Experimental Study on Oscillating Wing for Propulsor with Bending Mechanism Modeled on Caudal Muscle-Skeletal Structure of Tuna*

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The purpose of our study is to investigate the effect of the caudal fin behavior resulting from the caudal muscle-skeletal structure of tuna on the propulsive force. A propulsion system by tuna-like fin stroke using two air rubber artificial muscles and a multi-joint bending mechanism (a tuna-like bending mechanism) modeled on the antagonism muscles and the caudal skeletal structure of tuna was developed. In order to realize instructed oscillation of a wing, a method of continuous path follow-up control of a wing in water was discussed in regard to the control of the internal pressure of the artificial muscles. It was found that the optimum control method for the tuna-like bending mechanism was the pressure control of the artificial muscles with both feedforward and pressure feedback compensations. The propulsion performance on a deformable wing using the propulsion system was discussed.

Key Words: Biomechanics, Propulsion, Measurement and Control, Muscle and Skeleton, Caudal Fin of Tuna, Oscillating Wing, Air Rubber Artificial Muscle

1. Introduction

From the viewpoint of developing a propulsion system of ship or submersible vehicle with higher propulsion efficiency and higher safety than a conventional screw propeller, a propulsion method by oscillating a wing like fish-like tail fin stroke has been studied. It is known that such a fish as tuna with a lunate caudal fin can swim at high speed and the caudal fin plays an important role of generating propulsive force. So studies on oscillating fin of fish were theoretically and experimentally carried out by a number of researchers as M.J. Lighthill[1], T. Yao Tsu Wu[2], M. Chopra[3] and so on, showing that their fins have a possibility of having good propulsion efficiency. A series of study on propulsion system by fin stroke has been carried out by one of authors. First, a two-dimensional oscillating wing was analyzed under the assumption of quasi-steady flow. The relationship between the wing's behavior and the thrust force generated by the wing's oscillation was obtained theoretically and experimentally[4],[5]. Second, a ship equipped with various kinds of propulsion systems using an oscillating wing was developed and a feasibility test on the ship from the engineering standpoint was carried out. The propulsion system with a horizontal wing like a dolphin-like tail fin installed below ship bottom has proved to have good propulsion efficiency, very good safety and such characteristics as less mixing of water[6]-[9]. Therefore it is considered that the propulsion system using an oscillating wing is useful for development of future marine engineering from many viewpoints.

Recently, higher performance of propulsion and higher maneuverbility by an oscillating wing for propulsor of underwater vehicles, in particular, are required. From the bioengineering point of view, we paid attention to a caudal fin of tuna and a caudal muscle-skeletal structure related to the deformation of the fin for further improvement of the propulsive performance.

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In order to investigate the effect of the caudal fin behavior resulting from the caudal muscle-skeletal structure of tuna on the performance of propulsion, we have developed a multi-joint bending mechanism with a wing using two air rubber artificial muscles modeled on the antagonism muscles and the caudal skeletal structure of the fish. (We will call this "a tuna-like bending mechanism" here.)

In general, an air rubber artificial muscle cannot generate force larger than a value indicated in the relation between the internal pressure and the force for an excessive load[10]. Accordingly, the artificial muscle has such characteristics that it prevents the tuna-like bending mechanism from destroying the structure because of absorbing an impulsive force, the force generated by the muscle depends on the internal pressure applied to it, and the internal pressure is changed by load. The first characteristic is valuable for a safe propulsor, while the others suggest difficulty of control. Therefore, it is important to control the internal pressure of the artificial muscles in order to realize a set behavior of the wing because the oscillating wing in water causes load change every second.

In this paper, a method of continuous path follow-up control of a rigid wing in water mounted on the tuna-like bending mechanism is discussed in regard to the control of the internal pressures of the rubber artificial muscles. The performance of propulsion for a deformable wing using the control method is also discussed compared with that for a rigid wing.

2. Muscle-Skeletal Structure of Caudal Part of Tuna

We have examined a muscle and a skeletal structure of a caudal part of a tuna. Figure 1 shows a caudal skeleton of a bluefin tuna (Thunnus thynnus) which body length was 1.55 m. A caudal vertebral column has process-like plate bones, which both neural and haemal spines were deformed, and is connected each other. The up and down motion of the caudal vertebral column is restricted because each column is inserted into the space between the process-like plate bones. Some caudal vertebrae which cross section decreases have lateral flanges at both the sides. It is thought that the lateral flanges reinforce bending rigidity of the caudal peduncle.

A caudal fin is composed of fin rays and fin skin. The fin ray is composed of spinous rays from the leading edge to the middle part of the fin and soft rays in the rear part of the fin. Urostyles or hypurals of the fin are put between pairs of fin rays. The sweepback angle of the fin is larger than the angle of each spinous ray composed the fin.

Each white muscle's tendon reaches hypural and

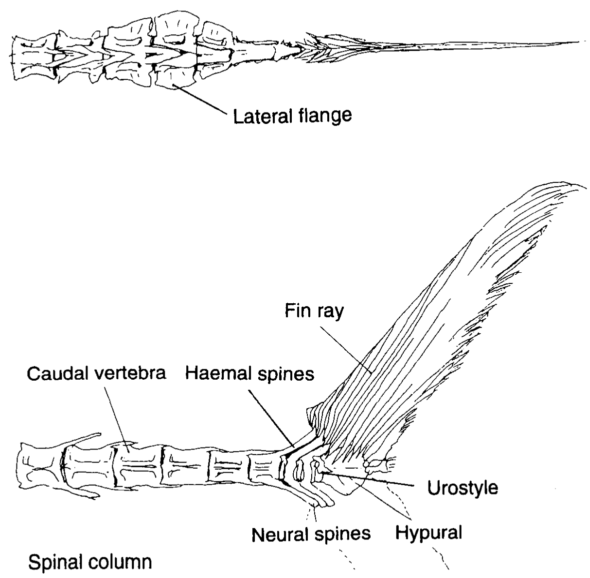


Fig. 1 Caudal skeleton of bluefin tuna

connects the ends of each fin ray. It is suggested that this tendon-fin ray structure enables the caudal fin to deform itself and generates wave motion of the fin. As the caudal part and fin of tuna are flexed by the alternative contraction of muscles arranged on both sides of the vertebrae, a phase difference between caudal vertebrae generates and transmits to fin rays. The phase delay exists between the leading edge and the middle part of the fin, and therefore the caudal fin deforms concave to the direction of oscillation. An instantaneous swim of fish is done to obtain a large propulsive force by bending its caudal part and deforming its caudal fin largely. On the other hand, in common swimming the part of the fish body where aerobic red muscles connected to the caudal vertebrae work is flexed.

3. Experimental

3.1 Tuna-like bending mechanism

We have developed a tuna-like bending mechanism modeled on the antagonism muscles and the caudal skeletal structure of a tuna. The tuna-like bending mechanism shown in Fig. 2 was a multi-joint bending mechanism with a wing using two air rubber artificial muscles as an actuator. The multi-joint bending mechanism, which mimicked a spinal column, consisted of four cylindrical rollers and four plates with a semicircle-shaped groove on both sides of each one as centrums[11] and was covered with a silicon rubber skin to reduce its drag in water. A wing mounted on the rear of the multi-joint bending mechanism behaved both a pitching and a heaving motions by controlling strokes of two tendons connected with a pair of rubber artificial muscles through the multi-joint mechanism.

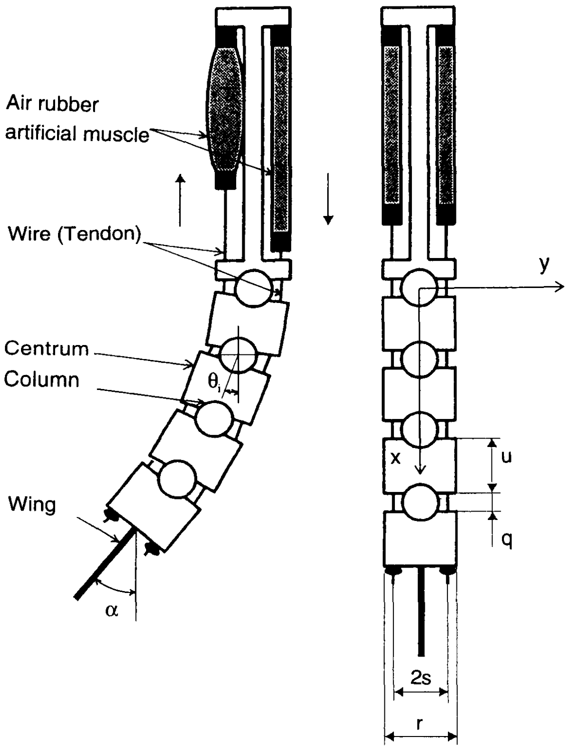


Fig. 2 Tuna-like bending mechanism

Let the coordinates of the rear point of the multi-joint bending mechanism corresponding to the wing tip be (x, y) shown in Fig. 2 :

$$x=u\sum_{i=1}^{n}\cos\theta_i,\qquad y=u\sum_{i=1}^{n}\sin\theta_i, \tag{1}$$

where u is the length of the vertebra (column), θ_i is the bending angle of the i-th joint and n is the number of the joint. A pitching angle α of the wing, which is a bending angle of the multi-joint mechanism, is expressed as follows :

$$\alpha=\sin^{-1}\left(\frac{dl_2-dl_1}{\sqrt{r^2+q^2}}\right), \tag{2}$$

where dl_1 and dl_2 are the stroke of each rubber artificial muscle respectively, r is the width of the vertebra and q is the gap between the vertebrae. The pitching angle α is also expressed as below using internal pressures of the artificial muscle P_1, P_2 and the standard pressure P_0 :

$$\alpha=\sin^{-1}\frac{P_0}{\sqrt{r^2+q^2}}\left(\frac{1}{P_2}-\frac{1}{P_1}\right). \tag{3}$$

In order to oscillate the wing, the stroke of a pair of the artificial muscles should be varied periodically with a phase lag of π. In the case of oscillating the wing sinusoidally, the instructive pressure or each internal pressure for the artificial muscle is expressed as follows :

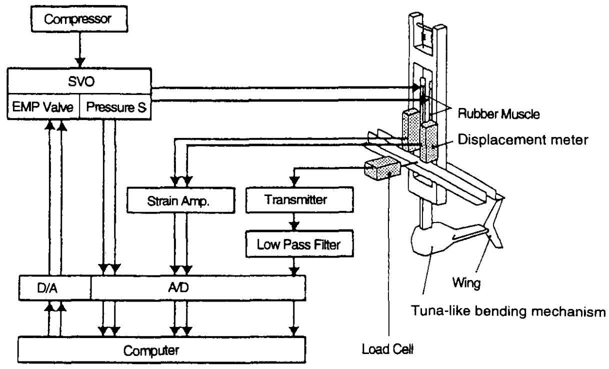


Fig. 3 Schematic diagram of experimental system of tuna-like bending mechanism as propulsor

$$P_1=\frac{P_0}{\sin\omega t+\frac{k_1}{k_2}},\qquad P_2=\frac{P_0}{\sin(\omega t-\pi)+\frac{k_1}{k_2}}, \tag{4}$$

where ω is the angular frequency and t is time.

According to the technical data (Bridgestone Co. Ltd.) on the air rubber artificial muscle(12), the relationship between the force F generated by the rubber artificial muscle and the internal pressure P is expressed as follows :

$$F=P(k_1+k_2dl), \tag{5}$$

where k_1 and k_2 are the constant values depending on a characteristic of a rubber artificial muscle.

3.2 Experimental equipment and method

Figure 3 shows a schematic diagram of experimental system of the tuna-like bending mechanism as propulsor. Two air rubber artificial muscles (Bridgestone Co. Ltd. Rubbertuator RUB-30) were arranged vertically over a water tank (1 m×2 m×0.4 m) and the multi-link bending mechanism with a wing was horizontally arranged under water. The tuna-like bending mechanism was mounted on the water tank through two slide bearing shafts to move back and forth freely and was fasten to a load cell (Minebea Co. Ltd. UT-2K) put on the tank. The thrust force generated by oscillating the wing of the tuna-like bending mechanism was measured with the load cell. The bending mechanism was unfasten from the load cell to measure its forward velocity. Two kinds of lunate-shaped wing were used in the experiment : One was a deformable wing made with a brass rod as its leading edge and covered with a rubber skin and another one was a rigid wing made of acrylic resin.

A pneumatics system consisted of two rubber artificial muscles, a servo valve unit (Bridgestone Co. Ltd. SVO-103C-06) and a compressor (Iwata Toso Kougyo Co. Ltd. SP-37). Compressed air supplied by the compressor was controlled with 2 ch. solenoid

Table 1 Specification of tuna-like bending mechanism

Full length (in water)	300 mm	Distance between wires: 2s	30 mm
Full length (in air)	40 mm	Distance between centrums: q	5 mm
Height	910 mm	Length of centrum: u	30 mm
Width (in water)	40 mm	Max. pitching angle	40 deg.
Width (in air)	110 mm	Max. heaving displacement	62 mm
Weight	36.8 N	Chord of wing	50 mm
Number of joint: n	4	Width of wing	180 mm
Width of vertebra: r	48 mm	Sweep-back angle of wing	30 deg.

control valves in a servo valve unit and was sent to the rubber muscles. A control system consisted of the servo valve unit, two displacement meters (NEC Sanei Co. Ltd. 9E08-D3-100), a strain amplifier (NEC Sanei Co. Ltd. AS2102), an A/D converter and a personal computer. A pressure signal in the computer was sent through a D/A converter to the solenoid control valve. Each internal pressure applied to the artificial muscles was measured and controlled through the servo valve connecting to the personal computer, and each stroke was measured with a displacement meter. The data on the pressures and the strokes of the artificial muscles, and the thrust force were processed with the computer. A specification of the tuna-like bending mechanism is shown in Table 1.

4. Results and Discussion

4.1 Control of tuna-like bending mechanism

An air rubber artificial muscle has such characteristics that the force generated by the artificial muscle depends on the internal pressure supplied and the internal pressure is changed by load. A pitching angle of the wing α can be decided with the stroke difference between the two artificial muscles arranged antagonistically as obtained from Eqs. (2) and (3). Actually, however, it is necessary to control the internal pressure of the artificial muscles in order to realize a set behavior of the wing because the oscillating wing in water causes load change every second.

At first, we focused on the method of continuous path follow-up control of a rigid wing in water. Figure 4 shows the static characteristics of the tuna-like bending mechanism which was obtained by the experiment of oscillating the wing slowly in water with applied internal pressure amplitude 392 kPa at the standard pressure P_0=294 kPa. The axis of ordinate indicates the stroke difference between two rubber artificial muscles and the axis of abscissa indicates the internal pressure difference. The result of the static test showed that the system had hysteresis and saturation characteristics. The rate of the variations on a pressure difference between maximum and minimum for time was constant, though the pressure difference depended on frequency within the range of our experiment (0 - 2 Hz). Figure 5 shows the dynamic characteristics of the tuna-like bending mechanism when a step input of pressure with the amplitude 392 kPa was applied at P_0=294 kPa. The upper figure shows internal pressure difference versus time and the lower one shows stroke difference versus time. As Fig. 5 shows, this system had a linear delay characteristic. It was found from the above results that the tuna-like bending mechanism has such characteristics as a linear delay system with hysteresis and saturation. As the tuna-like bending mechanism was modeled on the antagonism muscles and the caudal skeletal structure of tuna, we have applied the

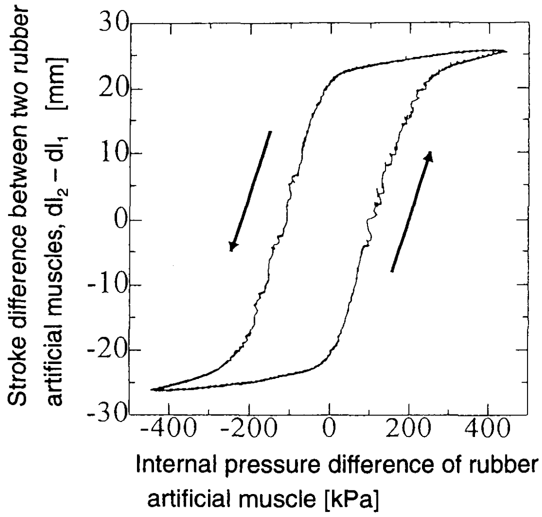


Fig. 4 Static characteristics of tuna-like bending mechanism

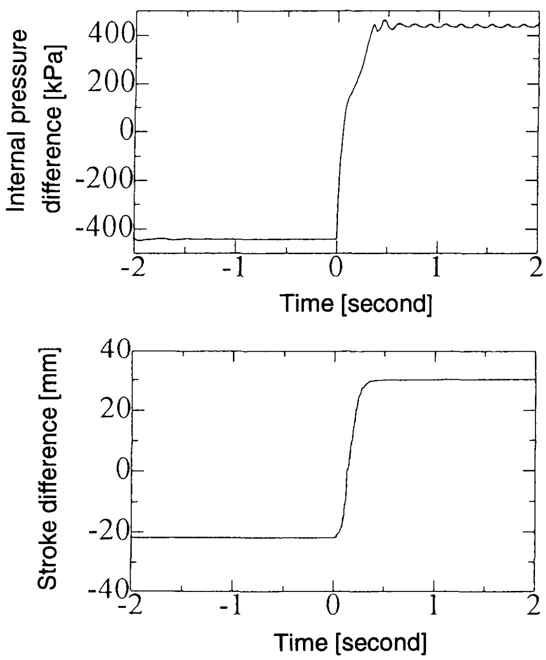


Fig. 5 Dynamic characteristics of tuna-like bending mechanism

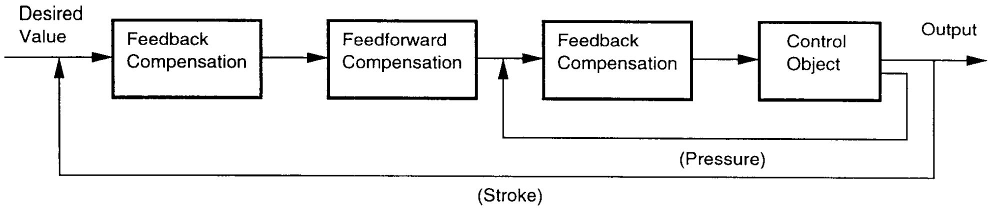
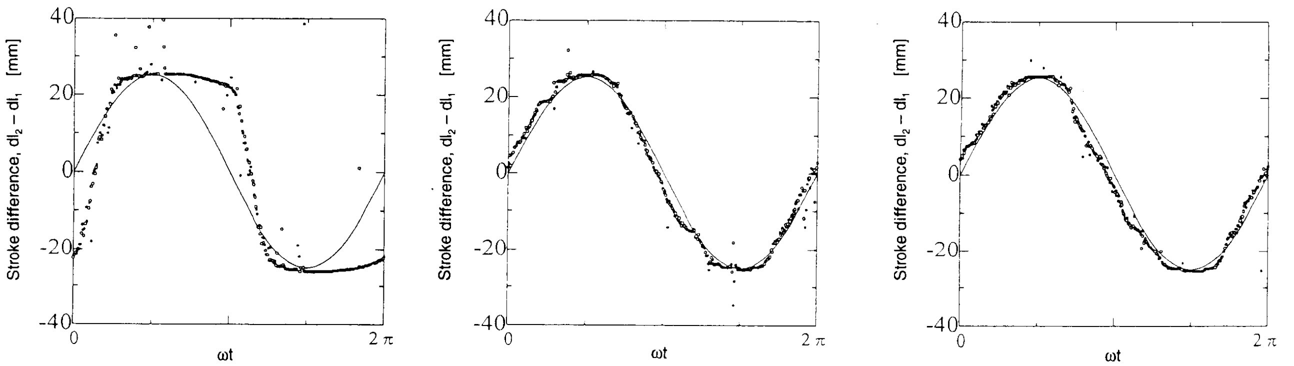


Fig. 6 Block diagram of control system (A position follow-up control system with both feedback and feedforward compensations)

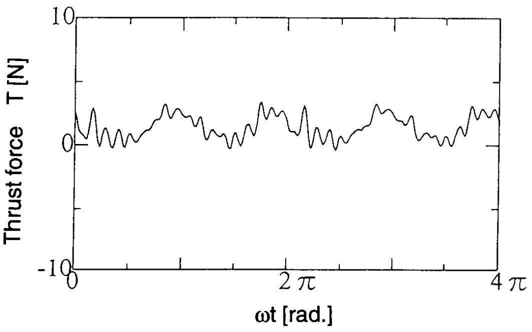


(a) Positioning follow-up control without feedforward and feedback compensation (b) Positioning follow-up control with feedforward compensation (c) Positioning follow-up control with feedforward and feedback compensation

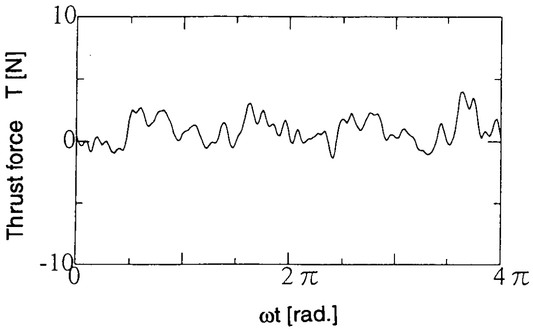
Fig. 7 Result of positioning follow-up control

motion control of a living creature proposed by Kawato[13] to a control system of the tuna-like bending mechanism. The designed control system was the positioning follow-up control which had both feedback and feedforward compensations. The block diagram of the control system is shown in Fig. 6. As the wing was oscillated by controlling strokes of two tendons connected with the antagonism artificial muscles through the multi-joint mechanism, control target, that is, a pitching angle of the wing indicated in Eq.(2) or (3) was an arbitrary continuous path that varied periodically. However, since a target value (a pitching angle of the wing) for the wing's behavior was limited, the stroke position of the artificial muscle was compensated by feedback control. The internal pressure of the artificial muscle was compensated by both feedforward and feedback control. The feedforward compensation of this system was obtained by approximately linearizing a curve of the hysteresis and saturation as the static characteristics. The system was optimized through adjusting gain.

Control experiments were carried out on condition that the instructive value of the wing's oscillation was a sinusoidal wave of pressure with the frequency of 1 Hz and the stroke amplitude of 50 mm. Figure 7 (a) shows the result of the positioning control without feedback and feedforward compensations. The plots in the graph indicate experimental values. The solid line indicates the instructive value. The experimental result was quite different from the sinusoidal curve. In the experiment, vibration of the tuna-like bending mechanism generated at frequency higher than the response frequency of a displacement meter and the oscillation of the displacement meter occurred frequently. Thus the performance of the control failed when the feedback compensation for the stroke position was added to this control system. Figure 7 (b) shows the result with feedforward compensation. Though a path following performance was improved by feedforward compensation, the error of the artificial muscle's stroke was still large (12.8%, max. 37.5%). Figure 7(c) shows the result with both feedforward and feedback compensations. An error became small (11.6%, max. 21.8%) by adding feedback compensation for the stroke position and the internal pressure of the artificial muscle compared with the control with the feedforward compensation. However, as for the feedback compensation for the stroke position, the feedback gain was adjusted to be so small as to prevent the displacement meter from oscillating. Sinusoidal positioning follow-up control was realized in the range of 2 Hz. It was found that the optimum control method for the tuna-like bending mechanism is the pressure control of the artificial muscles with both feedforward and pressure feedback

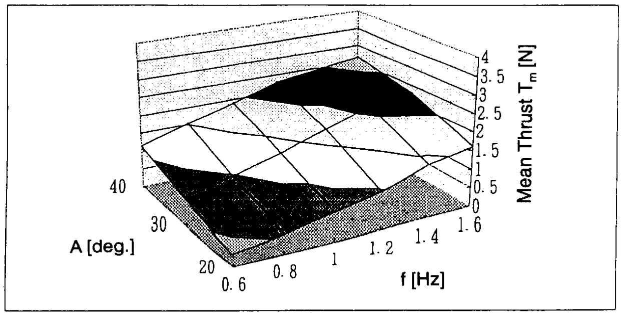


(a) Deformable wing



(b) Rigid wing

Fig. 8 Wave forms of thrust force in two cycles on deformable wing and rigid wing (Maximum pitching angle A=20 deg. and frequency f=1.4 Hz)



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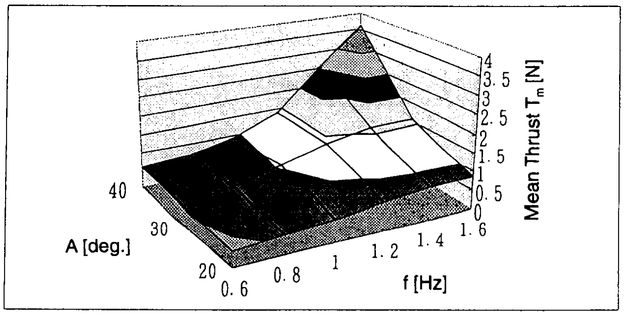
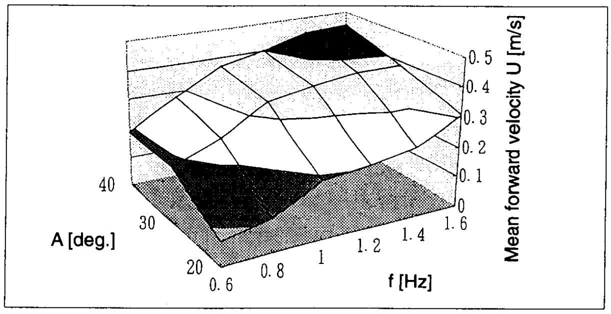
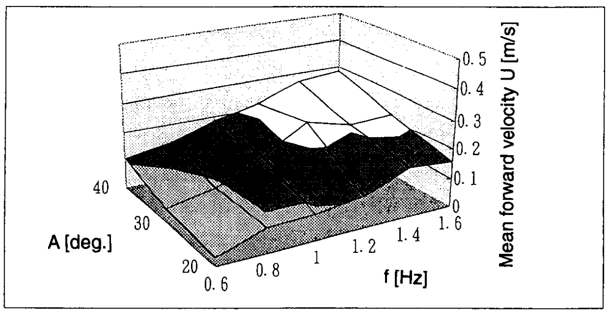


(b) Rigid wing

Fig. 9 Mean thrust force vs. frequency and maximum pitching angle on deformable wing and rigid wing



(a) Deformable wing



(b) Rigid wing

Fig. 10 Mean forward velocity of tuna-like bending mechanism vs. frequency and maximum pitching angle on deformable wing and rigid wing

compensations.

4.2 Propulsion performance of oscillating wing

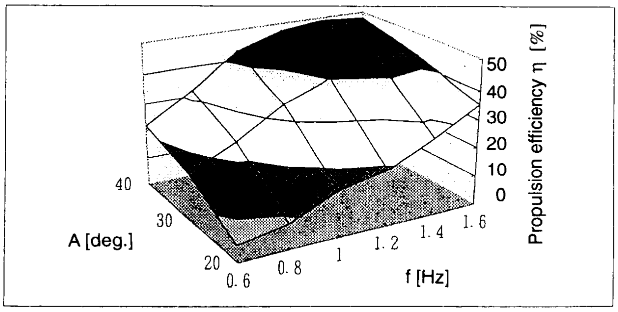
Here we note the result that we compared the propulsion performance on the deformable wing with that on the rigid wing and discussed. An example of wave forms of thrust force generated by oscillating a deformable wing and a rigid wing sinusoidally in the case of maximum pitching angle A=20 deg. and frequency f=1.4 Hz is shown in Fig. 8. Wave forms of thrust force for oscillating wings had two peaks of thrust force in one cycle in spite of including higher harmonics. The harmonic frequency was about 8 - 16 times the frequency of the oscillating wing. So it is considered that the harmonic noise was caused by the bending mechanism with four joints skeleton structure. The deformable wing generated positive thrust over one cycle. On the other hand, the rigid wing generated negative thrust around its maximum pitching angle. The thrust difference of the rigid wing was large compared with that of the deformable wing. Figure 9 shows mean thrust forces versus maximum pitching angle and frequency. Mean thrust of the deformable wing gradually increased with the increase of maximum pitching angle and frequency. Here, the mean forward velocity of the tuna-like bending mechanism is shown in Fig. 10. The mean forward velocities of the bending mechanism with the oscillating rigid wing were small compared with those with the deformable wing.

As for the rigid wing oscillating in the range of both high frequency and high maximum pitching angle, a steep increase of mean thrust occurred, though the rate of increase of mean velocity was small. It is thought that the load cell has measured the extra force resulted from reflection of wake against both the side walls of the static water tank and swaying surface of water in the tank. On the other hand, the deformable wing had little effect of the reflection of wake against the walls and gained the effective thrust because the wing deformed concave to the direction of oscillation and pushed water around the wing on to the rear. Therefore, it is said that the mean thrust force of the deformable wing was large compared with that of the rigid one.

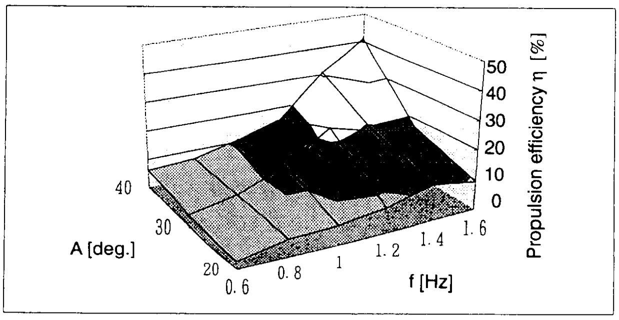
The efficiency of propulsion of the wing mounted on the tuna-like bending mechanism is defined as the following equation,

$$\eta=\frac{T_m\times U}{\frac{1}{\tau_0}\int_0^{\tau_0}F\times v_s dt}\times 100. \qquad (6)$$

The efficiency of propulsion is equivalent to the ratio of the power used for propulsion by the oscillating wing to the power consumed in actuating the air rubber artificial muscles for movement of the wing. Generally, the power for propulsion obtained by oscillating the wing is expressed as the product of the drag generated by the forward movement of the wing and its forward speed. Here, it is thought that the drag generated by the forward movement of the oscillating wing at a constant speed balances with the thrust force measured with a load cell in still water as the wing is oscillated at the same conditions as those of the forward movement test. Then the power used for propulsion by the oscillating wing is the product of the mean thrust force T_m and the mean forward velocity U of the tuna-like bending mechanism. The power used for actuation of the rubber muscles is the average in one cycle τ_0 of the value obtained by integrating the product of the force F generated by the rubber muscles and the velocity v_s of their stroke displacement. Figure 11 shows the propulsion efficiency of wings. The deformable wing shows the existence of maximum efficiency of propulsion over the range of this experiment shown in Fig. 11 (a). As for the rigid wing shown in Fig. 11 (b), the efficiency of propulsion was low compared with that on the deformable wing. The peak of the efficiency appeared with the same reason that the mean thrust had a peak. The experimental results described above and the observation of the deformable wing's behavior lead to the following: The deformable wing which had a phase difference between the leading edge and the trailing edge deformed concave to the direction of oscillation and generated the backward flow. Therefore, it is thought that the deformable wing obtained high mean thrust force and propulsion efficiency compared with the rigid wing.



(a) Deformable wing



(b) Rigid wing

Fig. 11 Propulsion efficiency vs. frequency and maximum pitching angle on deformable wing and rigid wing

5. Conclusions

A multi-joint bending mechanism using two air rubber artificial muscles modeled on the antagonism muscles and the caudal skeletal structure of a tuna was developed. A method of continuous path follow-up control of the wing in water was discussed in regard to the control of the internal pressure of the artificial muscles. Experiment on the performance of propulsion for a deformable wing with this control method was carried out.

The results of experiments were summarized as follows: The tuna-like bending mechanism with the wing had such characteristics as a linear delay system with hysteresis and saturation. A static characteristic was approximately linearized and was used to give feedforward compensation. As a target value for the wing's behavior was limited, the stroke position and the internal pressure of the artificial muscle were compensated by feedback control and adjusting gain optimized the system. A path following performance was improved by feedforward compensation and an error became small by feedback compensation. It was found that the optimum control method for the tuna-like bending mechanism is the pressure control of the artificial muscles with both feedforward and pressure feedback compensations.

As for the propulsion performance of the oscillating wings, the deformable wing generated positive thrust force in a cycle and obtained both high mean thrust force and high efficiency of propulsion because it deformed concave to the direction of oscillation and pushed water around the wing on to the backward. The rigid wing generated negative thrust force around its maximum pitching angle. As the fluctuation of the thrust force was large in a cycle, the mean thrust force and the propulsion efficiency were small compared with the deformable wing.

As the next target, we aim at developing the wing which is made up fin rays and soft skin like a caudal fin of tuna, and which actively deforms in order to improve the propulsion performance.

References

(1) Lighthill, M.J., Mathematical Biofluiddynamics, Soc. for Industrial and Applied Mathematics, (1975).

(2) Yao Tsu Wu, T., Hydromechanics of Swimming of Fishes and Cetaceans, Advances in Applied Mech. Vol. 11, No. 163 (1971).

(3) Chopra, M. and Kambe, T., Hydrodynamics of Lunate-tail Propulsion, Part 2, J. Fluid Mech., Vol. 79 (1977), pp. 49-69.

(4) Morikawa, H. and Isshiki, N., The Study on a Propulsion System by Fin Stroke, Bulletin of M.E.S.J., Vol. 8, No. 1 (1980), pp. 71-79.

(5) Morikawa, H. and Isshiki, N., Experimental Study on a Harmonically Oscillating Propulsion Wing, J. of M.E.S.J., (in Japanese), Vol. 18, No. 4 (1983), pp. 15-21.

(6) Isshiki, N. and Morikawa, H., Study on Dolphin-Style Fin Ship, Bulletin of SNAJ, (in Japanese), No. 642 (1982), pp. 684-691.

(7) Morikawa, H. and Isshiki, N., The Study on a Propulsion System by Fin Stroke—The Development of Fin Ship, J. of M.E.S.J., (in Japanese), Vol. 18, No. 5 (1983), pp. 33-40.

(8) Isshiki, N. and Morikawa, H., Development of Fin Ship Propelled by Dolphin-like Fin Stroke, Proc. 20th IECEC, Vol. 3 (1985), pp. 51-56.

(9) Isshiki, N. and Morikawa, H., Studies on Fin Ship Propelled by Oscillating Horizontal Tail fin, Proc. IMEC, Vol. 4 (1987), pp. 1-8.

(10) Noritsugu, T., Ando, F. and Yoshikawa, T., Control Performance of Rubber Artificial Muscle, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 60, No. 570, C (1994), pp. 557-562.

(11) Yamafuji, K., Kobayashi, T. and Kawamura, T., Elucidation of Twisting Motion of a Falling Cat and its Realization by a robot, J. of RSJ, (in Japanese), Vol. 10, No. 5 (1992), pp. 648-655.

(12) Bridgestone Co. Ltd., Technical Data for Rubbertuator, (in Japanese), No. 1 (1989).

(13) Kawato, M., Furukawa, K. and Suzuki, R., A Hierarchical Neural-Network Model for Control and Learning of Voluntary Movement, Biological Cybernetics, No. 57 (1987), pp. 169-185.