Simulation Study on the Body Side-Sway Characteristic for Rigid Robot Fish

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***Abstract*—This paper* reveals a new phenomenon of the body side-sway for rigid robot fish and proposes three effective restraining methods. The body side-sway problem is produced by the lateral component of hydrodynamic force and inertial force, while influenced by mass distribution of fish body and oscillating rules of caudal fin. Considering the body side-sway, a virtual prototype for two-joint robot fish, which is the simplified form of multi-joint robot fish, is established in MSC-ADAMS® to conduct the simulation. Simulation results indicate that the body side-sway can reduce the amplitude of tail peduncle and change the attack angle of caudal fin, and then affect the thrust and the propulsive efficiency. To inhibit the harmful body side-sway which also contributes to the energy loss, we last summarize three restraining methods: attaching dorsal fin and pelvic fin, using the vibration absorber and building two parallel tail mechanisms.**

***Keywords*—rigid robot fish, body side-sway, simulation study, restraining method.**

I. INTRODUCTION

Biomimetics, a new research area involving in both biology and robotics, has been receiving more and more attention. In this category, fishlike robot is modeled after real fish in nature having the virtue of high propulsive efficiency and excellent maneuverability [1]-[3]. These advantages are of great benefit to practical applications in marine and military fields such as undersea operation, military reconnaissance, leakage detection and so on [4].

Recent studies on robot fish focused on exploring the structural and functional variety [5]. To achieve fishlike motion, there are two kinds of design: 1) rigid, discrete body design, which corresponds to a “multi-motor-multi-joint” configuration; and 2) continuous body design, which often uses smart materials (e.g., polymers and elastomers) [6]. Due to the immaturity of the latter design, till now, the performance of the built artificial fish is mostly inferior to the former. Since we focus attention on the improvement body side-sway performance for rigid robot fish, the latter design is beyond the scope of this paper.

The body side-sway phenomenon can be defined as the lateral motion of the fish body is keeping pace with the oscillating movement of caudal fin for the rigid robot fish. The objective of this paper, as an extension of our previous work [7]-[9], is to reveal a new harmful phenomena of the body side-sway for rigid robot fish which can be seen in Fig.1, and propose the restraining strategy of the body side-sway. For a simulation research, a coordinate system and virtual prototype for the two-joint robot fish are established respectively. Considering the body side-sway problem with rigid robot fish, our works focus more on the influence of body side-sway for the propulsive motion. To further inhibit the harmful side-sway problem, we last summarize three restraining methods for designing the artificial robot fish.

Figure 1. Prototype of rigid robot fish (HRF-II).This prototype appears the body side-sway problem under a test.

II. SELECTION OF RESEARCH SUBJECT

A. Biomimetic Basis

In ichthyology, BCF (body and/or caudal fin) movement is usually categorized into anguilliform, carangiform and ostractiform mode [4]. Recent studies primarily concentrate on the anguilliform and carangiform mode. For latter, the body’s undulations are confined to the last 1/3 part, and thrust is produced by caudal fin. Since that evolving the body structure with fluid dynamic feature and using elastic tendon as the transmission spring, carangiform swimmers are generally faster and with higher propulsive efficiency. In this paper, only carangiform swimming is chosen as the model of robot fish. Based on the biological information as shown in Fig. 2, a entity model of the carangiform motion can be divided into three parts: rigid fish body in anterior portion, tail peduncle and lunate caudal fin in posterior portion, where tail peduncle is depicted by a series of hinge joints and the caudal fin by an oscillating foil [10], [11].

Biologically artificial systems mimicking real fish mostly concentrate on the fishlike motion mechanism [5]. Before

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building such a biomimetic fish system, it is necessary to simplify the swimming motion of real fish. In order to analyze the general body side-sway problems, we should select a representative subject.

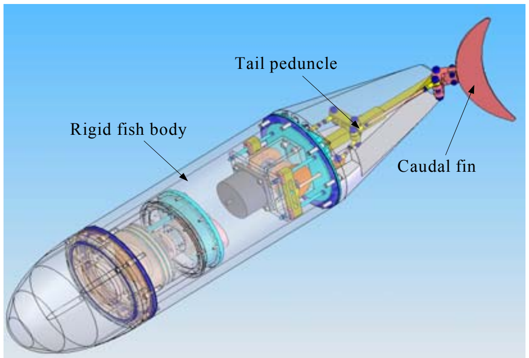

Figure 2. Entity model of carangiform swimming. A robot fish can be divided into three parts: rigid body, tail peduncle and oscillating caudal fin.

B. Selection of Research Subject

At present, robot fishes already made at home and abroad are varied [12]-[14], in this paper only a representative two-joint robot fish is selected as the research subject. Since the two-joint robot fish is the simplest form of multi-joint robot fish, so the research content has a general significance for the robot fish. The two-joint robot fish is composed of the fish body, tail peduncle, caudal fin and pectoral fin, which can be seen in Fig. 3. In this paper, we use rotary joints to connect the fish body to tail peduncle as well as the tail peduncle to caudal fin. During the swimming movement, the forward thrust is produced by caudal fin swinging and attacking the water.

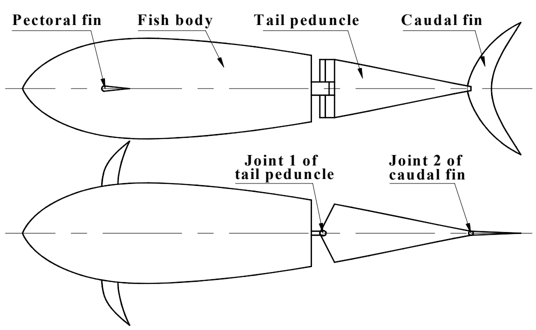

Figure 3. Structure scheme of two-joint robot fish.

In order to simplify the analysis, some assumptions were made as follows:

--The fish body, tail peduncle and caudal fin have sufficient rigidity to ensure that deformation of these three parts under the inertial force and hydrodynamic force is small enough to be negligible.

--Do not consider the change of the gravity center and the buoyancy point when tail peduncle and caudal fin swing.

--Robot fish is swimming in a large tunnel without size limitation and water flowing.

--The diving depth of robot fish is invariable, and it has no rolling and pitching movement.

III. Establishment of Virtual Prototype

A. Establishment of Coordinate System and Selection of Generalized Coordinates

For a simulation study, a coordinate system is established for two-joint robot fish as shown in Fig. 4, in which O_1, O_2, O_3 is located in the center line of the robot fish. In this coordinate system, O_1 is the mass center of fish body, O_2Z_2 is the rotary axis of tail peduncle joint, and O_3Z_3 is the rotary axis of caudal fin joint. $OXYZ$ is defined as the static coordinate system, while $O_1X_1Y_1Z_1$ is the dynamic coordinate system fixed to the fish body, and $O_2X_2Y_2Z_2$ is the one fixed to tail peduncle, and $O_3X_3Y_3Z_3$ fixed to caudal fin. When the robot fish swims along the straight line, relative to $OXYZ$, $O_1X_1Y_1Z_1$ fixed to the fish body moves along the directions of OX and OY, and turns around O_1Z_1. Similarly, relative to $O_1X_1Y_1Z_1$, $O_2X_2Y_2Z_2$ fixed to the tail peduncle turns around O_2Z_2, and $O_3X_3Y_3Z_3$ relative to $O_2X_2Y_2Z_2$ turns around O_3Z_3.

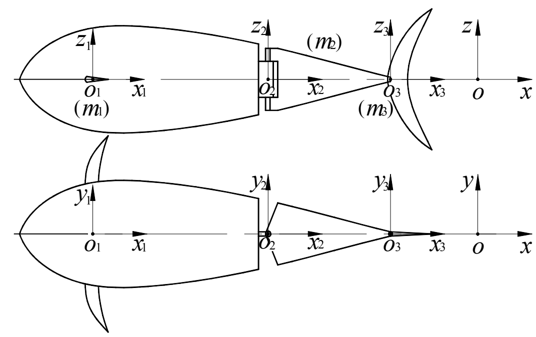

Figure 4. Coordinate system of two-joint robot fish.

Define mass parameters of robot fish as follows: m_1 is the mass of fish body, and m_2 is the mass of tail peduncle, as the same m_3 is the mass of caudal fin.

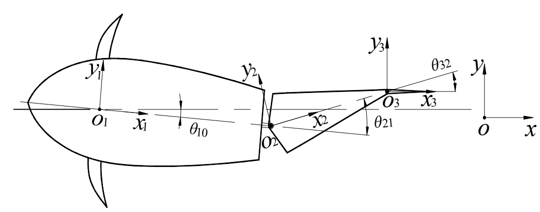

Figure 5. Generalized coordinate system of two-joint robot fish.

When the two-joint robot fish swims along the straight line, it has 5 degrees of freedom, and the number of generalized coordinates should be equal to the number of degrees of freedom. As shown in Fig. 5, here we choose x_{10}, y_{10}, θ_{10}, θ_{21} and θ_{32} as the generalized coordinates, where x_{10} is the coordinate of O_1 along the axis of OX, and y_{10} is the coordinate of O_1 along OY. θ_{10} is the angle between O_1X_1 and OX, similarly, θ_{21} is the angle between O_2X_2 and O_1X_1, and θ_{32} is the angle between O_3X_3 and O_2X_2, among this three angles, anti-clockwise is plus. Also the parameters are defined as $\theta_{20}=\theta_{21}+\theta_{10}$, $\theta_{30}=\theta_{32}+\theta_{21}+\theta_{10}$.

B. Establishment of Virtual Prototype

As to the rigid two-joint robot fish, simulation software MSC-ADAMS® is selected to study the body side-sway performance [15], [16]. A virtual prototype for two-joint robot fish is established according to the experimental prototype shown in Fig. 6, which consists of the fish body, tail peduncle and caudal fin. Tail peduncle is simplified as a cane, while caudal fin is simplified as a plane. A planar pair is installed between the fish body and ground to ensure that the robot fish can swim along the straight line, and the rotation pairs are fixed between the fish body and tail peduncle as well as the tail peduncle and caudal fin. This virtual prototype is similar to the structural scheme of two-joint robot fish as shown in Fig. 3.

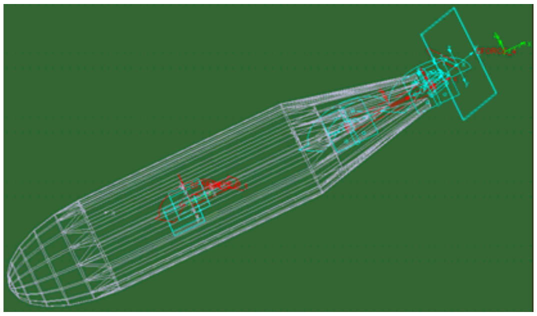

Figure 6. Virtual prototype of two-joint robot fish.

To ensure the caudal fin can produce thrust in the whole motion cycle, the oscillating rule of tail peduncle and caudal fin has the phase difference of ninety degree, which can be described as

$$\theta_{21} = \theta_{21\max} \sin \omega t \tag{1}$$

$$\theta_{31} = \theta_{31\max} \sin(\omega t + 90^\circ) \tag{2}$$

where ω represents the oscillating frequency, θ_{21} denotes the oscillating angle of tail peduncle, θ_{21max} is the amplitude of θ_{21}, θ_{31} indicates the attack angle of caudal fin, and θ_{31max} is the amplitude of θ_{31}.

IV. Simulation Study on Body Side-sway Characteristic

A. Amplitude Characteristic of Body Side-sway

The body side-sway can reduce the translational motion amplitude of caudal fin and change the attack angle, which deviates from the best scope, and further affect the thrust and the propulsive efficiency. Based on the underwater test of prototype HRF-II [9] and simulation study, the body side-sway problem is produced by the lateral component of inertial force and hydrodynamic force in the attacking water process of caudal fin, while influenced by the mass distribution of robot fish, the oscillating rule of caudal fin and other unforeknowable reasons. For a simulation study, here we only consider the former two causes as the research content, taking account of m_2=0.3kg, m_3=0.2kg, θ_{31max}=60° and θ_{21max} =25° analyze the relation among the body side-sway angle, mass distribution and the oscillating frequency in the simulation environment.

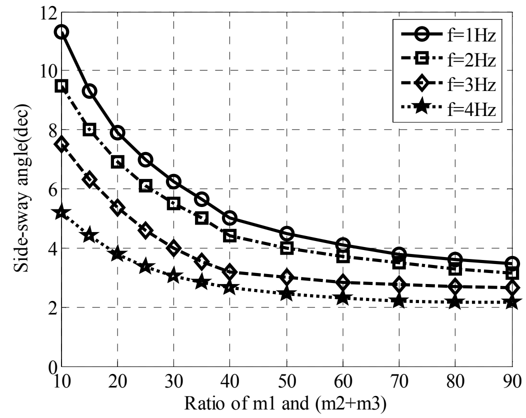

Figure 7. Relationship between the side-sway angle and mass ratio of m1 and m2+m3.

The relationship between the body side-sway angle and mass ratio of m_1 and m_2+m_3 can be shown in Fig. 7, with the parameter of oscillating frequency *f*. For any given value of *f*, the side-sway angle decreases with an increase in the ratio of m_1 and m_2+m_3 until it reaches a critical point 60 after which the side-sway angle begins to decrease slowly. Also the side-sway amplitude decreases with the higher oscillating frequency *f*. Therefore, during the design process of rigid robot fish, it is helpful for restraining the body side-sway to increase the anterior mass of fish body, reduce the posterior mass of tail peduncle and caudal fin, and improve the oscillating frequency.

B. Frequency Characteristic of Body Side-sway

Taking account of m_1=25.5kg for the simulation model and without change other parameters analyze the frequency characteristic of the body side-sway. Relationship between the body side-sway frequency of fish body and oscillating frequency of caudal fin can be shown in Fig. 8. The analysis curve indicates that this two frequency value is the same. This frequency characteristic result proves that the body side-sway motion is keeping pace with the oscillating movement of caudal fin.

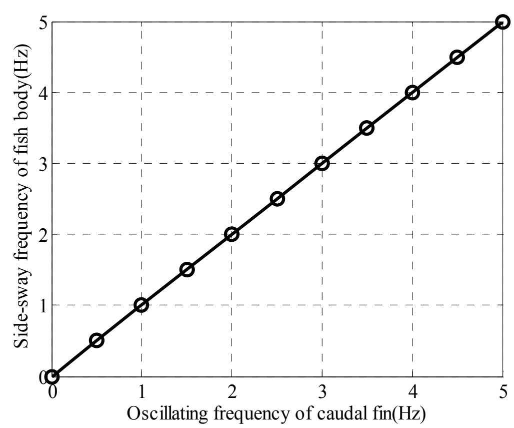

Figure 8. Relationship between the side-sway frequency of fish body and oscillating frequency of caudal fin.

Therefore, during the design process rigid robot fish, the body side-sway problem is always connecting to the propulsive motion to change the motion parameters and make the energy loss. So it is necessary to study the influence of the body side-sway for the motion parameters to propose some effective methods to restrain the body side-sway problem.

C. *Influence of Body Side-sway for Motion Parameters*

Most direct influence of the body side-sway for motion parameters is that it can reduce the translational motion amplitude and change the attacking angle of caudal fin. When the oscillating frequency f is set to 2 Hz, the decay factor including the maximum oscillating amplitude and maximum attack angle is changing with the parameter m1 vary as shown in Fig. 9. The curves show that the fish body side-sway can reduce the maximum oscillating amplitude of tail peduncle and the maximum attack angle of caudal fin respectively.

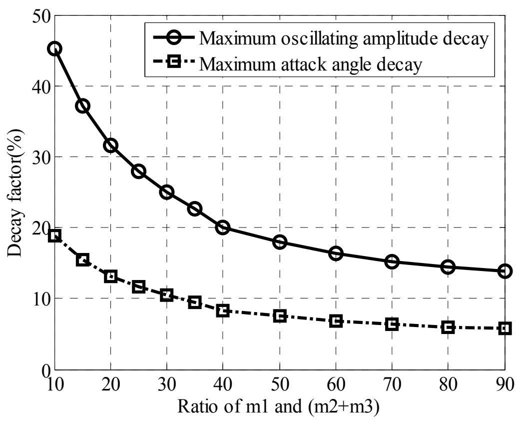

Figure 9. Relationship between the decay factors and mass ratio of m1 and m2+m3.

With the ratio of m_1 and m_2+m_3 decreasing the decay trend of the maximum oscillating amplitude becomes faster, and when the ratio of m_1 and m_2+m_3 is less than 40, the decay trend is very serious and the oscillating motion of caudal fin deviates from the set optimum value. In addition, with the ratio of m_1 and m_2+m_3 decreasing the decay trend of the caudal fin's maximal attack angle becomes faster as well. Thus, the effective of attacking water of caudal fin must be affected during the advance process. Due to the body side-sway problem, the propulsive performance of the robot fish containing thrust and propulsive efficiency can be harmfully contributed.

V. RESTRAINING METHODS FOR BODY SIDE-SWAY

A. *Attachment of Dorsal Fin and Pelvic Fin*

Based on the above simulation study, results indicate that the body side-sway can reduce the oscillating amplitude of tail peduncle and change the attack angle of caudal fin, and then affect the propulsive force and the propulsive efficiency. Moreover, the harmful body side-sway can reduce the stability and increase the energy loss in the propulsive process. Therefore, we must resolve this problem to improve the propulsive efficiency and prototype stability. This paper presents three kinds of methods for restraining the body side-sway.

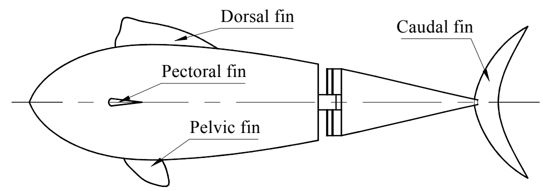

Figure 10. Simplified model with attachment of dorsal fin and pelvic fin.

With the attachment of dorsal fin and pelvic fin is adopted commonly to restrain the body side-sway. As shown in Fig. 10, by adding the dorsal fin and pelvic fin, the lateral projected area of fish body will be increased, thus the oscillating resistance moment will also increase to achieve restraining the fish body's lateral swing. The bigger the effective area of dorsal fin and pelvic fins is, the better the restraining effect is. This method is simple and reliable in application, but the dorsal fin and pelvic fin will destroy the streamline characteristic of the fish body and affect the turning performance of robot fish. As known to all, this manner to inhibit the body side-sway of rigid robot fish has been successfully adopted in the majority swimmers for its effective virtue.

B. *Attachment of Vibration Absorber*

The vibration absorber which consists of mass block, springs and damps, is installed within the fish body. The structural scheme can be shown in Fig. 11.

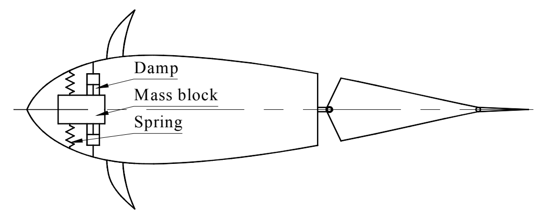

Figure 11. Simplified model with the attachment of vibration absorber. The vibration absorber consists of mass block, springs and damps.

With the attachment of vibration absorber, it is very easy for fish body to achieve the streamline shape which has small shape resistance, but the volume of robot fish will become bigger and accordingly the weight will increase. Considered that the vibration absorber is restricted by the volume of fish body and the mass block is not suitable to be large, therefore we focus more attention on exploring the influence of the damp coefficient and elasticity coefficient of the vibration absorber on the fish body side-sway characteristic.

For the given value of f =2 Hz, m_1 =10 kg, and making the mass block be 1.0 kg, and without attachment of the spring, the simulation research is conduct. At this condition, the effective of using the damp to reduce the side-sway angle can be described in Fig. 12. Correspondingly, with the damp coefficient is set to 30 N·m/s and carry on the simulation process by changing elastic coefficient of the spring, then the relationship between the body side-sway and elastic coefficient is depicted in Fig. 13.

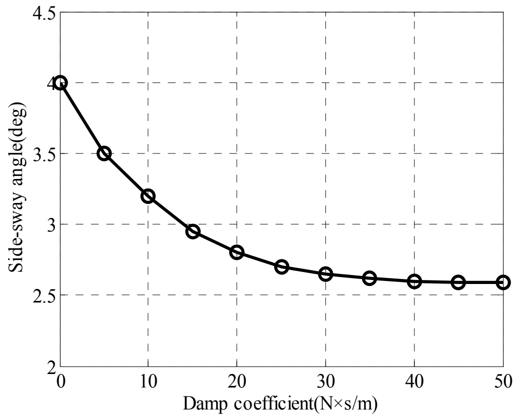

Figure 12. Relationship between the side-sway angle and damp coefficient.

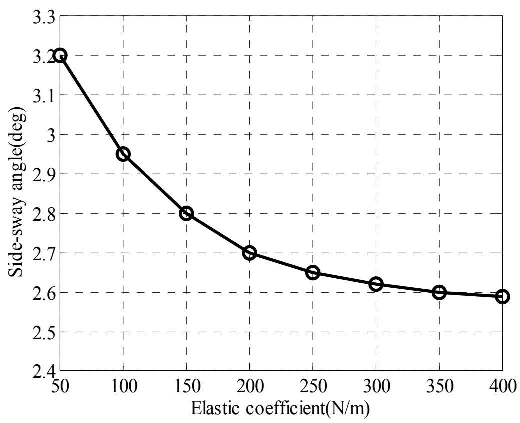

Figure 13. Relationship between the side-sway angle and elastic coefficient.

As shown in Fig. 12, for a given value of elastic coefficient is 0 N/m, the body side-sway angle will decreases with an increase in damp coefficient until it reaches a critical point 30 N·s/m after which the angle begins to decrease slowly. Similarly, as shown in Fig. 13, for a given value of damp coefficient is set to 30 N·s/m, the body side-sway angle will decreases with an increase in elastic coefficient until it reaches a critical point 250 N/m after which the angle begins to decrease slowly. Therefore, during the robot design, a vibration absorber with reasonable parameters can restrain the body side-sway.

C. Using Two Parallel Tail Mechanisms

The body side-sway is produced by the lateral component of inertial force and hydrodynamic force in the attacking water process of caudal fin. Therefore, through using two parallel tail mechanisms which are quite same and ensuring the oscillating rules complete symmetry, we can cancel the lateral force completely and make fish body have no side-sway. The robot fish with the parallel tail mechanisms, which is shown in Fig. 14, can ensure that caudal fin plays an oscillating-translational composite motion accurately according to the scheduled rule. It is helpful to enhance the swimming speed, improve the propulsive efficiency and motion stability, but it also makes the size of fish body increase and the structure complex, so the practical application is limited.

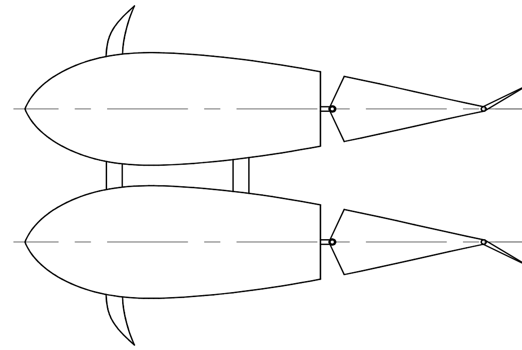

Figure 14. Simplified model using two parallel tail mechanisms.

VI. CONCLUSION AND FUTURE WORK

A new phenomenon of body side-sway in rigid robot fish has been revealed by simulation study. The body side-sway problem is produced by the lateral component of inertial force and hydrodynamic force in the attacking water process of caudal fin, while influenced by the mass distribution of robot fish and the oscillating rule of caudal fin. Simulation results indicate that the body side-sway can reduce the amplitude of tail peduncle and change the attack angle of caudal fin, and then affect the thrust and the propulsive efficiency. To inhibit the harmful side-sway which also contributes to the energy loss, we last summarize three restraining methods: attaching dorsal fin and pelvic fin, using the vibration absorber and building two parallel tail mechanisms.

Since the propulsive behaviors of the rigid robot fish are still unsatisfying to meet the application, further experimental research on the body side-sway performance and effectiveness of the restraining strategy would be paid more attention on to explore a novel robot fish with higher efficiency and remarkable stability.

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