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A computational study on system dynamics of an ocean current turbine*

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Abstract: In this paper, we present the study of system dynamics of the floating kuroshio turbine (FKT) system which is designed to harness ocean current energy. We focus on the mooring line system design and its interaction with the FKT system. The effects of line diameter and two different auxiliary line systems were studied. Their responses in waves were also investigated. We integrated several commercial and in-house packages. The system buoyancy and weight and their centers were estimated using the Rhino software. The system hydrodynamic coefficients were obtained through WAMIT, system drag coefficient through FLUENT, turbine propulsive force through lifting surface code, and system dynamics through OrcaFlex. The results show that the mooring line system can create strong influence on the FKT system operations in the ocean current environments.

Key words: Ocean current energy, current turbine, system dynamics, mooring line system

Introduction

Ocean currents are continuous vast seawater movement on the ocean surface. Unlike tidal currents which periodically switch flow directions, they are directed flows with a relatively stable speed. Ocean current power is a form of ocean energy obtained from harnessing their kinetic energy. According to Pontes and Falcão[1], power can be economically generated if the current speed is more than 1.0 m/s. If the current speed is 0.5 m/s-1.0 m/s, it depends on from site to site to tap the energy economically. They could provide base load power because of their relative steadiness in speed.

The technological development to harness ocean energy is relatively new, compared with that of tidal current energy[2]. A few areas have been devoted to deep ocean current devices. Among them are USA, Japan, Taiwan, UK, Canada, Norway, Australia and France[3]. Nevertheless, several interesting concepts are being proposed and tested[4-7]. Recently, a short-term real-sea test of the 50 kW Kuroshio ocean current power-energy pilot facilities developed by Wanchi company in Taiwan has been conducted in 2016. During towing test, an average value of 32.57 kW had been reached at the current speed of 1.43 m/s[8]. Nevertheless, more rigorous long-term tests need be systematically implemented before it can be deployed for commercial operations. More recently, NEDO and IHI have also conducted the 100 kW-class demonstration test of ocean current power generation in Kuchinoshima, Kagoshima Prefecture in 2017[9].

Mooring systems are indispensable in deploying ocean current turbines. There have been many studies and experiences available in the literature. For general studies, Cribbs et al.[10] discussed the existing mooring for offshore energy converters. A single mooring line system is usually adopted for floating ocean current turbines. Since the current technology readiness is at the stage of laboratory test, the study is often restricted to deployment at a depth of about 50 m. Several important factors which influence mooring line behaviors and system dynamics have been investigated. The issue of stability is fundamental because of the fluctuating nature of ocean currents. Van Zwieten et al.[5, 11] developed a three-dimensional model to study the system dynamics of ocean current turbines and proposed possible system control strategies. Three different control strategies were suggested. Tian et al.[12] also proposed a similar three-dimensional model

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to investigate moored platform dynamics under the operation of horizontal axis ocean current turbines. Gonoji et al.[13], Lo et al.[14] investigated system dynamics in some special scenarios such as failure due to one of the twin turbines, sudden turbine start-up, current flow fluctuations in time and direction, and giant vortex encounter. The results show that different current turbine designs lead to different system responses. Nevertheless, they concluded that with proper strategies, their systems could be properly controlled. Pyakurel et al.[15] considered by computations the effect of turbulence on the ocean current turbine system.

The second important factor which need be considered is the influence of waves on the system deployment. Van Zwieten et al.[16] conducted a series of computations to study the effects of periodic loading on the system dynamics in regular waves. Their investigations reveal that the variations of tension of the mooring lines, yawing, and pitching are very significant. For example, the tension varies from 0 kN to 20 kN and the yawing angle can reach up to 20°. As far as system fatigue is concerned, these variations must be taken into consideration for long-term operations. It appears that the ocean current turbine should operate in water deep enough to avoid wave effects[17]. Takagi[18] also compared the operations of a contra-rotating turbine system with those of a twin turbine system in waves. The vertical shear flow effect is another factor which may influence operations of an ocean current turbine. Lin[19] conducted a detailed study on this issue. He found that the hydrodynamic performance of single turbine was not affected significantly by vertical shear in the flow. However, the amplitudes of time varying hydrodynamic forces and moments acting on the blade root could be not negligible if the vertical shear is significant. This implies that these hydrodynamic loads should be taken into consideration in blade structure design.

A floating Kuroshio turbine (FKT) system has been developed in Taiwan to harness Kuroshio energy in east coast of Taiwan. At the current stage, the feasibility study is being conducted for a 1/5 model. The present study reports some investigations of the model system dynamics. In the following, we will describe the system first. Then several special scenarios were designed to study effects of waves and auxiliary mooring line design on the system dynamics.

1. The floating Kuroshio turbine system

Shown in Fig. 1, the 1/5 model of floating kuroshio turbine (FKT) is a system composed of five major components. The floating-foil is equipped with four buoyancy engines. These engines can be used for flooding or drainage in order to adjust the gravity center of the system, the buoyancy, and the attitude of the foil which produces dynamic lift. For the 1/5 model, the chord length and span are 4.0 m and 7.5 m, respectively. The rated power is 20 kW when the current speed is 1.5 m/s. Two vertical supports connect the foil float and the ocean current turbine generator system. The cross beam connects the twin turbines. The two rotors harness the kinetic energy of ocean current and transform it into electricity by the generators inside the nacelles. To maintain proper stability during deployment, operation, and recovery, the concept of the downwind turbine system is adopted.

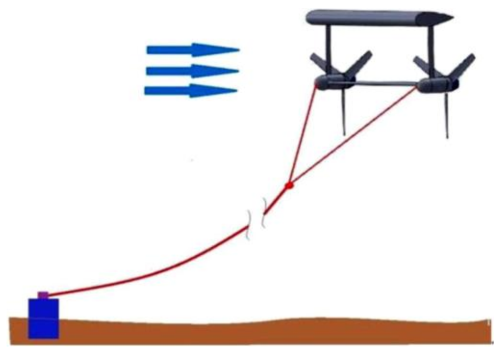


Fig. 1 (Color online) Schematic of the FKT system with the mooring lines

To harness the energy as much as possible, the system must submerge under the sea surface to reduce the impact of wave load and float at a proper depth in the deep ocean to take advantage of the strong Kuroshio. It has been known that more than 50% of the energy is concentrated near the surface within a depth of 100 m and its maximum velocity occurs at the sea surface[20]. This is the reason why a mooring line system must be introduced to the turbine system for operation.

For the present study, the water depth is assumed to be 50 m. The design operation depth for the model FKT system is 10-40 m. A single-line mooring system is provided. It consists of two short auxiliary lines and one main line to form a Y-shape system. The two auxiliary lines are connected to the foremost points of nacelles to the incoming current and join together with a connector to the main line which is then connected to the anchor on the bottom. We assume that the end of each line can freely slide on the connector. The length of the main line is 40 m long and each of the auxiliary lines connecting the turbine system and the main line is 5 m long.

2. Numerical procedures

The forces acting on the FKT system include buoyancy, weight, drag due to the current passing the system and the mooring lines, dynamic lift due to the floating-foil, tension force exerted by the mooring line, and the propulsive force produced by the rotation of the contra-rotating turbines. We also need to consider the effect of added mass. The system buoyancy and weight are directly related to the system design and known from the design data. The buoyancy comes from the weight of water displaced by the system. The design of the turbine blades was conducted computationally by lifting line theory and lifting surface theory. An in-house code has been developed for computations. The floating-foil of finite span provides most of the buoyancy and dynamic lift. The lift coefficient was taken from Ref. [21] with the aspect ratio $\mathrm{AR}=2$.

The system resistance was obtained by CFD method. The commercial software FLUENT was employed. The package employs the finite-volume method for discretization. The Reynolds-averaged Navier-Stokes equations were solved with standard k-ε turbulence model. The standard wall function was adopted for flow near the solid wall to handle the low-Reynolds-number flow near the walls. For nonlinear iterations, the SIMPLE algorithm was used. Under the condition of uniform incoming flow with a speed of 1.5 m/s, the resistance was computed and expressed in terms of non-dimensional drag coefficient.

$$C_\mathrm{d}=\frac{D}{\frac{1}{2}\rho U^2 A} \tag{1}$$

where D is the drag, ρ is the fluid density, U is the uniform incoming current speed, and A is the projected area of the system in the flow direction. According to Ref. [22], we have

$$(C_\mathrm{d})_x=0.173,\ (C_\mathrm{d})_y=1.184,\ (C_\mathrm{d})_z=1.318 \tag{2}$$

For the drag coefficients due to circumferential flows, we define

$$\mathrm{C}_\mathrm{d}=\frac{M}{\frac{1}{2}\rho\omega^2 A_\mathrm{M}} \tag{3}$$

where M is the drag, ω is the angular velocity, and A_M is the area moment of inertia corresponding to the axis about which the outer flow rotate. According to Ref. [22], we have

$$(C_\mathrm{d})_{x\text{-axis}}=0.364,\ (C_\mathrm{d})_{y\text{-axis}}=0.228,$$

$$(C_\mathrm{d})_{z\text{-axis}}=0.012 \tag{4}$$

The hydrodynamic coefficients were obtained via another commercial software WAMIT. This code uses boundary element method for discretization. We define several coefficients as follows. For linear motion

$$C_\mathrm{a}=\frac{m_\mathrm{a}}{\Delta} \tag{5}$$

where m_a is the added mass and Δ is the displacement of the system. For angular motion

$$C_\mathrm{a}=\frac{I_\mathrm{a}}{\Delta\times l_\mathrm{c}^2} \tag{6}$$

where I_a is the added moment of inertia and l_c is the characteristic length corresponding to the rotating axis. The product $\Delta\times l_\mathrm{c}^2$ represents the hydrodynamic moment of inertia about the center of gravity. According to Ref. [22], we have the following hydrodynamic coefficients due to linear and angular motions, respectively.

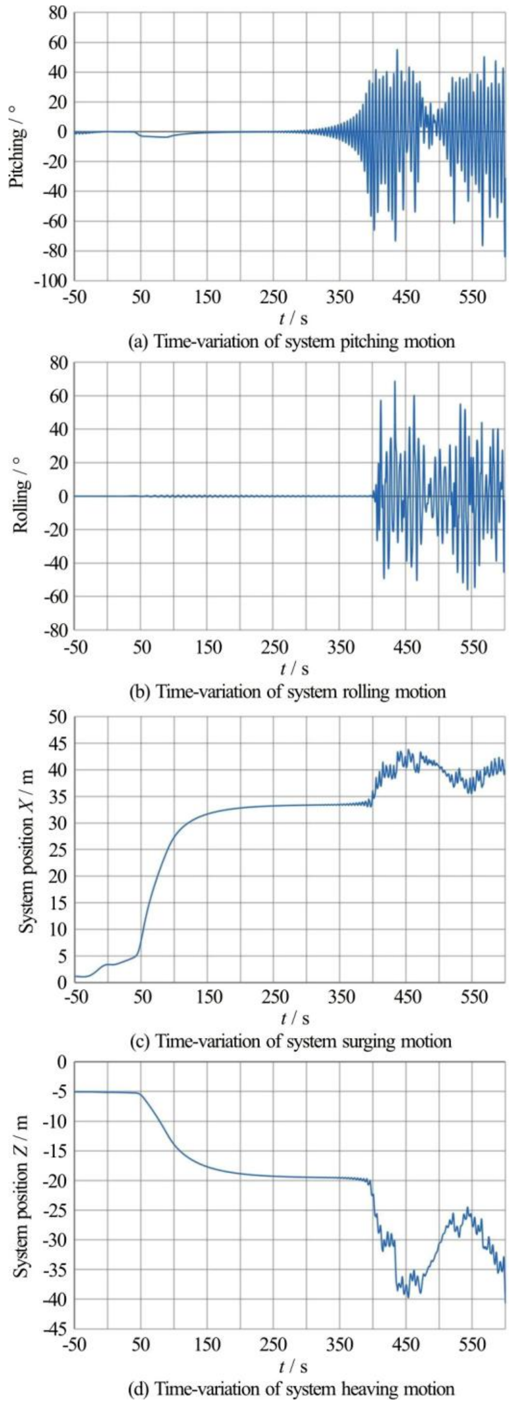
$$(C_\mathrm{a})_x=0.173,\ (C_\mathrm{a})_y=0.369,\ (C_\mathrm{a})_z=4.150 \tag{7}$$

$$(C_\mathrm{a})_{x\text{-axis}}=18.20,\ (C_\mathrm{a})_{y\text{-axis}}=4.16,\ (C_\mathrm{a})_{z\text{-axis}}=1.23 \tag{8}$$

Since the FKT system is moored to an anchor on the sea bed, the mooring line can be modelled with a catenary line. With all the forces shown above, we employed the commercial package OrcaFlex to analyze the system dynamics. This package conducts the simulation in the time domain with nonlinear models. It employs the finite element method for mooring line system discretization and lumped mass element for the FKT system for simplifications. For integration in time, we chose the implicit generalized-α method which damps numerical oscillations with high-frequency dissipations.

3. Results and discussion

Here we focus on system resonance due to surface waves and effects of mooring line with different diameters and different auxiliary mooring lines. The simulation was conducted with the following deployment procedure. The turbine floats on the free surface with an empty foil float. Then the water flooding takes place and the system submerges into water due to the current and the increase of the system weight. After the water flooding, the turbines start up to operate which makes the system going down even further.



(a) Time-variation of system pitching motion

(b) Time-variation of system rolling motion

(c) Time-variation of system surging motion

(d) Time-variation of system heaving motion

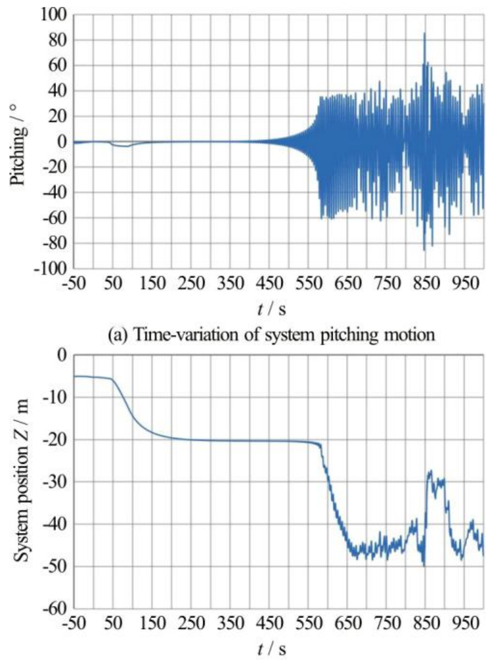
Fig. 2 (Color online) Results for system dynamics with $d = 0.03$ m

3.1 *Effects of mooring line fineness*

To study the effect of mooring line diameter on the system dynamics, we considered three cases in which the diameters are $d = 0.03$ m, 0.10 m and 0.30 m respectively. All mooring lines are identical in material and neutrally buoyant. In our computations, we assume that the bulk modulus is infinite, the axial stiffness 700 kN, the bending stiffness 120 kN·m^2, the torsional stiffness 80 kN·m^2, and the Poisson ratio 0.5. The mass per unit length is 0.707 kg/m, 7.854 kg/m, and 70.680 kg/m for $d = 0.03$ m, 0.10 m and 0.30 m, respectively. The results for d = 0.30 m has been thoroughly discussed in Ref. [14]. The FKT system behaves stably for various scenarios. Here, we focus on the cases for $d = 0.03$ m, 0.10 m. The incoming flow speed is 1.5 m/s and the angle of attack is 0°.

The dynamic responses of the system at $d = 0.03\,\mathrm{m}$ are shown in Fig. 2. No waves are present in this simulation. It is interesting to find that, shown in Figs. 2(a), 2(b), the system appears stable during the flooding process. However, when the turbines start to operate, the FKT system suffers serious pitching and rolling motion for which the amplitude is quickly amplified in a short time. After reaching its maximum, it then decreases and increases alternately. The pitching and rolling fluctuate hugely in the ranges of $(40°, -80°)$ and $(60°, -60°)$, respectively. The serious pitching motion takes place first and then the rolling motion follows later. The fluctuations are not symmetric. Since the pitching motion results in bigger negative angles of attack for the incoming current, a bigger downward force (negative lift) is induced and, hence, the system is forced to move deeper as shown in Fig. 2(d). Of course, due to the amplitude fluctuation of pitching, the heaving motion is also fluctuating, which makes the system move down and up repeatedly. Furthermore, since the length of the mooring line is fixed, the FKT system also has a surging motion which makes it move forwards and backwards repeatedly as shown in Fig. 2(c).

The results for $d = 0.10\,\mathrm{m}$ are shown in Fig. 3. The simulation is longer in time in order to reveal what could take place in long term. Similar system fluctuating phenomena are found; therefore, we show only the pitching and heaving motions. During the phase of flooding, the system behavior for $d = 0.10\,\mathrm{m}$ is stable. This is similar to that for $d = 0.03\,\mathrm{m}$. When the turbines start to operate, the pitching motion grows and its amplitude increases gradually as shown in Fig. 3(a). The fluctuations are irregular and asymmetric. Even though the diameter is increase, the temporal fluctuation in amplitude is almost as big as that for $d = 0.03\,\mathrm{m}$. The negative phenomena seem not improved significantly. However, the pitching growth rate is somewhat smaller and it takes a longer time for the pitching motion to develop. Again, the serious pitching motion induces significant fluctuation of hydrodynamic lift in both upward and downward directions, depending on the instantaneous value of the incident angle of the incoming current. Figure 3(b) shows similar heaving motion as that for $d = 0.03\,\mathrm{m}$. Since the previous study[14] shows that the system can reach its stable operation for $d = 0.30$ m, these computations imply that the diameter must be big enough for the system to exhibit the stable operation mode.



(a) Time-variation of system pitching motion

(b) Time-variation of system heaving motion

Fig. 3 (Color online) Results for system dynamics with d = 0.10 m

3.2 *Effects of auxiliary mooring line system*

We attempt to modify the mooring line system and simply introduce an additional auxiliary line in the system to study the possibility of improving the system dynamics. Shown in Fig. 4 is the new mooring line system with three auxiliary lines. The length of the two side lines is the same as the original design (i.e., 5 m in length) and the length of the additional middle one is 3.8 m.

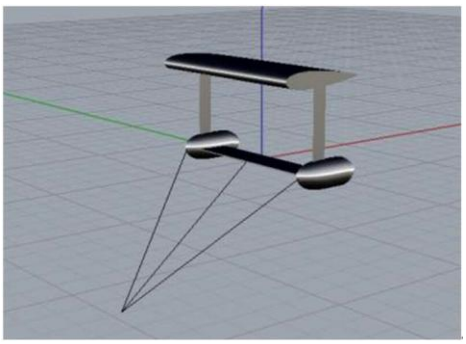


Fig. 4 (Color online) The mooring system with three auxiliary lines

If we set the diameter of all mooring lines to be 0.03 m, the computed results are shown in Fig. 5. It can be seen in Figs. 5(a), 5(b) that adding the third auxiliary line makes the system stable in surge and heave motions. These plots show that the new auxiliary mooring line system improves the FKT system dynamics and helps the turbine operate stably. Nevertheless, the new design brings forth a new problem as the stable attitude of the system is no long horizontal but rather has a pitch of about 3°, shown in Fig. 5(c). It leads to significant dynamic lift acting on the foil float and the tension of the main mooring line becomes higher. The computation shows that the tension of the middle auxiliary mooring line is about 45 kN and that of the other two side lines is about 10 kN when the system stably operates in the current as shown in Fig. 5(d). The middle line takes the major responsibility to balance the load of the FKT system. Furthermore, the dynamic lift force also reduced the submergence depth of the system. It is shown in Fig. 5(b) that the system operates at a much smaller depth of about 14.2 m. Obviously, the present 3-auxiliary-line design is not a proper one. We should redesign the centers of gravity and buoyancy so as to make the system float horizontally in the normal operation conditions. It is beyond the scope of the present study.

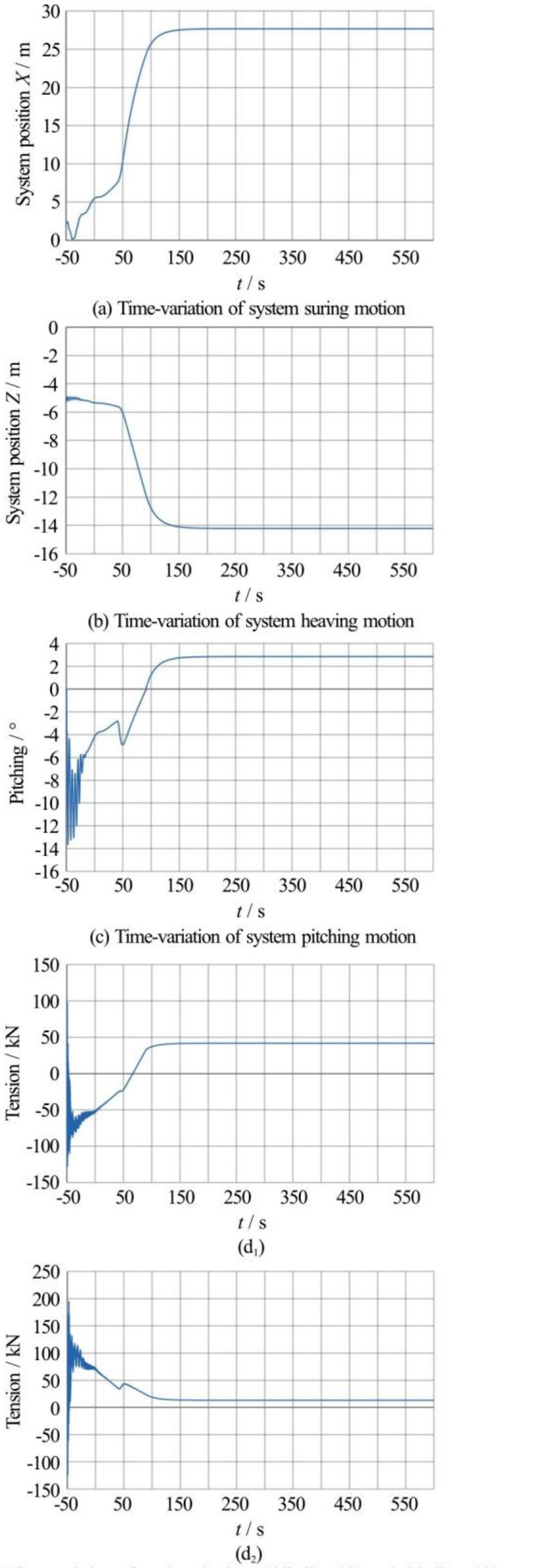
The results also show that there is small periodic yawing motion at the early stage of flooding. The maximum angular amplitude is about 3° only. This fluctuation gradually decays in time. The computational results indicate that the oscillation should be due to a small transverse displacement which makes the system not symmetric about the y-axis and the yaw motion subsequently occurs.

Finally, if we increase the diameter of the mooring line to 0.10 m, the computational results show that the system soon becomes stable without oscillations. Furthermore, the forces acting on the three auxiliary mooring lines do not deviate significantly from those in the last case. These cases show that the design of the mooring line system is vital to the operation of the FKT system. The two-line and three-line systems exhibit totally different dynamic behaviors in our investigations.

3.3 *Effects of waves*

The FKT system may suffer from actions of free surface waves during its deployment process even though we require that it submerge to some proper depth down under the sea for normal operations. Some free surface wave effects were studied.

In this series of investigations, two different conditions are particularly studies: wave propagating in the same direction as and on the opposite direction to that of the current. The wave amplitude is fixed at 1 m. For the two-auxiliary-line system with the mooring line diameter being 0.30 m, the amplitudes of pitching



(a) Time-variation of system suring motion

(b) Time-variation of system heaving motion

(c) Time-variation of system pitching motion

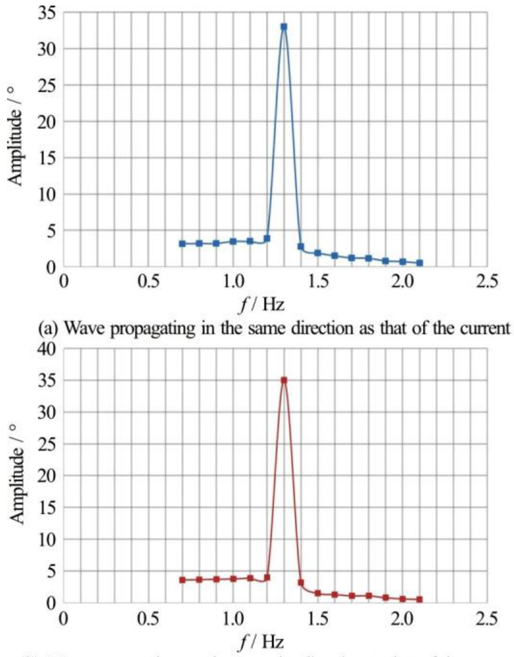
(d_1)

(d_2)

(d) Time-variation of tensions in the middle line (d_1) and side lines (d_2)

Fig. 5 (Color online) Results for system dynamics with $d = 0.03 l$ and three auxiliary lines

motion at various wave frequencies are shown in Fig. 6. It is interesting to find that for waves coming from either direction, the pitching responses are similar. There is a peak at $f = 1.3 \text{ rad/s}$ which may signify the resonance. The resonance period is then about $2\pi/f = 4.83 \text{ s}$. This is consistent to the finding in Ref. [22] which shows that only pitching motion induces resonance in waves and motions in other five degrees of freedom do not incur resonance within the frequency range of interests. Due to the effect of current flow speed, the encounter frequencies are different for waves in different directions. For the wave propagating in the current direction, we can easily find that $f_{\text{resonance}} = 1.56 \text{ rad/s}$, for the wave propagating in the opposite direction to that of the current, $f_{\text{resonance}} = 1.04 \text{ rad/s}$.



(a) Wave propagating in the same direction as that of the current

(b) Wave propagating on the opposite direction to that of the current

Fig. 6 (Color online) Pitching response of the FKT system with 2 auxiliary mooring lines

For the three-auxiliary-line system, Fig. 7 shows the results of pitching motion. Again, the pitching motions are similar for waves coming in either direction. However, the system pitching response is obviously different from that of the two-auxiliary-line one. There are two peaks for waves coming in either direction. The major one is 1.5 rad/s which has a shift from the one in the previous two-line system. The pitching motion at this frequency is significant, but its amplitude is smaller when compared to that with the two-line system. The minor one is 0.8 rad/s and has even minor effects on the pitching responses. The two peaks are not as sharp as the one with the two-line system. It seems to imply that the resonant effect is shifted and more or less suppressed. The pitching response has been improved. On the other hand, away from the two peak frequencies, the system pitching motion is generally somewhat bigger than the one with two-line systems. This can be understood because the results discussed in the last subsection shows that the FKT system positions at a smaller depth from the sea surface where the wave effect is stronger. If the system can be redesigned to reach a horizontal attitude at normal operation condition, the three-auxiliary-line system is a better choice for the FKT system.

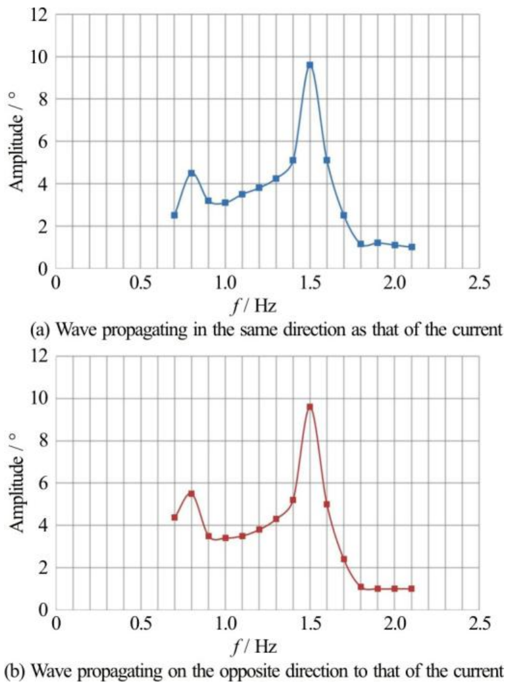


Fig. 7 (Color online) Pitching response of the FKT system with 2 auxiliary mooring lines

We also conduct some study when the wave propagates in the direction normal to the current flow. The results show that the effect on system rolling is small and no resonance is found. This conclusion is consistent to what has been studied in Ref. [22].

4. Conclusions

In this study, we have investigated the system dynamics of the floating Kuroshio turbine system developed by the joint team from National Taiwan University and National Taiwan Ocean University. The effects of mooring line design and waves were studied. We integrated several commercial and in-house codes for this study. It is found that the mooring line design has significant effects on the system dynamics. For the present system, the mooring line should have a larger diameter for stable operation at normal conditions. In addition, the design of auxiliary mooring lines can significantly influence the system dynamic behaviors. The surface waves induce system pitching oscillation which becomes significant when the wave propagation is parallel to the current flow and its period is close to the system resonant periods.

The study shows that for a particular ocean current device, the mooring line system plays a vital role in the system operations in the ocean current environments. The device resonance pattern is related to the mooring line system and should be identified. Therefore, the interaction between–the mooring line system and the device should be considered in the design process.

Acknowledgements

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