A Study on the Propulsive Mechanism of a Double Jointed Fish Robot Utilizing Self-Excitation Control*

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This paper describes a numerical and experimental study of a double jointed fish robot utilizing self-excitation control. The fish robot is composed of a streamlined body and a rectangular caudal fin. The body length is 280 mm and it has a DC motor to actuate its first joint and a potentiometer to detect the angle of its second joint. The signal from the potentiometer is fed back into the DC motor, so that the system can be self-excited. In order to obtain a stable oscillation and a resultant stable propulsion, a torque limiter circuit is employed. From the experiment, it has been found that the robot can stably propel using this control and the maximum propulsive speed is 0.42 m/s.

Key Words: Self-Excited Vibration, Moving Robot, Propulsion, Self-Excitation Control, Biological Engineering

1. Introduction

Many animals in the natural world have been adapting to the change of the environment and have acquired excellent locomotion functions to survive. Most underwater creatures locomote by bending their bodies. Fish can generate thrust as well as receive drag from the water. Thus, there exists such an optimal motion that the ratio of thrust to drag can be maximized. Nakashima et al. paid close attention to the motion of fish with high efficiency and high speed, and they have investigated the dolphin-like propulsive mechanism, which is composed of a streamlined body and a rectangular caudal fin⁽¹⁾⁻⁽⁷⁾. In particular, they developed a double jointed dolphin robot whose body

length is 1.75 m, and they obtained results that the maximum propulsive speed and the propulsive efficiency reach 1.15 m/s and 0.7, respectively⁽⁷⁾. For this dolphin robot, one joint at the caudal part is driven by a DC motor. This motor rotates at a constant rotational speed and the rotation is transformed into a flapping motion of the caudal fin through cranks and gears, that is, the joint motion of this dolphin robot is given as "forced motion".

On the other hand, as a means of evoking a natural efficient locomotion of an articulated mechanical system including the external environment, Ono et al. proposed "Self-Excitation Control". They have applied self-excitation control to the flapping motion of insects⁽⁸⁾, a propulsive system on the water^{(9),(10)}, and a biped walking mechanism⁽¹¹⁾. The merit of the self-excitation control is that an efficient motion can be obtained with the simple control algorithm because the self-excitation control utilizes the "natural motion" of the system, while the demerit is that applicable mechanical systems are limited and we have to examine whether the subject system is applicable or not.

In this paper, we try to apply self-excitation control to a fish robot whose mechanical constructure

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is similar to the dolphin robot stated before⁽⁷⁾. We first theoretically examine the self-exciting condition and the propulsive characteristics based on the equation of motion. Then we manufactured the experimental setup and validated the theoretical results.

2. Derivation of Basic Equations

2.1 Mechanism model and basic equations

We deal with a fish-like mechanism that can be modeled as a three link system as shown in Fig. 1. Figure 2 shows the analytical model of the fish robot's propulsion. To make a self-excited system, the model must have a spring k_1 and an actuator at the first joint and a spring k_2 at the second joint. The c_1 and c_2 are equivalent damping coefficients at the first and the second joints. T is an input torque by an actuator.

To make the analysis easier, we assume a thrust of F_F and a lateral force of F_C of a fluid force act on a caudal fin (third link) solely. A yawing and a motion in the y direction of the first link are constrained. In the following analysis, m_i is the i -th link mass, l_i is the i -th link length, a_i is the distance from the mass center of the i -th link and I_i is the inertia moment of the i -th link of the mass center. The equation of the second and the third links is written as follows:

$$\begin{aligned} & \begin{bmatrix} I_2 + m_2 a_2^2 + m_3 l_2^2 & m_3 a_3 l_2 \cos(\theta_3 - \theta_2) \\ m_3 a_3 l_2 \cos(\theta_3 - \theta_2) & I_3 + m_3 a_3^2 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} \\ & + \begin{bmatrix} 0 & -m_3 a_3 l_2 \sin(\theta_3 - \theta_2) \\ m_3 a_3 l_2 \sin(\theta_3 - \theta_2) & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_2^2 \\ \dot{\theta}_3^2 \end{bmatrix} \\ & + \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix} \\ & = \begin{bmatrix} F_C l_2 \cos \theta_2 - F_F l_2 \sin \theta_2 + T \\ F_C a_3 \cos \theta_2 - F_F a_3 \sin \theta_3 \end{bmatrix} \quad (1) \end{aligned}$$

Fig. 1 Fish-like mechanism model

Fig. 2 Analytical model

The equation of the propulsion motion of the whole body is given by

$$M\ddot{x}_G = F_F - F_D \quad (2)$$

where M is the mass of the whole body, x_G is the position of the center of the whole body's mass, F_F is the total thrust and F_D is the total drag.

2.2 Model of fluid force

In the analysis of fluid force, we suppose "carangiform propulsion"⁽¹²⁾ in which a fish oscillates the tail fin and the tail peduncle. Therefore, we assume that the thrust is generated mainly by the caudal fin. We also assume that the drag acts only on the body and that the flow is inviscid. Thus, we use the quasi-steady wing theory which is often used to approximately calculate fluid forces acting on a high-aspect-ratio wing. By using this theory, we regard a caudal fin as a very thin plate and we suppose that the fin is in a constant flow U_m . First, we derive the inertial force and the lift acting on the caudal fin, and then we calculate their thrust component F_F and lateral component F_C from them. Figure 3 shows a model of the inertial force acting on the caudal fin, while Fig. 4 shows a model of the lift acting on the caudal fin. U is the relative velocity at the center of the fin, θ_3 is the pitch angle of the fin, α is the instantaneous relative angle of attack, $2C$ is the chord length, L is the span, and ρ is the water density.

In Fig. 3, F_V is a force proportional to an acceleration acting in the opposite direction of the acceleration. F_V is expressed by the form:

Fig. 3 Model of inertial fluid force

Fig. 4 Model of lift force

$$F_V = -\pi\rho LC^2(\dot{U} \sin \alpha + \dot{a}U \cos \alpha) \quad (3)$$

The lift acts in the perpendicular direction to the flow and it is expressed as follows:

$$F_J = 2\pi\rho LCU^2 \sin \alpha \cos \alpha \quad (4)$$

These fluid forces are divided into thrust component F_F in x direction and lateral force component F_c in y direction. From Eqs. (3) and (4), F_F and F_c are written as,

$$\begin{aligned} F_F &= F_{FV} + F_{FJ} \\ &= -\pi\rho LC^2(\dot{U} \sin \alpha + \dot{a}U \cos \alpha) \sin \theta_3 \\ &\quad + 2\pi\rho LCU^2 \sin \alpha \cos \alpha \sin \theta_3 \end{aligned} \quad (5)$$

$$\begin{aligned} F_c &= F_{cV} + F_{cJ} \\ &= -\pi\rho LC^2(\dot{U} \sin \alpha + \dot{a}U \cos \alpha) \cos \theta_3 \\ &\quad + 2\pi\rho LCU^2 \sin \alpha \cos \alpha \cos \theta_3 \end{aligned} \quad (6)$$

On the other hand, the drag F_D is assumed to act on the main body in the flow direction. F_D is given in the form:

$$F_D = \frac{1}{2} C_D \rho V^2 S \quad (7)$$

where C_D is the drag coefficient, V is the relative propulsive velocity, and S is an area of the main body which is projected on the perpendicular plane of the flow. We assumed C_D to be 0.5 in the following calculation.

2.3 Equation of motion

We assume that the fish robot is in an equilibrium condition in the x direction under the relative propulsion velocity of U_m . The velocity of the mass center of the fin in the y direction is denoted by u , where u is given by:

$$u = l_2 \dot{\theta}_2 \cos \theta_2 + a_3 \dot{\theta}_3 \cos \theta_3 \quad (8)$$

Putting $U^2 = U_m^2 + u^2$ into Eqs. (3) - (7), Eq. (1) becomes

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} = \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} \quad (9)$$

where

$$\begin{aligned} M_{11} &= I_2 + m_2 a_2^2 + m_3 l_2^2 \\ &\quad - F_1 l_2 (\cos \theta_2 \cos \theta_3 - \sin \theta_2 \sin \theta_3) l_2 \cos \theta_2 \\ M_{12} &= m_3 a_3 l_2 \cos (\theta_3 - \theta_2) \\ &\quad - F_1 l_2 (\cos \theta_2 \cos \theta_3 - \sin \theta_2 \sin \theta_3) a_3 \cos \theta_3 \\ M_{21} &= m_3 a_3 l_2 \cos (\theta_3 - \theta_2) \\ &\quad - F_1 a_3 (\cos \theta_3^2 - \sin \theta_3^2) l_2 \cos \theta_2 \\ M_{22} &= I_3 + m_3 a_3^2 \\ &\quad - F_1 a_3 (\cos \theta_3^2 - \sin \theta_3^2) a_3 \sin \theta_3 \\ N_1 &= m_3 a_3 l_2 \sin (\theta_3 - \theta_2) \dot{\theta}_3^2 \\ &\quad + F_2 l_2 (\cos \theta_2 \cos \theta_3 - \sin \theta_2 \sin \theta_3) + \tau_1 - \tau_2 \\ N_2 &= -m_3 a_3 l_2 \sin (\theta_3 - \theta_2) \dot{\theta}_2^2 \\ &\quad + F_2 a_3 (\cos \theta_3^2 - \sin \theta_3^2) + \tau_2 \end{aligned} \quad (10)$$

F_1, F_2, τ_1, τ_2 in Eq. (10) are expressed by the following forms:

$$\begin{aligned} F_1 &= \pi\rho LC^2(u^2 \cos \theta_3 - U_m^2 \cos \theta_3 \\ &\quad + 2uU_m \sin \theta_3)/U^2 \\ F_2 &= -2\pi\rho LC(u \cos \theta_3 + U_m \sin \theta_3) \\ &\quad \times (U_m \cos \theta_3 - u \sin \theta_3) \end{aligned}$$

$$\begin{aligned} & -\pi\rho LC^2\{(u^2 \cos \theta_3 - U_m^2 \cos \theta_3 + 2uU_m \sin \theta_3) \\ & \times (l_2 \sin \theta_2 \dot{\theta}_2^2 + a_3 \cos \theta_2 \dot{\theta}_2^2)/U^2 \\ & - \dot{\theta}_3(U_m \cos \theta_3 - u \sin \theta_3)\} \end{aligned} \quad (11)$$

$$\tau_1 = -k_1 \theta_2 - c_1 \dot{\theta}_2 - A(\theta_3 - \theta_2)$$

$$\tau_2 = -k_2(\theta_3 - \theta_2) - c_2(\dot{\theta}_3 - \dot{\theta}_2)$$

We developed a simulation program which integrates the above equation by the Runge-Kutta method.

2.4 Self-excitation control

Self-excitation control is the method to drive an actuator so as to evoke the natural vibration of the system including the external environment. In this study we regard the second and the third links as a 2-DOF vibration system. In this system, it has been already clarified that the self-excited vibration can be generated if feedback torque,

$$T = -A(\theta_3 - \theta_2) \quad (12)$$

is fed back into the first joint⁽¹¹⁾, where A is a feedback gain.

3. Analysis of the Range of Feedback Gain Generating Self-excited Vibration

3.1 Eigenvalue analysis by a linearized equation

To analytically obtain the range of A , which generates self-excited vibration, Eq. (9) is linearized in the vicinity of $\theta_2 = 0$ and $\theta_3 = 0$. Thus, the linearized equation is written in the form:

$$\begin{bmatrix} M'_{11} & M'_{12} \\ M'_{21} & M'_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} C'_{11} & C'_{12} \\ C'_{21} & C'_{22} \end{bmatrix} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} + \begin{bmatrix} K'_{11} & K'_{12} \\ K'_{21} & K'_{22} \end{bmatrix} \begin{bmatrix} \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (13)$$

where $M'_{ij}, C'_{ij}, K'_{ij}$ are expressed by the forms,

$$\begin{aligned} M'_{11} &= I_2 + m_2 a_2^2 + m_3 l_2^2 + \pi\rho LC^2 l_2^2 \\ M'_{12} &= m_3 a_3 l_2 \cos (\theta_3 - \theta_2) + \pi\rho LC^2 l_2 a_3 \\ M'_{21} &= m_3 a_3 l_2 \cos (\theta_3 - \theta_2) + \pi\rho LC^2 l_2 a_3 \\ M'_{22} &= I_3 + m_3 a_3^2 + \pi\rho LC^2 a_3^2 \\ C'_{11} &= c_1 + c_2 + 2\pi\rho LCU_m l_2^2 \\ C'_{12} &= -c_2 + \pi\rho LCU_m (2a_3 - CU_m) l_2 \\ C'_{21} &= -c_2 + 2\pi\rho LCU_m l_2 a_3 \\ C'_{22} &= c_2 + \pi\rho LCU_m (2a_3 - CU_m) a_3 \\ K'_{11} &= k_1 + k_2 - A \\ K'_{12} &= -k_2 + 2\pi\rho LCU_m^2 l_2 + A \\ K'_{21} &= -k_2 \\ K'_{22} &= k_2 + 2\pi\rho LCU_m^2 a_3 \end{aligned}$$

Note that the skew of the stiffness matrix causes the self-excitation and the strength of the skew can be controlled with the feedback gain A .

By substituting $\theta_2 = p_2 e^{\lambda t}$ and $\theta_3 = p_3 e^{\lambda t}$ into Eq. (13), we obtain

$$\begin{bmatrix} \lambda^2 M'_{11} + \lambda C'_{11} + K'_{11} & \lambda^2 M'_{12} + \lambda C'_{12} + K'_{12} \\ \lambda^2 M'_{21} + \lambda C'_{21} + K'_{21} & \lambda^2 M'_{22} + \lambda C'_{22} + K'_{22} \end{bmatrix} \begin{bmatrix} p_2 \\ p_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (14)$$

where λ is an eigenvalue and $[p_2 \ p_3]^T$ is an eigenvector

for λ . The characteristic equation of this system becomes

$$(\lambda^2 M_{11} + \lambda C_{11} + K_{11})(\lambda^2 M_{22} + \lambda C_{22} + K_{22}) - (\lambda^2 M_{12} + \lambda C_{12} + K_{12})(\lambda^2 M_{21} + \lambda C_{21} + K_{21}) = 0 \quad (15)$$

If the solution of this characteristic equation becomes a complex eigenvalue of $\lambda = a \pm bi$ (a, b are real numbers) and if the real part of the eigenvalue a is positive, the self-excited vibration whose angular frequency is b occurs.

3.2 Range of feedback gain for self-excitation

Table 1 shows the parameter values used in the calculation. These values are taken from the experimental setup which will be explained later. We assume that the rotation and translation in the y direction of the first link is constrained in a steady fluid with the velocity of $U_m = 0.3$ m/s. Figure 5 shows the changes of a and b as functions of the feedback gain A when $k_2 = 3.54 \times 10^{-3}$ Nm/rad. From Fig. 5, we

Table 1 Parameters

1st link	moment of inertia	$I_1 = 1.23 \times 10^{-3} [\text{kgm}^2]$
	mass	$m_1 = 0.409 [\text{kg}]$
	length of link	$l_1 = 0.1875 [\text{m}]$
	center of gravity	$a_1 = 0.09375 [\text{m}]$
	spring	$k_1 = 4.91 \times 10^{-2} [\text{Nm/rad}]$
	damper	$c_1 = 3.0 \times 10^{-4} [\text{Nms/rad}]$
2nd link	moment of inertia	$I_2 = 3.7 \times 10^{-5} [\text{kgm}^2]$
	mass	$m_2 = 0.104 [\text{kg}]$
	length of link	$l_2 = 0.0625 [\text{m}]$
	center of gravity	$a_2 = 0.0255 [\text{m}]$
	damper	$c_2 = 1.0 \times 10^{-4} [\text{Nms/rad}]$
3rd link	moment of inertia	$I_3 = 6.75 \times 10^{-7} [\text{kgm}^2]$
	mass	$m_3 = 9.0 \times 10^{-3} [\text{kg}]$
	length of link	$l_3 = 0.03 [\text{m}]$
	center of gravity	$a_3 = 0.015 [\text{m}]$
fluid force	fluid velocity	$U_m = 0.3 [\text{m/s}]$
	density of water	$\rho = 998 [\text{kg/m}^3]$
	drag coefficient	$C_D = 0.5$
	body projected area	$S = 7.069 \times 10^{-4} [\text{m}^2]$
	fin span	$L = 0.075 [\text{m}]$
	fin chord length	$2C = 0.03 [\text{m}]$

Fig. 5 Change of eigenvalue as a function of A

have found that the eigenvalue has positive real and imaginary parts in the following range:

$$2.34 \times 10^{-2} < A < 5.30 \times 10^{-2} [\text{Nm/rad}] \quad (16)$$

In addition, we have also found that in the range of $A > 5.30 \times 10^{-2}$ the system has divergence instability because $b=0$ and a becomes two positive real numbers.

Figure 6 shows the comparison of the threshold of self-excitation between linear analysis and the non-linear simulation. We simulated Eq. (9) from the two initial conditions, that is, $\theta_3 = 1$ and 60° . The other common initial conditions are $\theta_2 = 0$ and $\dot{\theta}_2 = \dot{\theta}_3 = 0$. In Fig. 6, the threshold values of A are shown as a function of k_2 . A_{low} and A_{up} are the lower and upper limit values to generate self-excited vibration. In the range of $A \leq A_{low}$, the oscillation is attenuated. In the range of $A_{up} \leq A$, the amplitude of the tail fin diverges in one direction. From Fig. 6, it is found that the linear analytical results agree well with the simulation results and the generating range is hardly affected by the initial angle.

3.3 Control of the oscillation amplitude by a limiter

We simulated the motion of the fish robot in the design area shown in the previous section. Then we found that when the feedback gain A is not so large, the self-excited oscillation becomes a limit cycle because of the effect of the fluid forces. On the other hand, at a large A in the same area, there are cases where oscillation doesn't exhibit a limit cycle and the amplitude diverges. In order to prevent the divergence of oscillation, we limited the feedback torque such that,

$$T \leq T_{lim} \quad (17)$$

For example, Fig. 7 shows the motion with and with-

Fig. 6 Area of parameter values for self-excited vibration

(a) Without limiter

(b) $T_{lim} = 3.79 \times 10^{-2}$ Nm

Fig. 7 Effect of limiter

out the limiter at the same parameter values. In this simulation, $k_2 = 3.54 \times 10^{-3}$ Nm/rad and $A = 5.09 \times 10^{-2}$ Nm/rad. Figure 7(a) shows a divergence of oscillation without the limiter, whereas Fig. 7(b) shows that oscillation becomes a limit cycle due to the limiter. From the result of this simulation, we found that the limiter is effective in suppressing the divergence of the oscillation and in obtaining a stable limit cycle.

4. Characteristics of the Self-excited Fish Robot by Simulation

4.1 Parameter study of propulsive performance

We examine the propulsive efficiency η and propulsive speed of the mechanism in the steady state. The propulsive efficiency η is written in the form:

$$\eta = \frac{\bar{F}_F \bar{v}}{\bar{P}} \quad (18)$$

where $\bar{F}_F$ is an averaged value of thrust, $\bar{P}$ is an

(a) $k_2 = 1.77 \times 10^{-3}$ Nm/rad (b) $k_2 = 5.31 \times 10^{-3}$ Nm/rad

Fig. 8 Propulsive speed and efficiency

averaged consumed power and $\bar{v}$ is an averaged propulsive speed in the steady state. $\bar{P}$ is given as the averaged consumed power at the first joint, that is,

$$\bar{P} = \bar{\theta}_2 T \quad (19)$$

Figures 8(a) and (b) show the propulsive speed and the efficiency as functions of the limit torque for two cases of k_2 . From the relation of η to T_{lim} , A and k_2 , we note that the effect of T_{lim} on η is small and that the maximum difference of η due to T_{lim} is only 5%, however η widely changes by a change of A . As A decreases, η has a tendency to increase. The reason for this is that $\bar{P}$ increases in proportion to A . In addition, η can be increased by an increase in k_2 . On the other hand, from the relation of $\bar{v}$ to T_{lim} , A and k_2 , it is found that $\bar{v}$ increases as T_{lim} increases when k_2 is small and A is large, in other words, when the limiter is active. In this region, A does not affect $\bar{v}$

much because of the limiter. When k_2 is large and A is small, $\bar{v}$ is not changed by T_{lim} , and $\bar{v}$ depends on A because the oscillation becomes a limit cycle without a limiter.

The maximum propulsive efficiency η of 46% can be obtained at $k_2=5.31 \times 10^{-3}$ Nm/rad and $A \leq 4.88 \times 10^{-2}$ Nm/rad in the case of no limiter. The maximum propulsive speed is 0.45 m/s when $k_2=5.31 \times 10^{-3}$ Nm/rad, $A=5.63 \times 10^{-2}$ Nm/rad and $T_{lim} \geq 3.79 \times 10^{-3}$ Nm (no limiter condition).

In addition, let us consider how to control the propulsive speed of the fish robot. As shown in Figs. 8(a) and (b), the propulsive speed is affected by both the feedback gain A and the limit torque T_{lim} . However if A is used for the speed control, the occurrence such that the limiter is not active when A is low may take place as shown in Fig. 8(b). When the limiter is not active, the amplitude of the vibrating motion is largely affected by any disturbances. Therefore, in order to control the propulsive speed, it is desirable that the limit torque T_{lim} is used, setting the feedback gain A sufficiently high to keep the limiter active.

4.2 Response to disturbance

We investigated the response of the mechanism to a disturbance in order to examine the robustness of self-excited oscillation and propulsive speed. First, we calculated the bending propulsive motion of the whole body in stationary water. The propulsive speed increases from zero at the initial state to some constant value (we refer to it as steady state). Then, after the propulsive speed becomes steady, the flow velocity is suddenly changed to U_m . The parameters used in simulation are $k_2=3.54 \times 10^{-3}$ Nm/rad, $A=4.88 \times 10^{-2}$ Nm/rad, and $T_{lim}=3.79 \times 10^{-2}$ Nm. Figures 9 (1) and (2) show the results of the simulation from zero to 10 seconds for the cases of $U_m=0.47$ m/s and $U_m=1.0$ m/s given from the front side. Figure (a) is the joint angle motion, (b) is relative speed, and (c) is the traveling distance of the center of mass. From Fig. 9(1)(b), it is found that the relative speed instantaneously increases but returns back to the steady value in a few seconds. Figure 9(1)(a) shows that the amplitude of the oscillation decreases at the instance of the change of U_m . However, after a few seconds, oscillation becomes stable again. In Fig. 9(2), U_m is faster than the one in Fig. 9(1). The relative speed increases suddenly and the amplitude decreases significantly when it receives a change of flow velocity. In contrast, after about two seconds, the amplitude increases, the relative speed returns back to the steady value again and the mechanism enters a stable limit cycle though it is forced to move back (it is shown in Fig. 9(2)(c)). As a result, it

Fig. 9 Response to disturbance, (a) Link angle motion, (b) Relative speed, (c) Traveling distance

can be said that the self-excitation control has a robust stability to a sudden change of the flow speed.

5. Experiment

5.1 Experimental setup

We manufactured a fish robot, measured the characteristics of the self-excited propulsion by using this robot and compared the experimental results with the analytical ones. Figure 10 shows a schematic diagram of the fish robot. The driving parts such as the motor and the potentiometer are located above the water. The streamlined body and the rectangular caudal fin are in the water, and they are connected to the upper links by shafts. The shape of the main body is based on a wing section's shape (NACA0018). We used a linear guide so that the first link's yawing is constrained and the robot can move only in the propulsive direction. A DC motor drives the first joint using a pulley and a belt and the potentiometer detects the angle of the second joint. Each joint has a spring mechanism so that it produces a restoring torque which is proportional to a rotation angle. Parameter values of this robot have been already shown in Table 1 and k_2 is 3.54×10^{-3} Nm/rad. We experimented in the water tank shown in Fig. 11 (note-the tank size is 300 mm (width) $\times$ 300 mm (depth) $\times$ 980 mm (length)). We measured the flow velocity as a propulsive speed when the robot becomes stationary in the flow. Note that we could not measure the propulsive efficiency η because we did not have a sensor for joint torque in

Fig. 10 Schematic diagram of the fish robot

Fig. 11 Fish robot in water tank

this experimental setup.

5.2 Control circuit

To evoke a self-excited vibration of the mechanism, an angle of the second joint, which is detected by the potentiometer, is fed back into the DC motor of the first joint through the control circuit and a current amplifier. Figure 12 shows an analog control circuit that functions as a limiter. The limiter is achieved by limiting a power supply voltage of OP-amp 1. We can change the value of T_{lim} by two variable resistances. Feedback gain A can be adjusted by changing the input voltage V_{cc} of a potentiometer. We can also change V_{cc} from 6 V (A is 0.0413 Nm/rad) to 10 V (0.0713 Nm/rad).

5.3 Experimental results and discussions

Figure 13 shows the comparison between the experimental and simulated results. We measured the

Fig. 12 Control circuit with limiter

(a) $A=4.88 \times 10^{-2}$ Nm/rad, $T_{lim}=3.79 \times 10^{-2}$ Nm (b) $A=5.63 \times 10^{-2}$ Nm/rad, $T_{lim}=3.25 \times 10^{-2}$ Nm

Fig. 13 Comparison between experiment and simulation

second joint angle from an output voltage of the potentiometer. Figure 13(a) is the case where $A=4.88 \times 10^{-2}$ Nm/rad and $T_{lim}=3.79 \times 10^{-2}$ Nm, while

Fig. 13(b) is the case where $A=5.63 \times 10^{-2}$ Nm/rad and $T_{lim}=3.25 \times 10^{-2}$ Nm. It can be found that the experimental results agree well with the simulation results.

Figure 14 shows the effect of A and T_{lim} on the self-excited bending oscillations in the experiment. From Figs. 14(a) and (b), it is found that the amplitude of the vibration with the limiter are kept almost equal in the steady state for different A values. In addition, the amplitude of the vibration decreases with a decrease in T_{lim} . Figure 15 shows the changes of frequency due to the change of T_{lim} . From this figure, it is found that the frequency increases due to an increase in T_{lim} .

Figure 16 shows the experimental results of the propulsive speed when the feedback gain A and the limit torque T_{lim} are changed. In the case without the

limiter, the vibration amplitude diverges and a stable propulsion cannot be obtained when $A \geq 6.38 \times 10^{-2}$ Nm/rad. When $A=5.63 \times 10^{-2}$ Nm/rad, the amplitude is too large to propel stably, and the propulsive speed decreases. In addition, when $A < 4.13 \times 10^{-2}$ Nm/rad, the vibration amplitude decreases and the robot stops. This range of successful vibration is somewhat larger than the theoretical one shown in Fig. 5. The reason for this may be that the effect of the nonlinear force (such as the friction force) in the experiment is greater than that in the theory.

When $T_{lim}=3.25 \times 10^{-2}$ Nm and $T_{lim}=3.79 \times 10^{-2}$ Nm, the propulsive speed tends to increase in proportion to the feedback gain A in the range of 4.13×10^{-2} Nm/rad $\leq A \leq 6.38 \times 10^{-2}$ Nm/rad. Above this range, the propulsive speed tends to decrease because the amplitude becomes too large. When $T_{lim}=4.33 \times 10^{-2}$ Nm, the propulsive speed decreases slightly in a range of $A \geq 5.63 \times 10^{-2}$ Nm/rad.

Comparing the propulsive speed in the experiment with the simulation results shown in Fig. 8, it is found that the minimum value of the propulsive speed in the experiment is significantly lower than that in the simulation, while the maximum values in the

(a) $A=4.13 \times 10^{-2}$ Nm/rad

(b) $A=4.88 \times 10^{-2}$ Nm/rad

Fig. 14 Change of amplitude due to T_{lim}

Fig. 15 Change of oscillation frequency due to T_{lim}

Fig. 16 Propulsive speed vs feedback gain

experiment and the simulation are almost equal. The reason for this may be that the mechanical error of the experimental setup reduces the accuracy of the robot's motion and such effect becomes greater when the amplitude of the motion is small.

From the results of the experiment, we found that there are optimal combinations of A and T_{lim} . In the case of $T_{lim}=3.79\times 10^{-2}$ Nm, we note that the propulsive speed changes from 0.24 m/s to 0.42 m/s. On the other hand, when $A=4.88\times 10^{-2}$ Nm/rad, the propulsive speed changes from 0.17 m/s to 0.42 m/s. Thus, the propulsive speed is changed more greatly by T_{lim} than by A . Therefore, the control of propulsive speed can be achieved more efficiently by changing T_{lim} . This conclusion is also consistent with the conclusion by simulation, which is stated in Section 4.1.

6. Conclusions

In this paper we showed a three-link, two-joint fish robot based on the self-excitation control. We first theoretically analyze the self-exciting condition and the propulsive characteristics. Then we manufactured the fish robot and confirmed that the robot can propel with the self-excitation control. The results of this study are summarized as follows:

1. The parameter range to generate the self-excited vibration can be derived by the linearized analysis.
2. The propulsive efficiency η is mainly affected by the feedback gain A while the propulsive speed $\bar{v}$ is mainly affected by the limit torque T_{lim} in the numerical simulation.
3. The response of the mechanism to the change of the flow velocity is stable in the simulation.
4. The oscillation can be changed by the limiter also in the experiment.
5. The maximum propulsive speed is 0.42 m/s in the experiment.

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References

- (1) Nakashima, M. and Ono, K., Dynamics of Two-Joint Dolphinlike Propulsion Mechanism (1st Report, Analytical Model and Analysis Method), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 600, B (1996), pp. 3044-3051.
- (2) Nakashima, M. and Ono, K., Dynamics of Two-Joint Dolphinlike Propulsion Mechanism (2nd Report, Optimum Motion for Primary Body Form), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 602, B (1996), pp. 3599-3606.
- (3) Nakashima, M. and Ono, K., Dynamics of Two-Joint Dolphinlike Propulsion Mechanism (3rd Report, Parameter Study for High Propulsive Efficiency), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 602, B (1996), pp. 3607-3613.
- (4) Nakashima, M. and Ono, K., Dynamics of Two-Joint Dolphinlike Propulsion Mechanism (4th Report, Analysis of a Lunate Caudal Fin Model), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 62, No. 629, B (1999), pp. 100-107.
- (5) Nakashima, M. and Ono, K., Dynamics of Two-Joint Dolphinlike Propulsion Mechanism (5th Report, Analysis of a Model of Spring Support for Second Joint), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 66, No. 643, B (2000), pp. 686-694.
- (6) Nakashima, M., Ii, T. and Ono, K., Experimental Study of a Two-Joint Dolphinlike Propulsion Mechanism (1st Report, Experiment of Small Machine), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 66, No. 643, B (2000), pp. 695-702.
- (7) Nakashima, M., Tokuo, K. and Ono, K., Experimental Study of a Two-Joint Dolphinlike Propulsion Mechanism (2nd Report, Experiment of Self-propelled Large Robot), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 66, No. 643, B (2000), pp. 703-709.
- (8) Ono, K. and Okada, T., Self-Excited Vibratory Actuator (2nd Report, Self-Excitation of Insect Wing Model), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 60, No. 579, B (1994), pp. 3703-3710.
- (9) Nakashima, M., Ono, K., Hibi, K. and Imamura, T., Study of Self-Excited Aquatic Propulsion Mechanism (1st Report, Theory, Design and Experimental Verification of Propulsion Mechanism), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 65, No. 639, B (1999), pp. 4239-4244.
- (10) Nakashima, M., Ono, K. and Hibi, K., Study of Self-Excited Aquatic Propulsion Mechanism (2nd Report, Self-Excited Condition, Actuator Efficiency and Propulsive Efficiency), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 65, No. 639, B (1999), pp. 4245-4251.
- (11) Takahashi, R., Ono, K. and Shimada, T., Self-Excited Walking of a Biped Walking Mechanism, *Proc. on TITech COE/Super Mechano-Systems Symposium 2000*, pp. 218-230.
- (12) Lighthill, M.J., Note on the Swimming of Slender Fish, *Ann. Rev. Fluid Mech.*, Vol. 44, No. 2 (1970), pp. 265-301.