Effects of Nonlinearity of Restoring Springs on Propulsion Performance of Wave Glider

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Effects of Nonlinearity of Restoring Springs on Propulsion Performance of Wave Glider

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Abstract: Wave glider is an unmanned surface vehicle which can directly convert wave energy into forward propulsion and fulfill long-term marine monitoring. Previous study suggested that the wave motion and stiffness of restoring springs mounted on the hydrofoil are main factors affecting the propulsion performance of wave glider. In this paper, the dynamic responses and nonlinear characteristics of underwater propulsion mechanism considering the nonlinear stiffness of restoring springs are investigated based on a fluid-rigid body coupled model. Firstly, the models of propulsion mechanism with different kind of restoring spring are proposed, and the linear and nonlinear characteristics of restoring spring are considered. Then, a fluid-rigid body coupled model of wave glider is developed by coupling the rigid body dynamics model and hydrodynamic model. Dynamic responses are simulated by numerical analysis method and the nonlinear characteristics with different restoring springs are illustrated by time/frequency domain motion response and phase diagram analysis. The effects of wave excitation frequency and wave heights on the propulsion performance of wave glider are analyzed. The results show that, multi-frequency responses occurred in propulsion system. And the study suggests that the nonlinear restoring spring on the hydrofoil can be suitable for different sea condition and better propulsion performance can obtained than linear stiffness spring, which provides a reference for developing propulsion mechanism with high performance in complex marine environment.

Key words: Wave Glider; fluid-rigid body coupling, restoring springs, nonlinear characteristics, multi-frequency responses, propulsion performance;

1 Introduction

In recent years, the utilization of renewable energy for ocean exploration and environmental monitoring has become a focal issue. The wave powered vehicles, such as wave gliders, can absorb the wave energy from the ocean and convert it into forward thrust, which have received much attention [1, 2].

In 2005, Hine and Rizzi invented a wave powered underwater vehicle called ‘Wave Glider’, which is developed by Liquid Robotics and has been widely used in marine exploration [3]. Since then, scholars have carried out research on wave glider extensively. Kraus [4] and Chen et al. [5] established the 6 DOF nonlinear dynamics model of a Wave Glider, identified the hydrodynamic parameters and analyzed the relationship between the vertical liquid velocity and the forward speed respectively. Politis et al. [6] studied the performance of actively pitched biomimetic wing in converting wave energy into propulsion thrust under random heaving motion, and proposed a formula of instantaneous pitch angle of the wing. Ngo et al. [7] and Bowker et al. [8] predicted the behavior of wave glider and wave-propelled boat by using Gaussian process models and hybrid discrete time-domain numerical model respectively, and created effective methods for forecasting velocity of them. Liu et al. [9] and Wang et al. [10] studied the effects of wave parameters, foil number and flapping amplitude etc. on the propulsion performance of underwater flapping multi-foil, and found that multi-foil can produce higher propulsion than a single flapping foil due to the interaction of the multi-foil wake. Hu et al. [11] simulated the passive swing process of the hydrofoil under heave motion, analyzed the influences of wave parameters and aspect ratio on propulsion performance of hydrofoils, and obtained the relationship between these parameters and thrust coefficients. Zhang et al. [12] established the flexible multi-body dynamic model of wave-driven robot, and simulated the self-propelled process of the wave-driven robot by coupling with computational fluid dynamics. Wang et al. [13] developed an 8 DOF model of the wave glider based on the active propeller control, and investigated course response, course keeping and turning performance based on ‘SJTU Mouse’ wave glider. Sun et al. [14] improved an adaptive path following control method integrated an adaptive line-of-sight (ALOS) algorithm and an improved artificial potential field (IAPF) algorithm of wave glider, and verified by simulations and sea trials based on "Black Pearl" wave glider.

Restoring springs mounted on the hydrofoil are usually used for controlling the pitch angle of the hydrofoil when wave glider operating in marine environment, thus there are many researchers studied the effect of restoring stiffness on the propulsion performance of wave glider. Bøckmann et al. [15] studied the influence of the angle of attack and the heave and pitch phase difference on the propulsion performance of the wing by actively controlling the heave and pitch motion of the wing, and found that the propulsion efficiency of the wing can be improved by loading a spring. Thaweewat et al. [16] studied the influence of flapping frequency and spring stiffness on the propulsive performance of semi-active flapping foil by imposing heave motion and a passive pitch motion. Yu et al. [17] established a dynamic model of wave powered mechanism considered the spring limit, and obtained the relationship among the heave motion of the buoy, stiffness of the elastic components, and the forward speed. Qi et al. [18] studied the propulsive performance of the semi-active flapping foil of the wave glider, and the pitching motion is completely determined by the hydrodynamic force and torsion spring. Chang et al. [19] built the analysis scheme of fluid-mechanism coupling analysis, and studied the fluid and multi-body coupling dynamics of the wave glider, which is consisted of submersible frame body, fins and correspondent restoring springs. Yang et al. [20] optimized the propulsion performance of wave glider by changing the pivot position and the torsional spring stiffness of the hydrofoil based on STAR-CCM +, and obtained the optimum propulsive performance of six tandem hydrofoils with torsional spring.

In previous research of the restoring springs of wave glider, the linear stiffness of spring is mostly considered, but the effect of nonlinear stiffness on propulsion performance of wave glider is lack of deep study. In this paper, the effects of different restoring spring on the motion performance of the wave glider and the linear and nonlinear characteristics of restoring spring are investigated based on fluid-rigid body coupling method, and the influences of wave excitation frequency and wave heights are also studied, which can provide references for optimization of propulsion performance of wave glider.

2 Coupled Dynamics of Wave Glider

2.1 Propulsion mechanism and dynamic model of wave glider

A wave glider is usually composed of surface floating body, underwater propulsion mechanism, and connecting cable between them as shown in Fig. 1. The floating body captures the wave energy and converts it into heave motion, and drives the underwater propulsion mechanism through the connecting structure. The hydrofoils on the underwater propulsion mechanism will pitch periodically under the action of hydrodynamic force F_{fluid}, and generate the propulsion force $F_{x\text{-}fluid}$ to push the vehicle forward.

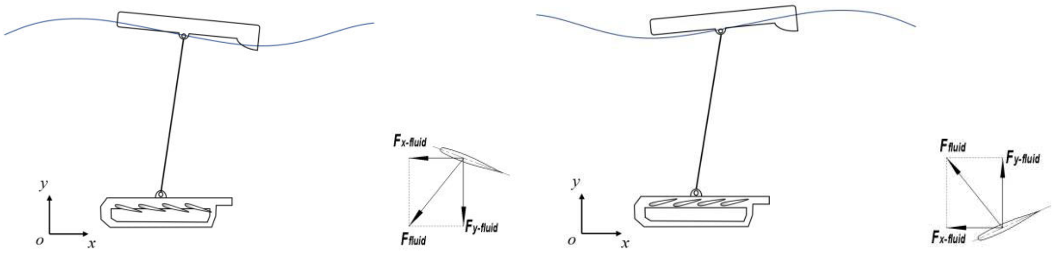


Fig. 1 The composition and movement principle of wave glider

Under the excitation of waves, the underwater propulsion mechanism performs imposed heave motion, passive forward motion and pitch motion of the hydrofoil as shown in Fig. 2.

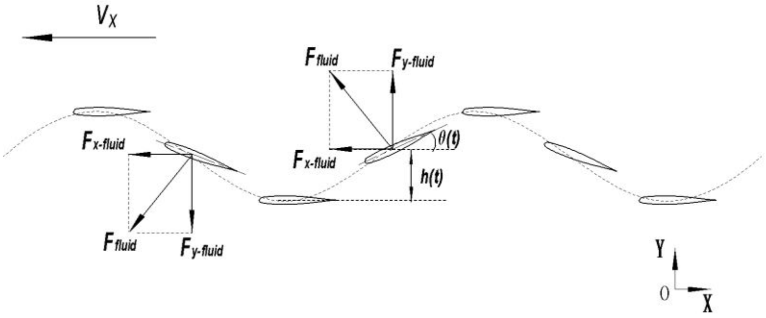


Fig. 2 Motion of hydrofoil

The following assumptions are proposed.

(1) The heave motions of floating body and underwater propulsion mechanism are simplified into harmonic movements. The motions of roll and pitch of floating body and underwater propulsion mechanism are neglected.

(2) The connecting cable is always tensioned and has no relative motion with the floating body and underwater propulsion mechanism.

(3) The interaction between the array hydrofoils is ignored, the propulsion performance can be characterized by a single hydrofoil.

The heave motion of mechanism is defined as,

$$h(t) = h_0 sin(2\pi f_w t) \tag{1}$$

Where h_0 is the heave amplitude and f_w is the heave frequency.

According to Morison equation, the resistance force of floating body is defined as

$$F_{float} = -\frac{1}{2} C_d \rho A v_x |v_x| \tag{2}$$

Where C_d is the drag coefficient, ρ is the fluid density, A is the projected area of the floating body per unit length perpendicular to the flow direction, and v_x is the horizontal velocity of the propulsion mechanism.

The forward motion and pitch motion equation can be expressed as

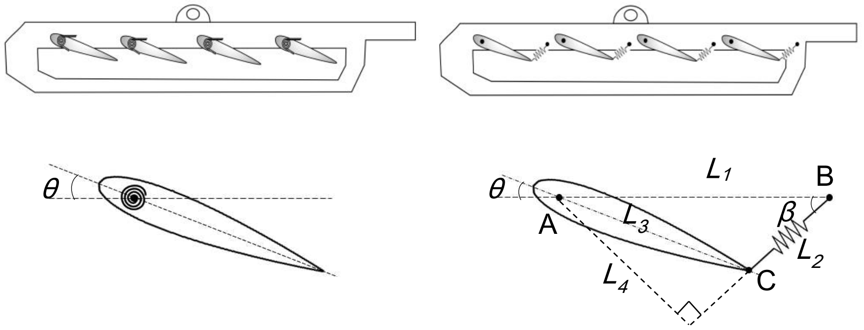
$$m\ddot{x} = F_{x-fluid} + F_{float} \tag{3}$$

$$I\ddot{\theta}(t) = M_{fluid} - M_s \tag{4}$$

Where $F_{x-fluid}$ is hydrodynamic force in x direction, M_{fluid} is hydrodynamic moment of hydrofoil, both of which are calculated by the CFD simulation. M_s is the restoring moment of restoring spring.

2.2 Models of restoring springs of wave glider

Two types of restoring springs, torsion spring and tension spring, are taken into consideration. And the models of them are established as shown in Fig. 3.



(a) (b)

Fig.3 Two types of restoring springs **(a)**Torsion spring **(b)** Tension spring

The restoring torsion spring is shown in Fig. 3 (a), and the restoring moment M_s can be described as

$$M_s = k_{tor}\theta \tag{5}$$

Where k_{tor} is the torsion spring stiffness, θ is the pitch angle of hydrofoil.

For restoring tension spring, it can be obtained from Fig. 3 (b) that,

$$F_s = k_{ten}\Delta L \tag{6}$$

$$M_s = F_s L_4 \tag{7}$$

Where

F_s is tension force of spring, k_{ten} is the tension spring stiffness,

$\Delta L = L_2 - L_s$ is the extension length of spring,

L_s is the original length of tension spring,

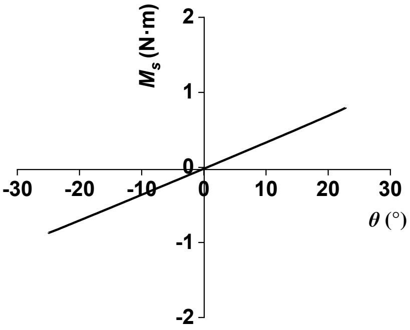
$L_2 = \sqrt{L_1^2 + L_3^2 - 2L_1L_3cos\theta}$ is the tension spring length of the hydrofoil in any position,

L_3 is the distance between the connecting point C of the spring on the hydrofoil and the pivot point of hydrofoil,

$L_1 = L_3 + L_s$ is the distance between the limit position B of the tension spring and the pivot point A of hydrofoil

$L_4 = L_1\sin\beta$ is the arm length of F_s,

$\beta = arccos\frac{L_1^2+L_2^2-L_3^2}{2L_1L_2}$ is the angle of spring in the horizontal direction.



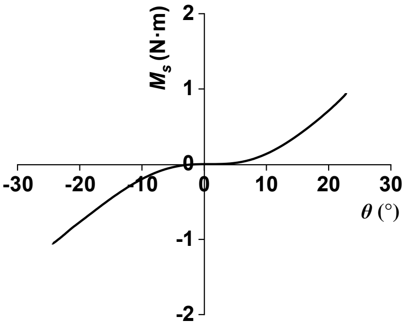


Fig. 4 $M_s - \theta$ relationship of torsion spring **Fig. 5** $M_s - \theta$ relationship of tension spring

The relationships between the restoring moment M_s and the pitch angle θ is shown in Fig. 4 and Fig. 5, the restoring moment and pitch angle have a linear relationship for torsion spring, while there is an obvious nonlinear relationship between M_s and θ for restoring tension spring.

2.3 Fluid-rigid body coupled dynamic model of underwater propulsion mechanism

A fluid-rigid body coupled method is developed based on the rigid body dynamic equation of underwater propulsion mechanism and computational fluid dynamics as shown in Fig.6. According to the initial motion conditions of the hydrofoil and the assumed boundary conditions, the hydrodynamic forces and moments of the hydrofoil can be obtained by solving RANS equation. Then the fluid loads are coupled to dynamic equation of the rigid body by UDF (User-Defined Function) codes to solve the hydrofoil motion such as forward and pitch velocity. Through continuous numerical iteration calculation, the interaction between hydrodynamic model and rigid body model of underwater propulsion mechanism can be realized.

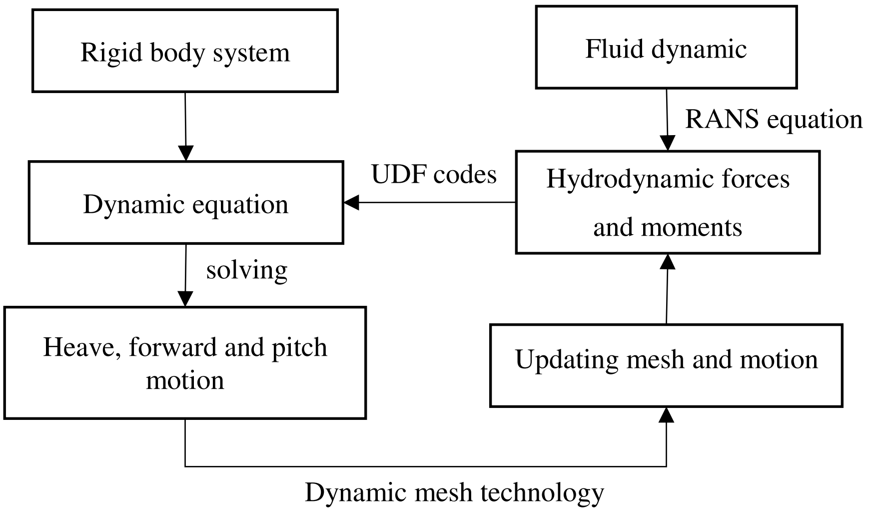


Fig. 6 Fluid-rigid body coupled method

The numerical simulations of the fluid-rigid body coupling are computationally challenging, since both the movement of mechanism and the fluid load are changing at the same time. In order to reduce heavy calculation burden, the forward velocity of the hydrofoil relative to the static fluid is converted into an incoming flow impacting on the hydrofoil with the same velocity, i.e., the forward velocity of the hydrofoil calculated in the rigid body dynamic equation at each moment is taken as the velocity of the incoming flow. Therefore, the hydrofoil only moves in the vertical and pitch directions, and the forward motion is transformed into a non-constant incoming flow, as shown in Fig. 7.

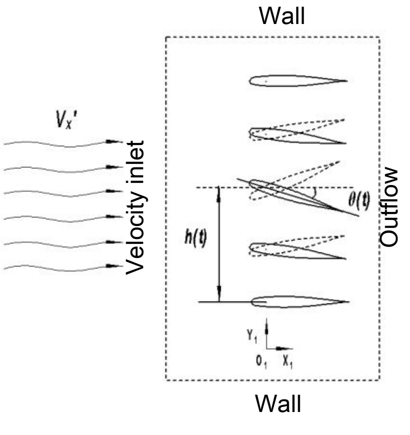


Fig. 7 Hydrodynamics of hydrofoil

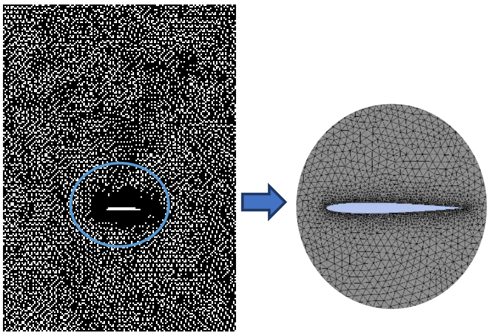


Fig. 8 Meshes around hydrofoil

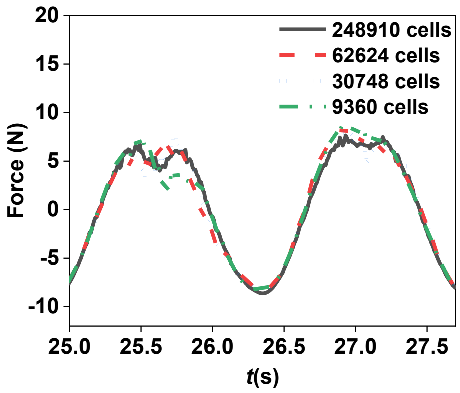


Fig. 9 Evaluation of the mesh independency

In the environment of Fluent software, the hydrodynamic force and moment of hydrofoil can be calculated by using UDF macro command DEFINE_CG_MOTION based on the motion equation of rigid body. The mesh model of the hydrofoil is shown in Fig.8 where two-dimensional unstructured triangular meshes are used, and the mesh around the hydrofoil is locally refined. The mesh independence is validated with different mesh cells of 248910, 62624, 30748 and 9360 cells to evaluate reliability of the mesh model. The propulsion force variations for meshes of 248910 cells and 62624 cells showed a similar trend, 30748 cells and 9360 cells show a little deviation due to coarse meshes as shown in Fig. 9. Therefore, the mesh of 62624 cells is chosen for numerical simulation, which can ensure both the calculation accuracy and efficiency. The inlet boundary of fluid domain is velocity inlet, the incoming flow is user-defined velocity, the outlet boundary is set to outflow, and the others are wall boundary. The transient and Pressure-Based solver is used for calculating, and the k-ε RNG turbulence model is used. The SIMPLE scheme is used for solution method, the Least Squares Cell based is used for gradient spatial discretization, and the second-order upwind scheme is applied for the spatial discretization of momentum, turbulent kinetic energy and turbulent dissipation rate. The maximum wall Y + is less than 5, and a time step of $\Delta t = 0.01$ is used in all simulations.

3 Results and Discussion

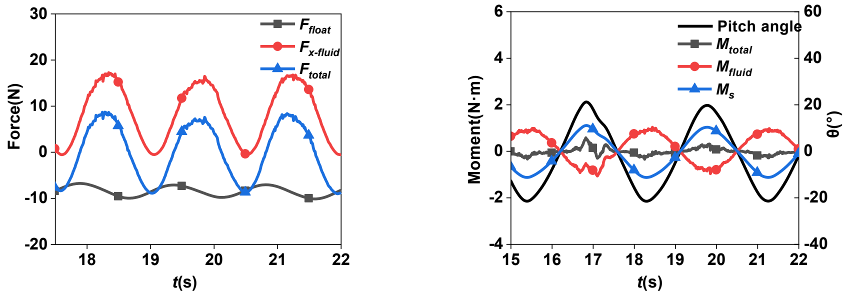
In this section, numerical simulations for wave glider with restoring torsion spring and tension spring are carried out, and the propulsion performance and nonlinear dynamic characteristics of propulsion mechanism are analyzed. The geometry dimension and physical parameters are shown in the Table 1.

Table 1 Parameters of wave-propelled mechanism

Parameter	Value

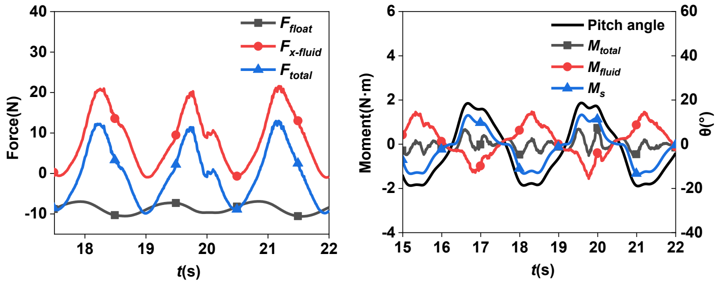
Mass of wave glider m (kg)	50
Projected cross section area of floating body in horizontal direction A (m^2)	0.02
Drag coefficient C_d	1.0
Hydrofoil profile	NACA0008
Chord length of hydrofoil c (m)	0.1
The distance between the leading edge and pivot point L (m)	0.015
The distance between the limit position of the tension spring and the pivot point of hydrofoil L_1 (m)	0.1
The distance between connecting point of the spring on the hydrofoil and the pivot point L_3 (m)	0.08
The original length of tension spring L_s (m)	0.02
Moment of inertia of hydrofoil I (kg·m^2)	0.20
Stiffness of torsion spring k_{tor} (N·m/rad)	3
Stiffness of tension spring k_{ten} (N/m)	1200
Wave frequency f_w (Hz)	0.34
Wave height H (m)	0.5

3.1 Dynamic responses with linear and nonlinear restoring springs



(a) (b)

Fig. 10 Forces **(a)** and moments **(b)** of hydrofoil with restoring torsion spring



(a) (b)

Fig. 11 Forces **(a)** and moments **(b)** of hydrofoil with restoring tension spring

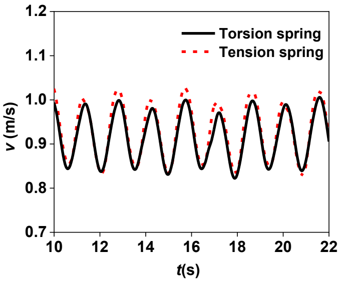
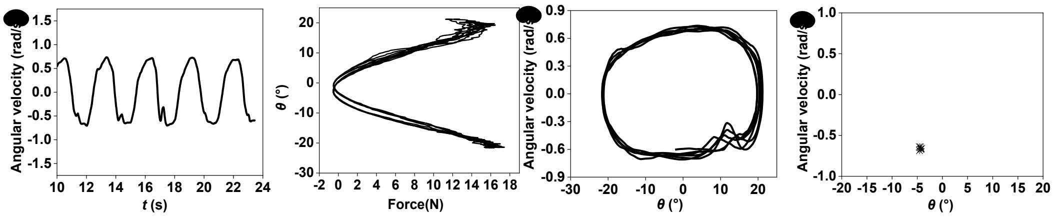


Fig. 12 Forward velocity of two restoring springs

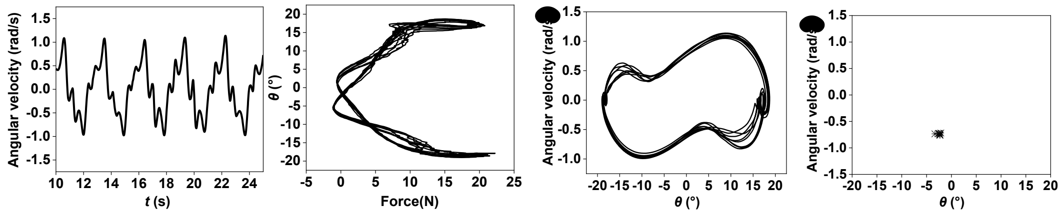
Comparing forces and moments of the hydrofoil with two types of restoring springs in Fig. 10 and Fig. 11, it is clearly noted that due to the influence of nonlinear stiffness of tension spring, the forces and moments curves have obvious fluctuations than those of torsion spring, which reduce the stability of the propulsion system. But the propulsion force and forward velocity are larger than that of the restoring torsion spring as shown in Fig. 10(a), Fig. 11(a) and Fig. 12. This may be due to the time interval of the optimal pitch angle of the hydrofoil with nonlinear stiffness, such as 15 ~ 20 ° becomes longer than linear stiffness as shown in Fig. 10 (b) and Fig. 11 (b), which can produce more propulsion force. Therefore, the nonlinear tension spring has better propulsion performance than linear torsion spring.



(a) (b) (c) (d)

Fig. 13 Motion responses of linear torsion spring

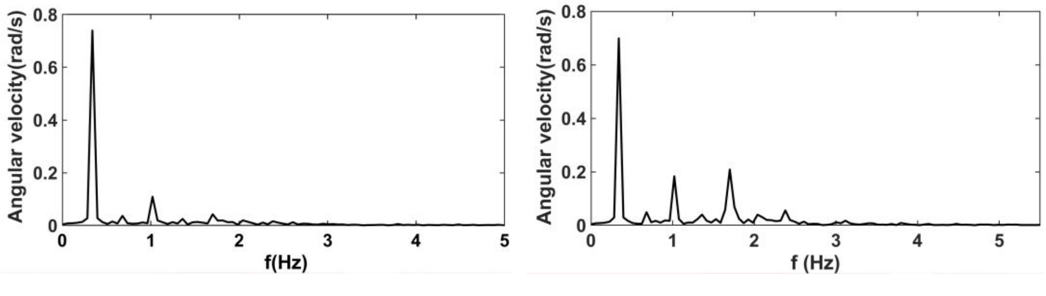
(a) Angular velocity of hydrofoil **(b)** Relationship between propulsion force and pitch angle **(c)** Phase portraits **(d)** Poincaré section



(a) (b) (c) (d)

Fig. 14 Motion responses of nonlinear tension spring

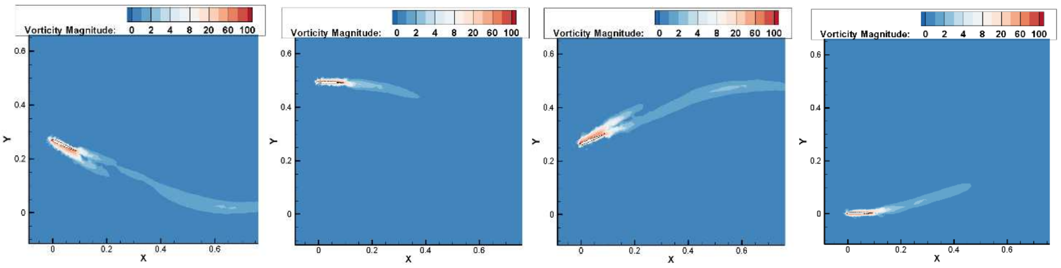
(a) Angular velocity of hydrofoil **(b)** Relationship between propulsion force and pitch angle **(c)** Phase portraits **(d)** Poincaré section



(a) Linear torsion spring **(b)** Nonlinear tension spring

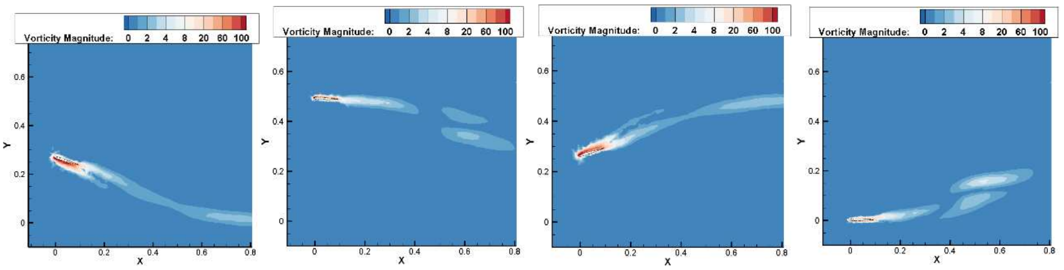
Fig. 15 Frequency spectrum

The propulsion force and pitch angle of linear torsion spring have regular and stable phase relationship as shown in Fig.13 (b), and as the pitch angle increases, the propulsion force increases approximately linearly. For nonlinear tension spring, it can be seen in Fig. 14 (b) that as the pitch angle increases, the propulsion force no longer increases linearly, but shows a nonlinear variation trend. The shape of the phase portraits has also changed significantly, and the symmetry characteristic becomes worse compared to the linear mechanism as shown in Fig.13 (c) and Fig. 14 (c). According to Mehmood's work, the system response is periodic when closed orbits in the state space are obtained, and the number of closed orbits is corresponding to the number of periods [21]. Although there are fluctuations in the motion of the nonlinear tension spring as shown in Fig.14, the phase portraits of the motion are closed, and there is only one point on the Poincaré section, so the motion of the nonlinear system is still a stable periodic motion. Besides, it can be seen from the frequency spectrum in Fig. 15 that the main responses of angular velocity of both linear and nonlinear restoring springs are at the excitation frequency, and the phenomenon of super harmonic vibration and multi-frequency responses can be observed.



(a) (b) (c) (d)

Fig. 16 Vortex contour of linear restoring mechanism **(a)** T/4 **(b)** T/2 **(c)** 3T/4 **(d)** T



(a) (b) (c) (d)

Fig. 17 Vortex contour of nonlinear restoring mechanism **(a)** T/4 **(b)** T/2 **(c)** 3T/4 **(d)** T

It can be seen from vortex contour of hydrofoil with two restoring springs in Fig. 16 and Fig. 17 that, the vortex distribution of linear torsion spring is uniform and stable, and due to fluctuations of the hydrofoil movement with nonlinear tension spring, there are more fluctuations in the vortex distribution compared to the linear spring, especially in T/2 and T as shown in Fig. 17. And the leading-edge vortex (LEV) and trailing edge vortex (TEV) meet at the tail of the hydrofoil and shed irregularly, causing fluctuations in forces and moments of hydrofoil.

3.2 Frequency responses of two restoring springs

Through the above frequency response, it is found that super harmonic vibration occurs in the pitching motion. In order to explore the motion response of propulsion system under different wave excitation frequencies and the relationship with natural frequency, the other three wave excitation frequencies, f_w = 0.616, 0.308 and 0.205Hz, are analyzed respectively. The natural frequency of linear system is 0.616Hz, and the natural frequency of nonlinear system is in the range of 0~ 0.716Hz.

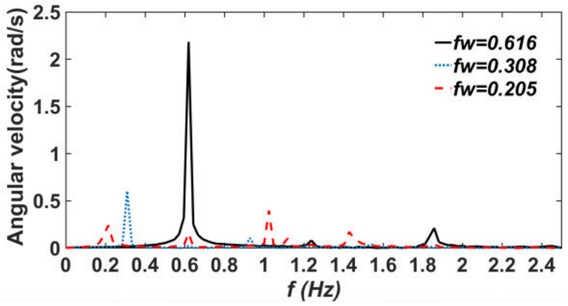
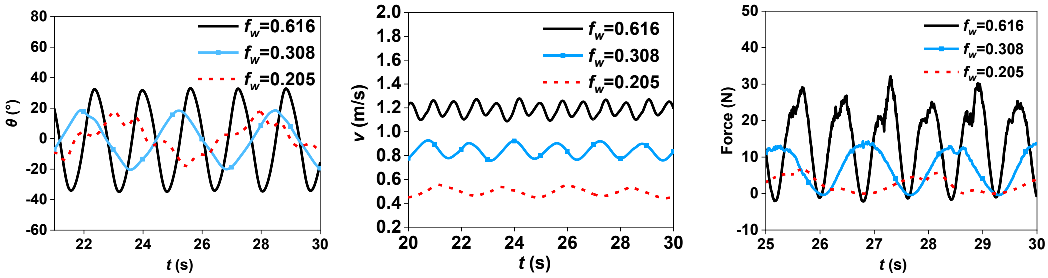


Fig. 18 Frequency spectrum of linear system under different wave excitation frequencies

It can be seen from the frequency spectrum of linear system that, no matter what excitation frequency is, there will be super harmonic vibration phenomenon as shown in Fig. 18. When excitation frequency is 0.616Hz, the angular velocity has a major peak at 0.616Hz, a neighboring smaller one at $3f_w$ = 1.848 Hz, and an additional peak at $2f_w$=1.232Hz. As the excitation frequency decreases, the vibration components increase, such as 5 f_w and 7 f_w. When the frequency is 0.205Hz, the system is dominated by 5 f_w vibration. The lower the frequency, the more obvious the super harmonic vibration.



(a) (b) (c)

Fig. 19 Time domain response of linear system under different wave excitation frequencies **(a)** Pitch angle **(b)** Forward velocity **(c)** Propulsion force

Fig. 19 (a) shows the time domain curve of pitch angle with different wave excitation frequencies, it is noted that the lower the excitation frequency, the more intense the pitch motion fluctuation such as f_w = 0.205 Hz, and the propulsion velocity and propulsion force are also decreased, which greatly reduces the propulsion performance of the wave glider as shown in Fig. 19 (b) and (c).

However, when the excitation frequency is high, although the system can produce large propulsion force, it is prone to sudden change of force as shown in Fig. 19 (c).

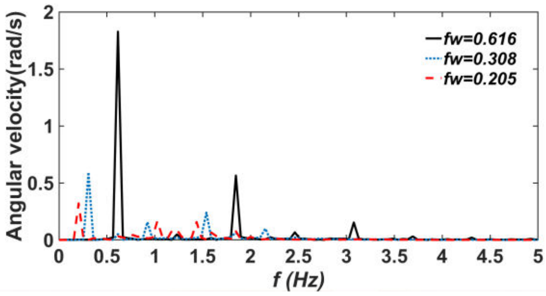
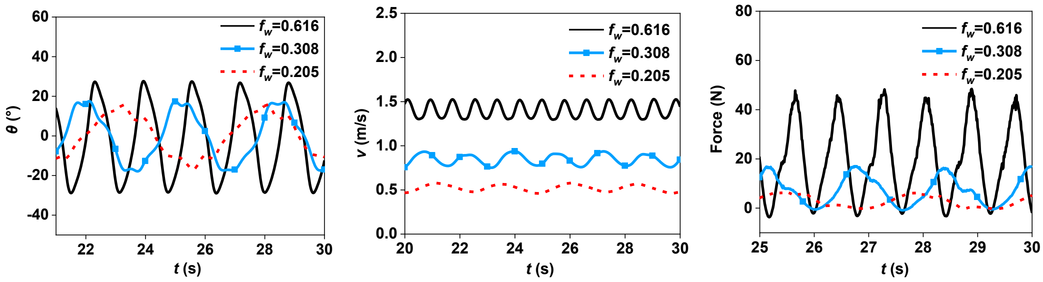


Fig. 20 Frequency spectrum of nonlinear system under different wave excitation frequencies

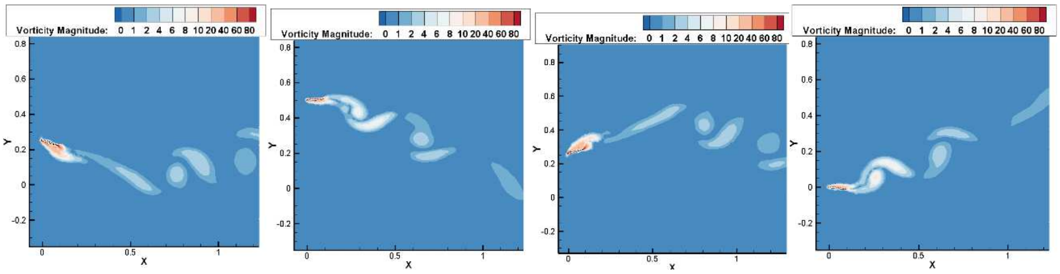


(a) (b) (c)

Fig. 21 Time domain response of linear system under different wave excitation frequencies

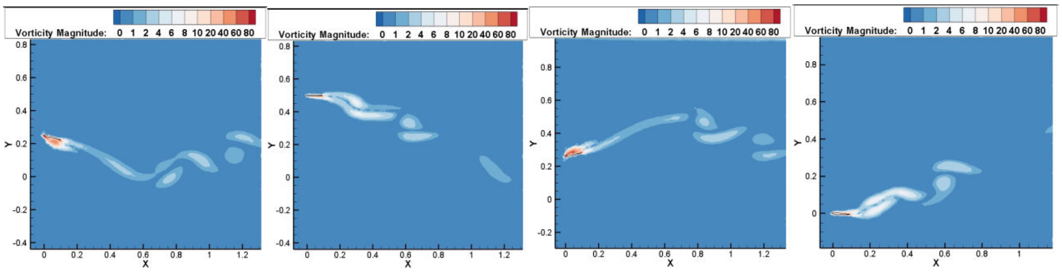
(a) Pitch angle **(b)** Forward velocity **(c)** Propulsion force

Similar vibration laws are observed in frequency spectrum of nonlinear system as the linear system as shown in Fig. 20, but there are more vibration components under high frequency excitation, such as 9 f_w. Moreover, the responses of nonlinear systems are all dominated by the excitation frequency. Besides, comparing the response in frequency domain, time domain and vortex contour in Fig. 21, 22 and 23 of linear and nonlinear systems with f_w = 0.205Hz, it can be seen that the fluctuation of pitch motion of nonlinear system is obviously smaller than that of linear system under low excitation frequency, which indicates that the nonlinear system behaves a better motion performance at low frequency than linear system.



(a) (b) (c) (d)

Fig. 22 Vortex contour of linear restoring mechanism in f_w =0.205Hz **(a)** T/4 **(b)** T/2 **(c)** 3T/4 **(d)** T



(a) (b) (c) (d)

Fig. 23 Vortex contour of nonlinear restoring mechanism in f_w =0.205Hz **(a)** T/4 **(b)** T/2 **(c)** 3T/4 **(d)** T

In addition, it can be concluded that the main vibration frequency is independent of the natural frequency, so there is no resonance in the system. Besides, there are super harmonic vibration phenomenon in both linear and nonlinear systems, so that the vibration is independent of nonlinear stiffness and may be caused by nonlinear loads in fluid.

3.3 Responses of two restoring springs under different sea conditions

In this section, motion responses of different restoring mechanisms at different wave heights H of 0.2, 0.4, 0.6 and 0.8m were calculated respectively.

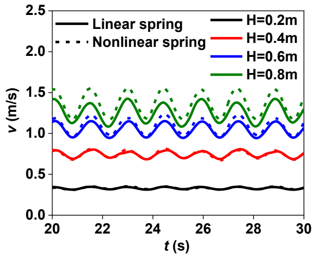


Fig. 24 Forward velocity under different sea conditions

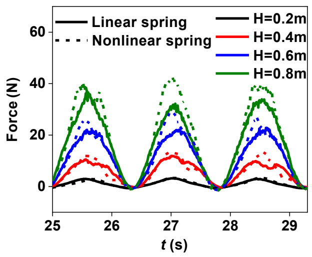
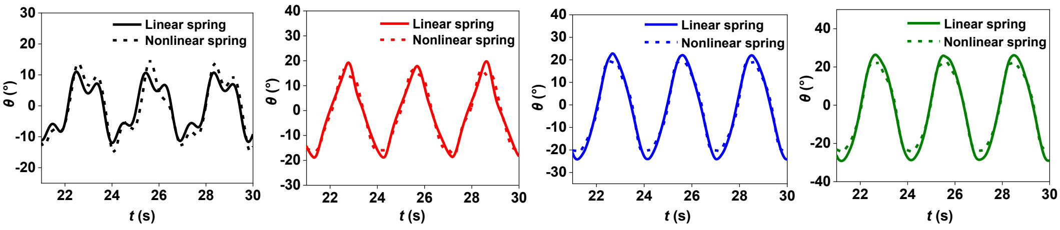


Fig. 25 Propulsion force under different sea conditions



(a) (b) (c) (d)

Fig. 26 Pitch angle under different sea conditions **(a)** H=0.2m **(b)** H=0.4m **(c)** H=0.6m **(d)** H=0.8m

When the wave height is small, the propulsion performance of wave glider with torsion and tension restoring springs are approximately the same. But in high sea condition, it is apparent from Fig. 24 and Fig. 25 that the forward velocity and propulsion force of nonlinear tension restoring spring are better than that of the linear spring. When H=0.2m, the pitch angle of hydrofoil is less than 10°，it can be seen from the M_s-θ curve of the nonlinear mechanism in Fig. 5 that the spring stiffness is small and the limit effect of the restoring moment is weak, contributing the pitch angle of nonlinear restoring spring is larger than that of linear spring after the hydrofoil motion is stable stage as shown in Fig. 26 (a). With the increase of pitch angle, the restoring moment increases exponentially. Therefore, in high sea condition, such as when H=0.4, 0.6, and 0.8m, the nonlinear stiffness can provide a larger restoring moment to avoid excessive pitch angle and keep the it in a reasonable range as shown in Fig. 26 (b), (c) and (d). As a result, nonlinear restoring spring have better adaptability in harsh marine environments.

4 Conclusion

In this paper, the motion responses and nonlinear characteristics of wave glider with linear and nonlinear restoring springs are investigated based on fluid-rigid body coupling method, several conclusions are obtained.

(1) The propulsion mechanism with restoring tension spring has obvious nonlinear characteristics, resulting in some fluctuations in the motion responses of wave glider. The nonlinear propulsion system has regular and closed phase portraits, and finite discrete points in Poincaré section, and the motion of the nonlinear system is a periodic motion.

(2) Super harmonic vibration and multi-frequency responses, such as 3fw, 5fw, and 7fw occur in the motion of both linear and nonlinear restoring springs and it is independent of the natural frequency and nonlinear stiffness, but may be caused by the fluid nonlinear load. And the propulsion mechanism with nonlinear spring has better motion performance at low wave excitation frequencies.

(3) The forward velocity and propulsion force of propulsion mechanism with nonlinear restoring spring are better than that of the linear restoring spring in general. And in the high sea condition, the propulsion performance of nonlinear system is significantly improved due to nonlinear stiffness, and has a better adaptability to harsh sea conditions.

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Competing Interests

The author(s) declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contributions

Conceptualization: [Zongyu Chang]; Methodology: [Zongyu Chang], [Zhanxia Feng]; Formal analysis and investigation: [Zhanxia Feng], [Chao Deng], [Jiakun Zhang]; Writing - original draft preparation: [Zhanxia Feng]; Writing - review and editing: [Zongyu Chang], [Zhanxia Feng], [Jia Chen]; Supervision: [Zhongqiang Zheng], [Lin Zhao]

Availability of data and materials

The authors declare that the data supporting the findings of this study are available within the article.

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