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Bionic asymmetry: from amiiform fish to undulating robotic fins

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Similar to bionic non-smooth which has been successfully applied in anti-resistance and anti-adhesion, bionic asymmetry is also an inherent property of biological systems and is worth exploring for conceivable pragmatic applications. Therefore, bionic asymmetry for undulations is of main interest in this paper. We initially investigate bionic asymmetry with a case study of the undulating robotic fin, *RoboGnilos*, which evolved from the long dorsal fin of *Gymnarchus niloticus* in the amiiform mode. Since the performance of the pre-existing undulating fins is hardly satisfactory, we obtain bionic inspirations of undulatory asymmetry through observations and measurements on the specimen of *G. niloticus*, to improve upon the performance. Consequently, the newly acquired innovation for bionic asymmetry is incorporated into the previously derived kinematics model, and also applied to the experimental prototype. Both computational and experimental results verify that bionic asymmetric undulation generates better propulsion performance (in terms of linear velocity and efficiency) than the traditional symmetric modes with the same undulatory parameters.

bionic asymmetry, undulating fins, *RoboGnilos*, undulatory propulsion, biomimetic inspirations

Bionics (or biomimetics) has been developing into a new discipline since the 1950s, and it studies living organisms to derive from them new principles, theories and technologies, and then applies them to man-made devices, to emulate the animal's function and performance[1]. Nevertheless, there are many biological systems worth learning from, so that people are puzzled to determine which should be chosen as the paradigm for special man-made systems. On the other hand, there are advantages as well as disadvantages in one creature to make us bewildered by what to accept or reject. Under such circumstances, scientists and engineers in bionic engineering focus on discovering more basic, inherent, and generally applicable inspirations from nature, on top of the pre-existing specific innovations taken from biology. As a result, biologists and bio-engineers find that asymmetry in structure and non-smooth in surface are both inherent properties of natural biological systems. Asymmetry[2] widely exists in biological systems and social systems, such as fiddler crabs that have one big claw and one small claw, flatfish whose two eyes are on the same side, and airfoils with unequal chords in the upper and lower profile. What's more important is that asymmetry plays a significant role for specific tasks. For instance, it is asymmetry of airfoils that causes dissimilar pressure distribution on the upper and lower profile to generate necessary lift for flight.

In the past decades, Ren and his colleagues[3,4] proposed and developed bionic non-smooth theory and methods. Inspiringly, these methods have been successfully utilized into anti-resistance and anti-adhesion of human designed products and systems. With the same objective, this paper originally proposes bionic asymmetry from the viewpoint of bionic engineering, and

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carries out a case study on the undulating robotic fin, *RoboGnilos*, which mimics undulatory propulsion from the long dorsal fin of *Gymnarchus niloticus* in the amiiform mode[5]. *RoboGnilos* can surely generate thrust for propulsion and moments for turning, but now its performance is hardly satisfactory, including propulsion velocity, efficiency, maneuvering, stability and quietness. The other existing undulating fins[6–8] are in the same box. Therefore, we attempt to adopt bionic asymmetry to improve propulsion velocity and efficiency of *RoboGnilos*, as will be presented in this paper.

1 Methods and procedures

This paper continues to follow the same trend as that of the design and implementation of *RoboGnilos*[5], to improve propulsion velocity and efficiency of the undulating fin, and thus the workflow consists of biological inspirations, kinematics modeling, mechanism design and experiments.

1.1 *RoboGnilos*

As shown in Figure 1, this study on bionic asymmetry was based on the previous achievements and test-beds[5,9,10,13] rather than starting it all over again. In addition, a new inspiration of undulatory asymmetric waveforms is extracted and fused into the undulating fin--*RoboGnilos*. In this case, we would make corresponding rectifications to the previously established biological prototypes[5] as well as computational or experimental models according to the requisites of bionic asymmetry.

By virtue of biomimetics, the specimen of *G. niloticus* is observed to extract the inspiration of asymmetry with

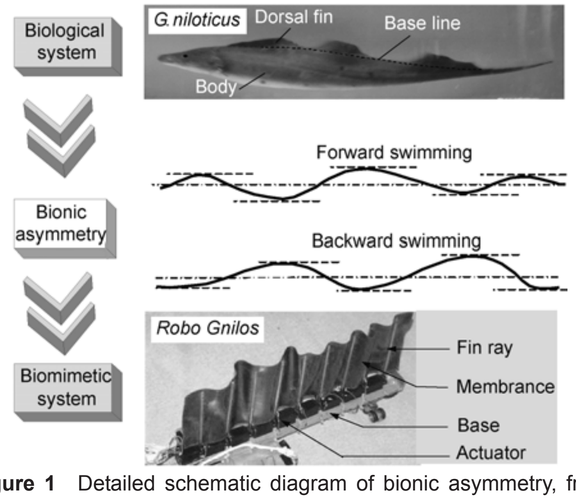

Figure 1 Detailed schematic diagram of bionic asymmetry, from top to bottom: the specimen of *G. niloticus*, inspiration of undulation asymmetry and the undulating fin-*RoboGnilos*[5].

the experimental setup[5,9,10]. The fish is confined within a space of fluid between the tank and mirror, so the lateral view and dorsal view can be synchronously recorded in the same image. The profiles of undulatory waveforms are achieved via image processing. The detailed procedure of morphological and locomotive observation on amiiform fish can be found in ref. [10]. In the present work, the previously proposed kinematics model[5,9] is extended to describe asymmetry in undulatory waveforms extracted from observation. The newly-extended ruled surface based model can represent both symmetric and asymmetric undulations via stimulating some kinematical parameters. Owing to the above extensive kinematics model, dynamic mesh method of computational fluid dynamics (CFD) is again applied into comparisons between asymmetric undulating motion and traditional symmetric undulations[9].

1.2 Experimental setup

The prototype experiments are carried out in *RoboGnilos*, respectively, with or without asymmetric rectification. As for the undulatory performance comparisons, *RoboGnilos* is upgraded to be compatible with the two modes-symmetry and asymmetry. The prototype undulating fin is tested in a water tank with the dimensions of 5.00 m long by 2.50 m wide by 1.25 m deep. The biomimetic fin is connected to an overhead guide track through a pair of fore-and-aft chain wheels, so it can either be towed at constant speed, or be propelled by its own undulations along the horizontal guide track (see Figure 2). Meanwhile, the data including displacements, the instantaneous voltage and current at every sampling point are recorded for further analysis.

In this study, experiments of undulatory propulsion were all carried out within still water environment. As for the circumfluence and vibration disturbance, the fish tank, the bracket frame and the raster ruler are fastened and retained during each trial.

1.3 Performance indices

In the present work, the undulatory performance will be focused on the linear velocity and the propulsive efficiency. Taking the time differentiations of the displacement s_i, we can obtain the velocity v_i and acceleration a_i, as follows:

$$v_i = \begin{cases} 0, & i=1, \\ \dfrac{s_i - s_{i-1}}{\Delta t}, & i=2,\cdots,N. \end{cases} \quad (1)$$

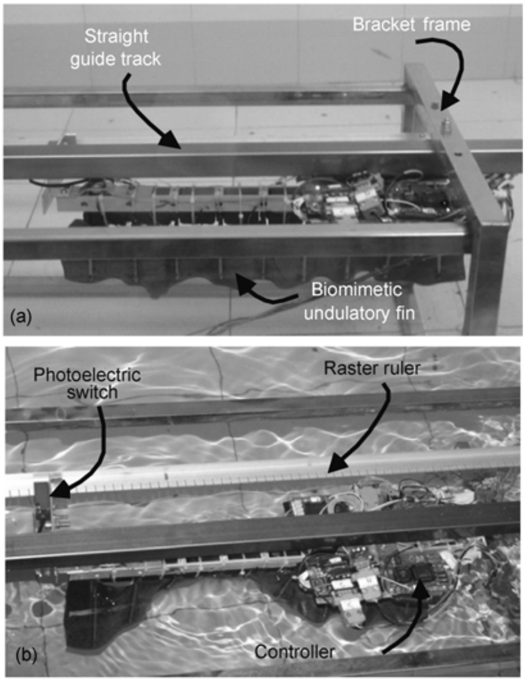

Figure 2 Experimental environment and measurement apparatus (a) The bracket frame, the guide track and the undulating fin; (b) the photoelectric switch and the raster rule for propulsion velocities.

$$a_i = \begin{cases} 0, & i = 1, \\ \dfrac{v_i - v_{i-1}}{\Delta t}, & i = 2, \cdots, N. \end{cases} \quad (2)$$

in which Δt is the sampling time interval and N is the number of sampling points.

Apart from the efficiency given by Lighthill[11], we define a measurable efficiency as the ratio of the mean available power ($\overline{P}_a$) against the mean consumed electrical power ($\overline{P}_c$). The undulatory propulsion implies the energy transfer from the biomimetic fin to the surrounding water, as well as the guide track. As the energy flow covers track friction, fluid drag, and acceleration forces, respectively, the available power ($\overline{P}_a$) is composed of $\overline{P}_f$, $\overline{P}_d$ and $\overline{P}_p$. Propulsion efficiency can then be defined as

$$\eta = \frac{\overline{P}_a}{\overline{P}_c} \times 100\% = \frac{\overline{P}_f + \overline{P}_d + \overline{P}_p}{\overline{P}_c} \times 100\%, \quad (3)$$

in which each mean power is defined by

$$\begin{aligned} \overline{P}_f &= \frac{1}{N}\sum_{i=1}^{N} f_r v_i, \\ \overline{P}_d &= \frac{1}{N}\sum_{i=1}^{N} C_d \tfrac{1}{2}\rho A_s v_i^3, \\ \overline{P}_p &= \frac{1}{N}\sum_{i=1}^{N} m a_i v_i, \\ \overline{P}_c &= \frac{1}{N}\sum_{i=1}^{N} U_i I_i, \end{aligned} \quad (4)$$

where U_i and I_i are respectively the voltage and current at the ith sampling interval, m represents the mass of the biomimetic fin, f_r is the friction caused by the guide track, C_d the fluid drag coefficient, and A_s the equivalent cross-section area during undulations. For this experiment, we have measured and estimated f_r = 1.00 N through the towing tests along the guide track. The other two parameters may refer to ref. [12]:

$$C_d = 1.68, \quad A_s = \theta_0 d^2. \quad (5)$$

2 Results and discussion

Undulations swimming sequences were imported into the computer by using a custom-designed digitizing program, which converted the image stream into digital files, and tagged them with extra information (such as index, imaging time). The tag information facilitated the subsequent work. The dorsal fin of *G. niloticus* is comparatively difficult to mark. However, images from the dorsal view provided enough contrast to allow the apices and lateral edge of the dorsal fin to be identified. By virtue of these features, the outline of the dorsal fin can be marked by using a script of Adobe Photoshop interactively. This outline was described as a series of cubic spline functions.

Bidirectional swimming is a distinguishing feature of amiiform fish, which can frequently reverse the direction of movement without turning by changing the direction of the traveling wave on the fin. Figure 3(a) shows the forward swimming image sequences and their related extracted top-view profiles. These profiles are an important parameter for the ruled surface kinematics model[5]. Correspondingly, the waveform profiles for backward swimming can also be achieved by using the same method, as shown in Figure 3(b). It is found that the amplitude profile along the dorsal fin of the propulsive wave and the phase relationships between the adjacent fin rays are not identical in forward and backward swimming. This is so-called undulatory asymmetry[5,9]. On one hand, undulatory asymmetry implies that forward undulation waveform is not identical to the backward waveform; on the other hand, bidirectional waveforms are different from the convectional sinusoid style

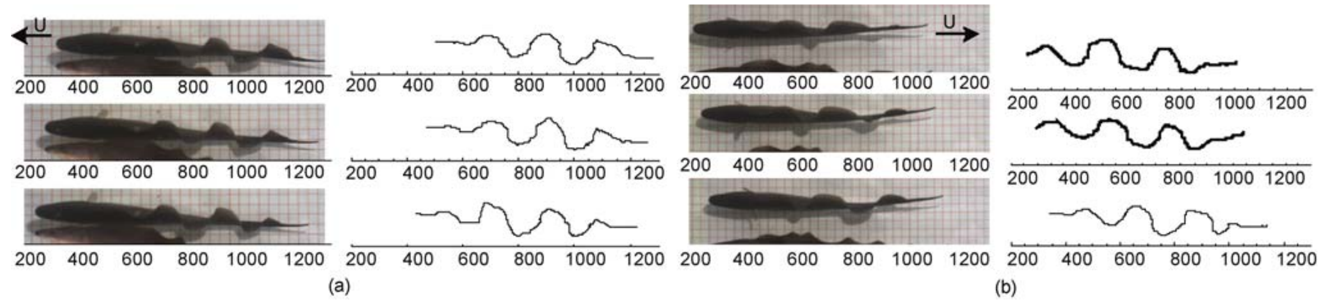

Figure 3 Image sequences and their top-view profiles of the undulatory dorsal fin during steady swimming. All the axes are labelled in pixels. (a) Forward swimming; (b) backward swimming.

which is a basic assumption for theoretical analysis and a design principle for the pre-existing undulating fin prototypes. In this paper, we propose undulatory asymmetry as a case study of *bionic asymmetry*. Since asymmetry between forward and backward swimming is achieved from biological observation, it will be useful to know whether the new inspiration is helpful or applicable in improving the propulsion velocity or efficiency of *RoboGnilos*.

In terms of the biomimetic workflow, it is necessary to find an appropriate model to describe undulatory asymmetry. It is found that the position of the peak between two adjacent troughs is closer to the back trough along the swimming direction. This suggests that the posterior peak-trough wave section provides the major propulsion, while the anterior section is just passively 'flagging'. Fortunately, the apparently conflicting wave profiles can be reconciled in one consistent pattern, if we introduce the parameter, φ, into the ruled surface based kinematics model[5], to represent the asymmetry in undulations, as follows:

$$\begin{bmatrix} p_x(r,s,t) \\ p_y(r,s,t) \\ p_z(r,s,t) \end{bmatrix} = \begin{bmatrix} s \\ 0 \\ 0 \end{bmatrix} + rd(s)\begin{bmatrix} \sin\left(\theta_0 \sin\left(\frac{2\pi}{\lambda}s + \frac{2\pi}{T}t + \phi\right)\right)\sin\varphi \\ \cos\left(\theta_0 \sin\left(\frac{2\pi}{\lambda}s + \frac{2\pi}{T}t + \phi\right)\right) \\ \sin\left(\theta_0 \sin\left(\frac{2\pi}{\lambda}s + \frac{2\pi}{T}t + \phi\right)\right)\cos\varphi \end{bmatrix}. \quad (6)$$

The description of all the parameters in eq. (6) can be found in ref. [5].

If β is defined as the inclined angle between fin rays and its base line, we have $\beta + \varphi = \pi/2$ as φ is the complementary angle of β[5,9]. Li[9] has carried out CFD analysis on undulatory asymmetry with the specified parameters: U=0.8L/s, T=0.3s, λ=0.3L, and θ_0=30°, and the asymmetry parameter φ is respectively set as φ=20° for asymmetric undulations and φ=0° for the convectional symmetric modes. The simulation time interval for CFD is 3T, while the thrust coefficient C_T with asymmetry is twice or more than that with symmetric waveform in the steady period, as shown in Figure 4.

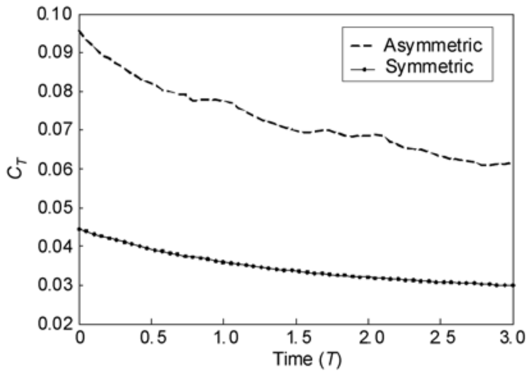

Figure 4 Coefficients of thrust with symmetric or asymmetric undulatory waveforms (adapted from ref. [9]).

The undulation kinematics model reveals that propulsive waveforms are related with the inclined angle of fin rays, that is, it can generate a symmetric propulsive wave with β = 90° and an asymmetric mode with β<90°. Thus, the fin-ray inclined angle, β, should be regulable in the undulating fin. Given that the fin-ray inclined angle can hardly be regulated automatically in the pre-existing prototype, several sets of fin rays with different inclined angles are provided for experiments. As shown in Figure 5, both symmetric and asymmetric waveforms are kept in the same mechanical structure, whereas the assembling process is a little different by only replacing upright fin rays with inclined fin rays. The modular mode enables us to easily shift one specified angle to another.

As for the present mechanism, the space between fin rays is limited by the geometrical dimension of the single joint driven mechanism. Two sets of fin rays are designed and used in this experiment for bionic asymmetry

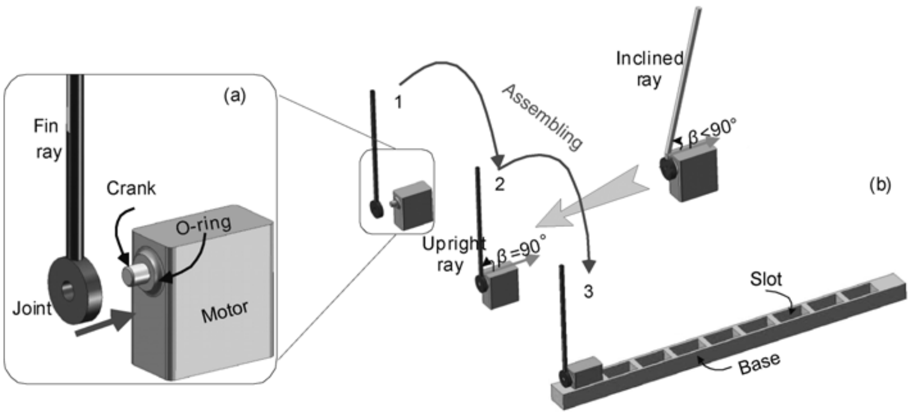

Figure 5 Assembling process of the biomimetic undulating fin. (a) Detailed connection of the fin ray to the motor; (b) three-step assembling procedure.

of the undulating fin, and their inclined angles are respectively β = 70° and β = 90°. Again, the asymmetry parameters are φ = 20° and φ = 0°. The experimental environment and evaluation indices are kept identical for comparisons on asymmetric and symmetric undulations. Several sets of undulation parameters are tested in bionic asymmetry experiments, and can be itemized as $\lambda = L$, $f \in$ {1.5, 2.0, 2.5} Hz, $\theta_0 \in${10°, 15°, 18°, 20°, 23°, 25°, 28°, 30°}. The mean velocity and mean efficiency in each trial of undulatory propulsion are obtained and compared.

Figure 6 compares the propulsion velocity against undulatory amplitude with three frequencies f = 1.5, 2.0, 2.5 Hz, respectively in the two modes-asymmetric and symmetric. It is noted that the propulsive velocity increases linearly with incremental amplitudes given the same frequency and wavelength. Certainly, a reverse turning-point appears when the amplitude is greater than 25°. It might be caused by the time-delay property of the servo-motor-driven fin rays. As for the fixed amplitude, the velocity is increased against the undulatory frequency, and the maximum velocity is nearly 1 L/s. All these phenomena are in accordance with those in ref. [13], with which the effectiveness of the experimental results was also confirmed.

It is obvious that the asymmetric undulation produces faster velocity than that of the symmetric mode, in spite of variations of the undulatory amplitude and frequency within the experimental scope. When the undulatory amplitude is lower than 25°, the undulating fin rays work in the linear section, and the velocity with asymmetric undulations retains twice or more than the corresponding velocity with the symmetric modes. Typically, the above-mentioned velocity enhancement attaches to

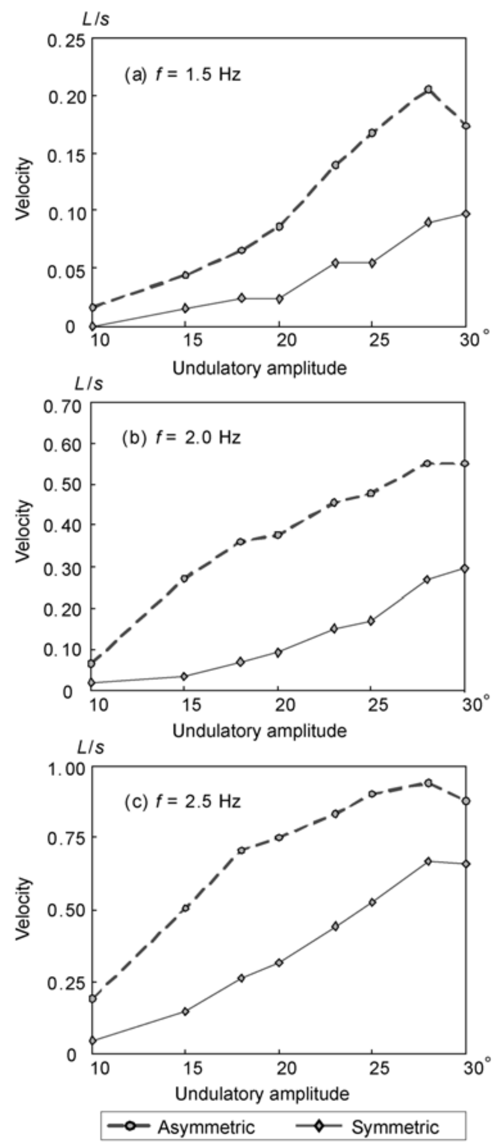

Figure 6 Mean undulation velocity against undulatory amplitudes with three frequencies f = 1.5, 2.0, 2.5 Hz. The circle 'o' represents the asymmetry mode and the diamond '◊' corresponds to the symmetry mode.

four times or more with f = 2.0 Hz and $\theta_0 \in$ {18°, 20°, 23°, 25°} in Figure 6(b).

Similarly, Figure 7 shows the propulsion efficiency against undulatory amplitude with three frequencies f = 1.5, 2.0, 2.5 Hz, respectively in the two modes – asymmetric and symmetric. As the consumed power from the electricity input to the robotic fin's locomotion is taken into account, propulsion efficiency in this study is apparently lower than theoretical results which are greater than 80% in ref. [11]. In some cases, the propulsion efficiency is below 1%.

As shown in Figure 7, the propulsion efficiency increases linearly with incremental amplitudes given the same frequency and wavelength. Certainly, there exists a turning point at θ_0 = 25° or θ_0 = 28°. This character is similar to the velocity in Figure 6 and might also be caused by the time-delay property of the servo-motor-driven fin rays. It is obvious that the asymmetric undulation produces remarkably higher efficiency than that of the symmetric mode with the same undulatory parameters. When the undulatory amplitude is lower than 25°, that is, the undulating fin rays work in the linear section, the efficiency with asymmetric undulations retains twice or more than the corresponding efficiency with the symmetric modes. Typically, the above-mentioned efficiency enhancement attaches to five times with f = 2.0 Hz and $\theta_0 \in$ {23°, 25°, 28°} in Figure 7(b).

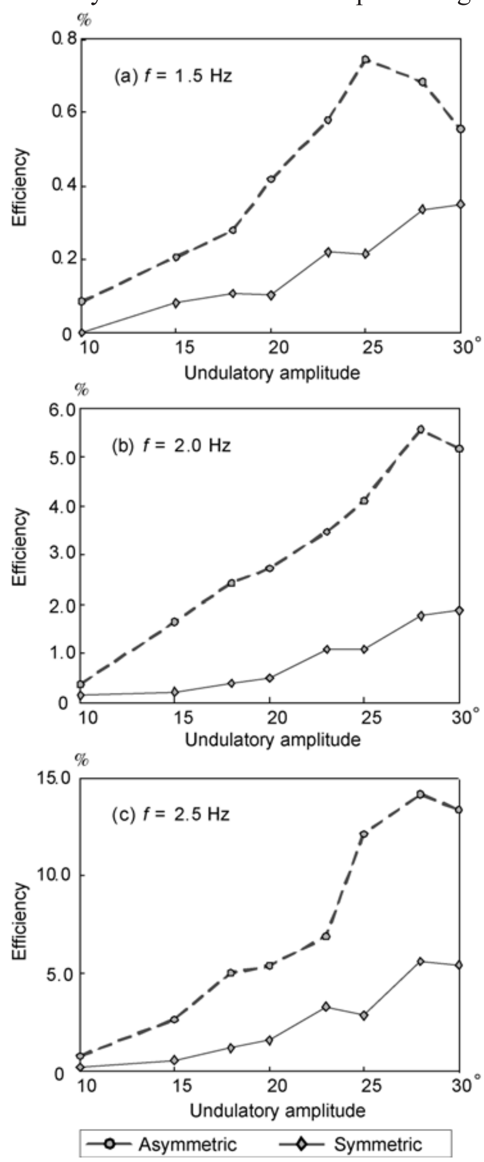

Figure 7 Mean propulsion efficiency against undulatory amplitudes with three frequencies f = 1.5, 2.0, 2.5 Hz. The circle 'o' represents the asymmetry mode and the diamond '◊' corresponds to the symmetry mode.

On the whole, the experimental results verify that bionic asymmetry has a remarkable effect on enhancing linear velocity and propulsion efficiency for the undulating fin, *RoboGnilos*. Therefore, undulatory asymmetry inspired by amiiform fish plays an important role in enhancing the performance of pre-existing biomimetic undulating fins. It is the inherent purpose of biomimetics to learn inspirations from nature and meaningfully act on engineering. As for pragmatic applications, another biomimetic joint is expected to automatically adjust the inclined angle of fin rays during propulsion. For instance, as bidirectional swimming is one of the characteristics of undulatory propulsion, the inclined angle should be adjusted from positive to negative, when forward swimming is switched into backward motion (or vice versa).

3 Concluding remarks

In this paper, asymmetric undulations are proposed, analyzed and applied into the mechanical fin, *RoboGnilos*, by virtue of biomimetics. Biomimetics would not only inspire engineers to design new-type robots, but also teach us how to improve the performance of the pre-existing robots by using instructive revelation. The proposed study focuses on finding new inspirations from familiar fish, to investigate and apply its potential in improving linear propulsion velocity and efficiency of *RoboGnilos*. In terms of biomimetics workflow, the undulatory asymmetry is found and proposed in the natural amiiform fish's propulsive waveforms. Some valuable adjustment is then made into the previously proposed kinematics model for its compatible description on undulatory asymmetry. Correspondingly, the computational and experimental models should be adjusted for investigation on asymmetric undulations. Both computational and experimental results verify that bionic asymmetry can effectively improve both the linear velocity and the propulsion efficiency of the undulating fin-*RoboGnilos*.

The motivation of biomimetics is inspiration rather than imitation. Recently, Vincent and his colleagues[14] have suggested and initiated a "biological patents" database, named BIO-TRIZ, that integrates biologists' findings and achievements in bionic inspirations. This database will enable engineers to directly tap into nature's ingenuity by consultations with biologists. In fact, undulatory asymmetry is only a case study on bionic asymmetry, which is quite amazing and inspiring in both nature and engineering. We should make an in-depth research on discovering the mystery of bionic asymmetry with more cases. Furthermore, we should integrate this inherent natural property into BIO-TRIZ for its feasibility and generalization in practical applications.

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