Numerical Study on Hydrodynamic Characteristics of Two Ships Advancing in Parallel for Underway Replenishment of Luxury Cruise Ships

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Abstract. For a long time, seakeeping data has been the basis for judging ship amenities and seaworthiness. Luxury cruise ships, as large passenger ships, put forward higher requirements for seakeeping. To analyze the seakeeping response of luxury cruise ships, AQWA is used to build a model and conduct numerical simulations. The hydrodynamic characteristics of cruise ships and replenishment tankers with different typical sea conditions, various ship spacing and wave directions are studied. According to the results, when two ships are advancing in parallel, the cruise ship should pay attention to the movement of the replenishment tanker while considering its seakeeping to avoid collision danger. The conclusions can avoid dangerous situations in the replenishment and improve the safety of the replenishment operation.

Key Words: Luxury Cruise Ship, Parallel Replenishment, Ship Seakeeping, Numerical Simulation, Coupled Motion.

1. Introduction

Seakeeping is a vital index to measure whether a ship is seaworthy or not. For a given environmental condition, determining the wave force and its motion response on the ship is fundamental to ship seakeeping research. As for general ships, seakeeping is a critical performance index, with seakeeping data as the basis for judging ship amenities and seaworthiness. The luxury cruise ship, deemed as "the jewel in the crown" by the world shipbuilding industry, is characterized by wide moulded breadth, small moulded depth, high center of gravity, large passenger capacity and high seasickness rate. Thus, it proposes higher requirements for ship seakeeping and it is necessary to further study the hydrodynamic performance of luxury cruise ships.

In-depth research on ship seakeeping emerged in the 1950s, represented by the vessel swaying theory in irregular waves proposed by St. DENIS and PIERSON and the strip theory of KORVIN-KROUKOVSKY. The combination of these theories promotes the development of the ship motion theory in waves. The International Towed Tank Conference (ITTC) [1] integrates different physical problems, which isolates the seakeeping research from the study of a certain performance to a comprehensive study. Because of the influence of waves, many studies on static water states can not be applied, and many mathematical problems originally described as linear and steady have been nonlinear and unsteady problems. Nowadays, after more than 70 years of development, many research achievements have been achieved on ship seakeeping, which have been used to guide the selection of ship shape coefficient, main dimension and even the design of ship profile. For the calculation of ship motion and hydrodynamic force, a series of theories have also been developed. Strip theory (also called STF method), which was proposed in 1970, is still the most widely used method to calculate ship seakeeping.

Large cruise ships have unique requirements for amenities and seaworthiness, with their seakeeping performance different from that of ordinary ships. Thus, it is necessary to conduct related research. In addition to extending the frequency domain linear prediction method based on strip theory, Wang Jianfang and Cao Yu [2] studied the seakeeping characteristics of the nonlinear motion of a large luxury cruise ship and concluded that it is suitable for ship longitudinal nonlinear motion prediction. Cao Yu et al. [3] predicted the cruise performance of luxury cruise ships based on potential flow theory, but the results based on this theory lack flow field details. Zhang Mu et al. [4] used the self-developed CFD solver of ship hydrodynamics to simulate the seakeeping of luxury cruise ships at the model scale, which provided reference data for the safety and amenity evaluation of cruise ships, laying the theoretical foundation for cruise ship design. To meet the stability requirements of SOLAS 2020, Wang Jianfang and Cao Yu [2] gave some suggestions on the principal dimension planning of large cruise ships. Jae Han Kim et al. [6] studied the seakeeping of cruise ships in actual operation from the perspective of passenger comfort and evaluated the effect of fin stabilizers on improving the seakeeping of cruise ships. Dallinga et al. [7] discussed the influence of combined motion and rolling of large cruise ships on seasickness rate and the discomfort caused by wave slamming. In the current literature, there are many researches on the industrial development law, operating routes, ship appearance and ship layout of luxury cruise ships, while relatively few researches are on the seakeeping of cruise ships.

Ocean cruise ships constantly consume stored materials when sailing at sea. To improve their viability, replenishment is needed at sea. Ohkusu [8] first used a two-dimensional method to study the heave motion of a boat approaching a large structure under transverse wave conditions. Chen et al. [9] studied the hydrodynamic interaction between two ships sailing in waves based on the three-dimensional potential flow theory of distributed source technology. AQWA was also developed based on this algorithm. Gourlay [10] inspired by the linear slender body theory established the dynamic and static equilibrium methods for calculating the heave and trim of two ships when they approach and overtake each other. Zhang et al. [11] studied the coupled motion and hydrodynamic force of two warships advancing in parallel by using the three-dimensional Rankine source panel method. Apart from studying the seakeeping and maneuverability of two ships advancing in parallel in waves, Skejic et al. [12] simulated the hydrodynamic interference when two ships entered and left the recharge array during the sea recharge, where the wave interference force and motion response were still calculated by strip method. The existing literature has shown that the hydrodynamic interference between two ships may aggravate the motion response of ships, but there is no research on the replenishment of cruise ships. However, cruise ships have high requirements for seakeeping, which may trigger difficulties in replenishment. Thus, it is of great practical significance to implement numerical research on the hydrodynamic characteristics of two ships advancing in parallel.

This paper mainly studies the seakeeping of two ships advancing in parallel for underway replenishment, and investigates the hydrodynamic response characteristics of cruise ships and replenishment tanker under different wave directions and spacing. Via AQWA, numerical simulation is conducted for various working conditions. Irregular sea state prediction and time domain analysis are also implemented by using the response amplitude operator (RAO) function of swaying motion. In this paper, the high-order elements of boundary conditions and transient conditions are taken into account, and the seakeeping characteristics of cruise ships during sailing and replenishment under different sea conditions are summarized through calculation and analysis. At the same time, advancing in parallel at sea, the cruise ship and the replenishment tanker sail at the same speed and direction within a limited distance, with the flow fields interfering with each other, which affects the motion response and wave load of the two ships. The hydrodynamic response characteristics of the cruise ship are observed through control variables. The research results can provide theoretical support for the organization and implementation of replenishment operations for large ships at sea.

2. Numerical Model

2.1 Cruise Introduction

The cruise ship selected in this paper has a gross tonnage of 135,500 tons, a length of 298.32 meters, a width of 38.64 meters and a maximum height of 72.2 meters. There are 15 floors and 2,826 cabins in the whole ship, including 2,125 passenger cabins and 701 crew cabins, with a total area of about 34,600 square meters and a maximum capacity of 5,246 passengers. As for safety and security, the cruise ship is equipped with 20 lifeboats and a helipad. The main dimensions of the luxury cruise ship are shown in Table 1 and Figure 1 is the schematic diagram of the model of the luxury cruise ship.

Table 1. Principal Dimensions of Cruise Ships

Principal Dimension	Value	Unit
Length Between Vertical Lines Lpp	298.32	m
Moulded Breadth B	38.64	m
Moulded Depth D	27.36	m
Design Draft T	8.56	m
Square Coefficient Cb	0.7387	m

Figure 1. Schematic Diagram of Cruise Mode

2.2 Simulation Parameters

In the numerical simulation, five typical wave directions including 0°, 45°, 90°, 135° and 180° are considered, and the motion response of a regular wave with the wave period of 3-30s is studied. To explain the influence of wave period on typical ships, the following relevant pictures and texts use wave period instead of the ratio of wavelength to captain.

Table 2. Simulation Wave Parameters

Wave Direction (°)	0, 45, 90, 135, 180
Wave Period (s)	3, 5, 7, 9, 11, 15, 20, 25, 30

AQWA in Ansys is used in the simulation. Because only the influence of ship surface is considered in the hydrodynamic calculation with the negligible influence of superstructure on ship hydrodynamic performance. Thus, only the geometric model of ship main shell is calculated and analyzed. To ensure the accuracy of the numerical simulation results of the hydrodynamic model in this paper, variation trends of the heave wave response amplitude operators and the specific values of three different element divisions are compared, which are 0.6m, 0.8m and 1.0m. It is found that the variation trends of the three division data are not much different. Finally, the grid element size is set at 0.8m, with the overall calculation grid shown in Figure 2.

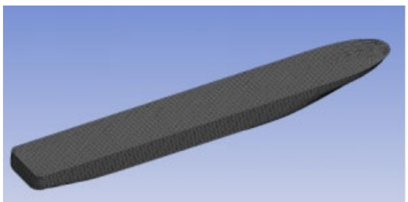


Figure 2. Element Size Division of Ship Surface

The forward direction of the x axis in AQWA is also set to be the same as the forward direction of the ship. Besides, the ship is moved to a position 4m below the waterline and cut into two parts. The ship moment of inertia data Kxx is set as 5.6m, Kyy 37.7m and Kzz 37.9m, with remaining hydrostatic parameters shown in Figure 3.

Hydrostatic Results

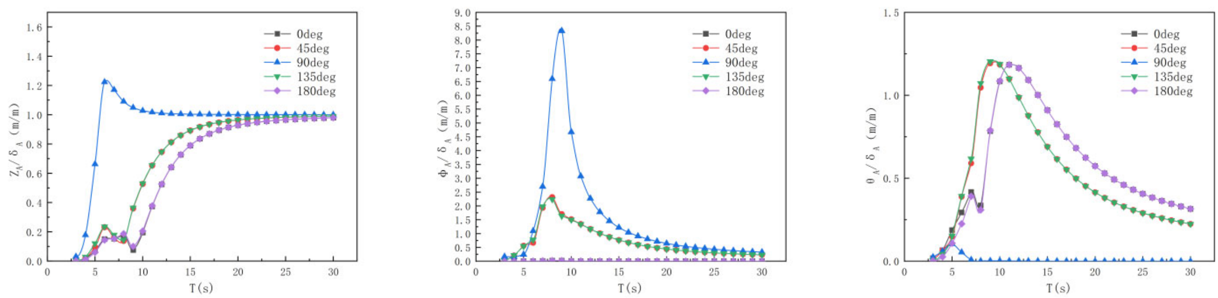
Structure		cruiser				
Hydrostatic Stiffness						
Center of Gravity (CoG) Position:	X:	65.72506 m	Y:	4.1606e-3 m	Z:	2. m
		Z		RX		RY
Heave (Z):		21334470 N/m		-37877.98 N/rad		42542260 N/rad
Roll (RX):		-37877.98 N.m/m		1.81777e8 N.m/rad		-75643.617 N.m/rad
Pitch (RY):		42542260 N.m/m		-75643.617 N.m/rad		2.9055e10 N.m/rad
Hydrostatic Displacement Properties						
Actual Volumetric Displacement:		7366.0024 m³				
Equivalent Volumetric Displacement:		7365.9927 m³				
Center of Buoyancy (CoB) Position:	X:	65.739944 m	Y:	4.219e-3 m	Z:	-1.8609407 m
Out of Balance Forces/Weight:	FX:	1.9611e-9	FY:	-2.2158e-7	FZ:	-2.1609e-7
Out of Balance Moments/Weight:	MX:	5.9792e-5 m	MY:	-1.489e-2 m	MZ:	-1.5341e-6 m
Cut Water Plane Properties						
Cut Water Plane Area:		2122.4492 m²				
Center of Floatation:	X:	63.730999 m	Y:	2.3852e-3 m		
Principal 2nd Moments of Area:	X:	46523.727 m⁴	Y:	2910559.8 m⁴		
Angle between Principal X Axis and Global X Axis:		-3.9097e-9 rad				
Small Angle Stability Parameters		*with respect to Principal Axes*				
CoG to CoB (BG):		3.8609407 m				
Metacentric Heights (GMX/GMY):		2.4550669 m		391.27332 m		
CoB to Metacentre (BMX/BMY):		6.3160076 m		395.13425 m		
Restoring Moments (MX/MY):		1.81777e8 N.m/rad		2.8971e10 N.m/rad		

Figure 3. Hydrostatic Parameters of Ship

3. Hydrodynamic Performance Analysis

3.1 Motion Response Analysis of Wave Height Per Unit

This paper analyzes the motion response of the cruise ship under the wave parameters, because the vertical motion of the ship is the main factor affecting the passenger amenity during the cruise ship, including heave, pitch and roll. Therefore, this study ignores the motion of other degrees of freedom, and simulates the wave responses of ships in five wave directions, including heave, roll and pitch. Different curves in the following figure represent RAO with various incident angles of waves. δA, ZA, φA and θA represent wave amplitude, heave amplitude, roll amplitude and pitch amplitude respectively. T is the wave period and δW is the wave height.



(a) Heave (b) Roll (c) Pitch

Figure 4. RAO of Cruise Ships with Each Downward Wave (0deg, 45deg, 90deg, 135deg, 180deg)

According to the analysis of the above calculation results, the corresponding maximum heave period is relatively small at about 6s when transverse waves occur, while the corresponding maximum heave period of other wave angles is about 20s. The roll of 90° shear wave is the largest and affected by the wave period, followed by oblique wave, while the roll along and facing waves is less and affected by the wave period. In addition, according to Figure 4 (c), the pitching difference in various wave directions is apparent, and the pitching amplitude of transverse waves is almost 0 when the wave period is greater than 7.5s.

3.2 Analysis of Hydrodynamic Characteristics of Typical Sea Conditions

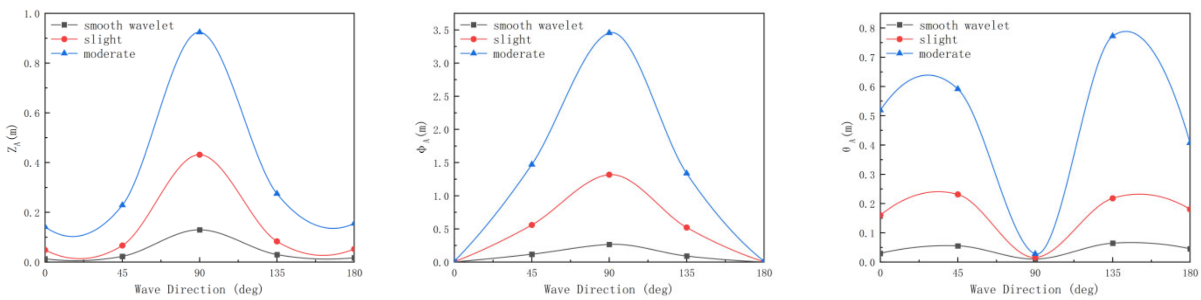
Under severe sea conditions, cruise ships are less likely to sail. However, cruise ships inevitably encounter wind and waves during sailing, which proposes more stringent requirements for seakeeping and amenity of cruise ships. Thus, this paper selects three design sea conditions in the North Pacific Ocean as the calculated sea conditions as shown in Table 3. Then, the heave, roll and pitch positions, velocities and accelerations of ships under three sea conditions are simulated respectively.

Table 3. Calculation of Sea Conditions

Sea Condition	Significant Wave Height m	Peak Period s
Smooth Wavelet	0.30	6.3
Slight	0.88	7.5
Moderate	1.88	8.8

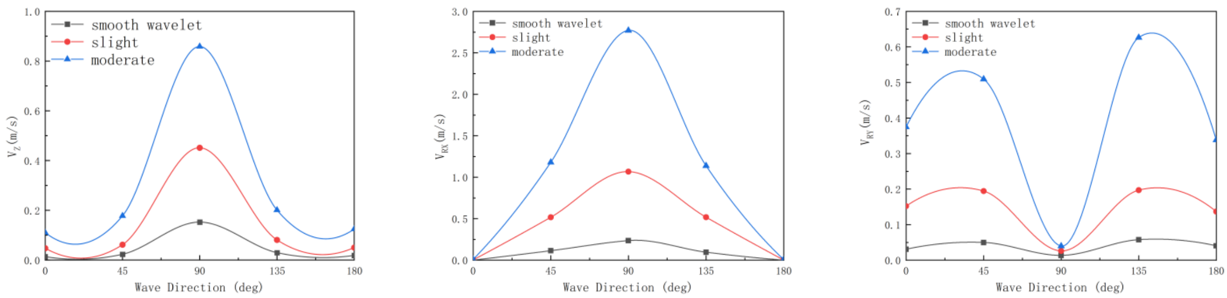
Different curves in the same Figure 5-7 show the motion response of various sea conditions. According to Figure 4-6, the changing trend of position, velocity and acceleration of the cruise ship heave, roll and pitch is roughly the same under the same sea conditions. However, due to the large size of the luxury cruise ship, its motion characteristics are insensitive to the change of wave direction under the smooth wavelet. Under moderate sea conditions, the significant value of the luxury cruise ship's motion changes greatly with the wave direction, with the ship's motion more sensitive to the change of wave direction. Compared with the slight sea conditions, the moderate sea conditions are obviously aggravated, and the amplitude of swaying motion is greatly increased, which will significantly affect passenger amenities and even navigation safety in actual navigation.

Figure 5-7 also shows that the position, velocity and acceleration of heave and roll reach the maximum, while the amplitude of pitch is the smallest among the three sea conditions. Maximum are greatly affected by sea conditions, while minimum roll and pitch are not affected by sea conditions. Besides, heave has a great relationship with sea conditions, and the moderate sea conditions are about twice as large as the slight sea conditions. In addition, the pitching value of the cruise ship increases greatly when the waves are oblique, which is sensitive to the sea conditions.



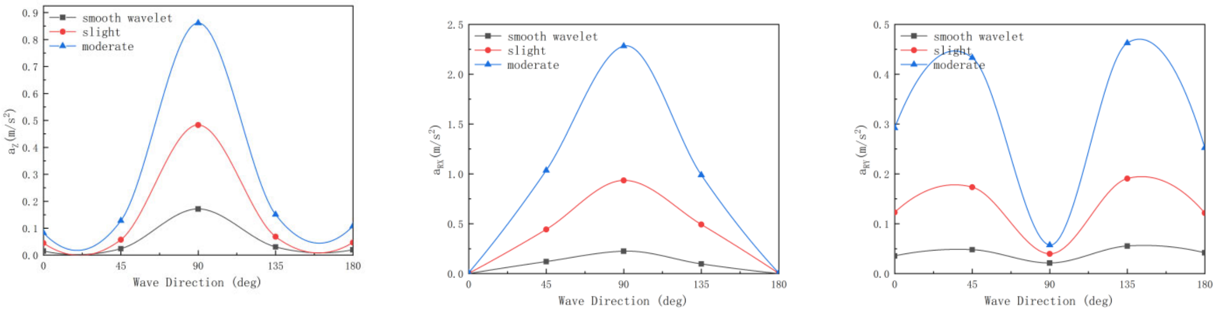
(a) Heave (b) Roll (c) Pitch

Figure 5. Position of Motion Response Under Smooth Wavelet, Slight and Moderate Sea Conditions



(a) Heave (b) Roll (c) Pitch

Figure 6. Velocity of Motion Response Under Smooth Wavelet, Slight and Moderate Sea Conditions



(a) Heave (b) Roll (c) Pitch

Figure 7. Acceleration of Motion Response Under Smooth Wavelet, Slight and Moderate Sea Conditions

4. Study on Hydrodynamic Characteristics of Cruise Ships Advancing in Parallel With Replenishment Tanker

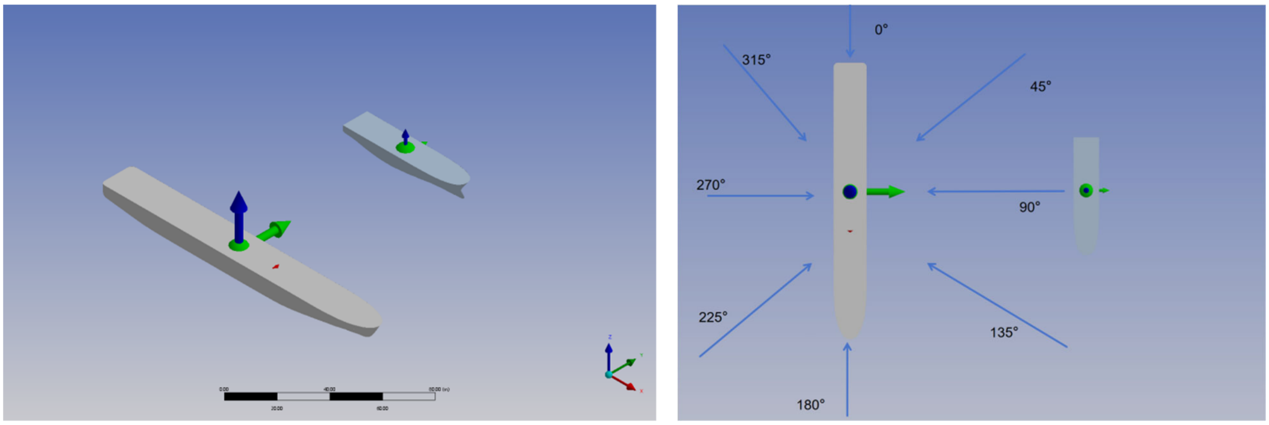
4.1 Model Setting and Simulation Parameters of Two Ships Advancing in Parallel

In the process of two ships advancing in parallel for transverse replenishment, it is not only affected by wind and waves, but also interfered by hydrodynamic forces between two ships, which will produce a stronger swaying motion than a single ship. Thus, it is necessary to ensure safe distance between two ships. To study the influence of ship seakeeping during replenishment, the basic data of simulated replenishment tanker are set as shown in Table 4, and the full wave motion response of two ships advancing in parallel is studied.

Table 4. Principal Dimensions of Cruise Ships

Principal Dimension	Value	Unit
Length Between Vertical Lines Lpp	58.8	m
Moulded Breadth B	11.76	m
Design Draft T	5.70	m
Radius of Gyration of Replenishment Tanker Kxx	4	m
Radius of Gyration of Replenishment Tanker Kyy	14.7	m
Radius of Gyration of Replenishment Tanker Kzz	14.9	m
Gravity Coordinates	(65,0,7.2)	m

In this paper, the longitudinal alignment of ships is from ship to ship, and the transverse spacing is 0.5L, 1L, 1.5L and 2L respectively. The parallel model of replenishment tanker and cruise ship is established in AQWA as shown in Figure 8(a). The design variables are set as follows. ① The spacing between the replenishment tanker and the cruise ship is 30m, 60m, 90m and 120m respectively. ② Nine typical wave directions are considered, which are 0, 45, 90, 135, 180, 225, 270, 335 and 360 as shown in Figure 8(b). ③ Consider the common sea conditions of three cruise ships in smooth wavelet, slight and moderate sea conditions. The motion response of the above-mentioned cruise ship under wave parameters is analyzed, including heave, roll and pitch, while other degrees of freedom are ignored, so simulation calculation is implemented.



(a) Schematic Diagram of Two Ships Advancing in Parallel

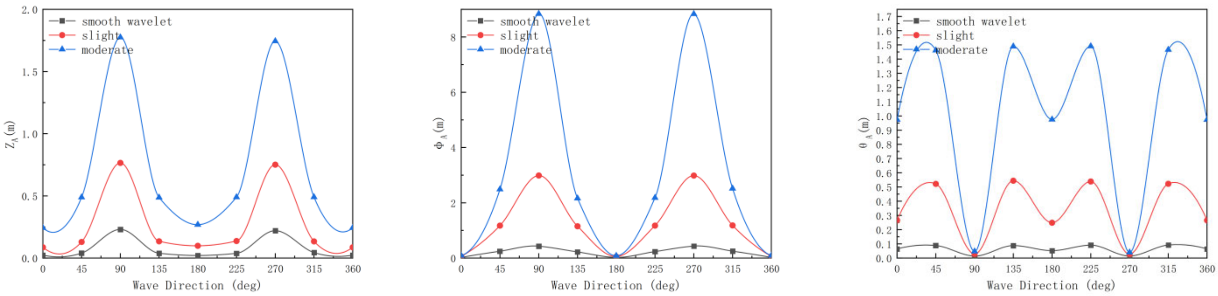
(b) Schematic Diagram of Wave Direction

Figure 8. Model of Two Ships Advancing in Parallel

4.2 Analysis of Cruise Motion Response in Two Ships Advancing in Parallel

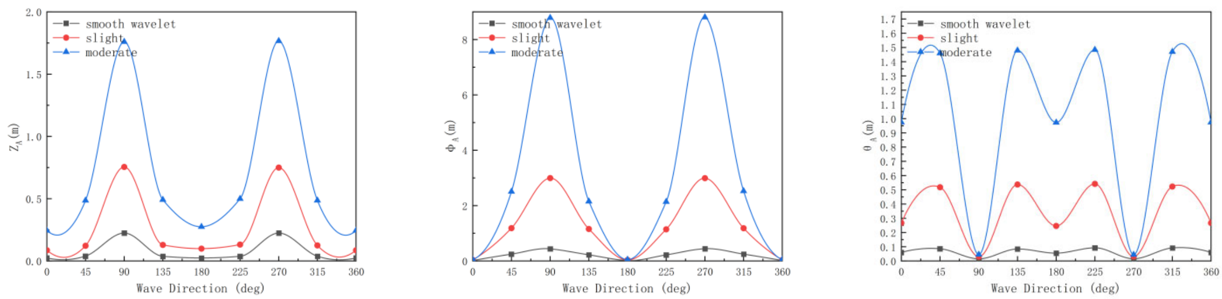
Under the above-mentioned simulation conditions, the simulation calculation is conducted. Meanwhile, the statistical results of cruise ship motion under the conditions of different spacing, sea conditions and wave angles are obtained and analyzed as shown in Figure 9-12. According to Figure 9-12, (1) the heave and roll of the cruise ship are obviously intensified and reach the maximum in transverse waves, and the sea conditions have a great influence on the motion amplitude of the cruise ship. Nonetheless, the pitch of the cruise ship tends to disappear. For heave, the motion response of the moderate sea conditions in transverse waves is about twice that of the slight sea conditions. For roll, the motion response of the moderate sea conditions in transverse waves is about three times that of the slight sea conditions. (2) The pitch amplitude of the cruise ship is obvious in oblique waves, which is greatly affected by sea conditions, and the heave response of the ship in moderate sea conditions is about three times that of the slight sea conditions. (3) When sailing along the waves, the roll and heave of the cruise ship are small, while the pitch is obvious. At the head sea, the roll of the cruise ship is small, while the heave and pitch are obvious.

Based on this analysis, we can see that different spacing has little influence on the motion response of cruise ships, but sea conditions and wave direction angle have great influence on the motion response of cruise ships. In addition, according to Figure 9-12, the replenishment tanker has a shielding effect on the cruise ship, which makes the motion characteristics of the cruise ship numerically asymmetric with the changing wave direction. However, due to the large drainage and large characteristic scale of cruise ships, the shielding effect of supply ships is not obvious.



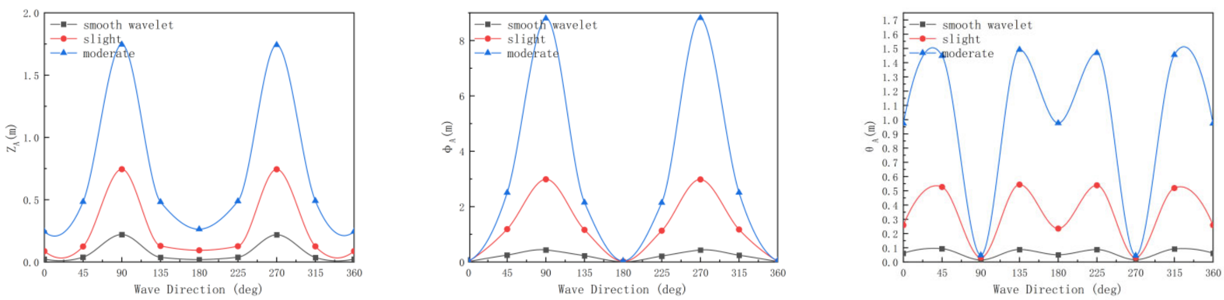
(a) Heave (b) Roll (c) Pitch

Figure 9. Motion Response of Cruise Ships at an Interval of 30m



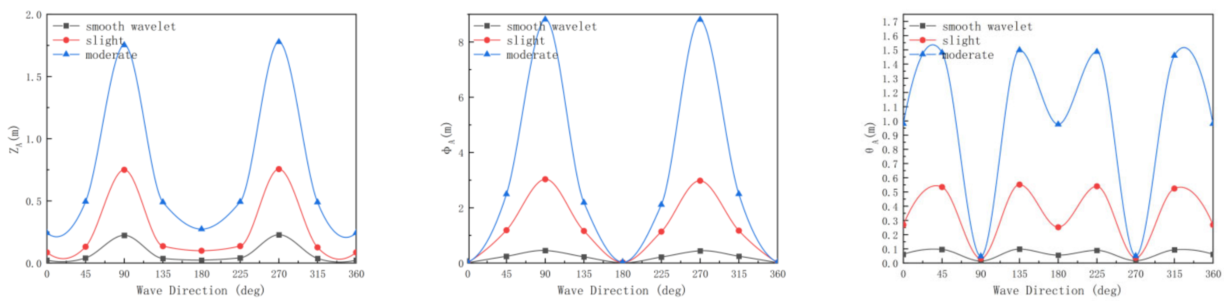
(a) Heave (b) Roll (c) Pitch

Figure 10. Motion Response of Cruise Ships at an Interval of 60m



(a) Heave (b) Roll (c) Pitch

Figure 11. Motion Response of Cruise Ships at an Interval of 90m

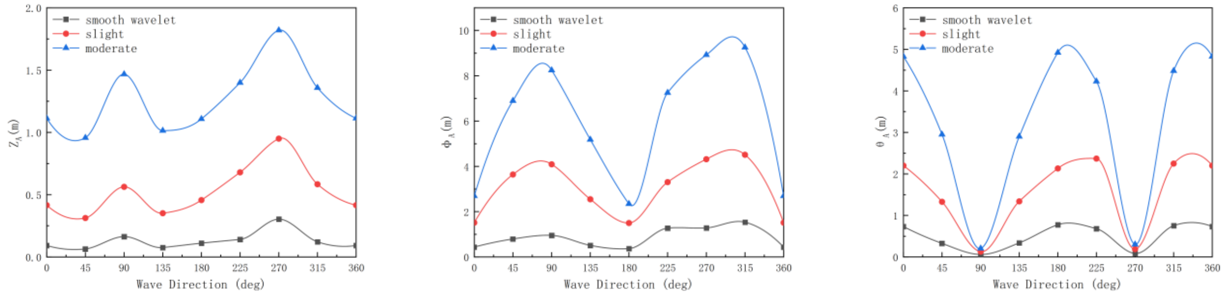


(a) Heave (b) Roll (c) Pitch

Figure 12. Motion Response of Cruise Ships at an Interval of 120m

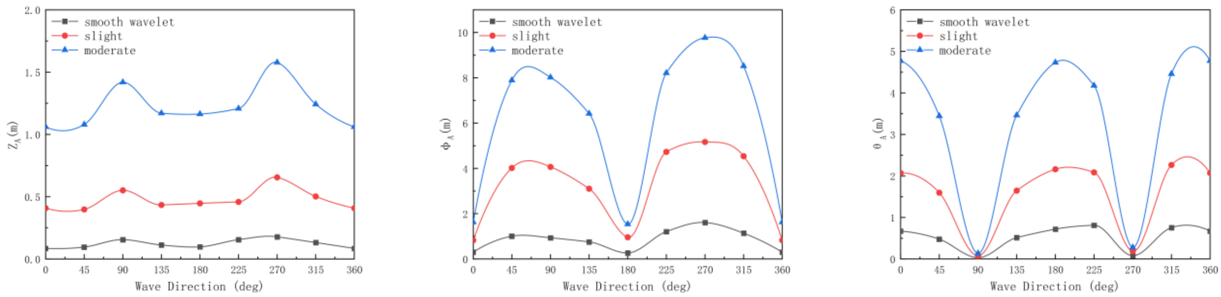
4.3 Motion Response Analysis of Replenishment Tanker Ship When Two Ships Advancing in Parallel

In addition to the cruise ship, the wave motion response of two ships advancing in parallel for replenishment is equally important. The simulation calculation shows the movement of the replenishment tanker under three sea conditions, different spacing between the two ships and different heading angles. According to Figure 13-16, (1) the heave and roll motion of the replenishment tanker is apparently strengthened in transverse waves, and the sea conditions and ship spacing have a great influence. In transverse waves, the amplitude of the heave and roll of the replenishment tanker is more than twice that in moderate sea conditions. Meanwhile, the larger the distance between the two ships, the greater the heave and roll amplitude. (2) the pitching of the replenishment tanker is obvious in wave and head sea, and the pitching amplitude is small and approaches 0m in transverse waves. (3) the movement of the replenishment tanker in three directions changes greatly with wave direction, which is greatly affected by wave direction in moderate sea conditions. Nonetheless, the movement of the replenishment tanker in three directions changes little with wave direction, which is little affected by wave direction in smooth wavelets. (4) the cruise ship has obvious shielding for the replenishment tanker. Because of the shielding effect, the movement characteristics of the replenishment tanker are asymmetrical with the changing wave direction, and the influence is great.



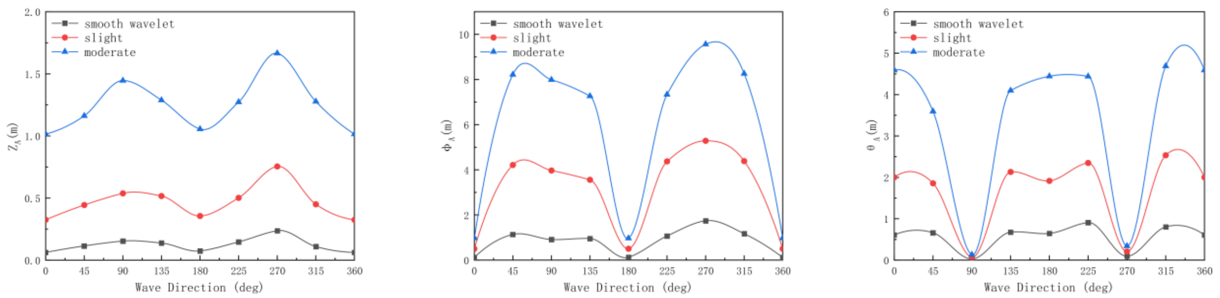
(a) Heave (b) Roll (c) Pitch

Figure 13. Motion Response of Replenishment Tanker at an Interval of 30m



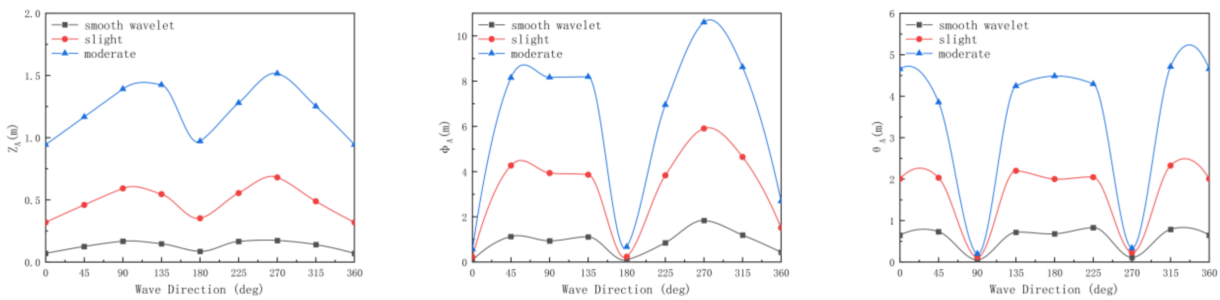
(a) Heave (b) Roll (c) Pitch

Figure 14. Motion Response of Replenishment Tanker at an Interval of 60m



(a) Heave (b) Roll (c) Pitch

Figure 15. Motion Response of Replenishment Tanker at an Interval of 90m



(a) Heave (b) Roll (c) Pitch

Figure 16. Motion Response of Replenishment Tanker at an Interval of 120m

5. Conclusions

In this paper, AQWA is used to simulate the hydrodynamic responses of a single ship and a replenishment tanker under three different sea conditions with the following conclusions and suggestions.

1) Because the luxury cruise ship is large, its motion characteristics are insensitive to the changing wave direction when the sea conditions are good, such as smooth wavelets sea conditions. However, with the increasing severity of sea conditions, the range of the movement significant value of luxury cruise ships changes with the increasing wave direction, and the ship movement is more sensitive to the changing wave direction. As a large passenger ship, a luxury cruise ship has a high seasickness rate, so it is particularly important to choose the appropriate wave angle under severe sea conditions.

2) When two ships advance in parallel for replenishment, there is a large swaying motion under both transverse and oblique wave conditions, and the motion increases significantly with the increasing sea condition level. Therefore, in the actual offshore operation, a calm sea environment should be selected as much as possible, and transverse waves and oblique waves should be avoided. Both ships should keep going along or facing waves.

3) When two ships advance in parallel, comparing the hydrodynamic response of the cruise ship with that of the replenishment tanker, it is found that the replenishment tanker is greatly affected by the traveling waves of the cruise ship, which is prone to danger. Hence, during the replenishment, the cruise ship should always pay attention to the position and movement of the replenishment tanker besides its movement to avoid collision danger.

References

[1] Zhu, R. C. (2019). Theory of Ship Motion in Waves. Shanghai: Shanghai Jiaotong University Press.

[2] Cao, Y. & Wang, J. F. (2011). Research on the nonlinear motion prediction method of a large luxury cruise in head sea. Naval Architecture and Ocean Engineering, (3): 1-7. DOI:10.3969/j.issn.1005-9962.2011.03.002.

[3] Cao, Y., Yu, B. J. & Wang, J. F. (2010). Modeling the seakeeping performance of luxury cruise ships. Journal of Marine Science and Application, 9(3): 292-300.

[4] Zhang, M., Wang, J. H. & Wan, D. C. (2022). Multi-state luxury cruise ship seaking performance based on overlapping grids. Chinese Journal of Ship Research, 17(2): 57-62. DOI:10.19693/j.issn.1673-3185.02277.

[5] Ma, W. K., Wang, L., Dong, L. Z. et al. (2019). Impact of SOLAS2020 damage stability on main dimensions planning of large cruise ships. Shipbuilding of China, 60(3): 46-54. DOI:10.3969/j.issn.1000-4882.2019.03.005.

[6] Jea, H. K. & Yonghwan, K. (2012). Study on assessment of passenger comfort and its improvement by using motion stabilization for a cruise ship. International Conference on Maritime Technology.

[7] Dallinga, R. P. & Bos, J. E. (2010). Cruise ship seakeeping and passenger comfort. Cruise Ship Seakeeping & Passenger Comfort TNO Repository.

[8] Ohkusu, M. (1976). Ship motions in vicinity of a structure. Proc. BOSS, 76: 284-306.

[9] Chen, G. R. & Fang, M. C. (2001). Hydrodynamic interactions between two ships advancing in waves. Ocean Engineering, 28(8): 1053-1078.

[10] Gourlay, T. (2009). Sinkage and trim of two ships passing each other on parallel courses. Ocean Engineering, 36(4): 1119-1127.

[11] Zhang, S., Weems, K. M. & Lin, W. M. (2007). Numerical simulation and validation of ship-ship interactions in waves. Proceedings of the 9th International Conference on Numerical Ship Hydrodynamics, Ann Arbor, Michigan, USA.

[12] Skejic, R. & Faitinsen, O. M. (2018). A unified seakee-ping and maneuvering analysis of ships in regular waves. Journal of Marine Science and Technology, 13(14): 371-394.