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Locomotion Performance of the Amphibious Robot on Various Terrains and Underwater with Flexible Flipper Legs

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Abstract

Amphibious robots are attracting more and more attentions from researchers worldwide for their broad applications in resource exploration, disaster rescue, and reconnaissance. Amphibious robot with transformable flipper-leg composite propulsion mechanisms can adapt various terrestrial and water environments. In this paper, we explored the locomotion performance of a amphibious robot with flexible flipper legs on various terrains and underwater through dynamical simulation. The influence of the stiffness of the flipper legs on the locomotion performance in various environments was investigated comprehensively. The results indicate that the locomotion with flexible flipper legs is very stable, and the stiffness of the flipper legs has a great impact on the locomotion performance. The verification experiments demonstrate the accuracy of the simulation results. The study facilitates the design of the amphibious robot and indicates that the passively transformable flipper-leg mechanisms also enable amphibious robot to conquer various complex terrestrial environments.

Keywords: amphibious robots, flexible flipper legs, various terrains, locomotion performance

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1 Introduction

Amphibians possess unique abilities to adapt to various environmental conditions and terrains. Inspired by the great locomotion performance of amphibians developing a bionic amphibious robot is a challenging but an attractive task that has gained much attention from researchers worldwide. An amphibious robot should have the ability to adapt to various environments, such as rough land terrains, underwater environments, even the transitional zone between land and water occupied by soft substrates. Amphibious robots have broad applications in resource exploration, rescue and so on. To achieve amphibious locomotion in complex environmental conditions, many researches have been made to propose various interesting robots or robotic platforms in recent years, which can be generally divided into two categories: (1) biomimetic amphibious robots. Snake-like robots, are the most typical amphibious robots which can propel on land and underwater by undulating their bodies[1–3]. ACM-R5 is one of the snake robots, which can propel at about 0.4 $m \cdot s^{-1}$ both on the ground and underwater[1]. Salamander Robot, an amphibious robot can utilize body undulation and limb walking to transit between terrestrial and aquatic locomotion[4,5]. Also, a turtle robot was designed with a spherical body and four legs with two Degrees of Freedom (DOF) that is capable of walking on land and cruising underwater[6]; (2) bioinspired robots that utilize multiple propulsion mechanisms to achieve amphibious locomotion in various environments. AmphiRobot-II can demonstrate fish-like swimming and wheeled crawling with both wheel and fin propulsion[7]. Amphibious Whegs possesses a combination of legs and propellers that enable it a good locomotion performance on rough terrains and underwater[8]. A newly designed hexapedal robotic platform, RHex, can achieve high stability on ground locomotion and have advantages in stable running on water[9]. Moreover, among various amphibious robots, AUQA series robots stemming from the RHex[10], a cockroach-inspired hexapod robot possessing an outstanding terrestrial locomotion performance[11,12] is most attractive. AQUA2 with replaceable flipper legs has been better developed to transition be-

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tween locomotion modes autonomously[13]. Besides the above mentioned robots, more other amphibious robots or platforms have been developed[14–16]. However, utilizing two sets of propulsion mechanism leads to complex structure and control strategy which hinders the applications of the amphibious robots.

To overcome the limitations of the existing amphibious robots[17], we have proposed and developed an amphibious robot, AmphiHex-I, with actively transformable flipper-leg composite propulsion mechanisms[18–22], which allows AmphiHex-I to propel underwater and on loose and muddy terrains with a good performance. However, the active deformation of the flapper-legs brings more DOFs and the complex structure of AmphiHex-I, which leads to a complex control strategy and a lower durability of the robot. A new design of the leg structure is required to overcome these shortcomings. Recently, more and more attention has been given to analyze the influence of elastic legs on the locomotion performance. These researches show that elastic legs provide many advantages in locomotion performance. First of all, elastic legs can improve the ability of robots to achieve a robust, efficient and stable dynamic movement[23]. Robot with elastic legs can even leap[24] and climb stairs[25]. Besides, an appropriate leg stiffness is necessary to close the locomotion performance gaps between robots and animals[26] and change of the stiffness of legs has a great mechanical value in improving adaptability of the absolute elastic leg to achieve an efficient locomotion[27]. Inspired by these results, we developed a new flexible flipper leg structure applied on the former AmphiHex-I's body. We removed the transform cable through the flipper legs and the corresponding transformation motors. The simplified flexible flipper leg can transit between fin and leg during the locomotion, which allows the robot to propel underwater and adapt complex terrains. When flexible flipper legs are loaded during the locomotion, they could passively transform into curved leg shape due to the force that the terrains applied. When the loads disappear or the robot swims underwater, the legs turn into flipper legs passively due to the elastic restoring force. In this paper, the locomotion performance of the amphibious robot with flexible flipper legs on various terrains and underwater is extensively studied by simulation. The influence of the flexibility of flipper legs on locomotion performance is investigated and discussed comprehensively. The experimental results are presented to verify the accuracy of the simulation results. The study indicates that the flexible flipper leg structure enables the amphibious robot to propel effectively on rough land, slope, stairs and underwater, and the experimental results of the influence of the stiffness of the legs lays a foundation on the structural design of the amphibious robot.

The remainder of this paper is organized as follows. Section **2** describes the materials and methods of our research that includes the detailed design of flexible flipper leg structure, theoretical and simulation analysis of locomotion performance with flexible flipper legs. In section **3**, the setting-up of verification experiment and the experiment results are described. All of the results of on terrain simulation and underwater simulation are summarized and analyzed. Further discussions are presented in section **4**. Finally, the conclusion and future work are given in section **5**.

2 Material and methods

2.1 Configuration of the flexible flipper leg

Thanks to the flexible flipper leg structure, the amphibious robot possesses locomotion ability to adapt watery and terrestrial environments. The flexible flipper leg can switch between curved leg state and flexible straight flipper state passively. As shown in Fig. 1, the amphibious robot equipped with six flexible flipper legs can walk like a cockroach when performing locomotion on terrain. For aquatic propulsion, those flipper legs act as straight flippers to oscillate and propel the robot underwater.

The structure of the flexible flipper leg is shown in Fig. 2a. The flipper leg composes of seven segments

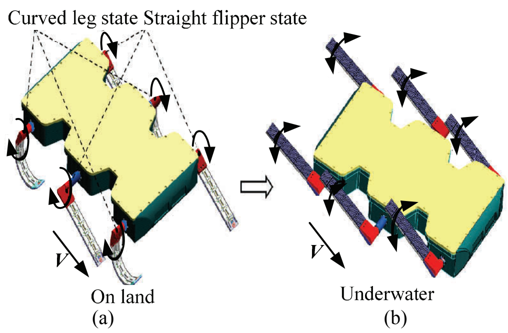


Fig. 1 Two locomotion modes with flexible flipper legs. ***V*** denotes the locomotion speed and the arrow shows the direction of locomotion. (a) AmphiHex-I adopts a tripod gait to locomote on terrains, three flipper legs bend to curved legs state to support the body, the other three legs are in straight state without external forces; (b) AmphiHex-I adopts a swimming gait underwater, its six flipper legs are all in straight state.

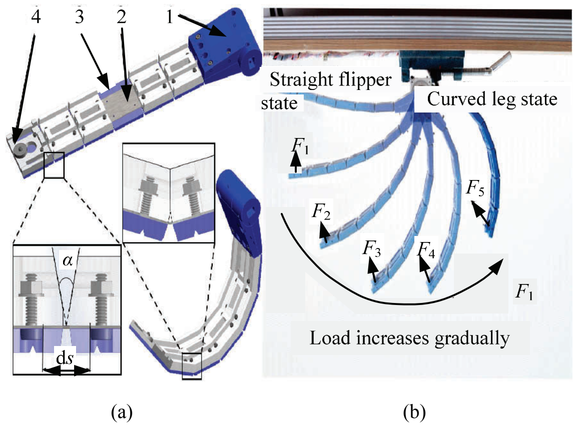


Fig. 2 The flexible flipper leg. (a) Structure of the flipper leg. 1 head segment, 2 spring steel plate, 3 soft rubber piece, 4 end segment; (b) transformation process when the load increases gradually to show the leg state during walking.

including head segment and end segment as basic units. A steel plate is incorporated to connect the seven segments. The stiffness of the flexible flipper leg can be adjusted by varying the thickness of the steel plate. d*s* represents the length of the flexible parts, since the steel plate is fixed on the segments with screws directly and the soft rubber pieces exert a small influence on the deformation of steel plate. During the simulation of terrestrial locomotion, we simplify the spring steel plate into six torsional springs which connect every two adjacent segments. Through changing the stiffness of the torsional springs, we can simulate the locomotion under different flexibility of the flipper legs. Fig. 2b shows the shapes of the flipper leg under different loads (F_1–F_5) clearly, this changing process is just like the leg walking on terrains. The final shape of the curved leg mode can be adjusted by varying the value of angle α. Different shapes of curved leg lead to different locomotion performance[21]. In this study, we chose the angle α to be 26°, which makes the shape of curved leg to be a semi-circular. This simplified structure enables the flipper legs to propel the robot both on rough terrains and underwater without actively transforming the flipper legs.

2.2 Simulation of locomotion on terrains

To analyze the locomotion performance of the robot with flexible flipper legs comprehensively, we have set up two series of simulation experiments. The first one is set to analyze the locomotion performance on various rough terrains, and the second one is set to analyze the locomotion performance underwater. As for the locomotion performance with flexible flipper legs on various rough terrains, we have designed three kinds of terrains, which are ground, slope, and stairs. Besides, we have chosen two gaits[19] for the robot in the simulation. The first gait that the robot adopted in crawling on the ground and climbing the slope is 'tripod gait'. In this gait, as shown clearly in Fig. 3a – 3f, the front and the rear legs on one side keep the same movement with the middle leg on the other side. When three legs in the same movement are about to leave the ground, other three legs should touch the ground already. The values of the phase difference between two groups of legs are fixed. The second gait that the robot adopted in climbing stairs is 'tetrapod gait'. In this gait, as shown in Figs. 3g – 3i, two front legs, two middle legs and two rear legs keep the same movement, respectively. The initial phase differences between each group of legs are preset. This gait is efficient in locomotion on complex terrain such as stairs.

In the simulation experiments on rough terrains, we have simplified the steel plate of the flexible flipper leg structure into six torsion-springs connecting the segments of flexible legs. The transformation equations are defined as:

$$K = \frac{G \cdot I}{L}, \tag{1}$$

$$G = \frac{E}{2(1+v)}, \tag{2}$$

where K denotes the strength of torsion-springs, G denotes the shear elasticity of steel plate. I is the moment of inertia of steel plate. L denotes the length of steel plate. E represents the Young's modulus of steel plate, and υ

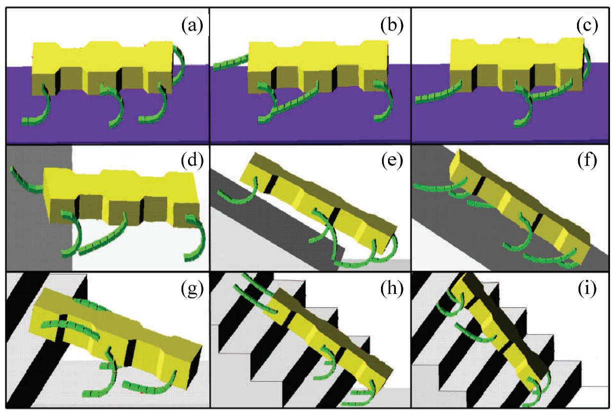


Fig. 3 Locomotion process on rough terrains. (a), (b) and (c) show the locomotion with tripod gait on flat land; (d), (e) and (f) show the locomotion with tripod gait on climbing slope; (g), (h) and (i) show the locomotion with tetrapod gait on climbing stairs.

means the Poisson ratio which we chose 0.3 in the study, t denotes the thickness of steel plate. The values of the parameters in the simulation are listed in Table 1.

All the simulations on various terrains were conducted in software ADAMS. Since the rubber plates were stuck on the surface of every segment of six legs, so the friction coefficient between the legs and terrains is set as 0.5[28]. The gradient of the slope is 30˚ and the gradient of the stairs is 40˚. The weight of the body is set as 15 kg, 20 kg, 30 kg, 50 kg, and 70 kg, respectively. As for each leg, the weight of head segment is 60 g, and the weight of the rest six elements is 47 g, respectively. We also apply 'contact' constraints between every element and ground to generate propulsion during the process of movement. The 'contact' constraints between every two adjacent elements are also set. Besides, each leg has been applied a fixed rotating speed. The thickness of steel plate is set from 0.1 mm to 0.6 mm or to 0.7 mm due to different environments.

2.3 Simulation of propulsion underwater

To investigate the locomotion performance with flexible flipper legs underwater, the simulation experiment model is also developed. Since the robot usually oscillates the flipper legs to propel the robot underwater, the dynamics of the flipper legs works similarly as straight flipper during propelling. The simplified model is shown in Fig. 4a. Here we just adopt one flipper leg to study.

The computational domain for the simulation of the flexible flipper leg is presented in Fig. 4b. The leg model is placed at the middle line of the domain in z-direction. The total length and width of the domain is 8 times and 10 times of the length of L, which is large enough to avoid the boundary effect. The flexible flipper leg is simplified into a long flat plate consisting of two parts: the rigid parts and flexible parts, which are presented in black and gray respectively. The rigid parts possess an infinity Young's modulus, while we define the flexible parts possess a Young's modulus at 198.6 GPa, which is the exact Young's modulus of the steel plate. Through changing the thickness of the leg model, the leg model could possess different stiffness.

Table 1 Parameter values in the simulation

Parameter	Value
I	$2.92\times10^{-12}\times t^3$
L	12.2 mm
E	198.6 GPa
υ	0.3

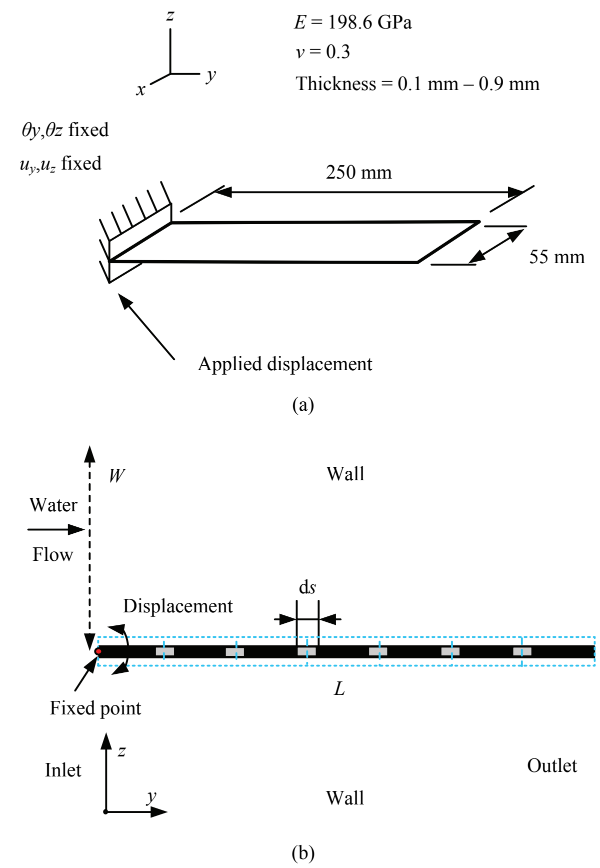


Fig. 4 (a) Simplified model of the flexible flipper leg; (b) model of the flexible flipper leg underwater and the computational domain for the study.

Around the fixed point which is in the middle of the edge of the leg model, we applied a displacement with pitching motion which is defined by:

$$\alpha = \varphi_a \cdot \sin(2\pi\omega t), \tag{3}$$

where α denotes the angle of every moment, φ_a denotes the pitching amplitude, ω denotes the pitching frequency.

For the fluid domain, an Arbitrary-Lagrangian-Eulerian (ALE) method is used which can solve the deformation of boundaries compared with traditional Eulerian method. The continuity and momentum equations are expressed as[29]:

$$\nabla_{\bar{x}} \bullet \boldsymbol{u} = 0, \tag{4}$$

$$\rho_f\left(\left.\frac{\partial \boldsymbol{u}}{\partial t}\right|_{\bar{x}}+\left(\boldsymbol{u}-\boldsymbol{u}_g\right)\bullet\nabla_{\bar{x}}\boldsymbol{u}\right)=\nabla_{\bar{x}}\bullet\sigma+\omega, \tag{5}$$

where $\boldsymbol{u}$ denotes the flow velocity vector, $\bar{x}$ denotes the ALE coordinate system, ρ_f denotes the fluid density, and $\boldsymbol{u}_g$ denotes the velocity vector of reference coordinate system, σ denotes the Cauchy stress tensor.

As for the structure domain, the Lagrangian method is chosen to calculate the displacement and the force. On the coupling interface, we have other two equations to solve the kinematics and dynamics equilibrium[29]:

$$d_f = d_s, \tag{6}$$

$$n\cdot\tau_f = n\cdot\tau_s, \tag{7}$$

where d_f and d_s denote the displacement of the fluid and structure, respectively, τ_f and τ_s denote the stress of the fluid and structure, respectively. Firstly, the location of fluid nodes on the coupling interface is determined by the kinematic equilibrium. Moreover, the force applied on the structure nodes by fluid is calculated by formula $F(t)=\int h^d\tau_f \mathrm{d}s$, h^d denotes the displacement of the structure nodes. The direct coupling is adopted which is a strong interaction between structure and fluid compared with iterative couple since it solves the fluid equations and structure equations in one equation set of every step. The oscillating frequency and oscillating amplitude are the most important keys to determine the locomotion performance[30].

Software ADINA is used for the fluid-structure interaction simulation. Triangular mesh is chosen to discretize the fluid domain to obtain a more precise result. The grid independency is confirmed by checking different number of the grids. The leg model performs large motions in the fluid, so adaptive mesh is applied in the fluid domain for mesh regeneration to reduce mistakes during the simulation. Thus propelling experiments underwater with different thickness of steel plate, oscillating frequency and oscillating amplitude were conducted to explore the locomotion performance of the flexible flipper legs. The oscillating frequency is set as 0.5 Hz, 1 Hz, 1.5 Hz, and 2 Hz, respectively. The oscillating amplitude in the experiments is set as 10˚, 20˚, and 30˚, respectively. The thickness of steel plate is set from 0.1 mm to 0.7 mm. Applying of the water flow makes it a more real environment as underwater, and the velocity of water flow is set as 0.2 $\mathrm{m\cdot s^{-1}}$.

2.4 Evaluation criteria

In order to explore locomotion performance of the robot in various environments, evaluation criteria should be defined in advance. Two parameters to evaluate the locomotion performance of robot on rough terrains are defined, that are locomotion velocity $\boldsymbol{V}$ and the locomotion efficiency η. Locomotion velocity can be exported directly through the simulation, while the locomotion efficiency needs to be calculated. To calculate the locomotion efficiency, we need to define another three important parameters, including the value of the frictional force from the ground $\boldsymbol{f}$, the effective power of locomotion P_1 and the output power of motor P_2. Friction force $\boldsymbol{f}$ can also be exported through the software, P_1 and P_2 are expressed as:

$$P_1=\boldsymbol{f}\cdot\boldsymbol{V}, \tag{8}$$

$$P_2=T\cdot\omega, \tag{9}$$

where ω denotes the angular velocity of legs, T denotes the output torque of each motor.

Thus, the equation to calculate locomotion efficiency η on rough terrains can be expressed as:

$$\eta=\frac{\int_0^\tau P_1\cdot t\mathrm{d}t}{\int_0^\tau P_2\cdot t\mathrm{d}t}\times 100\%=\frac{\int_0^\tau \boldsymbol{f}\cdot\boldsymbol{V}\cdot t\mathrm{d}t}{\int_0^\tau T\cdot\omega\cdot t\mathrm{d}t}\times 100\%, \tag{10}$$

where τ stands for the period of motion, which is set as 4 s in the tripod gait while 6 s in the tetrapod gait.

In the analysis of the performance of flexible flipper leg underwater, the mean thrust force and propulsive efficiency are two key important factors to evaluate the locomotion performance. Similar to analyzing the performance of flapping fish tail[31], equations to calculate the efficiency η underwater can be expressed as:

$$P=\boldsymbol{F}_0\bullet\boldsymbol{V}_f, \tag{11}$$

$$E=\int_0^T\int_\Omega \boldsymbol{F}_s\cdot\boldsymbol{V}_s\mathrm{d}l\mathrm{d}t, \tag{12}$$

$$\eta=\frac{P}{E}\times 100\%. \tag{13}$$

where P denotes the effective output power, E denotes the input power of flapping leg, $\boldsymbol{F_0}$ denotes the average reaction in opposite y-direction, $\boldsymbol{V_f}$ denotes the water flow velocity, $\boldsymbol{F_s}$ denotes the reaction force of every point on the surface of the leg, $\boldsymbol{V_s}$ denotes the velocity of every point on the surface of the leg.

3 Results

With the above methods, we have explored the locomotion performance of the robot with flexible flipper legs during locomotion on rough terrains and propelling underwater.

3.1 Verification experiments on rough terrains

Besides the simulation analyses of the locomotion performance of robot with flexible flipper legs, an experimental study was conducted to verify the simulation model on rough terrains. We chose the ground and slope as the experimental terrains. The experiment on ground is set as shown in Fig. 5a. The experimental method on slope is the same as the method on ground.

To verify the accuracy of the model, we need to investigate whether the results of the experiment can match the results of the simulations. Comparing the velocity results of simulations and experiments is a direct way. Locomotion speed measured by a camera in the experiment is compared with that obtained from simulation. The factors that affect the locomotion velocity include the weight of robot, the friction coefficient, rotating speed of legs and the thickness of steel plate. In order to reach the same friction coefficient in the simulation, which is set as 0.5, we stick pieces of rubber to each segment of legs. As for the weight and rotating speed, we choose exactly the same as the 20 kg case. Besides, three kinds of thickness of the steel plate are selected, which is 0.2 mm, 0.4 mm, and 0.6 mm, respectively. For each case, we conduct the experiments three times at least to obtain the average locomotion velocity and the variance.

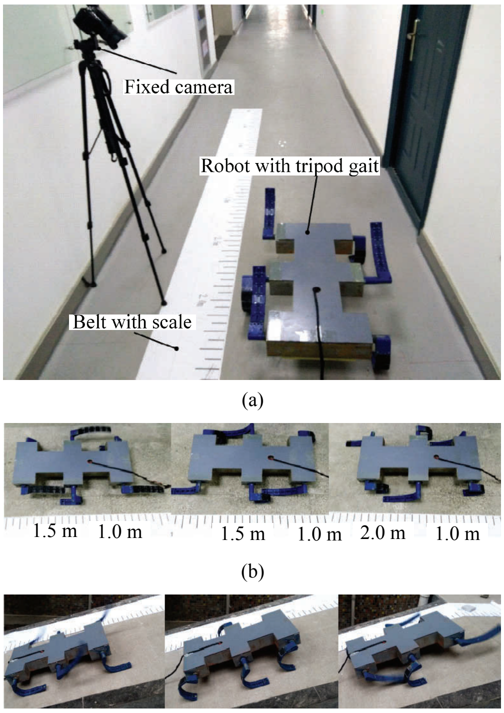


Fig. 5 Verification experiments on rough terrains. (a) Verification experiment setting-up; (b) walking on flat ground; (c) walking on a slope with 30°.

Through series of experiments, we have obtained the locomotion velocity as shown in Fig. 6. According to the results, the locomotion velocity in verification experiments and simulations exhibit similar trends and close results during locomotion on ground and slope, which verify the simulation model of the robot on the terrains. Thus, we can use the model to investigate other cases and obtain more locomotion results on other terrains. Besides, we have observed following phenomenon during the process of verification experiments: (1) increase of the thickness of steel plate cannot improve the locomotion velocity obviously; (2) thickness of the steel plate shows greater impact on the stability of locomotion, since the increase of the thickness makes it harder for flexible flipper leg to transform into curved leg during the locomotion. The error bar of the results also increases with the increasing of thickness, which meets the phenomenon of experiment; (3) when the steel plate is too thick, the robot would even bounce off the ground during the locomotion.

3.2 Verification experiments underwater

The verification experiments of underwater locomotion were also carried out. Since there exist difficulties to measure the thrust force underwater directly, we measured the cruising speed underwater as an alternate

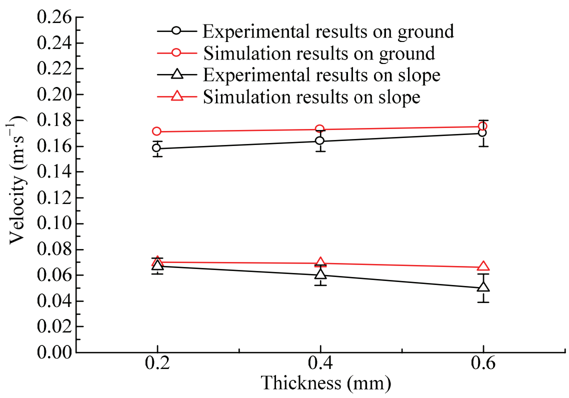


Fig. 6 Results of the verification experiments. The simulation results are from the 20 kg case.

selection, which can reflect the change of the thrust force underwater.

The factors that affect the cruising speed include oscillating amplitude, oscillating frequency, and the thickness of steel plate. In the verification experiments, oscillating amplitude was set as 30°, and the oscillating frequency was set as 1 Hz and 1.5 Hz, respectively. Besides, the thickness of the steel plate are selected as same as that in verification experiment on terrains, that is 0.2 mm, 0.4 mm, and 0.6 mm, respectively. For each case, we conduct the experiments three times at least to obtain the average cruising speed and the variance. Fig. 7 displays the cruising process underwater of the robot with various stiffness flipper legs.

Fig. 8 shows the result of verification experiments and corresponding simulation underwater. The comparative results indicate that the cruising speed in verification experiments exhibits a similar trend to the thrust force in simulation. Higher stiffness of the flipper legs exerts an essential contribution to the cruising speeds and the larger thrust force. For 1.5 Hz oscillating case, the difference between the case of thickness 0.4 mm and the case of thickness 0.6 mm is not as obvious as these two cases in simulation. This phenomenon can be explained from Fig. 7, flipper legs with 0.6 mm thickness steel plate almost did not deform, and parts of the straight flippers oscillated out of water during the cruising process, which causes a loss of propulsion force. The similar trends of the cruising speed in experiments and the thrust force in simulation verify the simulation model underwater.

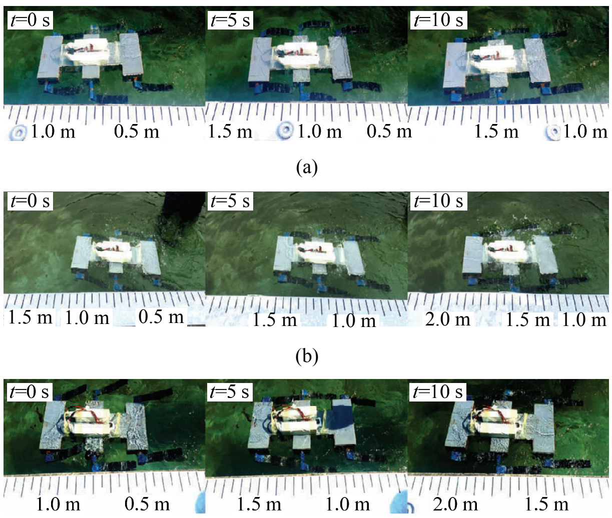


Fig. 7 Verification experiments underwater with oscillating amplitude 30° and oscillating frequency 1.5 Hz: (a) locomotion process with the flexible flipper legs of the thickness 0.2 mm; (b) locomotion process with the flexible flipper legs of the thickness 0.4 mm; (c) locomotion process with the flexible flipper legs of the thickness 0.6 mm.

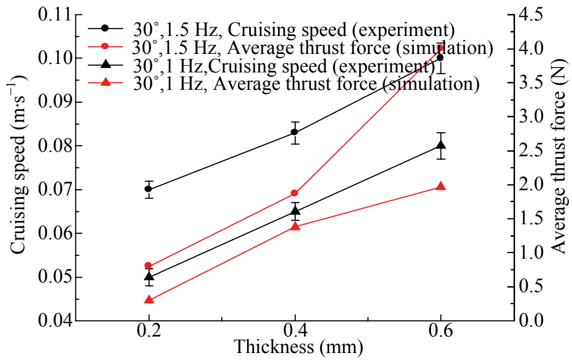


Fig. 8 Comparison between verification experimental results (black) and the simulation results (red).

3.3 Locomotion performance on rough terrains

After the verification of locomotion model on various terrains, we conducted numerous experiments on the locomotion performance of the amphibious robot on flat ground, slope, and stairs.

3.3.1 Locomotion performance on flat ground

Locomotion performance of the amphibious robot on flat ground is displayed in Fig. 9. Basically, the dynamics of the locomotion velocity with various loads grow gradually as the thickness of steel plate grows, as shown in Fig. 9a. Besides, as the weight of robot grows, the velocity decreases. When the weight is below 30 kg, the locomotion velocities are really close. However, when the weight is above 30 kg, the velocity drops more dramatically. At the 15 kg and 20 kg cases, the robot shows the trend to bounce off the ground and the locomotion is not as stable as at other cases when the thickness is 0.7 mm, which leads to a little decrease in the velocity. Fig. 9b displays the locomotion efficiency of the robot during locomotion on flat terrains. From the figures, we can obtain that larger peaks can be seen as the load of robot increases. With a larger load, the peak value of the efficiency reaches almost twice than that of small loads. Fig. 9b also shows that the peaks of the efficiency appear when the thickness is 0.2 mm, simultaneously. In the simulation, we also found that the legs shake heavily during the locomotion when the thickness is above 0.5 mm, which is not efficient for terrain locomotion. The simulation results indicate that thickness of the steel plate cannot improve the locomotion velocity obviously, but it does have a greater influence on the locomotion efficiency. Besides, the load has a large impact on locomotion performance. So, an appropriate thickness of steel plate and an appropriate load of robot will be very important in robot locomotion on flat land.

3.3.2 Locomotion performance on slope

Locomotion velocity and locomotion efficiency of the amphibious robot on flat ground is displayed in Figs. 10a and 10b, respectively. At 15 kg and 20 kg cases, the robot would bounce off the slope when the thickness is 0.7 mm. Generally, the velocity decreases gradually as the weight and the thickness grow. Similar to the result of locomotion on flat ground, the velocity is really close when the load is below 30 kg and the velocity drops more obviously when the load is above 30 kg. As for the locomotion efficiency, it generally decreases as the thickness increases, except for a peak at the 0.2 mm thickness, which is similar to that of flat ground. Besides, the values of the velocity and efficiency are much smaller than the values on flat ground. There are two

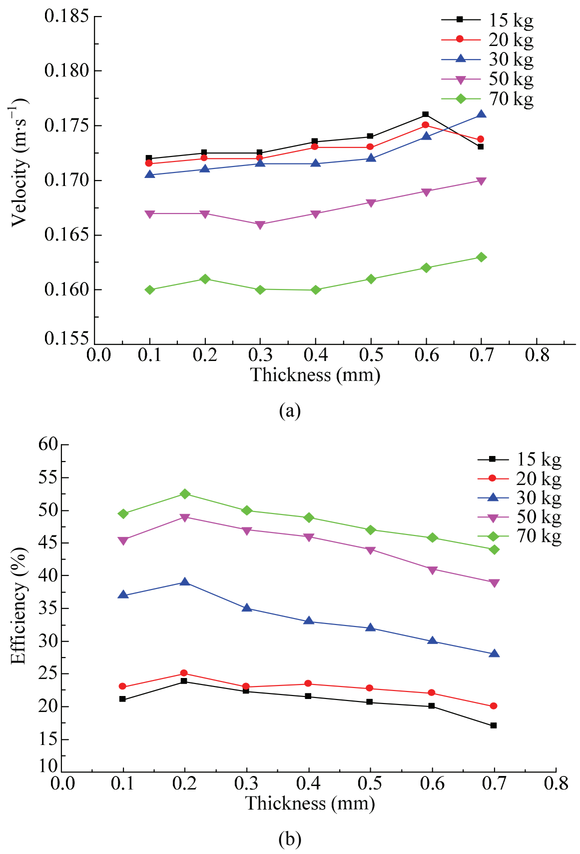


Fig. 9 Locomotion performance on flat land. (a) Locomotion velocity, v; (b) locomotion efficiency, η.

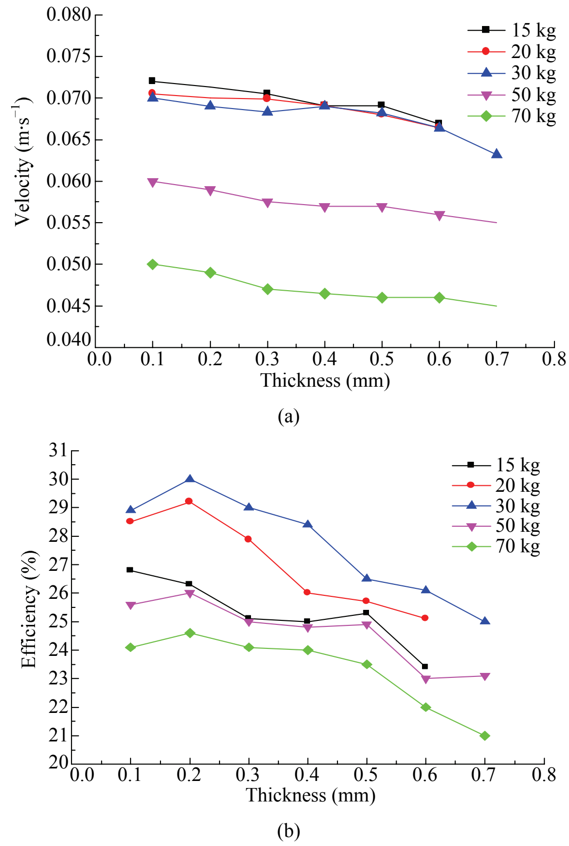


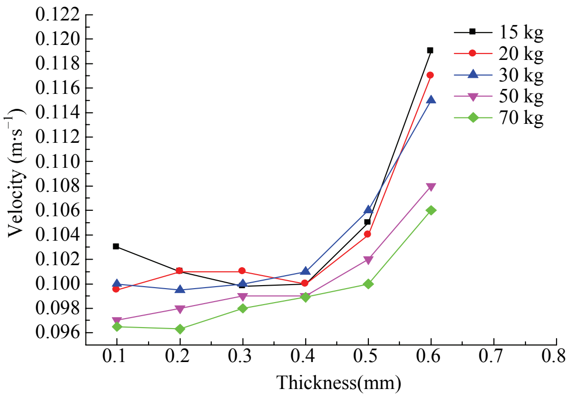
Fig. 10 Locomotion performance on climbing the slope. (a) Locomotion velocity, v; (b) locomotion efficiency, η.

reasons to explain the result: (1) the majority of the output energy transformed into the gravity potential energy; (2) the gradient of slope has a negative effect on locomotion performance.

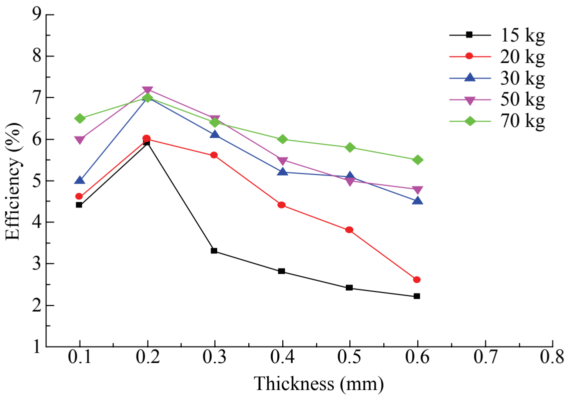
3.3.3 Locomotion performance on stairs

Locomotion performance of the amphibious robot on stairs is displayed in Fig. 11. In the simulation, the robot would bounce off the stairs when the thickness of the plate is above 0.6 mm since the gradient of stairs is larger than other terrains. So the thickness of the plate from 0.1 mm to 0.6 mm is chosen to be analyzed.

From Fig. 11a we can obtain that the velocity of each load is almost the same, but the trend is very clear: the velocity increases as the thickness increases clearly due to the elastic potential energy of steel plate, which is different from the locomotion on flat ground and slope. Fig. 11b indicates a higher efficiency can be seen under a larger load, since the model can be more stable in climbing the stairs. Moreover, there is also a peak when the thickness of the plate is 0.2 mm. The velocity and efficiency in this case are the smallest in three kinds of terrains.



(a)



(b)

Fig. 11 Locomotion performance on climbing stairs. (a) Locomotion velocity, v; (b) locomotion efficiency, η.

During the simulations on different terrains, we found that locomotion with smaller thickness is much more stable. Combined with the results discussed above, we can conclude that flexible flipper legs with a smaller strength leads to better comprehensive locomotion performance on rough terrains.

3.4 Locomotion performance underwater

The simulation of propelling underwater of one flexible flipper leg is shown in Fig. 12. The pressure contours of the fluid field and the strain of the flipper leg in one period are also clearly displayed in the figure. Red parts represent the high pressure centers, and blue parts represent the low pressure centers. During the oscillation period, the flexible leg generates waves around the tail to propel the robot.

Through series of numerical experiments conducted to investigate the effect of thickness, oscillating frequency, and oscillating amplitude on the locomotion performance underwater, we have acquired thrust force and propel efficiency with various parameters to analyze.

Fig. 13a shows the dynamics of mean thrust force underwater with various oscillating frequencies and amplitudes. From the figure, it can be seen that the thrust force increases as the thickness of the plate increases. When the thickness of the plate is too small, the flipper leg can nearly generate no thrust force at any frequency and amplitude. The peaks of the curves almost appear at the 0.6 mm thickness, then the thrust force keeps nearly the same, which indicates that 0.6 mm is almost the limit of thickness to generate a larger thrust force. At the same

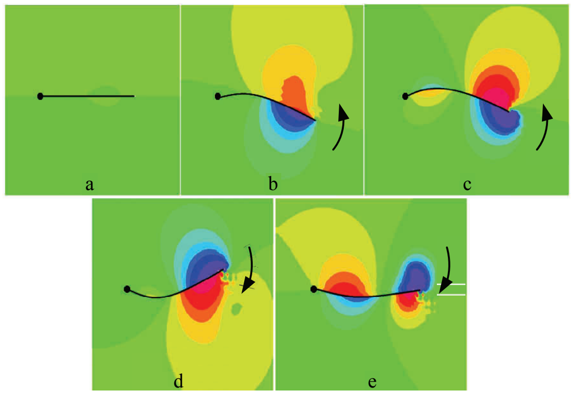
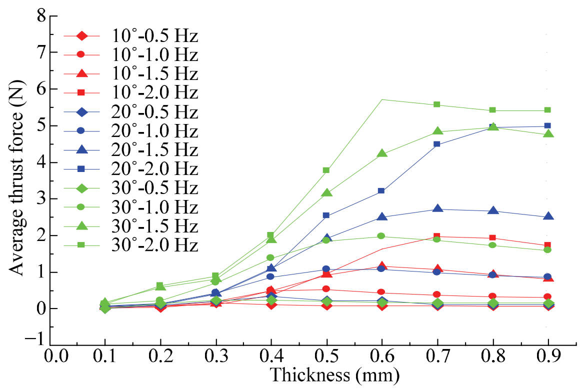
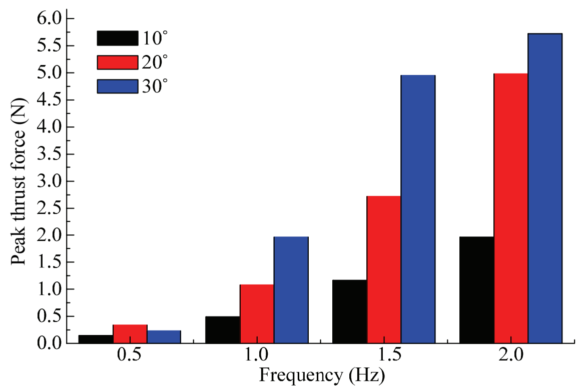


Fig. 12 Pressure contours of the fluid field in one period.



(a)



(b)

Fig. 13 (a) Average thrust force during an entire rotating period; (b) peak values of the thrust force in different oscillating frequency and amplitude. All the results are from 0.7 mm cases.

thickness and oscillating frequency, the thrust force increases as expected with the increasing of oscillating amplitude. Besides, at the same thickness and oscillating amplitude, the thrust force also increases with the increasing of oscillating frequency. The peaks of the curves are shown in Fig. 13b. Similarly, larger oscillating frequency and oscillating amplitude lead to larger peak thrust force. At the 20˚ amplitude case, oscillating frequency shows greatest impact on generating larger thrust force. The results also indicates that frequency has a larger influence on generating thrust force in larger oscillating amplitudes, which is also coincident with the result conducted by Jin *et al.*[32]. Meanwhile, larger oscillating frequency and amplitude require the motor provide large torque to propel the flexible flipper legs, which need be considered in the development of the amphibious robot.

Fig. 14a shows the dynamics of locomotion efficiency underwater with various oscillating frequencies and amplitudes. Considering the effect of the thickness, the result shows that there also exists an optimal thickness of the plate for the locomotion efficiency of the flexible flipper leg underwater. Similar to the results

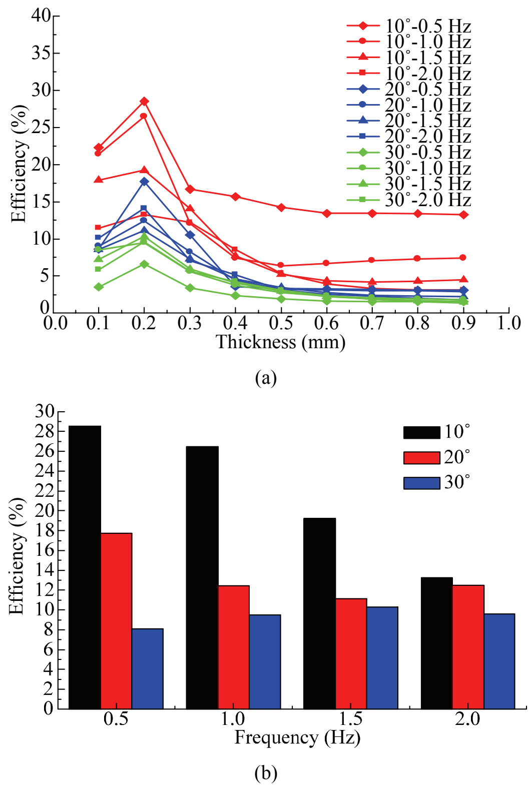


Fig. 14 (a) Thrust efficiency during an entire rotating period; (b) peak values of the efficiency in different oscillating frequency and amplitude. All the results are from 0.2 mm cases.

on rough terrains, the peaks of efficiency appear at the 0.2 mm thickness, which indicates that flexible flipper legs with 0.2 mm thickness steel plate lead to a more efficient locomotion both on rough terrains and underwater. When the thickness is above 0.6 mm, the efficiency of locomotion keeps nearly the same. When the oscillating amplitude is 10˚, we can see that the efficiency decreases with the increasing of oscillating frequency in the vertical direction. While in the 20˚ and 30˚ amplitude case, the efficiency values are close mostly. For the flexible flipper legs, this phenomenon indicates the increasing of oscillating frequency will have a small impact on the locomotion efficiency when the oscillating amplitude is larger. Fig. 14b shows the peak value of locomotion efficiency underwater with various oscillating frequencies and amplitudes. From the figure, it can be concluded that the increase of frequency has a negative impact on the peak values of efficiency. All the results indicate that larger frequency and amplitude are not efficient for locomotion performance underwater.

4 Discussions

Since the robot with the flexible flipper legs of thickness 0.2 mm possesses the highest efficiency in locomotion both on rough terrains and underwater environments. Further explanation about this phenomenon is presented here. From the locomotion efficiency on terrains defined in Eq. (10), f and ω are invariants during the locomotion process, V and T decide the value of efficiency. Fig. 15 shows the output torque of one motor during locomotion on flat ground (the trend of the results of the other two cases are similar). As shown in Fig. 15, the output torque grows as the thickness increases. Comparing the changes of V and T, we can find that the increase of T is much more obvious than the increase of V as the thickness increases, which leads to the decrease of the locomotion efficiency when the thickness is above 0.2 mm. As for the 0.1 mm case, flexible flipper leg cannot provide enough support force before the leg transformed into curved leg state, and leads to an impact between the robot and the ground, which causes a loss on the efficiency.

As for the locomotion performance underwater, flexible flipper legs of large stiffness cannot store and release the elastic potential energy efficiently during propelling process to increase the propulsive efficiency, while legs with small stiffness cannot provide an enough

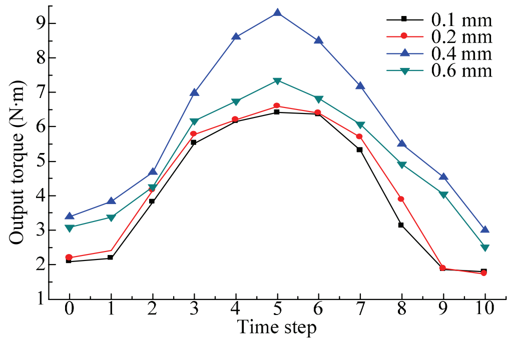


Fig. 15 Output torque of the motor during the process that the flexible flipper legs supporting and propelling on flat ground. Results with four kinds of stiffness of the flexible flipper leg are illustrated (30 kg case).

thrust force. From the result in Fig. 14a, the appropriate thickness of the steel plate is 0.2 mm, which is consistent with the result of the optimal stiffness of the flexible flipper leg with higher locomotion efficiency on rough terrains. This phenomenon can inspire and guide the design the structure of the legs.

5 Conclusions and future work

In this paper, we have investigated the locomotion performance of the amphibious robot propelling by flexible flipper legs both on various terrains and underwater. The general description of the structure flexible flipper leg, the setting-up of simulation experiment, and the setting-up of verification experiments are presented. All the results have been discussed and analyzed comprehensively. The verification experiments have been conducted to investigate the accuracy of the model on rough terrains. Series of simulation experiments and preliminary theoretical analysis have been carried out to investigate the effects of kinematic parameters on the locomotion performance both on rough terrains and underwater. Some conclusions can be derived from the study: (1) a flexible flipper leg could propel the robot on various rough terrains stably and propel underwater efficiently with the same stiffness; (2) the stiffness of the flipper leg has a small influence on the locomotion velocity, but has a larger impact on the locomotion efficiency and stability; (3) the flexibility has great impact on the locomotion performance: flexible flipper legs with smaller strength leads to better comprehensive locomotion performance on rough terrains and underwater; (4) larger frequency and amplitude are not efficient for locomotion performance underwater. The results facilitate the design of the amphibious robot and indicate that the flexible flipper-leg mechanisms also enable amphibious robot to conquer various complex terrestrial environments such as flat ground, slopes, stairs, and water.

Future work will mainly focus on the following aspects: (1) the locomotion performance of the flipper legs composite propulsion mechanism working in more complex environments should be considered comprehensively; (2) the coordination of the flipper legs propelling underwater should be further considered; a complete robot model is need to investigate the locomotion performance underwater; (3) since the shape of curved leg has impact on the locomotion performance, experiments and analysis should be conducted to investigate the locomotion performance of flexible flipper legs with various shapes.

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