Effects of nonlinearity of restoring springs on propulsion performance of wave glider

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Abstract Wave glider is an unmanned surface vehicle that can directly convert wave energy into forward propulsion and fulfill long-term marine monitoring. A previous study suggested that the wave motion and stiffness of restoring springs mounted on the hydrofoil are the main factors affecting the propulsion performance of the wave glider. In this paper, the dynamic responses and nonlinear characteristics of the underwater propulsion mechanism considering the nonlinear stiffness of restoring springs are investigated based on a fluid–rigid body coupled model. Firstly, models of propulsion mechanism with different kinds of restoring springs are proposed, and the linear and nonlinear characteristics of the restoring spring are considered. Then, a fluid–rigid body coupled model of a wave glider is developed by coupling the rigid body dynamics model and hydrodynamic model. Dynamic responses are simulated by the numerical analysis method, and the nonlinear characteristics with different restoring springs are illustrated by the time/frequency domain motion response and phase diagram analysis. The effects of the wave excitation frequency, wave heights and the location of the connection point of springs on the propulsion performance of the wave glider are analyzed. The results show that multi-frequency responses occurred in the propulsion system, and the nonlinear restoring spring on the hydrofoil can provide a larger restoring moment to avoid excessive pitch angle and is more suitable for different sea conditions, which provides a reference for developing propulsion mechanisms with high performance in complex marine environments.

Keywords 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. Wave-powered vehicles, such as wave gliders, can absorb wave energy from the ocean
and convert it into forward thrust, which has 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 extensively carried out research on wave glider. 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. 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 their velocities. Liu et al. [9] and Wang et al. [10] studied the effects of wave parameters, foil number and flapping amplitude 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 a hydrofoil under heave motion, analyzed the influences of wave parameters and aspect ratio on the propulsion performance of hydrofoils and obtained the relationship between these parameters and thrust coefficients. Zhang et al. [12] established a flexible multi-body dynamic model of a 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 a wave glider based on active propeller control and investigated the course response, course keeping and turning performance based on the ‘SJTU Mouse’ wave glider. Sun et al. [14] improved an adaptive path following control method that integrated an adaptive line-of-sight (ALOS) algorithm and an improved artificial potential field (IAPF) algorithm of wave glider and verified the results by simulations and sea trials based on a ‘Black Pearl’ wave glider.

Restoring springs mounted on the hydrofoil are usually used to control the pitch angle of the hydrofoil when the wave glider operates in a marine environment, and thus, many researchers have studied the effect of restoring stiffness on the propulsion performance of the wave glider. Bøckmann et al. [15] studied propulsion performance of the wing by actively controlling the heave and pitch motion of the wing by loading a spring and compared the motion characteristics of wing with soft and stiff 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 passive pitch motion. Yu et al. [17] established a dynamic model of wave-powered mechanism considering the spring limit and obtained the relationship among the heave motion of the buoy, stiffness of the elastic components and forward speed. Qi et al. [18] studied the propulsive performance of the semi-active flapping foil of the wave glider, and the pitching motion was completely determined by the hydrodynamic force and torsion spring. Chang et al. [19, 20] built the analysis scheme of fluid-mechanism coupling analysis and studied the fluid and multi-body coupling dynamics of the wave glider, which consists of a submersible frame body, fins and corresponding restoring springs, and analyzed the effects of restoring spring stiffness and wave heights. Yang et al. [21] optimized the propulsion performance of a 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 a torsional spring.

In previous research on the restoring springs of wave glider, the linear stiffness of springs was mostly considered, but the effect of nonlinear stiffness on the propulsion performance of wave glider lacks in-depth study. In this paper, the effects of different restoring springs on the motion performance of the wave glider and the linear and nonlinear characteristics of the restoring spring are investigated based on the fluid–rigid body coupling method, and the influences of wave excitation frequency and wave heights are also studied, which can provide references for the optimization of the 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 a surface floating body, an underwater propulsion mechanism
and a 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 $F_{\text{fluid}}$ and generate the propulsion force $F_{x,\text{fluid}}$ to push the vehicle forward.

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.

The following assumptions are proposed.

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

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

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

The heave motion of mechanism is defined as,

$$ h(t) = h_0 \sin(2\pi f_w t) $$

where $h_0$ is the heave amplitude and $f_w$ is the heave frequency.

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

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

where $C_d$ is the drag coefficient, $\rho$ 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

$$ m\ddot{x} = F_{x,\text{fluid}} + F_{\text{float}} $$

$$ I\ddot{\theta}(t) = M_{\text{fluid}} - M_{\text{f}} $$
where $F_{x,\text{fluid}}$ is the hydrodynamic force in the $x$ direction and $M_{\text{fluid}}$ is the hydrodynamic moment of the 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. Their models are established as shown in Fig. 3.

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

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

where $k_{tor}$ is the torsion spring stiffness, and $\theta$ is the pitch angle of hydrofoil.

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

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

$$M_s = F_s L_4$$

where $F_s$ is the tension force of the 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, $L_2 = \sqrt{L_1^2 + L_3^2 - 2L_1L_3 \cos \theta}$ 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 the hydrofoil, $L_1 = L_3 + L_s$ is the distance between limit position B of the tension spring and pivot point A of the hydrofoil, $L_4 = L_1 \sin \beta$ is the arm length of $F_s$, and

$$\beta = \arccos \frac{L_1^2 + L_2^2 - L_3^2}{2L_1L_2}$$

is the angle of spring in the horizontal direction.

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

2.3 Fluid–rigid body coupled dynamic model of the underwater propulsion mechanism

A fluid–rigid body coupled method is developed based on the rigid body dynamic equation of the 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

![Fig. 3 Two types of restoring springs (a) torsion spring, (b) tension spring](image)

![Fig. 4 $M_s-\theta$ relationship of torsion spring](image)
moments of the hydrofoil can be obtained by solving the RANS equation. Then, the fluid loads are coupled to the dynamic equation of the rigid body by UDF (user-defined function) codes to solve the hydrofoil motion such as forward and pitch velocities. Through continuous numerical iteration calculations, the interaction between the hydrodynamic model and rigid body model of the underwater propulsion mechanism can be realized.

Numerical simulations of fluid–rigid body coupling are computationally challenging since both the movement of the mechanism and the fluid load change at the same time. To reduce the 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.

In the environment of Fluent software, the hydrodynamic force and moment of the hydrofoil can be calculated by using the UDF macro command DEFINE_CG_MOTION based on the motion equation of a 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 248,910, 62,624, 30,748 and 9360 cells to evaluate the reliability of the mesh model. The variations of resultant force, pitch angle and hydrodynamic moment of hydrofoil for meshes of 248,910 cells and 62,624
cells showed a similar trend, 30,748 cells and 9,360 cells show a little deviation due to coarse meshes as shown in Fig. 9. Therefore, the mesh of 62,624 cells is chosen for numerical simulation, which can ensure both the calculation accuracy and efficiency. The inlet boundary of the fluid domain is the velocity inlet, the incoming flow is the 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 calculation, and the $k$-$\varepsilon$ RNG turbulence model is used. The SIMPLE scheme is used for the 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 the propulsion mechanism are analyzed. The geometry dimension and physical parameters are shown in Table 1.

3.1 Dynamic responses with linear and nonlinear restoring springs

Comparing the forces and moments of the hydrofoil with two types of restoring springs in Figs. 10 and 11, it is clearly noted that due to the influence of the nonlinear stiffness of the tension spring, the forces and moments curves have obvious fluctuations compared to those of the torsion spring, which reduces the stability of the propulsion system. However, the propulsion force and forward velocity are larger than that of the restoring torsion spring as shown in Figs. 10a, 11a and 12. This may be due to the time interval of the optimal pitch angle of the hydrofoil with nonlinear stiffness; for example, 15–20° becomes longer than linear stiffness as shown in Figs. 10b and 11b, which can provide greater propulsion force and velocity.

The propulsion force and pitch angle of the linear torsion spring have a regular and stable phase relationship as shown in Fig. 13b, and as the pitch angle increases, the propulsion force increases approximately linearly. For the nonlinear tension spring, it can
be seen in Fig. 14b 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 also changes significantly, and the symmetry characteristic becomes worse compared to the linear mechanism as shown in Figs. 13 and 14c. 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 corresponds to the number of periods [22]. 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. In addition, it can be seen from the frequency spectrum in Fig. 15 that the main responses of the 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.

It can be seen from the vortex contour of the hydrofoil with two restoring springs in Figs. 16 and 17 that the vortex distribution of the linear torsion spring is uniform and stable, and due to fluctuations of the hydrofoil movement with a 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. The leading-edge vortex (LEV) and trailing-edge vortex (TEV) meet at the tail of the hydrofoil and shed irregularly, causing fluctuations in the forces and moments of the 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 the 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 \( 0.205 \) Hz, are analyzed, respectively. The natural frequency of the linear system is \( 0.616 \) Hz, and the natural frequency of the nonlinear system is in the range of \( 0–0.716 \) Hz.

It can be seen from the frequency spectrum of the linear system that, regardless of the excitation frequency, there will be super-harmonic vibration phenomenon as shown in Fig. 18. When the excitation frequency is \( 0.616 \) Hz, there is resonance in the system. The angular velocity has a major peak at \( 0.616 \) Hz, a neighboring smaller one at \( 3f_w = 1.848 \) Hz and an additional peak at \( 2f_w = 1.232 \) Hz. As the excitation frequency decreases, the vibration components increase, such as \( 5f_w \) and \( 7f_w \). When the frequency is \( 0.205 \) Hz, the system is dominated by \( 5f_w \) vibration. The lower the frequency is, the more obvious the super-harmonic vibration.

Figure 19a shows the time domain curve of the pitch angle with different wave excitation frequencies. It is noted that the lower the excitation frequency is,
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. 19b and c. However, when the excitation frequency is high, although the system can produce a large propulsion force, it is prone to a sudden change in force, as shown in Fig. 19c.

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

3.3 Responses of two restoring springs under different sea conditions

In this section, the motion responses of different restoring mechanisms at different wave heights $H$ of 0.2, 0.4, 0.6, 0.8 and 1.0 m were calculated. According to the corresponding relationship between wave height and period in Bretschneider’s studies [23], the parameters of wave height and frequency set for the numerical simulations performed in this study are listed in Table 2.

When the wave height is small, the propulsion performance of the wave glider with torsion and tension restoring springs is approximately the same. However, under high sea condition, it is apparent from Figs. 24 and 25 that the forward velocity and propulsion force of the nonlinear tension restoring spring are better than that of the linear spring. When $H = 0.2$ m, the pitch angle of the hydrofoil is less than $10^\circ$. It can be seen from the $M_s-\theta$ curve of the nonlinear mechanism in Fig. 5 that the spring stiffness is small and the limit effect of the restoring moment is weak, and contributing to the pitch angle of the nonlinear restoring spring is larger than that of linear spring after the hydrofoil motion is stable, as shown in Fig. 26a. With increasing pitch angle, the restoring moment increases exponentially. Therefore, under high sea conditions, for example, when $H = 0.4, 0.6,$ and $0.8$ m, the nonlinear stiffness can provide a larger restoring moment to avoid excessive pitch angle and keep it in a reasonable range as shown in Fig. 26b, c and d. As a result, nonlinear restoring spring has higher adaptability in harsh marine environments (Fig. 27).

3.4 Effects of location and preload on propulsion performance

The effects of location of tension spring on propulsion performance of hydrofoil are analyzed in this section, and the distance between connecting point of the spring on the hydrofoil and the pivot point $L_3$ is set to different lengths as shown in Fig. 28. In addition, the preload of spring is taken into consideration.

Two cases of spring with and without preload are considered, and the parameters in the initial position of the hydrofoil in Fig. 27 are shown in Table 3.

It can be seen in Fig. 29a that the greater the $L_3$, the greater the slope of the $M_s-\theta$ curve, and when $L_3$ is
small, the $M_s$ increases slowly as the pitch angle increases due to the short arm length of tension force. The velocity and propulsion force of hydrofoil are proportional to the change of $L_3$, and the propulsion performance of the hydrofoil will be significantly reduced as $L_3$ decreases as shown in Fig. 29b and c.

When considering the preload, there is an initial value of tension force of spring, and the smaller the $L_3$, the greater the initial tension force as shown in Fig. 30a. And the slopes of tension force and arm length decrease as $L_3$ decreases as shown in Fig. 30a and b, so the nonlinear characteristics of the spring moment and the pitch angle are also significantly weakened, tending to be a linear relationship as shown.
in Fig. 30c. Besides, when \( L_3 \) is 0.07 m, the forward velocity of hydrofoil is the largest, and the fluctuations of propulsion force are small as shown in Fig. 30d and e. Therefore, proper preload is beneficial to improve the propulsion performance of the hydrofoil.

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

2. Super-harmonic vibration and multi-frequency responses, such as $3f_w$, $5f_w$, and $7f_w$, occur in the motion of both linear and nonlinear restoring springs, and there are more vibration components under high-frequency excitation in nonlinear restoring springs. Besides, the propulsion mechanism with a nonlinear spring can reduce fluctuations in motion responses at low wave excitation frequencies.

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

4. The propulsion performance of the hydrofoil reduced significantly as the distance $L_3$ decreases without considering the preload. As the preload increases, spring moment and the pitch angle tend to be a linear relationship, and a proper preload of spring can improve the forward velocity and reduce fluctuations of propulsion force.

### Declarations

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

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