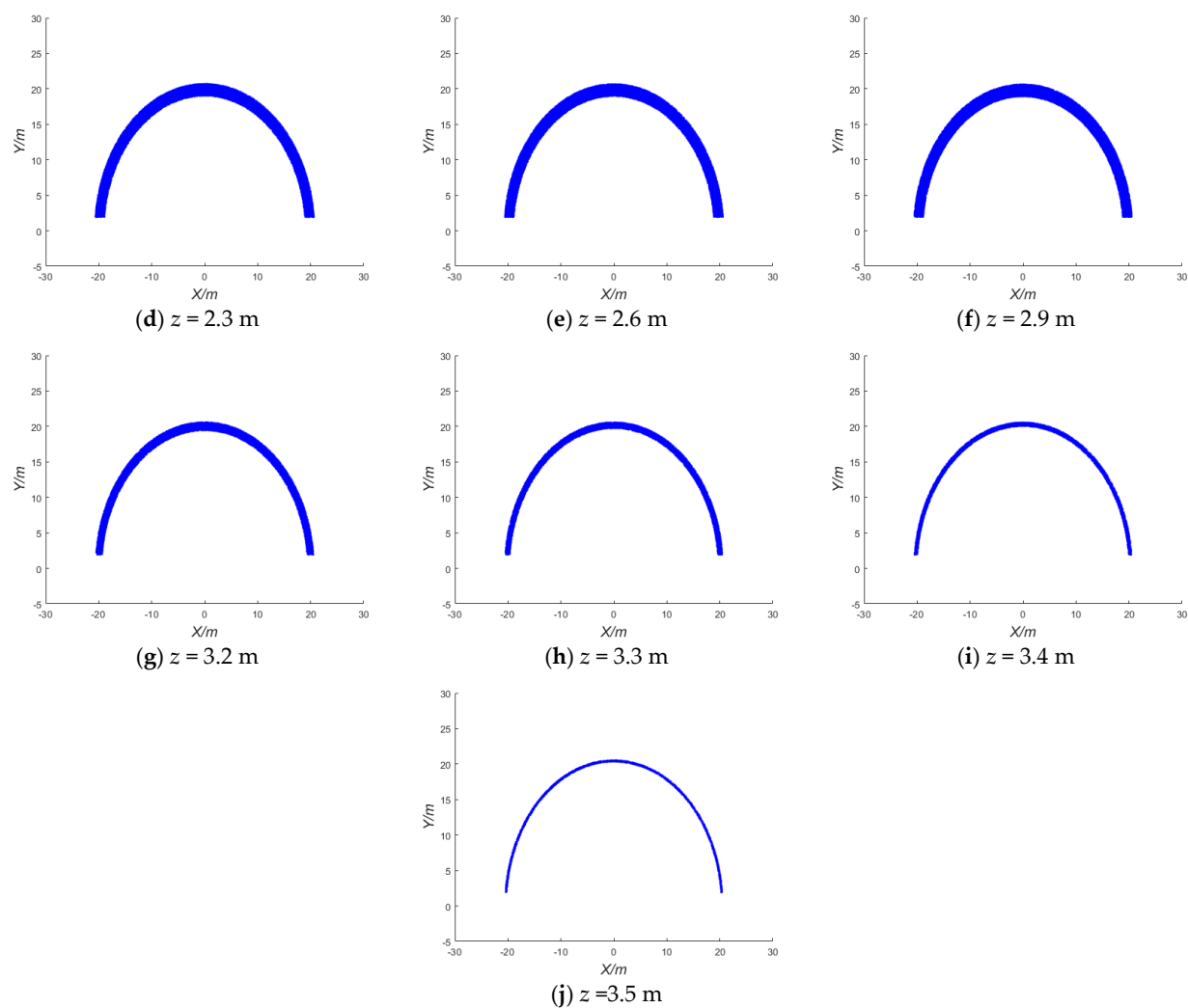


Figure 26. Suitable fixed-point operation areas corresponding to different z under level 4 sea conditions.

Under sea state 4, the variation trends of the maximum and minimum annulus radii as well as the annulus width corresponding to different height differences are presented in the Figures 27 and 28 below.

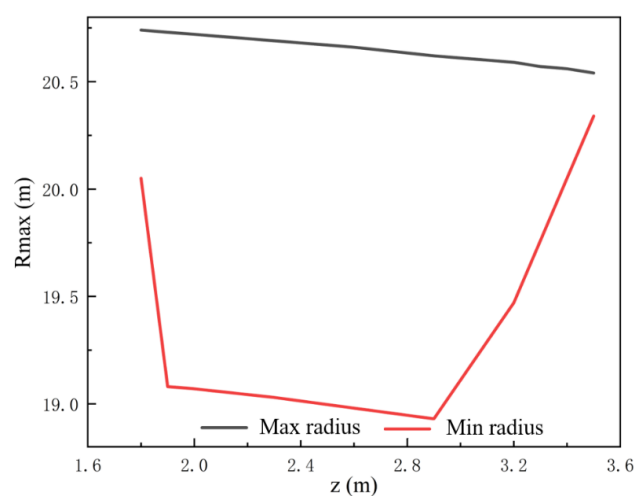


Figure 27. Maximum and minimum radius of suitable operating area under different z conditions under level 4 sea conditions.

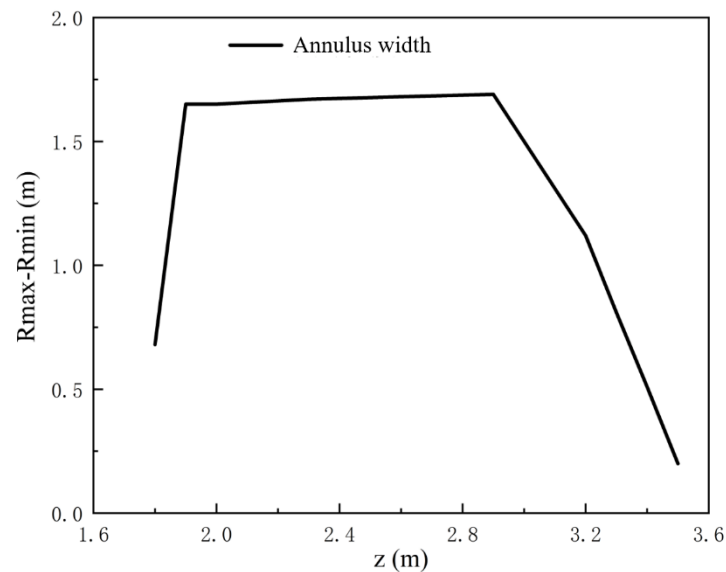


Figure 28. Circle width of suitable operating area under different z conditions under level 4 sea conditions.

Calculations of the suitable fixed-point operation areas at different transfer point heights reveal that as the height of the transfer point increases, the annulus width follows a trend of initial substantial increase, followed by slow growth, and eventual sharp decline. These variations are caused by the constraint of the gangway pitch angle.

5.3. Verification of Method to Determine Suitable Fixed-Point Operation Areas of the Gangway

Based on the method proposed in this chapter, the suitable fixed-point operation areas for the transfer gangway studied in this paper under sea states 3 and 4 were obtained, and it was found that operation was infeasible for this transfer gangway under sea state 5. Verification of this conclusion is presented in this subsection.

First, for sea states 3 and 4, three working conditions were defined for each sea state by generating random wave directions and random seed numbers via random number generation. The height of the transfer point was taken as the maximum z value, the minimum z value, and a random value within the feasible z range, respectively. Correspondingly, the annulus radius of the suitable fixed-point operation area was set to its maximum value, minimum value, and a random value within the corresponding radius range.

Following the method described above, the settings of the calculation cases are presented in Table 5 below.

Table 5. Example settings for validation.

	Sea State	Wave Direction	Wave Seed	z (m)	r (m)
Case 1	3	90	3	8.7	22.14
Case 2	3	150	3	0.2	20.35
Case 3	3	30	2	−2.7	23.05
Case 4	4	150	1	1.8	20.74
Case 5	4	180	3	2.0	20.67
Case 6	4	60	3	3.5	20.34
Case 7	5	120	2	3.0	19.80

Based on the setup of the aforementioned calculation case, the wave compensation values of each joint of the transfer gangway were calculated using the coupling method for the gangway and vessel presented in this paper, and the results are listed in Figures 29 and 30.

Therein, taking Case 1 and Case 2 as examples, the time-history curves are presented, and the corresponding statistical data are summarized in Table 6.

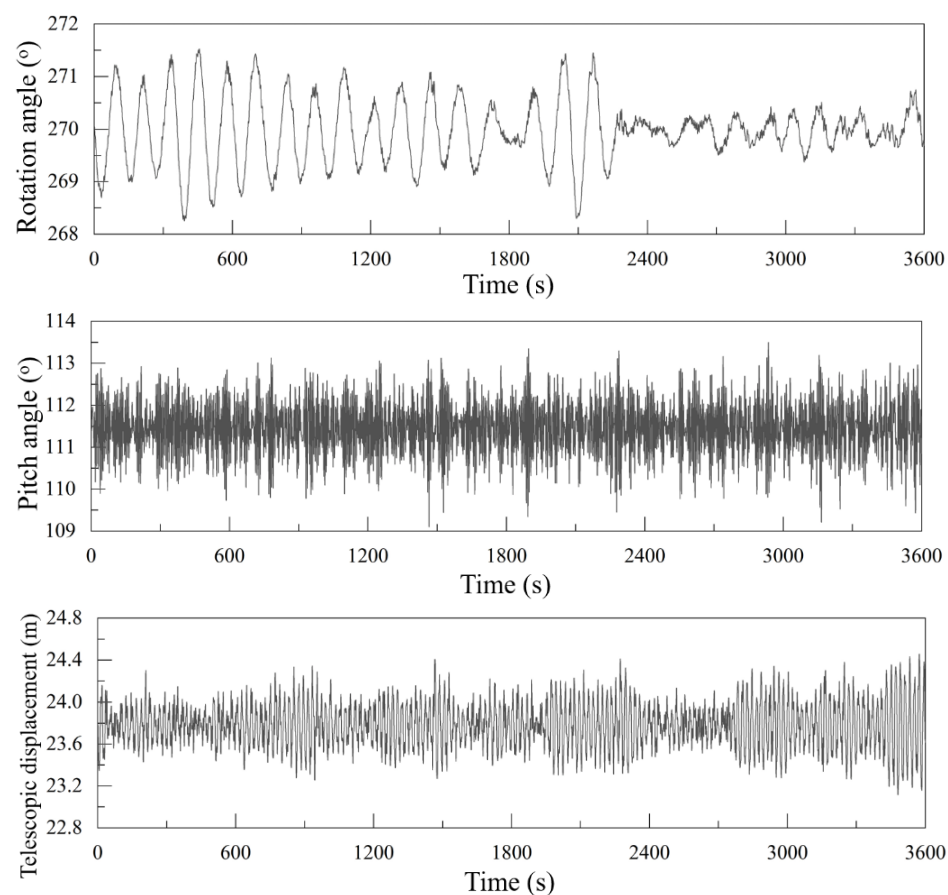


Figure 29. The compensation amount for each joint of the transfer gangway in Case 1.

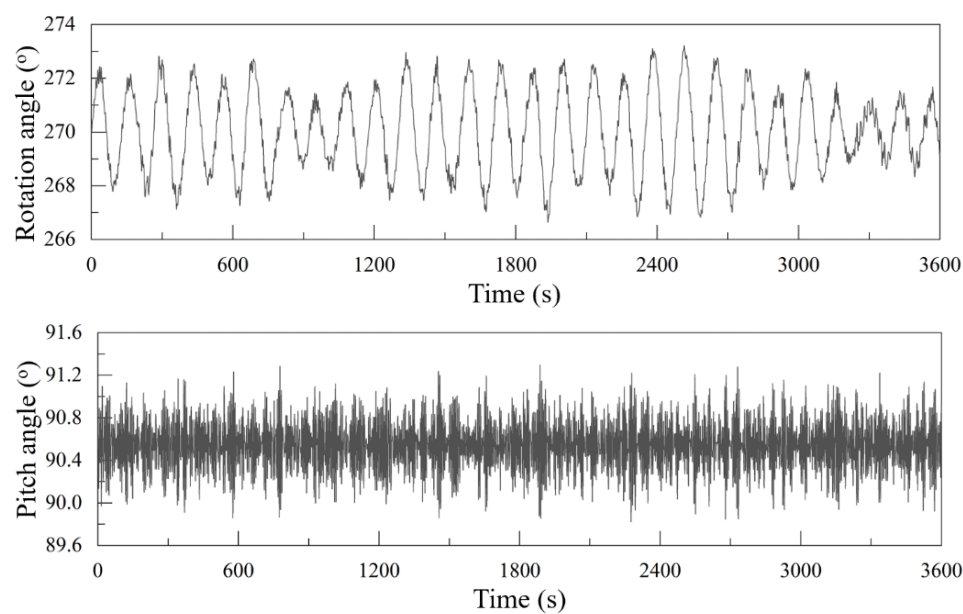


Figure 30. Cont.

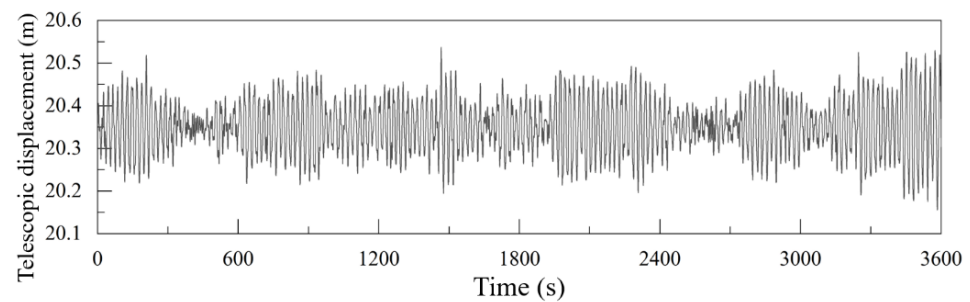


Figure 30. The compensation amount for each joint of the transfer gangway in Case 2.

Table 6. Maximum compensation values for each joint of transfer gangway in Cases 1~7.

		Rotation Angle (°)	Pitch Angle (°)	Telescopic Displacement (m)
Case 1	Min	268.25	109.10	23.12
	Max	271.53	113.50	24.46
Case 2	Min	266.64	89.82	20.16
	Max	273.22	91.30	20.54
Case 3	Min	267.17	82.67	22.98
	Max	273.11	83.96	23.45
Case 4	Min	253.69	89.99	20.11
	Max	284.52	99.93	21.54
Case 5	Min	266.41	93.49	20.71
	Max	273.13	97.59	20.86
Case 6	Min	257.82	92.53	18.79
	Max	278.92	105.45	22.40
Case 7	Min	258.63	77.49	16.32
	Max	280.46	118.84	23.76

Based on the results in Table 6 and the gangway joint limits (rotation angle: 180° ~ 360° , pitch angle: 80° ~ 115° , telescopic displacement: 15 m~25 m), the safety margins for the feasible cases and the exceedance for the infeasible case are summarized as follows.

For sea state 3, the minimum pitch angle margin is 2.67° (Case 3, lower limit), while all telescopic and rotation displacements remain well within their allowable ranges. For sea state 4, the minimum pitch angle margin is 9.55° (Case 6, upper limit). These margins indicate that the gangway maintains sufficient operational reserve under the tested sea state 3 and 4 conditions.

For sea state 5 (Case 7), the pitch angle exceeds the upper limit by 3.84° and the lower limit by 2.51° , confirming that the gangway cannot satisfy the wave compensation requirements. The telescopic displacement in Case 7 remains within the allowable range (16.32 m~23.76 m), indicating that the pitch joint is the primary limiting factor for operability under sea state 5.

Compared with the ranges of each gangway D-H parameters (rotation angle [180° ~ 360°], pitch angle [80° ~ 115°], telescopic displacement [15 m~25 m]), it can be shown that the outcomes of Cases 1 to 6 all fall within the motion range of the gangway specified in previous sections, while the pitch angle in Case 7 exceeds the joint limit. This confirms that the gangway can operate under sea state 3 and sea state 4 but is unable to operate under sea state 5. This conclusion is also consistent with the findings of the previous analysis.

5.4. Limitations and Future Work

Although the proposed method provides an analytical framework for determining the operational sea states and station-keeping ranges of maintenance vessels equipped with transfer gangways, several limitations should be acknowledged.

First, the transfer gangway is modeled as a rigid-body multibody system in the current study. The elastic deformation of gangway components and the resulting influence on joint motion responses are neglected. For large-scale and long-arm gangways, structural flexibility may affect the actual compensation capability and should be considered in future studies.

Second, the environmental conditions considered in this study mainly focus on wave-induced vessel motions. The effects of wind and current loads, which may influence dynamic positioning performance and vessel station-keeping accuracy, are not included. Further investigations considering combined wind, wave, and current conditions are required to improve the applicability of the proposed method.

Third, the present analysis is based on numerical simulations and specific vessel-gangway configurations. Although the proposed framework can quantitatively evaluate the operational range under given conditions, experimental validation and additional case studies involving different vessel types and gangway configurations are necessary to further verify its general applicability.

Future work will focus on incorporating flexible gangway dynamics, coupled environmental loads, and probabilistic operational assessment methods to establish a more comprehensive evaluation framework for offshore wind turbine maintenance operations. The significance of this study lies in providing a systematic analytical framework that bridges the gap between gangway kinematic constraints and vessel operational planning, which has been lacking in previous research. The proposed method can serve as a basis for developing operational guidelines for maintenance vessel operators and for optimizing the design of future gangway systems.

6. Conclusions

This paper focuses on the fixed-point operation range of operation and maintenance (O&M) vessels. Based on the analysis of gangway kinematics and ship motion response, it proposes an analysis strategy for the fixed-point operation range that comprehensively accounts for gangway joint constraints and wave effects and establishes a method to determine the fixed-point positions that ensure safe gangway operation throughout the entire operation window. Through this method, the following conclusions are drawn:

- (1) For different sea states, the area suitable for fixed-point ship operation shrinks gradually as the sea state level rises until operation becomes completely infeasible. According to calculations for sea states 3 to 5, for the modeled vessel, gangway parameters, wave spectrum, DP assumptions, and environmental conditions considered in this study, the current gangway is capable of safe operation under sea states 3 and 4 but cannot operate safely under sea state 5, which is further verified by random case studies.
- (2) Under the same sea state, the operation area corresponding to different height differences between the gangway base point and the transfer point presents a partial circular ring shape. The width of the ring first increases and then decreases with the growth of the height difference. The gangway imposes a limit on the height of the transfer point, and the allowable height range narrows as the sea state level increases. Even under calm water conditions, the operational capacity of the gangway requires the height of the transfer point relative to the gangway base point to fall within $[-4.34, 10.57]$. For sea states 3 and 4, the corresponding z-axis height ranges

of the transfer point relative to the gangway base point are $[-2.7, 8.7]$ and $[1.8, 3.5]$, respectively.

- (3) For feasible operation sea states, this method can generate a three-dimensional diagram of the suitable fixed-point operation area for the ship. According to the height difference between the transfer point and the gangway base point, the XOY plane of the suitable range at different z values can be obtained, which takes the shape of a partial circular ring. The width of the circular ring shows a trend of first increasing sharply, then rising slowly, and finally decreasing significantly with the increase of z .

The developed approach provides decision support for the pre-planning of offshore wind farm maintenance transfer tasks in engineering practice. By predicting the safe operation window and feasible vessel docking positions based on sea state forecasts, it can reduce the risk of joint limit violations during transfer operations and improve both the efficiency and safety of personnel access. In addition, this work fills the theoretical gap between gangway kinematic analysis and vessel operability assessment, offering a systematic framework that can be extended to different gangway configurations and vessel types by substituting the corresponding geometric and motion parameters.

Furthermore, this study focuses on wave-induced motion for the time being. Wind and current mainly cause steady drift of the vessel, which can be offset by the DP system, and has little influence on the high-frequency motion amplitude. The coupled effect of wind, wave, and current will be included in the follow-up study. In the current study, the extreme motion calculated by three seeds can meet the accuracy requirement of preliminary operational assessment. In the subsequent studies, simulation cases versus more seeds should be studied and discussed. Moreover, we should perform the sensitivity analysis in subsequent studies (including vessel RAO error, wave spectrum selection, DP gain variation, gangway mass distribution, wave seed randomness, Monte Carlo sampling convergence, etc.).

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