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Structure Design and Analysis of Ray-like Amphibious Robot Propeller

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Abstract

Underwater vehicles play a vital role in the fields of resource exploration and safe cruising. In order to overcome the defects of traditional underwater vehicles such as noise pollution, poor concealment performance, low endurance, damage to marine life, and pollution of the marine environment, we propose the design of a stingray-like amphibious robot. In this paper, the multi-wave fin of the stingray is the bionic object, the principle of bionics is used, and the cam swing lever mechanism is used as the movement unit. The fins can swing approximately at a constant speed within a certain angle range, and multiple fins are combined to form a propeller. There is a certain phase difference between adjacent actuation units to form the propulsion waveform of the thruster. By optimizing the cam contour, it has excellent transmission characteristics and less impact. And the structural performance of the robot is verified by ADAMS software and Tracker software. Prototype movement experiment is also carried out to verify its rationality and reliability.

Keywords

Amphibious robot; structure design; cam swing lever mechanism; simulation analysis.

1. Introduction

With the development of the marine economy, the development of marine resources by mankind has been continuously enhanced. The research and design of various underwater vehicles are aimed at developing and exploring submarine resources and completing tasks. With the diversity tasks of resource detection, safety inspection and environment detection, robots that are only suitable for underwater are no longer sufficient for human needs. Humans need a kind that can crawl on land and swim in water. Therefore, amphibious robots have great research value.

At present, domestic and foreign underwater vehicles generally use traditional propellers, paddle wheels, straight blade propellers, water jets, etc. These commonly used propellers have the disadvantages of large noise, poor concealment, and poor endurance, especially for motion in the process, it will cause harm to marine life and plants, and cause greater pollution to the marine environment. Therefore, underwater bionic robots have attracted widespread attention. The pectoral fin structure of the manta-ray-like robot designed by Zhang Yixin [1] and others uses a mutually independent support structure. Based on the manta ray's trunk and pectoral fin structure, Zhang Shihao [2] adopted a similar fin design idea to design a propeller with two degree of freedom for each independent mechanism. Low and Zhou Chunlin [3] adopted a configuration structure with six flexible fins, three on the left and three on the right, in which the middle fin was the longest, and the two side fins gradually became shorter to simulate the side fins of real manta rays. Wu Jiannan [4] used ten sets of fins and five sets of flapping wings on both sides. The semi-active manta ray robot was also designed with the longest middle fin and gradually shorter side fins. Malcolm A. MacIver [5] designed an underwater vehicle with long anal fin propulsion by imitating the shape and swimming pattern of the devil saury. Shen Lincheng [6] adopted a modular design idea, adopting a modular independent motor drive scheme as a whole, and each motor independently drives the corresponding fin. Chen Jian [7] simplified the structure of the undulating fin and adopted a crank-rocker mechanism with no quick return characteristic as the oscillating fin unit. K.H.Low [8] uses a combination of crank and slider to form a wave fin structure. Zhang Yonghua [9] took advantage of the shape memory effect of shape memory alloy (SMA) to design a bionic fish fin. Sun Tan [10] designed a stingray-like robot that uses a swinging guide rod mechanism as the actuation mechanism of the propeller.

The propeller designed by the above research institute has made a certain breakthrough, but the propulsion effect is not stable. This article takes the stingray's multi-wave fin as the research object, and designs the stingray-like robot propeller. The propeller uses the structure and movement mode of the stingrays, uses (MPF) as the propulsion mode [11]. And it is based on the swing cam mechanism to realize the sinusoidal swing law of multi-wave fins.

2. Multi-motion fin propulsion mechanism and structure design

2.1. Analysis of the propulsion mechanism of multi-motion fins

Multi-wave fin fish rely on the fin waves to produce the main propulsion. Take the stingray as an example, its fish body remains straight during swimming, and the propulsion mainly depends on the interaction between its wavy long fins and water. During the wave of the long fin, its waveform propagates at one direction in the water, and the reaction force of the water on the long fin pushes the fish to the opposite direction, that is, the propagation direction of the propulsion wave is opposite to the swimming direction of the fish, as shown in Figure 1.

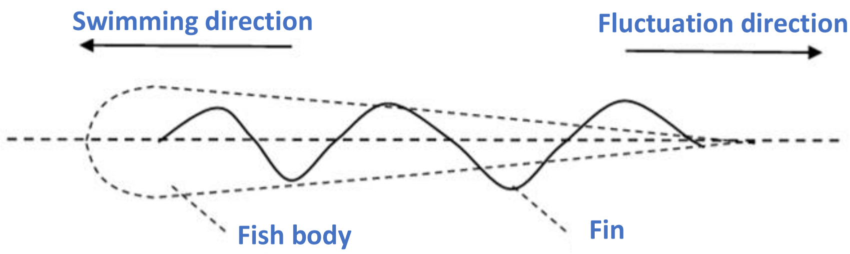

Figure 1: Schematic diagram of ray propulsion

The swimming speed of multi-wave fin fish in the water mainly depends on the swimming amplitude and speed of their undulating fins, while the swimming amplitude of undulating fins mainly depends on the swing amplitude of muscle fibers, and the swimming speed depends on The swing rate of muscle fibers. Wave-fin fishes generally move forward in the water, so the direction of their wave-fin advancement is single, which mainly depends on the physiological characteristics of the fish's forward swimming.

2.2. Multi-motion fin structure design

2.2.1 Structure selection

Due to the special propulsion mechanism of the stingray, the propeller needs to generate a sinusoidal waveform, which requires a single structure to achieve reciprocating swing. Common swing mechanisms are shown in Table 1. After comprehensive consideration, this article adopts the swing cam mechanism to design the propeller.

Table 1: Structural comparative analysis

name	feature
Swing guide rod mechanism	It has the characteristics of quick return. The greater the swing angle φ, the more obvious the characteristics of quick return. The return stroke approximately satisfies the uniform swing of the oscillating fin, but the angular velocity of the forward stroke changes significantly. There is a greater impact.
Crank rocker mechanism	There is a quick return characteristic, and the extreme position angle θ can indicate the degree of the quick return characteristic of the crank-rocker mechanism. Therefore, when the extreme angle θ is 0, the crank-rocker mechanism does not have the characteristic of quick return, and the reciprocating swing rate of the rocker is equal. But this structure has a greater impact.
Swing cam mechanism	Use the cam's unique cam profile to achieve the desired motion trajectory. It is widely used and can meet a wide range of complex and complex actuator motion trajectories. The disadvantage is that it is not suitable for high-speed working conditions, and the cam has an impact during operation. Effect, so it is only suitable for relatively low-speed scenes.

2.2.2 Structure design of swing cam mechanism

The contour design of the cam adopts the reversal method, that is, assuming that the cam does not move, the follower makes a reversal movement in the direction opposite to the actual rotation direction of the cam. According to the fin design criteria, the ideal fin design requirement is that the fin unit swing angular velocity is uniform and the acceleration is 0, so that the actuating mechanism composed of the fin unit has repeatability, which is simulated by the fin with constant swing angular velocity. The fin muscle fiber has better bionic effect and propulsion performance. In order to compare with the crank-rocker mechanism with no quick-return characteristics, we set the same conditional parameters to design the cam in the software of ADAMS and SOLIDWORKS, including the fin ray swing angle is 60°, the angular velocity is uniform and the angular acceleration is 0. The different methods required to design the cam according to the respective software, including parameter settings and importing angular velocity equations, etc., the cam design function of ADAMS and SOLIDWORKS is used. According to the design requirements, the cam contours designed in the two softwares are all heart-shaped lines, as shown in Figure 2.

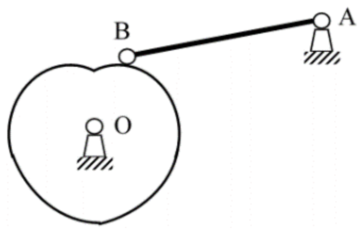

Figure 2: Heart-shaped profile of swing cam

2.2.3 Simulation and optimization of swing cam mechanism

The contact method between the cam and the roller adopts the groove track contact method. The groove cam is modeled by SOLIDWORKS, as shown in Figure 3. It can be seen from the

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figure that the groove cam of the heart-shaped line is not smooth, and there is a contoured peak at the swing angle, which will cause the cam to jam with the swing rod during the rotation or have a large impact at these two points, which is not conducive to motion transmission.

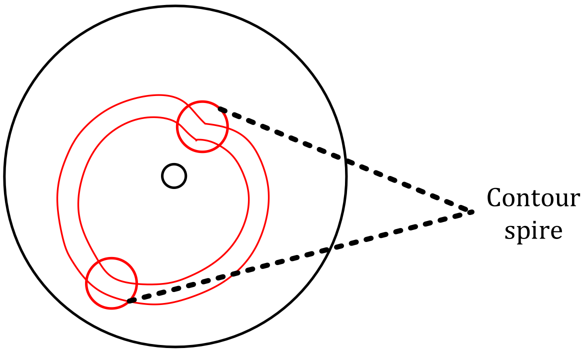

Figure 3: Heart-shaped slot-shaped cam profile

Aiming at the influence of the peak point, the two spires at the starting position and the maximum swing angle of the heart-shaped cam are transitioned by an arc through the arc transition method to make the contour line more sleek. As shown in the figure, the two points are both equal-diameter circles. The arc transition is used to transit the apex of the contour line, as shown in Figure 4.

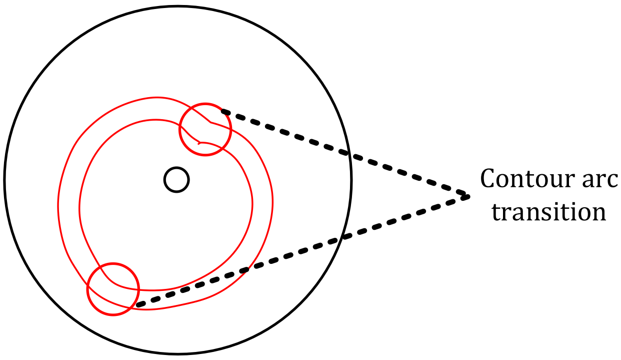

Figure 4: Improved heart-shaped slot cam

In order to observe and measure the effect of the improved swing cam mechanism, the cam and the swing rod were assembled, and the effect on the transmission performance of the swing rod was tested in the simulation software. The swing cam model, including the cam and the swing rod, were assembled. Import the assembly model of the cam and swing rod into ADAMS, add constraints, drive and contact forces, and set the friction factor and Coulomb force related parameters in the contact force to simulate the simulation results closer to the actual effect. Measure the angular displacement, angular velocity and angular acceleration of the pendulum rod in one cycle by ADAMS. The results show that the angular displacement A has changed from the original step mutation effect to the angular displacement rest, and the angular velocity B has a larger amplitude from the original fluctuation change and becomes a uniform angular velocity. The angular acceleration is constant at 0. Therefore, the improved cam profile reduces the impact effect and the angular velocity mutation effect, and its swing effect is closer to the design requirements.

3. Multi-motion fin structure configuration

3.1. Structure design of propeller unit

The multi-wave fin propeller uses multiple fin ray as the driving device to drive the flexible material to wave and generate propulsion. Therefore, each fin ray is a component unit of the propeller, and there are different initial phase differences between adjacent fin ray. But its mechanical structure is exactly the same. As shown in Figure 5, the propeller unit is a swing

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cam mechanism, in which the contact between the cam and the swing lever is a groove type, and the groove shape is an improved heart-shaped line. The cam rotates around the common center of rotation to drive the fin swing lever around the rotation center of the pendulum rod bearing makes a reciprocating swing motion.

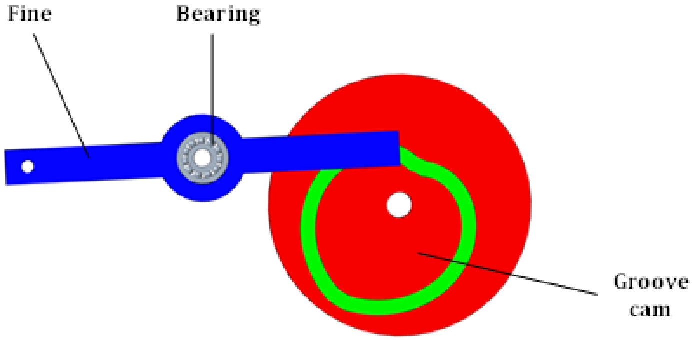


Figure 5: Structural unit of multi-wave fin thruster

3.2. The overall structure configuration of propeller

The overall structure of the propeller adopts a symmetrical configuration scheme, with a pair of side fins distributed on both sides of the robot body. The basic propulsion function can be realized by the swinging method of the fins on both sides. The symmetrical configuration method can ensure that the robot is advancing and has strong stability. The multi-wave fin propeller has a total of 8 swing cam mechanisms, and the initial phase difference between each mechanism is 90°. Four swing cams can realize a complete swing cycle, as shown in Figure 6.

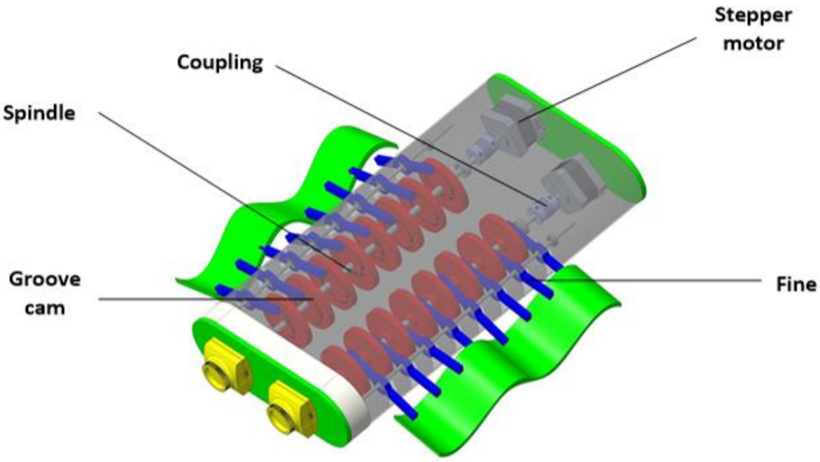


Figure 6: Symmetrical configuration structure

3.3. Multi-wave fin surface design and material selection

Since the fin base line is an approximately straight line, when the flexible web of the wave fin is similar to a sine wave, the outer side of the flexible web is a wave, and the internal baseline is an approximately straight line. So the shape of the flexible material that meets the requirements should be a pair of concentric circles. The fin surface material shape is shown in Figure 7.

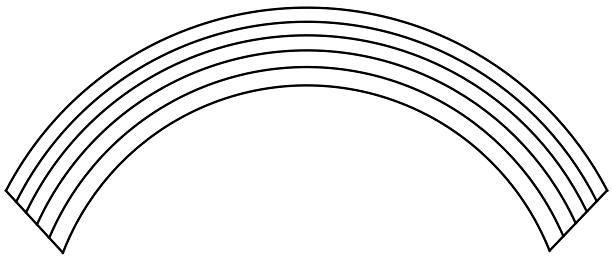


Figure 7: Fin surface material shape

Based on the design requirements of the flexible web with multiple wave fins, it should have good ductility and strong deformability to form a wave shape. The flexible materials commonly used in industry and daily life are shown in the following table 2. By comparing the relevant parameters of natural rubber and ordinary silica gel, we selected silica gel as the flexible web material with multi-wave fins.

Table 2: Performance comparison of natural rubber and silica gel

type	Tensile strength	Tearresistance	Abrasion resistance	Imper meability	Oxidation resistance	Compression set
natural rubber	Excellent	Excellent	Excellent	Excellent	good	medium
natural rubber	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent

4. Experimental analysis of multi-wave fin propeller

4.1. Experimental analysis of propeller fin ray motion

It is troublesome to measure the angular displacement, angular velocity, angular acceleration and other related parameters of the fins on the propeller. So the Tracker software is used to handle the motion videos of the fins through a camera shoot with a high frame rate, and then imported the video into Tracker software perform exercise verification analysis. In the Tracker software analysis interface, a Cartesian coordinate system is established, and then the size is calibrated. Because the size calibration has a certain error, the Tracker software is mainly used to verify the motion law of the fin, and the specific motion parameters of the fin have a certain error.

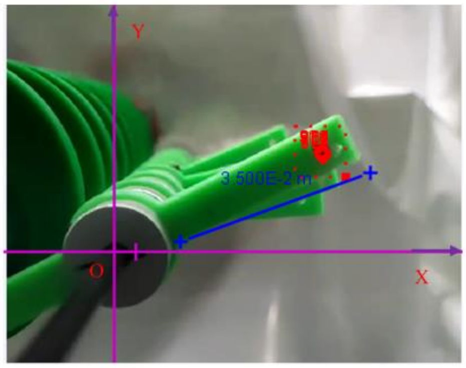
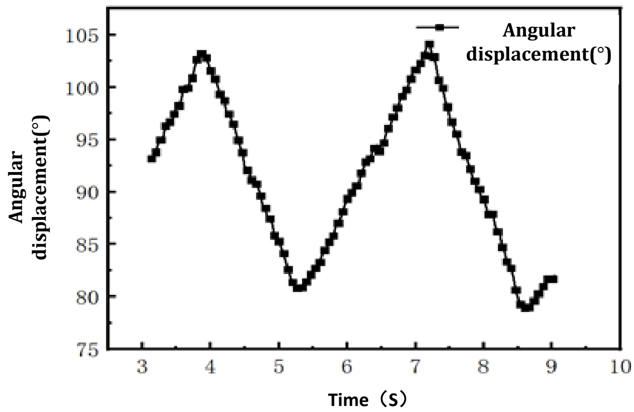


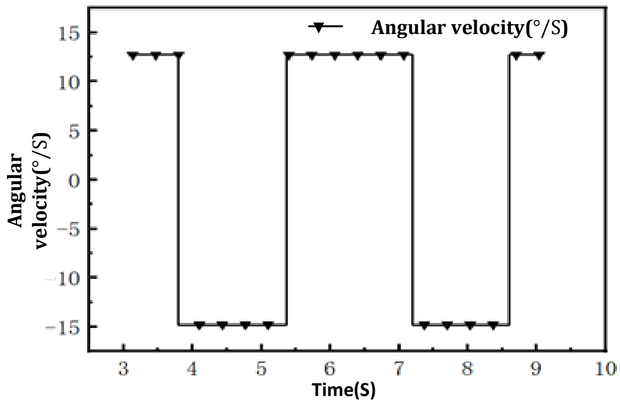
Figure 8: Verification of fin ray motion

After the size calibration is completed, the mass point at the end of the fin ray is selected, and the motion of the mass point is collected to reflect the motion law of the fin ray. As shown in Figure 9, the angular displacement curve of the fin measured by the Tracker software is a linear function in a complete cycle, indicating that the angular displacement of the fin increases at a constant speed, as shown in (a). the angular velocity of the fin is approximately uniform velocity. Since the mass point collection method is discrete collection, through curve fitting, the angular velocity curve is shown in (b), and the angular velocity is uniform. The angular acceleration is shown in (c), which is also a discrete curve, and its value is 0, the angular acceleration approaches infinity at the position where the angular velocity changes suddenly.

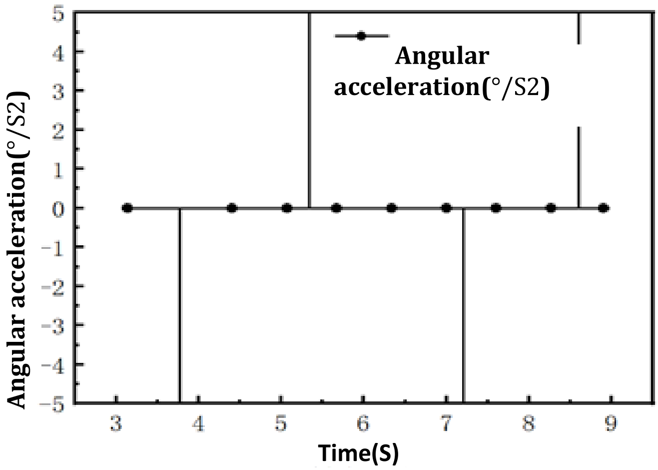
The motion analysis of the fin ray through the Tracker software shows that the angular displacement meets the basic conditions of uniform increase, constant angular velocity, and zero angular acceleration, which are consistent with the design criteria of the motion law when design the fin. After verifying that the basic motion of the fins is consistent with the design, the motion waveform of the complete propeller composed of the mutual matching fins is further verified by experiments.



(a). Angular displacement



(b). Angular velocity

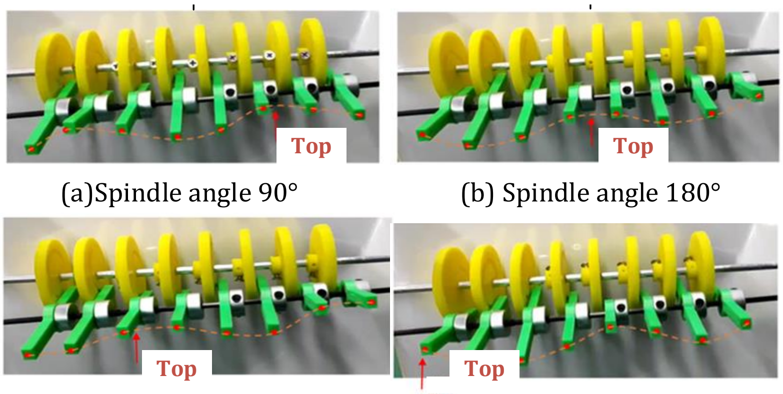


c. Angular acceleration

Figure 9: The law of fin ray movement

The experimental verification method also uses a camera with a high frame rate to capture the motion of the propeller. Through video post-processing analysis, four tense images with the spindle rotation angles of 90°, 180°, 270°, and 360° are selected. The same characteristic point on each fin ray describes the wave motion law formed by the fin ray, as shown in Figure 10.

In the four tenses of 90°, 180°, 270°, and 360°, the main shaft rotation angle is 90°, 180°, 270°, and 360°. By connecting the characteristic points on each fin with a smooth curve, the propellers of the four tenses can form a complete waveform. When the rotation angle of the main shaft is from 90° to 180°, as shown in (a) and (b), the wave crest in (a) transmits a certain distance backward with the rotation of the main shaft, indicating that the waveform is propagating backward. When the rotation angle is from 180° to 270°, as shown in (b) and (c), the wave crest continues to propagate backward. When the main shaft rotation angle is from 270° to 360°, as shown in (c) and (d), the wave crest disappears, (d) appears in the next wave crest cyclically, the waveform can continue to propagate.



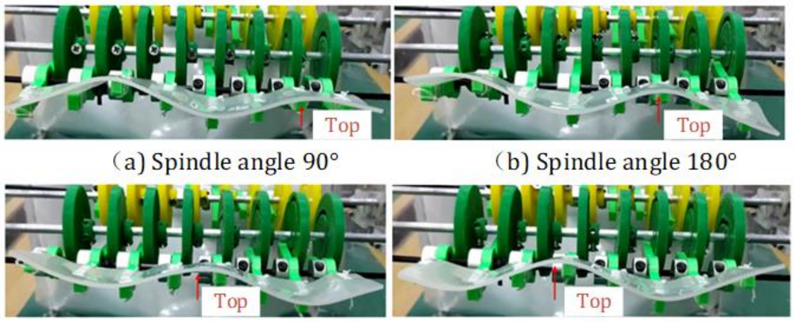
(a)Spindle angle 90° (b) Spindle angle 180°

(c) Spindle angle 270° (d) Spindle angle 360°

Figure 10: Fin ray waveform transmission law

4.2. Experiment analysis of multi-wave fin propeller prototype

In order to compare with the experiment of fin ray, a camera with a certain frame rate was also used to capture the motion of the propeller. Through video post-processing analysis, four spindle angles of 90°, 180°, 270°, and 360° were selected. This time, our goal is to verify that the wave generated by the flexible material driven by the movement of the fin after the flexible web is added. As shown in Figure 11, when the main shaft rotates 90°, the flexible web produces a wave crest. As shown in (a), when the main shaft rotates 180°, the wave crest moves in the direction of the wave, indicating that the wave is transmitted during the movement of the fin. In the same way, when the main shaft rotates from 180° to 270°, and from 270° to 360°, the wave crest moves again, and the wave generated by the flexible web can be continuously transmitted.



(a) Spindle angle 90° (b) Spindle angle 180°

(c) Spindle angle 270° (d) Spindle angle 360°

Figure 11: Waveform transmission law of flexible web

Comparing the waveform characteristics of the flexible web at different rotation angles of the main shaft, it can be found that the waveform characteristics generated by the flexible web are almost the same as the waveform formed by the connection of the fin characteristic points. The waveform generated by the web is distorted at the two ends of the flexible web. The main reason for this is the shape of the flexible material and the connection between the fin and the flexible material. The flexible material cannot continue to transmit the waveform at both ends of the fin, so it is generated part of the waveform which is distorted.

5. Conclusion

In this paper, a stingray with undulating fins is used as a bionic object. According to the morphological structure and propulsion mechanism of the long undulating fin, a undulating fin propeller with two degrees of freedom is designed, which simplifies the motion control scheme. The research content of this article is summarized as follows:

The flexible long fin of the stingray is selected as the bionic object, and the morphological structure and movement characteristics of the long fin are summarized. The propulsion mechanism of the long fin is qualitatively analyzed, which provides a theoretical basis and design idea for the design of the multi-wave fin propeller. By simplifying the undulating fin model, a kinematic model of the undulating fin is established, which can describe the motion state of the undulating fin at different times.

According to the movement characteristics and propulsion mechanism of the long fins of the stingray, a multi-wave fin propeller is designed in this paper. The propeller is composed of a swing cam mechanism as the actuating unit, which can realize the fin ray reciprocating at a constant speed within a certain angle range, combining multiple fin rays to form the propeller, and there is a certain phase difference between adjacent actuating units to realize the propeller through optimizing the cam contour line, the propulsion waveform has good transmission performance, and it is verified by ADAMS software simulation and by Tracker software to verify the motion of the prototype.

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