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多浮筒全潜式海上风机整机拖航运动特性试验对比

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摘要：[**目的**]基于搭载了 DTU 10 MW 风机的三四筒型全潜式浮式风机整机海上拖航过程，开展了物理模型试验，对比研究三浮筒型式和四浮筒型式的 SFOWT 在拖航过程中各自由度运动响应及拖缆力在不同工况下的变化规律。[**方法**]首先在静水中开展自由衰减试验，随后在规则波和不规则波浪环境中开展拖航过程试验，研究不同的拖缆点高度、波高以及周期对拖航过程的影响。[**结果**]结果表明：（1）对 SFOWT 的垂荡、横摇和纵摇自振周期进行分析，发现相同自由度下 2 种结构 SFOWT 的自振周期相差在 5 s 以内，三浮筒式 SFOWT 与四浮筒式 SFOWT 相比，三浮筒式 SFOWT 垂荡加速度更小，纵摇和横摇的自然周期更大；（2）随着波高的增加，SFOWT 在各自由度上的响应以及拖缆力都在增大，规则波和不规则波工况下波高的增加对三浮筒型式 SFOWT 垂荡加速度、横摇角的影响更大，纵摇角以及拖缆力较小；（3）当波浪周期与 SFOWT 自身的固有周期相差较大时，随着波浪周期的增大，除垂荡加速度外 SFOWT 各自由度上的响应呈现减小的趋势；（4）当拖缆点高度与水线面齐平时，2 种型式 SFOWT 的拖缆力幅值较其他两种工况最大分别减小 11.1% 和 14.7%。[**结论**]四浮筒型式 SFOWT 的拖航运动性能更佳。在实际工程中，应当将拖缆点高度布置在结构自浮时水面线所在的位置，以减小拖航过程中的运动响应。

关键词：DTU 10 MW；全潜式浮式风机；一体化拖航；动力响应；自由衰减；模型试验
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论文二维码

Comparision of Integrated Towing Motion Performance for Multi-Column Semisubmersible Floating Offshore Wind Turbines

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Abstract: [**Introduction**] A comparative research was conducted to investigate the variation rules of motion responses in various degrees of freedom (DOF) and towline forces in the towing process of three-column submerged floating offshore wind turbines (TC-SFOWT) and four-column submerged floating offshore wind turbines (FC-SFOWT) under different working conditions, through a physical model test using a DTU 10 MW wind turbine. [**Method**] Firstly, a free attenuation test was carried out in still water. Then towing process tests were carried out in regular wave and irregular wave environments. The research focuses on the effects of different towline point heights, wave heights, and wave periods on the towing process of SFOWTs. [**Result**] These tests yielded the following findings. (1) The analysis related to heave, roll, and pitch natural vibration periods of SFOWTs reveals that the difference in natural vibration periods between the

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two SFOWT structures in the same DOF is within 5 seconds, the TC-SFOWT exhibits a smaller heave acceleration and longer natural periods of pitch and roll; (2) As wave height increases, the response of SFOWTs in each DOF and the towline force also increase, and the increase in wave height has a greater influence on the heave acceleration and roll angle of the TC-SFOWT under both regular wave and irregular wave conditions, while it has a smaller impact on the pitch angle and towline force; (3) When the wave period differs greatly from the natural period of SFOWTs, an increase in wave period results in a decreasing trend in the SFOWTs' responses across various DOFs, except for heave acceleration; (4) When the towline point is flush with the water level, the towline force amplitudes of the TC-SFOWT and FC-SFOWT are respectively 11.1% and 14.7% lower than those of the other two working conditions. [**Conclusion**] In conclusion, the towing motion performance of the FC-SFOWT is better. In actual engineering practices, the towline point height when the structure is self-floating should be arranged at the water surface line, so as to reduce motion response during the towing process.

Key words: DTU 10 MW; submerged floating offshore wind turbine; integrated towing; motion response; free attenuation; model test

0 Introduction

Wind resource has the advantages of higher wind speed, stable propagation direction, lower turbulence intensity, and free surface roughness in the far-reaching sea[1]. With the exhaustion of shallow wind power resources, exploring offshore wind power towards deeper and farther ocean areas is of great interest. Due to the dramatically increased costs and limitations about the maximum operational depth of wind turbine installation vessels, the traditional fixed foundation may no longer be feasible for sea areas with a water depth greater than 60 m. The floating offshore wind turbine (FOWT) seems to be a feasible solution for the development of wind power in the deep sea. In 2017, Hywind Scotland, the world's first commercial floating wind power project, was officially put into operation in Scotland[2]. By the end of 2020, the wind power generation of FOWTs around the world has reached 125 MW[3]. In recent years, engineering and academia around the world have put forward various forms of foundations for FOWTs[4]. The FOWTs have many advantages, for example, it is not limited by water depth and geological conditions, is easy to dismantle, has little impact on the environment, and is suitable for high-power wind turbine[5]. On the other hand, it can be wet towed to the installation sites through self-floating, which is another significant advantage of the FOWTs.

For the wet towing performance of marine structures, scholars have carried out a few researches that mainly focus on the stability of towing system and towing resistance. Strandhangen et al.[6-7] studied the towing system based on linear theory and found that changing the towing point's frequency and the towing line length could make the towing system have better stability. Inoue et al.[8] used the linear theory to study the course stability of towing system under multiple tugboats and found that the elasticity of the towing line and the weight of the object being towed had a great influence on the course stability of the towing system. Bernitsaa et al.[9] analyzed the influence of elastic streamers on the stability of towing. Varyani et al.[10] carried out a numerical simulation on towing operation of the damaged ships and pointed out that wind load was the main factor affecting the stability of towing system. FOWTs have a high center of gravity and are subjected to complicated environmental loads such as wind, waves, and current in addition to the towing force during the transport phase. How to ensure the safety of transportation for FOWTs is one of the urgent problems to be addressed. In recent years, scholars have carried out preliminary research on the towing operation process for FOWTs with different types of foundations. Collu et al.[11] studied the static stability criterion of the towing process of FOWT under normal and severe environments, and provided the calculation guidelines for the maximum values of the metacentric height and the maximum height of the towing lines, then applied the results to design the semi-submersible floating foundation for NOVA FOWT to evidence the overall good performance of these rules. Adam et al.[12-13] experimented to study the towing stability of the GICON®-TLP under two different carriage speeds in calm water and two different regular wave conditions. Two different configurations including a squared configuration and a diagonal configuration of the GICON®-TLP were performed to determine which configuration had a lower resistance and a better seakeeping performance. The results showed that the towing speed and wave height significantly influenced the stability and towing resistance. The diagonal configuration had a lower resistance than the squared configuration because the truss structure of the squared configuration had no hydrodynamic permeability. Moreover, the non-stationary flow which detachment at the cylindrical buoyancy bodies would generate an oscillating sway motion. Ding et al.[14] designed a submerged floating foundation for supporting an NREL 5 MW wind turbine and researched the dynamic response of the SFOWT in complex environmental conditions. Han et al.[15] put forward a towing system model of the SFOWT based on multi-body dynamics theory to study the wind, wave, current, and height of towing point on the motion response of the SFOWT during towing phase. The results showed that under the standard environmental conditions, the inclination of the SFOWT met the requirements of the standard that the absolute acceleration of heave was less than 0.2 g, but the viscous damping of the SFOWT did not consider in the towing analysis. Le et al.[16] analyzed the four SFOWTs exhibited good performance under both conditions and the effect of wind-wave misalignment under extreme conditions. Zhang et al.[17] analyzed the influence of the subdivision structure on the towing resistance of the CBF and compared it with the tow test in hydrostatic water. Büttner et al.[18] examined the influence of wave direction, and a range of model orientations towards the incident waves were tested in still water and together with the simulated towing state.

Therefore, physical model tests of both TC-SFOWT and FC-SFOWT structures were carried out to study the inherent periods of the two structure types and carry out the hydrostatic, regular wave, and irregular wave towing tests to investigate the effect of wave height, period, and towing point height on the acceleration, longitudinal rocking, transverse rocking, and towing force under fixed water depth.

1　Setting up of model test

1.1　Similar theory

During the SFOWT whole machine towing test, it is necessary to ensure that the test model and prototype meet the similarity criteria, including geometric similarity, motion similarity, and dynamic similarity.

1) Geometric similarity

When making the TC-SFOWT or FC-SFOWT test models, it is necessary to scale the prototype according to the similarity ratio, and it is necessary to ensure that the shape of the model is completely similar to the prototype. In addition, the environmental water depth, wind, wave and current elements, and other conditions involved in the model test also need to be compared with the same physical quantities of the actual sea state according to the similarity ratio. The similar ratio in the experiment is $\lambda = 1:80$.

$$\lambda = L_m / L_p \tag{1}$$

2) Motion similarity

Models and prototypes are similar to F_r (Froude number) and S_t (Strouhal number). The F_r equally guarantees the correct similar relationship between the inertia and gravity of the model and the prototype. The S_t is equally guaranteed that the movement and force of the floating fan of the entire machine trailer under the wavy load can present periodic changes. The expressions of F_r and S_t are shown below.

$$F_r = V_p / \sqrt{gL_p} = V_m / \sqrt{gL_m} \tag{2}$$

$$S_t = L_p / V_p T = L_m / V_m T_m \tag{3}$$

3) Power similarity

Power similarity means that the model and prototype are under the same conditions, the ratio of the same force in the same position is the fixed value, and the direction is the same. Including gravity G, viscous T, pressure p, inertial force i, etc. The expression is shown below.

$$S_F = \frac{F_m}{F_p} = \frac{G_m}{G_p} = \frac{T_m}{T_p} = \frac{P_m}{P_p} = \frac{I_m}{I_p} \qquad (4)$$

In the formula, G is the acceleration of gravity. L, V, and T respectively represent length, speed, and period, respectively. The bids p and m represent the prototype and model, respectively. Table 1 shows a similar relationship between the SFOWT prototype and the model.

Tab. 1 SFOWT prototype and model similar to the model

Project	Symbol	Ratio	Project	Symbol	Ratio
Length	L_p/L_m	λ	Period	T_p/T_m	$\lambda^{0.5}$
Angle	Φ_p/Φ_y	1	Force	F_p/F_m	λ^3
Velocity	v_p/v_m	$\lambda^{0.5}$	Linear acceleration	A_p/A_m	1
Angle speed	ω_p/ω_m	$\lambda^{-0.5}$			

1.2 Foundation of SFOWT

A submerged floating offshore wind turbine (SFOWT) is composed of the upper turbine (DTU 10 MW RWT), tower, and submerged floating foundation, as shown in Fig. 1. The submerged floating foundation is composed of a central column, a vertical float, a horizontal floating tank, and a diagonal brace. The submerged floating foundation has the following structural features. In the bit state, as shown in Fig. 1(a), the wind turbine's foundation is submerged below the water surface under the operation of the tension leg anchorage system. Therefore, it has a relatively small waterline area and is less affected by wave loads, which is SFOWT. In the state of self-floating and towing, as shown in Fig. 1(b), the wind turbine foundation belongs to the semi-submersible platform, which has a large water plane and good stability, and the self-floating towage of SFOWT can be realized by using this advantage.

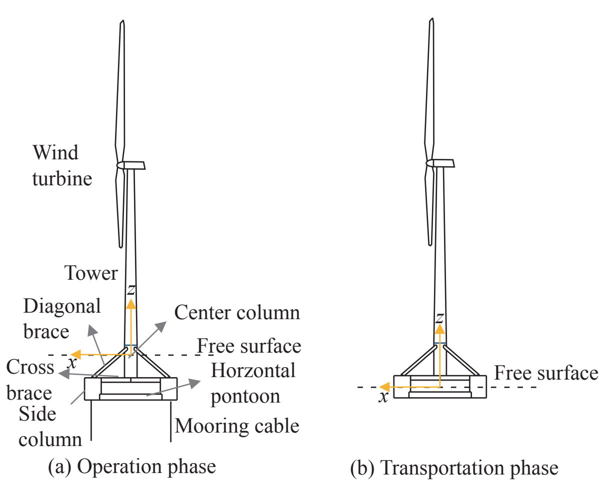

Fig. 1 The structure of SFOWT

1.3 DTU 10 MW turbine

In 2013, the Wind Energy Research Center of the Technical University of Denmark released the model parameters of the wind turbine prototype with a power of 10 MW, called DTU 10 MW RWT[19]. The prototype has the advantages of being lightweight and having high strength of the blade.

The tower of the DTU 10 MW turbine adopts a layered design method, which is divided into 10 sections from the bottom to the top, and the wall thickness of each section remains the same, vary from the bottom diameter to the top diameter. The bottom diameter is 8.3 m (the elevation is 0 m, corresponding to a wall thickness of 38 mm), and the top diameter is 5.5 m (the elevation is 115.63 m, corresponding to a wall thickness of 20 mm).

During the actual towing process, the wind turbines are in a shutdown state, there is no need to consider the rotation of the blade and the aerodynamic load it receives. Therefore, the model of the turbine blade in the test is based on the parameters of the DTU 10 MW turbine blade and is made of hard foam according to the change of its airfoil to ensure that its shape and quality are similar. The main design parameters of the turbine are shown in Table 2. The main design parameters of the turbine blades are given in the paper[20]. According to a similar theory, the tower and the engine room are made of plexiglass.

1.4 Model setting

The TC-SFOWT or FC-SFOWT foundation is

Tab. 2　DTU 10 MW turbine prototype and model basic parameters

Project	Prototype	Model
Blade length/m	86.366	1.080
Impeller quality/kg	227 962	0.445
Cabin quality/kg	446 036	0.871
Tower quality/kg	628 442	1.227
Hub height/m	119	1.488
Diameter of impeller/m	178.3	2.229

made of plexiglass, and towing rope is made of steel wire rope and spring. During the production process, the shape and quality of each part are strictly controlled, to ensure that the position of the center of gravity of the SFOWT model is similar to that of the prototype. The basic parameters of the foundation and model are shown in Table 3, the SFOWT model of self-floating state is shown in Fig. 2.

Tab. 3　Submerged floating foundation prototype and basic parameters of the model

Project	TC-SFOWT		FC-SFOWT	
	Prototype	Model	Prototype	Model
Column diameter/m	8.3	0.104	8.6	0.108
Column height/m	22	0.275	22	0.275
Diameter of float/m	12.68	0.159	11	0.138
Float height/m	15	0.188	15	0.188
Axis distance of float/m	61.24	0.765	50	0.625
Bracing Diameter/m	2	0.025	2	0.025
Basic quality/kg	4.819×10^6	8.710	4.812×10^6	9.400
Static draft/m	6.0	0.075	5.2	0.065


(a) TC-SFOWT model


(b) FC-SFOWT model

Fig. 2　SFOWT towing physical test model

1.5　Test conditions setting

The size of the laboratory pool and the arrangement of sensors are shown in Fig. 3, the test water depth is 0.9 m. During the test, the main focus is on the heave, pitch, roll, and tow cable force response values of SFOWT during the towing process. Choose from three measurement sensors. The inclinometer is used to measure the roll and pitch angles of the SFOWT during towing. The acceleration sensor is used to measure the heave acceleration of the SFOWT during towing. Tension sensors are used to measure the towing force of the SFOWT during towing.

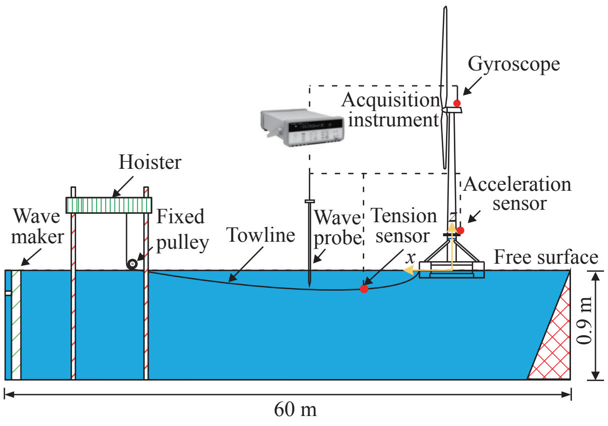

Fig. 3　Test tank size and sensor layout

It mainly includes the following three test schemes. Both TC-SFOWT and FC-SFOWT are towed by head sea. Static water-free decay test, the TC-SFOWT, and the FC-SFOWT are released after a certain displacement in the three main degrees of freedom of roll, pitch, and heave respectively, and their motion response time history curves decaying with time were collected. The regular wave towing test is to study the influence of wave height on the dynamic response of each degree of freedom during the SFOWT towing process. Irregular wave towing test uses the Jonswap wave spectrum. During the test, the speed is fixed. According to the test conditions, measure the towed motion response and towing force of SFOWT under the action of irregular waves with different significant wave heights and spectral peak periods, and explore the effect of the height of the towline point on its motion.

2 Comparative analysis of test results

2.1 Free decay test

Carry out the free decay test of TC-SFOWT and FC-SFOWT. The motion time-history curves of the heave, roll, and pitch degrees of freedom are collected and Fourier transformed respectively, to obtain the natural frequencies of TC-SFOWT and FC-SFOWT, the natural periodic frequency of the model test is converted into the natural periodic frequency of the prototype through similarity theory, and compared with the numerical simulation results, as shown in Table 4. From the comparison results, it can be seen that the model test results are in good agreement with the numerical simulation results.

Tab. 4 Comparison of SFOWT free attenuation frequency numerical simulation and test results

Degrees of freedom		Frequency/Hz		
		Numerical Simulation	Prototype	Relative error
Heave	TC-SFOWT	0.070	0.073	4.3%
	FC-SFOWT	0.056	0.057	1.8%
Roll	TC-SFOWT	0.025	0.027	8.0%
	FC-SFOWT	0.026	0.028	7.7%
Pitch	TC-SFOWT	0.024	0.023	4.2%
	FC-SFOWT	0.026	0.027	3.9%

2.2 Regular wave towing test

Carry out regular wave towing tests to study the influence of wave height and spectral period on the towing performance of SFOWT, the test conditions are shown in Table 5.

Tab. 5 Design of regular wave test conditions

Conditions number	Wave height/m		Wave period/s	
	Model	Prototype	Model	Prototype
1	0.037 5	3.0	1.0	8.9
2	0.050 0	4.0	1.0	8.9
3	0.062 5	5.0	1.0	8.9
4	0.062 5	5.0	1.3	11.6
5	0.062 5	5.0	1.7	15.2

Take any 30 s during the towage process for analysis, Fig. 4 and Fig. 5 respectively show the towing time history curve and motion response statistics under the regular wave environment. Research shows that the increase in wave height will obviously increase the response amplitude of each degree of freedom of SFOWT. When the wave height is 6.25 cm, the maximum heave acceleration of the TC-SFOWT is 1.26 m/s^2, the maximum pitch is 1.58°, the maximum roll is 1.18°, and the maximum towline force is 3.61 N. The maximum heave acceleration of the FC-SFOWT is 0.97 m/s^2, the maximum pitch is 2.27°, the maximum roll is 1.01°, and the maximum towline force is 3.71 N.

2.3 Irregular wave towing test

In the towing test of TC-SFOWT and FC-SFOWT in irregular waves, the design sea state has a significant wave height H_s= 6.25 cm and a spectral peak period T_p= 1.0 s. Fig. 6 shows the comparison results of test wave making and Jonswap spectrum, which are very close, so the test simulation is feasible and reasonable.

When studying the influence of wave height and period, the height of the towline point is located at the water plane. The tow point height of the TC-SFOWT model is 7.5 cm, and the tow point height of the FC-SFOWT model is 6.5 cm. Table 6 is the design of irregular wave test conditions.

2.3.1 Influence of significant wave height on SFOWT towing motion response

Fig. 7 is the time-history curves of heave acceleration, pitch, roll, and towing force of SFOWT under different significant wave heights during the towing process, and takes any 30 s during the towage process for analysis. With the increase of wave height, the response of SFOWT on each degree of freedom and the towing force is increasing, the heave acceleration response value of SFOWT under different working conditions fluctuates between ±2 m/s^2, the pitch response value fluctuates between ±4°, the roll response value fluctuates between ±4°, both the heave acceleration and inclination angle meet the requirements of the towing specification.

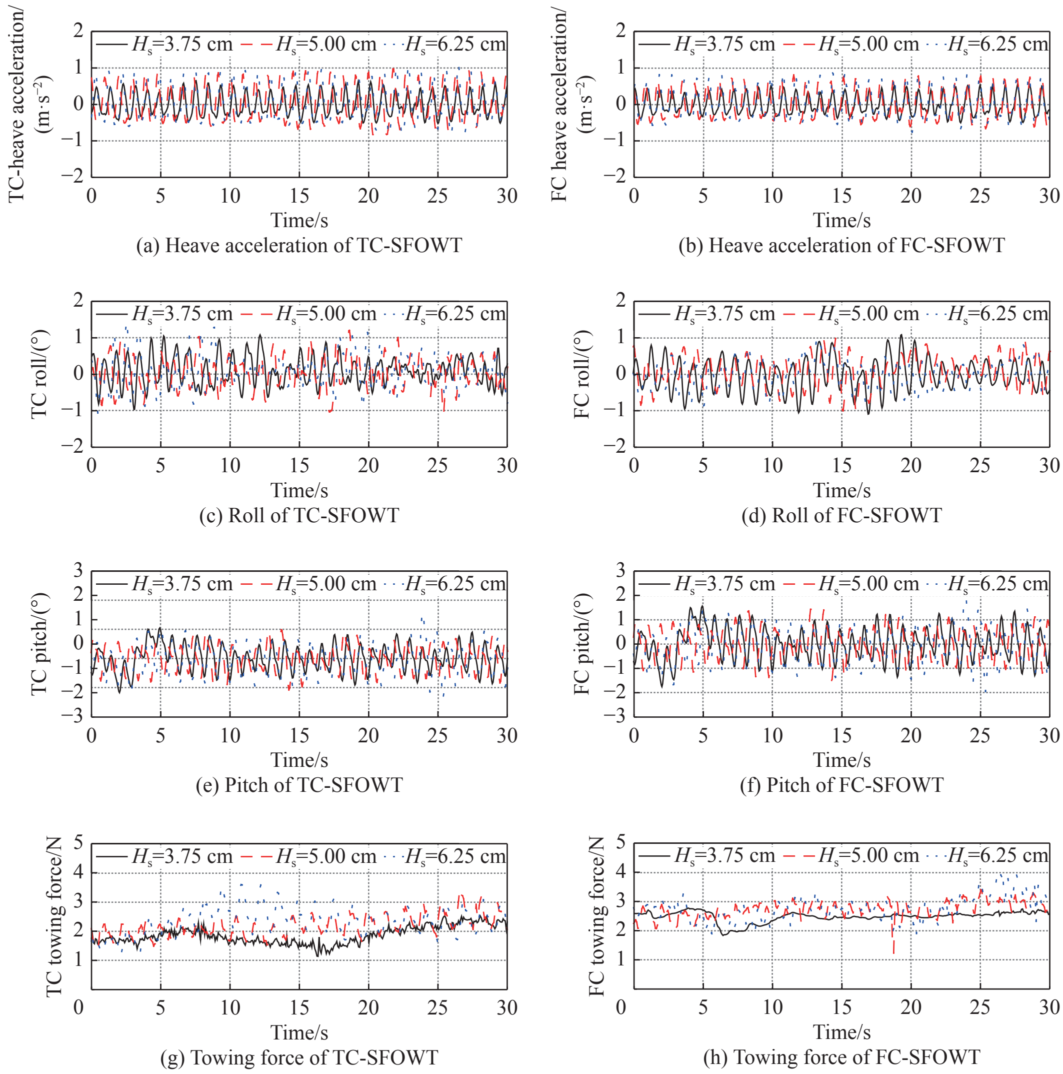

Fig. 4　Response time-history curves of SFOWT towing motion at different wave heights (T_p=1.0 s)

Fig. 8 shows the statistical characteristics of heave acceleration, pitch, roll, and tow cable force of SFOWT under different significant wave heights during towing. It can be found that when the significant wave height is 6.25 cm, the heave acceleration amplitude of the TC-SFOWT is 1.28 m/s^2, compared with working conditions 1 and 2, it increased by 100.0% and 50.0% respectively. The amplitude of the heaving acceleration of the FC-SFOWT is 0.96 m/s^2, compared with working conditions 1 and 2, it increased by 74.6% and 41.8% respectively. It can be seen that the increase of the significant wave height has a greater influence on the motion in the heaving direction of the TC-SFOWT. To compare the responses of the respective degrees of SFOWT of the two structural types under the same working conditions, the TC-SFOWT has slightly larger heave acceleration, roll angle, slightly smaller pitch angle, and towline force than the FC-SFOWT. When the significant wave height is 6.25 cm, the average towing force of the two structural types of SFOWT is 2.45 N and 3.46 N respectively. Since the FC-SFOWT has a larger underwater area than TC-SFOWT, the viscosity of water is stronger, so a greater towing force is required.

2.3.2　Influence of spectrum peak period on SFOWT towing motion process

Fig. 9 and Fig. 10 respectively show the time-history curves and statistical values of heave

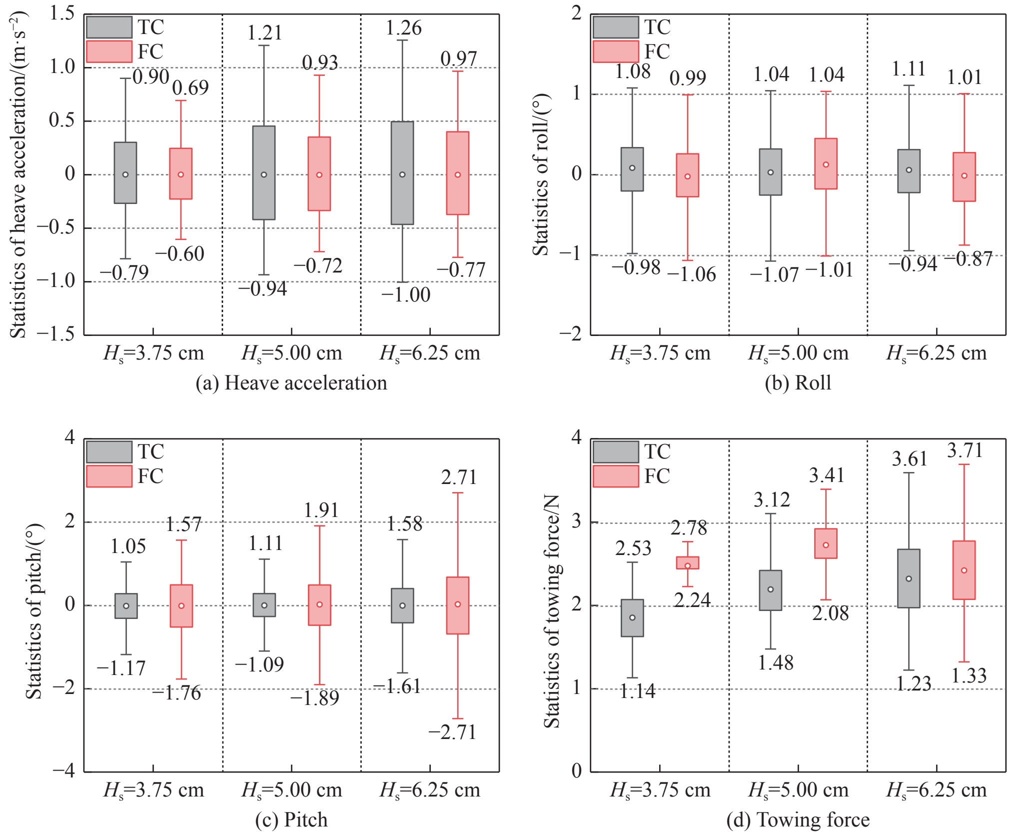

Fig. 5 Motion response statistics of the SFOWT under different tow point heights (T_p=1.0 s)

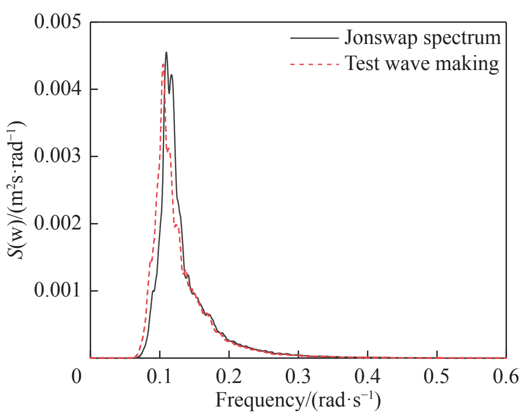

Fig. 6 Wave spectrum comparison (H_s=6.25 cm, T_p=1.0 s)

acceleration, pitch, roll, and towline force of SFOWT, during towing under different spectral peak periods. When the wave period differs greatly from the inherent period of SFOWT itself, with the increase of the wave period, except for the heave acceleration, the response of each degree of freedom of SFOWT presents a decreasing trend. Compared with the FC-SFOWT, the TC-SFOWT also has larger heave acceleration, roll

Tab. 6 Design of irregular wave test conditions

Conditions number	Significant wave height (H/m)		Peak period (T_p/s)	
	Model	prototype	Model	prototype
6	0.0375	3.0	1.0	8.9
7	0.0500	4.0	1.0	8.9
8	0.0625	5.0	1.0	8.9
9	0.0625	5.0	1.3	11.6
10	0.0625	5.0	1.7	15.2

value, and smaller pitch value and towline force. When the peak period is 1.7 s, the natural period of the heave of TC-SFOWT is 1.6 s, and the natural period of heave of FC-SFOWT is 1.9 s. The wave period is close to the natural period of the test model heave, resulting in resonance, when the spectrum peak period is 1.6 s, the heave acceleration value of SFOWT is relatively large.

2.3.3 Influence of tow point height on SFOWT towing motion response

Explore the SFOWT in the process of towing the

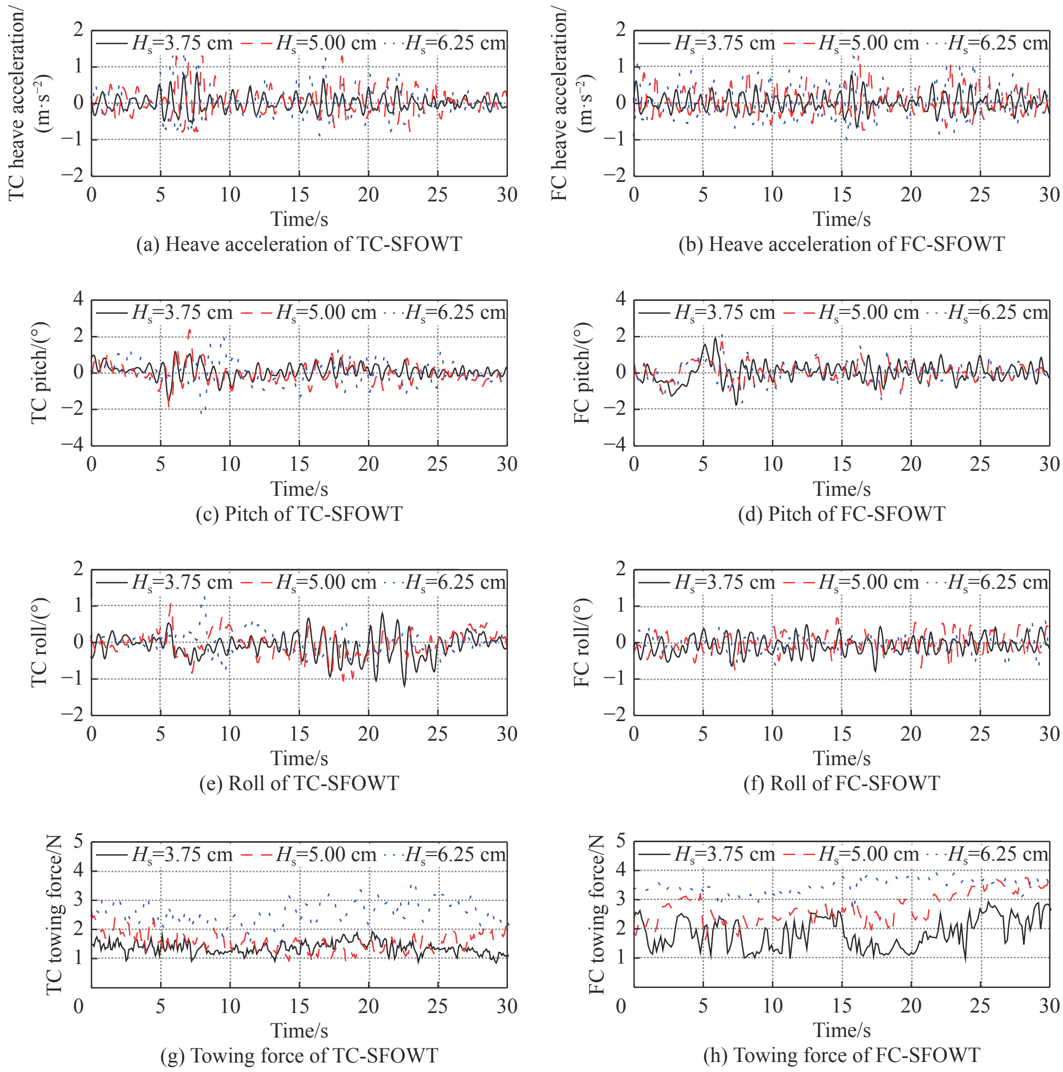

Fig. 7　Response time-history curves of SFOWT towing motion at different significant wave heights (T_p=1.0 s)

whole machine, the response of the streamer point height to the motion of each degree of freedom, and the effect of the height of the towline point on the magnitude of the towline force, to determine the best towing point location and lay the foundation for the analysis of subsequent working conditions. In this paper, *h* is used to replace the height of the towing point. The working conditions design is shown in Table 7.

Fig. 11 and Fig. 12 respectively show the time-history curves and statistical values of the heave acceleration, pitch, roll, and towline force of the SFOWT during towage at different towline point heights. Analysis shows that the height of the towing point above and below the waterplane will increase the response of SFOWT in each degree of freedom, but has little effect on the average value of the towing force. Because the high tow point and low tow point will increase the overturning moment of SFOWT, it has a larger pitch value, but the effect on a roll is not great. When the towing point is below the waterplane, the pitch angle amplitudes of the two types of SFOWT are 1.59° and 2.08° respectively, compared with the conditions where the towing point is located at the waterplane, it increases by 3.1% and 26.8% respectively. When the towing point is above the water surface line, the pitch angle amplitudes of the two types of SFOWT are 1.86° and 2.27° respectively, compared with the conditions where the towing point is located at

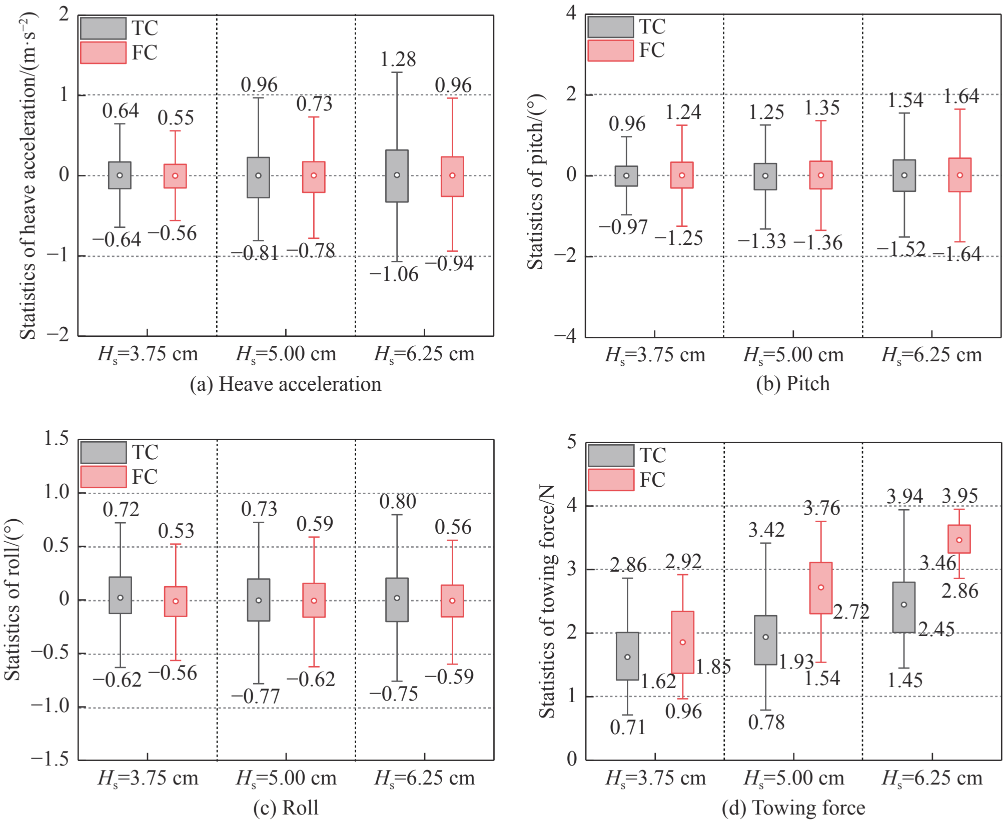

Fig. 8 Motion response statistics of the SFOWTs under different significant wave heights (T_p=1.0 s)

the waterplane, it increases by 20.8% and 38.4% respectively. When the height of the towing point is level with the waterplane, the towing force amplitudes of the two types are respectively 11.1% and 14.7% lower than those of the other two working conditions. Therefore, in actual engineering, the height of the towing point should be arranged where the waterplane of the structure is self-floating, to reduce motion response during towing.

3 Conclusion

Based on the towage process of the foundation structure of the TC-SFOWT and FC-SFOWT, a physical model test was carried out in an irregular wave environment. The motion response of the two types of floating wind turbines in each degree of freedom and the force of the towing cable is compared and analyzed during the towing process.

The free attenuation test in still water shows that the natural periods of heave, pitch, and roll of the TC-SFOWT prototype are 14 s, 42 s, and 42 s, respectively, the natural periods of heave, pitch, and roll of the FC-SFOWT prototype are 18 s, 39 s, and 39 s.

Under different working conditions, the heave acceleration amplitude of SFOWT all meets the requirement of less than 0.2 g in the towage specification, the roll and pitch amplitudes meet the requirement of ±5°, and the FC-SFOWT has better towing motion performance than the TC-SFOWT.

When the wave period is close to the natural period of the structure itself, the structure will resonate at the corresponding degrees of freedom, when the spectrum peak period is 1.7 s, SFOWT has a larger heave acceleration.

When the towing point is at the position of the water plane when the structure is self-floating, the response amplitude of the whole structure towing motion of SFOWT is small. Therefore, in the actual towing process, the towing point should be set flush with the water plane.

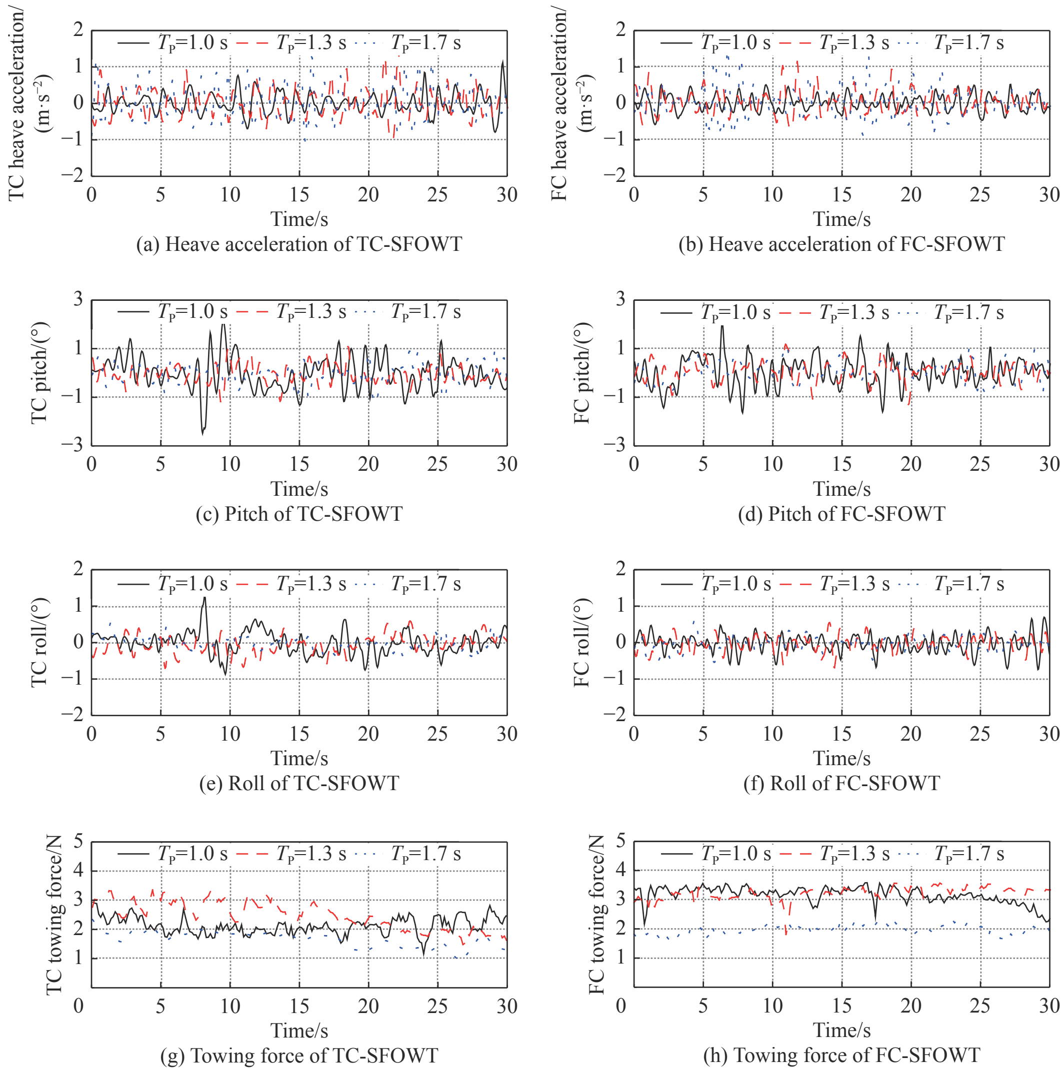

Fig. 9　Response time-history curves of SFOWT towing motion at different peak periods (H_s=6.25 cm)

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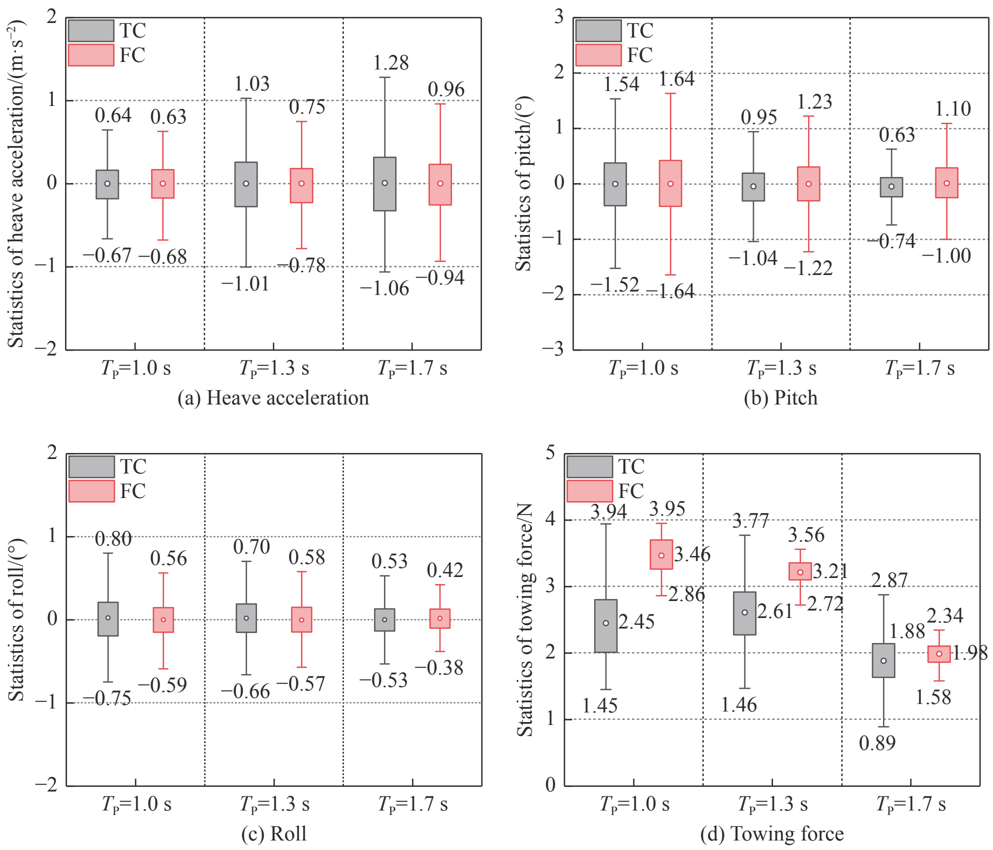

Fig. 10 Motion response statistics of the SFOWTs under different peak periods (H_s=6.25 cm)

Tab. 7 Experimental conditions of the influence of towing point height on the towing process

Working conditions number		11	12	13
TC-SFOWT	Model/cm	5.5	7.5(Free surface)	9.5
	Prototype/m	4.4	6.0(Free surface)	7.6
FC-SFOWT	Model/cm	4.5	6.5(Free surface)	8.5
	Prototype/m	3.6	5.2(Free surface)	6.8

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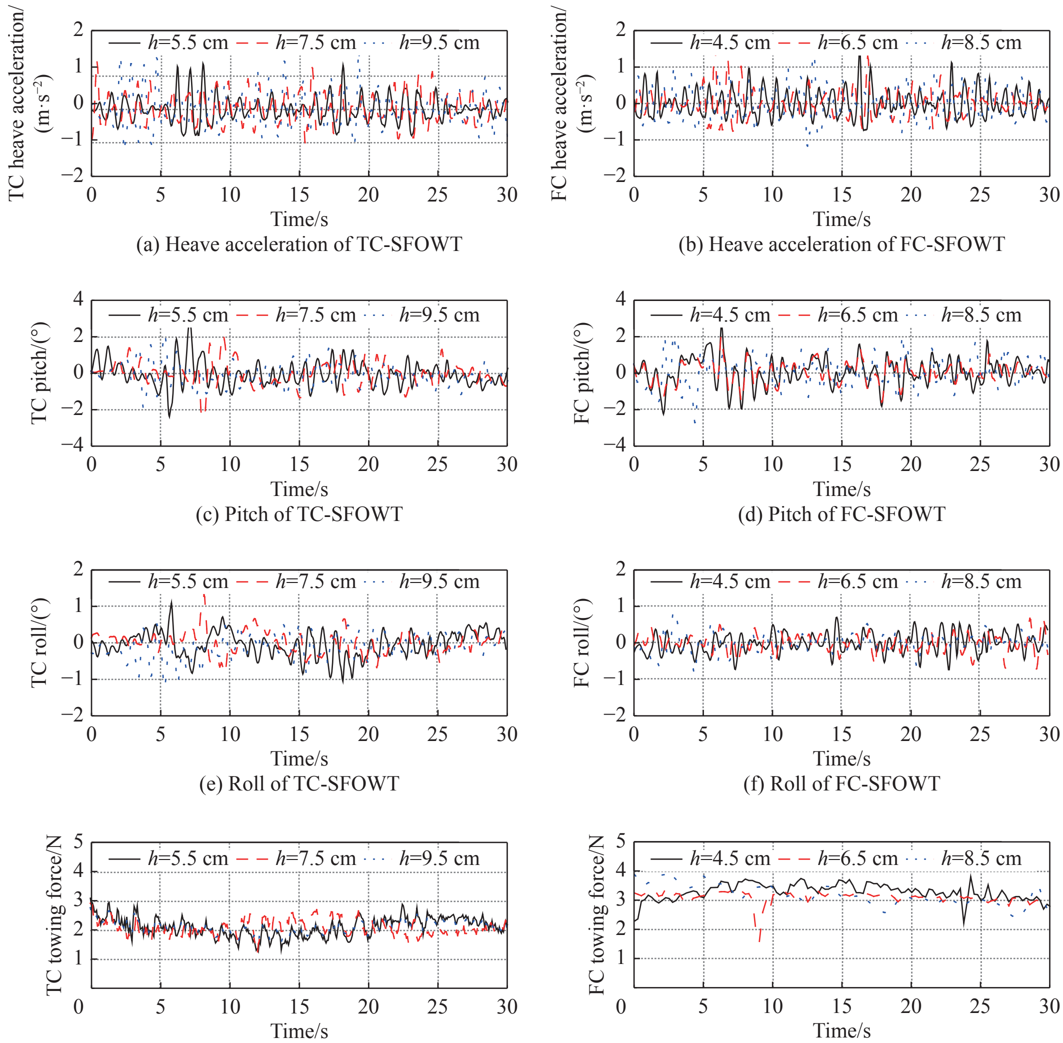

(a) Heave acceleration of TC-SFOWT　(b) Heave acceleration of FC-SFOWT

(c) Pitch of TC-SFOWT　(d) Pitch of FC-SFOWT

(e) Roll of TC-SFOWT　(f) Roll of FC-SFOWT

(g) Towing force of TC-SFOWT　(h) Towing force of FC-SFOWT

Fig. 11　Response time-history curves of SFOWT towing motion at different towing point heights (H_s=6.25 cm, T_p=1.0 s)

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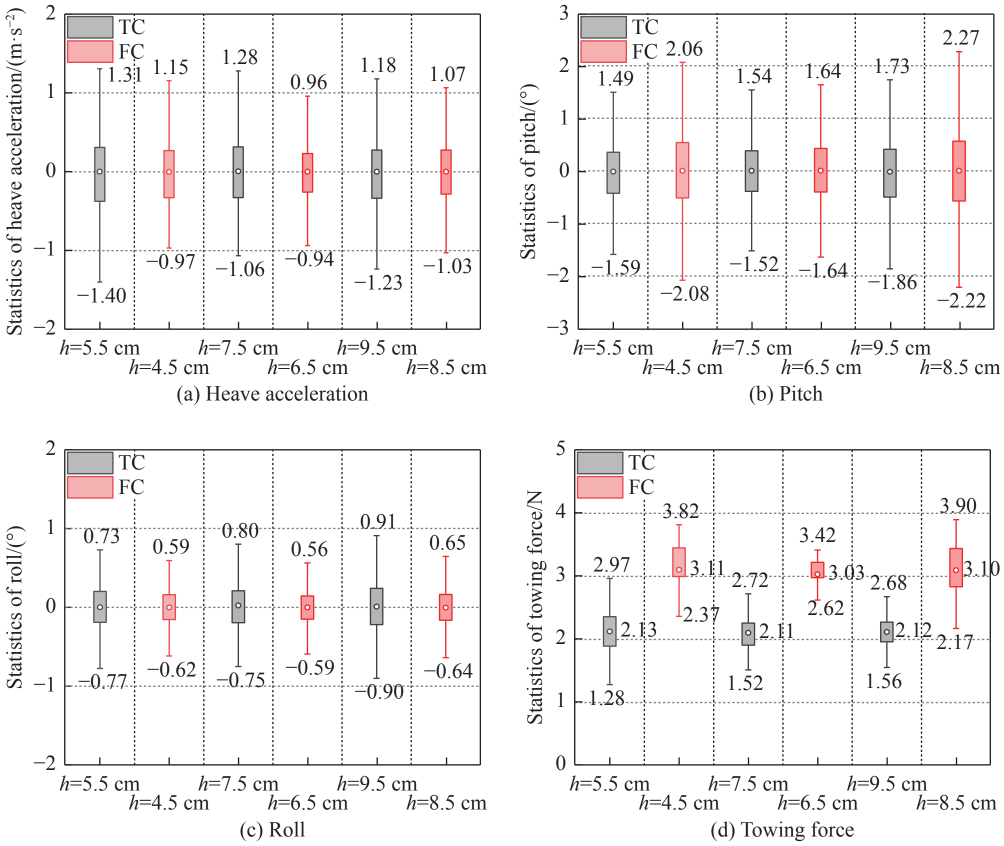

Fig. 12 Motion response statistics of the SFOWTs under different towing point heights (H_s=6.25 cm, T_p=1.0 s)

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