A Semi Free Piston Stirling Engine for a Fish Robot

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ABSTRACT

Underwater robots are widely used in the fields of ocean development, ocean investigation and marine environmental protection. We have taken much interest in the highly efficient propulsion of fish and attempt to apply the mechanism of fish-like swimming to the underwater robot.

In this paper, the author examined to adopt a semi-free-piston Stirling engine (SFPSE) for the power source of a fish robot. One of characteristics of the SFPSE is that the output power can be obtained directly from the reciprocating motion of a power piston. Typical thermal engines convert the reciprocating motion of the piston to rotary motion through a crank mechanism. The rotary motion is suitable for applications such as a screw propeller of a ship. However, in the case of a fish robot, it is the best way that the reciprocating piston drives the oscillating tail fin directly. A great deal of mechanical frictional loss can thus be reduced. This mechanism should result in high potential for efficiency.

Two types of experiments were done in this paper. First, the performance of a simple experimental SFPSE - tail fin system was examined experimentally, and it is compared with calculated results based on a simple simulation model. Second, a model boat with a fish-like swimming mechanism driven by a SFPSE was developed. The ship performance was investigated and the adaptability of SFPSE for fish robots was discussed.

INTRODUCTION

Underwater robots are widely used in the fields of ocean development, ocean investigation and marine environmental protection [1], [2]. As the request that the underwater operation should be carried out more efficiently becomes strong, autonomous underwater robots are planed, and several robots have been already developed. They need higher efficiency of propulsive performance.

The author has taken much interest in highly efficient propulsion of fish, and attempts to apply it to the underwater robot with fish-like swimming mechanism. In order to develop a high-performance underwater robot, we have studied and developed fish robots since 1999 [3], [4].

The purpose of this study is to develop new technologies, such as a highly efficient propulsion device, the fish robot which has high propulsive and dynamics performance, an intelligent fish robot, a suitable power source for a fish robot. Many types of the power source and tail fin driving system can be adopted for fish robots,

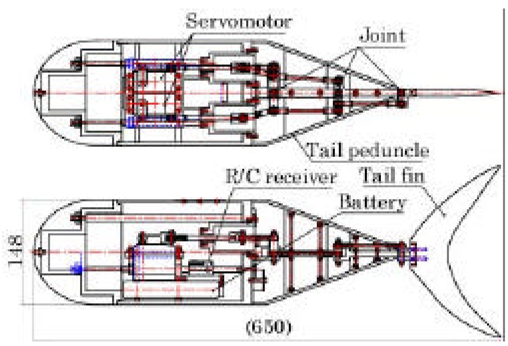


Fig. 1. An Experimental Fish Robot Powered by Servomotors

such as electric motors, thermal engines and air or oil hydraulic operation systems. They have peculiar characteristics respectively. Thus we must decide a suitable power source based on detailed discussions of the application, size and required performance of the developed fish robot.

In this paper, as one of the power sources for the fish-like swimming mechanism, the author examined to apply a semi-free-piston Stirling engine (SFPSE). Then, based on calculated results of a simple simulation model and experimental results of two types of prototype engines, the new application of a Stirling engine is discussed.

OUTLINE OF A FISH ROBOT AND A SEMI FREE PISTON STIRLING ENGINE

Fish Robot

Figure 1 shows one of the experimental fish robots. It has the body length of about 650 mm. The fish robot swims with an oscillating tail fin. Two servomotors are used as the power source, and the maximum frequency of the tail fin is about 3 Hz. It is worthy of notice that the fish robot uses oscillating motion for the propulsion, though a general ship uses rotating motion of a screw propeller.

Semi-Free-Piston Stirling Engine

Figure 2 shows the structure of a SFPSE that is the target in this research. A displacer piston is moved by an electric motor. Because a pressure difference on both side of the displacer piston is very small, the power input to the motor is very small. When the displacer piston moves, the pressure in the engine changes. As the power piston has no mechanical connection, it is forced to oscillate by the pressure change with one-degree of freedom. If the

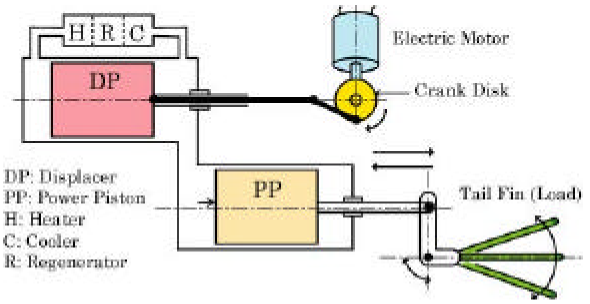


Fig. 2. Basic Structure of a SFPSE

displacer piston is driven to reciprocate with the same frequency as the resonant frequency of the power piston, the stroke of the power piston becomes progressively greater and both pistons keep suitable phase angle. This works on the same general principle as typical Stirling engines. One of characteristics of the SFPSE is that the output power can be used directly from the reciprocating motion of the power piston.

Until now, several types of SFPSEs have been developed as the electric power source for space application [5]. They drive a linear generator using reciprocating motion of the power piston, and get the electric power. They do not use the reciprocating motion directly.

Adaptability for a Fish Robot

In the past, an electric battery and electric motor have been used as the power source of an underwater robot. Electric motors are highly controllable, but the problem is that batteries do not allow for a long operation on a single charge. This is because electric batteries have low energy density. On the other hand, the Stirling engine has been researched for the underwater application [6]. If the Stirling engine can be used as the power source, it can use any source of heat; and there are any numbers of high-density heat sources available, such as fossil fuels. The Stirling engine has the potential for long un-refueled operation because of both high energy density fuel availability and the high efficiency potential of the Stirling engine itself.

Typical thermal engines convert the reciprocating motion of the piston to rotary motion through a crank mechanism. When the thermal engine with the rotary motion is used as the power source of a fish robot, the rotary motion must be converted to the oscillating motion of the tail fin. On the other hand, the SFPSE has a characteristic that the output power can be obtained directly from reciprocating motion of the piston. In the case of the fish-like swimming mechanism, the piston can drive the oscillating tail directly. A great deal of mechanical frictional loss can thus be reduced. This mechanism should result in high potential for efficiency

The SFPSE for a fish robot has lower operating frequency than that of typical kinematics Stirling engines. Then, pressure loss in the heat exchangers and inertia force of the displacer piston becomes very small. Thus it is expected that the electric energy to drive the displacer piston becomes small. Also, the SFPSE can be much controllable concerning operating frequency compared with the typical Stirling engines, because the displacer piston is controlled by an electric motor, and the movement of the power piston follows it automatically. Based on the above discussions, it is considered that the SFPSE is suitable for the power source of a fish robot.

SIMULATION MODEL AND THE FIRST PROTOTYPE ENGINE

In this chapter, a simple simulation model is developed for the mechanical design of a SFPSE. Furthermore, in order to investigate the engine performance when a tail fin in water is connected to it, a prototype engine is developed. The effects of the operating parameters are measured, and it is compared with the calculated results of the simulation model.

Simulation Model

Figure 3 shows a simulation model of a SFPSE. The working space is divided into four spaces, which are an expansion space, a regenerator space, a compression space and a power piston space. A pressure loss in the heat exchangers is not considered in the calculation. When the displacer piston moves along sine waves, the pressure in the engine, P is calculated by Eqs. (1)~(4) based on an isothermal model used in a general Stirling engine.

$$V_E = \frac{V_{SC}}{2}\left(1-\cos 2pft\right)+V_{DE} \tag{1}$$

$$V_C = \frac{V_{SC}}{2}\left(1+\cos 2pft\right)+V_{DC} \tag{2}$$

$$V_p = A_p x \tag{3}$$

$$P = \frac{M_0 R}{\dfrac{V_E}{T_E}+\dfrac{V_R}{T_R}+\dfrac{V_C}{T_C}+\dfrac{V_P}{T_P}} \tag{4}$$

Here, V is volume, and T is gas temperature. Additional characters E, R, C and P indicate the expansion space, the regenerator space, the compression space and the power piston space respectively. Also, V_{SE} is a swept volume of the displacer piston, V_{DE} is a dead volume of the expansion space, V_{DC} is a dead volume of the compression space, f is frequency, M_0 is total mass of the working gas, and R is gas constant.

Two mechanical springs are attached to an output rod of the power piston as shown in Fig. 3. The rod is connected to a plate through a link mechanism. The plate moves in water, thus the damping force, F_{fin} is obtained. The equation of motion of the power piston is shown in Eq. (5) as the forced vibration with viscous damping.

$$m\frac{d^2 x}{dt^2} = F_P - F_{fin} - 2k\left(x - x_S\right) \tag{5}$$

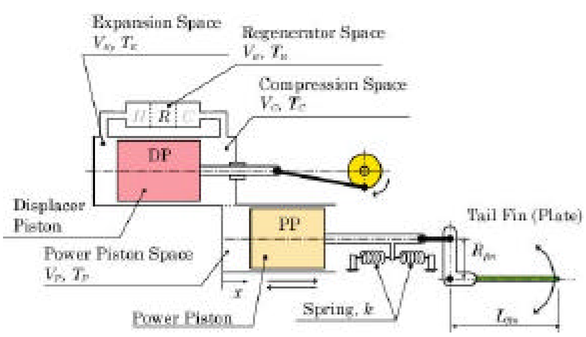


Fig. 3. Simulation Model of a SFPSE

Here, m is total reciprocating mass, which consists of the mass of the power piston, m_P and equivalent mass of the plate, m_{fin}. x is position of the power piston, t is time, x_s is the central position of the springs, and k is the spring constant.

Force, F_p, which is caused by a pressure difference on both side of the power piston, is calculated by Eq. (6) with sectional area of the power piston, A_p, pressure, P and pressure at the behind the power piston, P_B (atmospheric pressure).

$$F_p = A_P\left(P - P_B\right) \qquad (6)$$

In Eq. (5), F_{fin} is the damping force caused by the moving plate in water. It is calculated as the drag force of a flat plate by Eqs. (7) and (8).

$$F_{fin} = C_D \frac{1}{2} r\left|v_{fin}\right| v_{fin} S \qquad (7)$$

$$v_{fin} \cong \frac{L_{fin}}{2R_{fin}} \frac{dx}{dt} \qquad (8)$$

Here, C_D is a drag coefficient, and it is set to C_D=1.1 in the following calculation. ? is density of water, and v_{fin} is velocity of the plate at the center of gravity. R_{fin} is length of the crank arm, L_{fin} is length of the plate, and S is area of the plate.

From Eqs. (5)~(8), Eqs. (9)~(11) are derived with coefficient, c'.

$$m\frac{dy}{dt} = A_P\left(P - P_B\right) - c' y^2 - 2k\left(x - x_S\right) \qquad (9)$$

$$y = \frac{dx}{dt} \qquad (10)$$

$$c' = \frac{1}{8} C_D r S \left(\frac{L_{fin}}{R_{fin}}\right)^2 \qquad (11)$$

The position of the power piston, x is calculated by the solution of Eqs. (9) and (10) with the Runge-Kutta method.

Structure of the Prototype Engine

Figure 4 shows the structure of the prototype engine. Table 1 lists specifications of the engine. The engine has a simple structure without a regenerator. A displacer piston does not have any seal device, and has a clearance of 1 mm with a cylinder. In order to decrease a gas leakage and a friction loss, a glass syringe is used as the power piston and cylinder. Two mechanical springs are attached to a rod of the power piston. In the experiments, an aluminum plate, which has 3 mm of thickness, is attached to the rod through a crank mechanism. The plate oscillates in a small water tank.

Measuring System and Experimental Condition

Figure 5 shows a measuring system for the experiment. Photo-micro-sensors measure the top dead center and rotating angle of the displacer piston. A laser displacement sensor measures stroke of the power piston. Thermocouples measure gas temperature, and a strain gage type pressure sensor measures the gas pressure in the power piston space.

Table 2 lists an experimental condition. Three springs and three plates are used in the experiments. Characteristics of the forced vibration with viscous damping are adjusted by the change of the spring constant, k and length of the plate, L_{fin}. Heat input using an electric wire is adjusted to keep the expansion gas temperature at

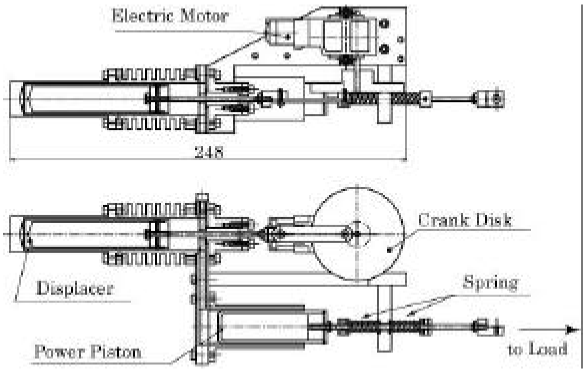


Fig. 4. Structure of the Prototype Engine

Table 1. Specifications of the Prototype Engine

Displacer Piston	
Bore	18 mm
Stroke	16 mm
Power Piston	
Bore	20mm
Stroke	～20 mm
Reciprocating Mass	46.6 g
Frequency	0～12 Hz
Mean Pressure	101.3 kPa
Heating Device	Electric wire
Cooling Device	Air cooling

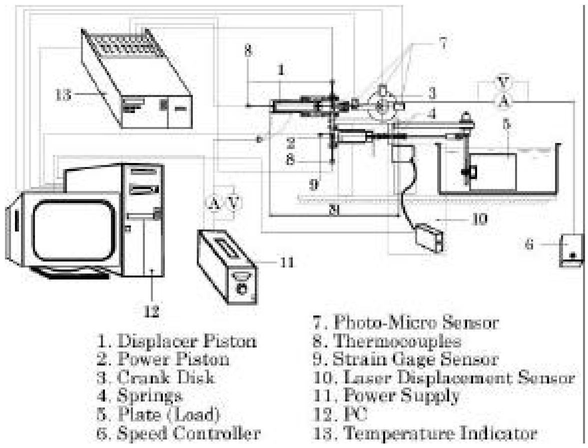


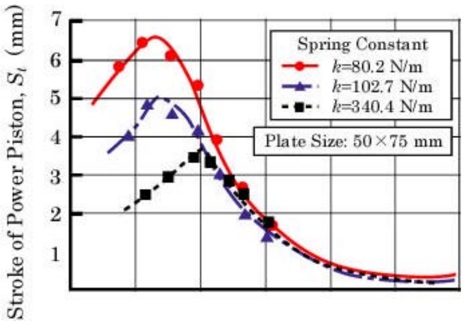
Table 2. Experimental Condition

Mechanical Spring Spring Constant, k	80.2 N/m, 210.8 N/m, 340.4 N/m
Plate Height x Length (Equivalent Mass, m_{fin})	50×50 mm (28.2 g), 50×75 mm (63.5 g), 50×100 mm (112.9 g)
Expansion Space Gas Temperature, T_E	600 deg C.

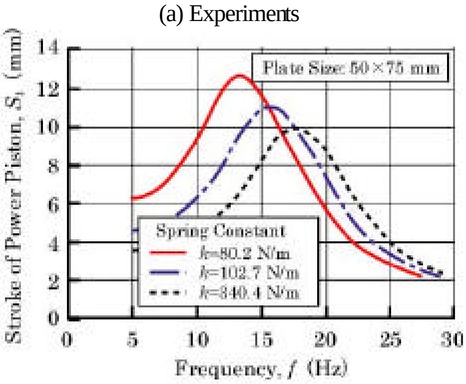
600 deg C.

Experimental Results and Comparison to the Simulation Model

Figure 6 shows the relation between the frequency, f and the stroke of the power piston, S_t with k as parameter, for both the calculation and the experiment. In the figure, it is clarified that the motion of the power piston has the resonant frequency. The resonant frequency becomes higher with increase of k. The stroke, S_t decreases with increase of k. Also a tendency of the calculated

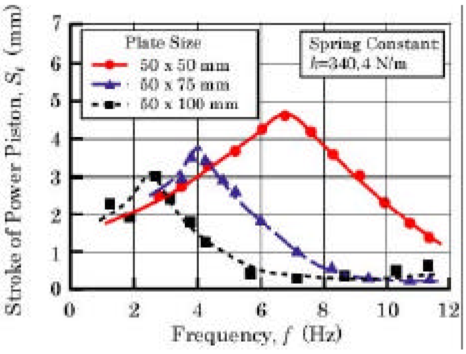


(a) Experiments

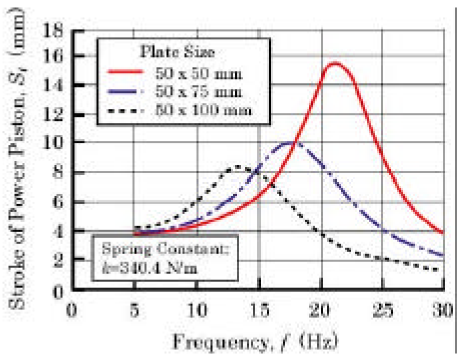


(b) Calculations

Fig. 6. Effects of the Spring Constant



(a) Experiments



(b) Calculations

Fig. 7. Effects of the plate size

results agrees with that of the experimental results, though they differ quantitatively. The calculated results of the resonant frequency are higher by 3~4 times than the experimental results, and the calculated results of the stroke are 2 times of the experimental results approximately.

Figure 7 shows the relation between the frequency, f and the stroke of the power piston, S_t using the different size of the plate both the calculation and the experiment. Each plate has each equivalent mass, m_{fin} shown in Table 2. Therefore the change of the plate size means the change of both the damping force, F_{fin} and the total mass, m_{fin} in Eq. (5). In the figure, the resonant frequency and the maximum stroke of the power piston decrease with increase of the plate size. Tendency of the calculated results agree with that of the experimental results, though they differ quantitatively, which is similar to Fig. 6.

It is considered that the effects of water flow around the plate cause the difference of quantitative characteristics. The damping force, F_{fin} of Eq. (7) shows the drag of a moving plate with a constant velocity. On the other hand, in the experiments, the plate has oscillating motions. Thus, there is a possibility that the damping force is affected by generation of eddies strongly. Also, if the engine is applied to a swimming fish robot, it is expected that the water has more complicated flow. It is needed that the damping force in the simulation should be discussed more in detail.

Volume change in the working space of a SFPSE becomes suitable when the engine is operated at the resonant frequency. From the above experiments, it is clarified that the resonant frequency is affected by the mass, m, the spring constant, k and the damping force, F_{fin} strongly. Namely, it is important that these parameters be determined in a design stage of the engine or be controlled in the operation of the engine.

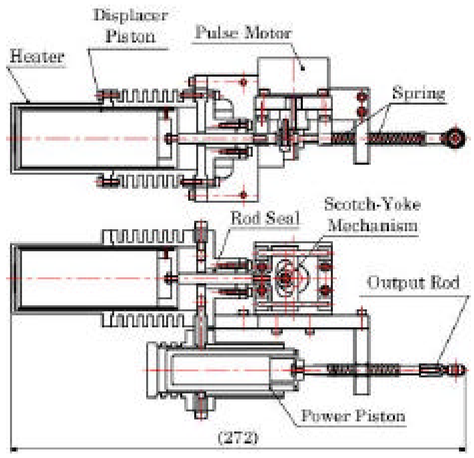
DEVELOPMENT OF A MODEL BOAT WITH THE FISH-LIKE SWIMMING MECHANISM

In the previous experimental researches on the fish robot, it was clarified that the swimming speed of a fish robot is affected by the frequency, amplitude and feature of the tail fin. However, the damping force of the tail fin attached to a fish robot has not been measured yet. Ideally, the power source of a fish robot should be discussed and designed after grasping the performance of propulsive efficiency and the damping force characteristics. However, the above simulation model cannot analyze accurately the performance with the damping force. Therefore, in order to investigate the engine performance and any problems for_adaptability for a fish robot, a model boat with the fish-like swimming mechanism driven by a SFPSE was developed

Structure of the Engine and the Model Boat

Figure 8 shows the structure and appearance of the prototype engine. The engine specifications are listed in Table 3. The basic structure of the engine is the same of the first prototype engine shown in Fig. 5. It has a simple heater and a displacer piston, and does not have a regenerator. A pulse motor is used to drive the displacer piston, because it can set the frequency easily. The frequency of the pulse motor is controlled from 0.5 to 4.0 Hz with 0.5 Hz steps by a microcomputer. A Scotch-yoke mechanism is adopted as the drive mechanism for the displacer piston. A slide bearing, which is made of PTFE, is used as a rod seal of the displacer piston. A glass syringe is used as the power piston and cylinder. Two mechanical springs, which have k of about 360 N/m are attached to the rod of the power piston.

Figure 9 shows the structure and appearance of the model boat. A twin-hull type boat is adopted with considerations of stability. The prototype engine is located on the central position of the boat. A small gas burner is located at the front of the engine, and heats the



(a) Structure

(b) Appearance

Fig. 8. The Prototype Engine for a Model Boat

Table 3. Specifications of the Engine for the Boat

Displacer Piston Bore Stroke	 36 mm 10 mm
Power Piston Bore Stroke	 27.5 mm ~15 mm
Frequency	0~4 Hz
Mean Pressure	101.3 kPa
Heating Device	Gas burner
Cooling Device	Air cooling

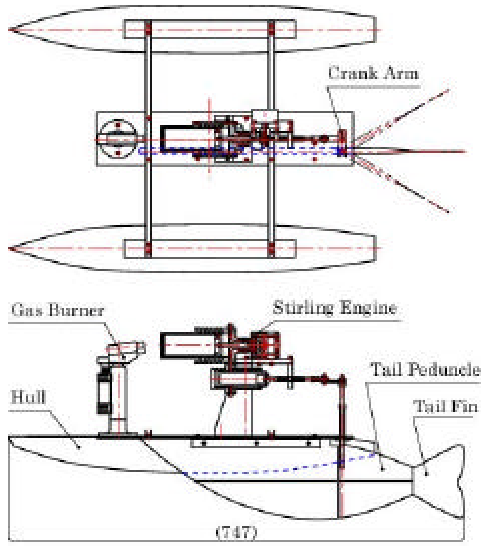
heater head directly. The fish-like swimming mechanism is located at the rear end of the boat. The mechanism is connected to the rod of the power piston through a crank mechanism. A tail peduncle is made of a hard wood, and the tail fin is made of a soft plastic plate, which has 0.75 mm of thickness. The total weight, including the engine, is about 2 kg.

Four different sized tail fins are used in the following experiments, and the characteristics of the vibration changes depending on the tail fins. The four tail fins have similar figures as shown in Fig. 10. Type B, Type C and Type D have 80 %, 60 % and 40 % of projected area of Type A respectively.

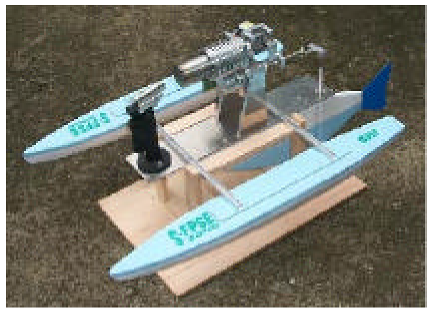
Performance of the Model Boat

Swimming speed of the model boat is measured at a water tank, which has 10 m length and 3 m width. After the pre-swimming of about 3 m to have a stable velocity, the measurement to get the swimming speed begins. The average speed is calculated by measuring time in which the boat swims 1 m.

Figure 11 shows experimental results of the first trial for the



(a) Structure



(b) Appearance

Fig. 9. The Model Boat with the SFPSE

relation between the frequency, f and the speed of the boat, V. In the experiment, top speed reaches about 0.12 m/s at 3 Hz of frequency using Type B (80 %) tail fin. From the considerations of the size of boat and tail fin, the author thinks that the speed is not enough high. If the spring constant and the size of the tail fin are adjusted suitably, it is expected that the boat can get higher speed. Also, it is considered that the experimental results have no good accuracy, because the model boat was affected by disturbance such as a wind, and could not keep a straight coursesuitably.

On the other hand, it was checked by eye measurement that the

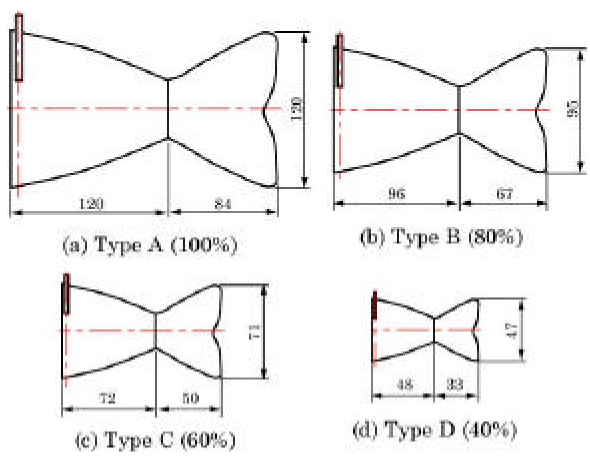


Fig. 10. Tail Fins using the Experiments

stroke of the power piston was larger at lower frequency than the frequency at which top speed is obtained. This means that the resonance frequency, at which the stroke becomes largest, is in the lower range than the frequency of top speed. That is, since the amplitude of the tail fin decreased with increasing frequency, it is considered that the propulsive force did not increase enough.

It is clarified that the speed is affected by the resonant frequency. It is necessary to measure the stroke change of the power piston and the pressure change in working space in order for the detailed evaluation. It is thought that higher efficiency of the fish-like swimming mechanism is attained when the stability of the spring and the damping force of the tail fin are controlled pertinently with the measurements of the stroke and pressure.

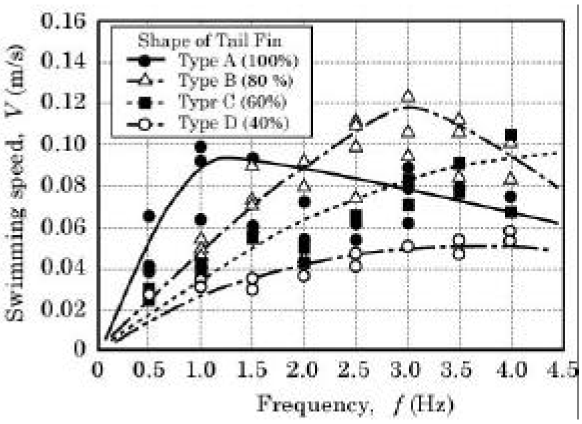


Fig. 11. Experimental Results

CONCLUSION

In this paper, the applicability of a SFPSE to a fish robot was examined. And, in order to grasp the basic characteristic of the engine, the check of operation by a simple prototype SFPSE was performed. Furthermore, the model boat, which was driven by a SFPSE, was developed, and the examination was performed. Although it has not reached the development of performance analysis, which is useful for the engine design or the optimum control, it is thought that much knowledge was acquired in these experiments.

It is considered that a fish-like swimming mechanism has possibility of highly efficient propulsion. However, when an electric motor or a thermal engine is applied to the fish robots, it is necessary to convert the rotating motion to oscillating motion. Because the large mechanical loss caused by the re-changing is expected, the system efficiency may become low remarkably. If a SFPSE can be applied to the mechanism, it is possible to develop a highly efficient propulsive system.

On the other hand, there are many subjects left behind, such as large-sized engine with lower operating frequency or selection of the suitable heat source for fish robots. After solving the problems by new technologies, the high performance fish robot powered by the Stirling engine will be able to developed.

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