Development of Oscillating Fin Propulsion System and Its Application to Ships and Artificial Fish

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The purpose of this paper is to describe the feasibility research of the application of oscillating fin propulsion control system to vehicles. The system was designed and constructed to be combined with a ship model. Tank tests using the ship model have confirmed the system's feasibility. As a result, several advantages of the oscillating fin system have been found out. A neural network was successfully applied for an identification of the ship model dynamics with the oscillating fin, and its effectiveness was confirmed. Artificial fish, intended as an amusement attraction for aquariums, using the oscillating fin propulsion system have been developed. Its capability of un tethered 3-dimensional movement was confirmed.

1. Introduction

It is well known that marine creatures such as fish swim using small power even at high speeds (dolphin: 60 km/h, swordfish: 80 km/h\textsuperscript{3}) and sweetfish, etc. are superior in their resting state maintenance characteristics. These characteristics as creatures have been of interest as science from the old times and much research has been conducted\textsuperscript{4}, however, it is rare to study these characteristics from the viewpoint of an engineering subject\textsuperscript{5}.

One such research is on a flexible oscillating fin control system which could be used for the propulsion of marine vehicles by positively making the most of the characteristics of the flexible part. This method obtains a propulsion force by oscillating fins equipped to vehicles on the analogy of the motion of marine creatures.

The linear theory analysis has been applied to the rigid oscillating fin which regards the oscillating fin as a rigid part, and past experiments and research\textsuperscript{6} have reported that the flexible fin is superior to the rigid fin. Theoretical studies\textsuperscript{7} on flexible oscillating fins have been partly conducted, while studies on the flexible fin including the control system have not yet been performed. In this research after the control system for a flexible oscillating fin propulsion device and the oscillating fin driving device were designed and manufactured, a cruising test was performed first by a numerical simulation and then with a model ship, and the fundamental performance has been grasped and prospects of putting them to practical use have been obtained. And artificial fish for amusement in aquariums, etc. have been developed as an applied product.

2. Outline of the system

In many cases the kinetic parameters of the oscillating fin cannot be directly detected in control of an oscillating fin and there are problems choosing and identifying parameters to be used for control, and a control system able to cope with such problems should be architected.

In this research, to cope with the above problems, a study on the application of neural network learning control\textsuperscript{8} has been made using a model ship, the control algorithm is architected and the control computer software has been mounted, and then the cruising test was made in a test tank.

Fig. 1 shows the outline of the test device for the oscillating fin propulsion system which has been developed this time.

\textbf{Fig. 1 Test devices}
Test devices for oscillating fin are shown.

The neural network learning algorithm has been architected in the control device. It consists of a hierarchy network of three layers: an input, middle, and output layers. The Hess & Smith method\textsuperscript{9} has been expanded to a nonstationary problem and furthermore, a model applying the method of solving deformation of the wake vortex using the discrete vortex method\textsuperscript{10} has been used and the I/O variables and node numbers of the middle layer have been determined by simulation. By this the input signals are formed to give the ship speed, propulsion thrust, the learning signal, and the output signal to give the vibrating frequency, phase angle, sway angle and yaw angle amplitudes. The node number of the middle layer was determined to be four from the viewpoint of error energy function and simplification of the system.

The two-phase control oscillator, AC servo control amplifier, oscillating fin driving device and small-sized 3-component force block gauge for fluid measurement were designed and manufactured for this test. The oscillating fin driving device was designed to be actuated linking sway direction motion with yaw direction motion by mounting the yaw direction driving device on the sway direction driving device.

3. Configuration of the control system

The oscillating fin is actuated by varying the amplitude, phase difference and oscillating frequency of sway and yaw

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motion. The oscillating fin consists of rigid and flexible parts and the propulsion efficiency is improved by the flexibility of the flexible part. The control computer consists of the neural network software and the command generator. The command generator gives the command values of the sway and yaw motion parameters of the oscillating fin. During the optimal adjustment of motion parameters of the oscillating fin in the cruising test, etc., the neural network gets the learning data for back propagation. After the network was constructed by back propagation, the oscillating fin is actuated only by the neural network control and can self-cruise the vehicle.\(^\text{19}\).

4. Study by simulation

The oscillating fin propulsion system is used as a vehicle's actuator. In this paper this system is applied to a marine ship as a vehicle.

A ship motion model\(^\text{19}\) in surge, sway and yaw direction was constructed and the model shown in Fig. 2 was constructed as an oscillating fin motion mode\(^\text{19}\). After numerical simulation and the tank test were performed in case the oscillating fin propulsion system were loaded on a model ship of 3.5 m in length, 0.5 m in breadth and 194 kg in weight, oscillating characteristics in the numerical simulation agreed well with that in the tank test as an example is shown in Fig. 3.

Through this result, a case study on motion performance using simulator, including, for example, a study on installation of plural oscillating fins became possible.

5. Trial production and test of the flexible oscillating fin propulsion device

The flexible oscillating fin propulsion device was produced experimentally and only the flexible oscillating fin propulsion device was independently tested before loading it onto a model ship to examine the influence of the oscillating fin shape and the flexible part on propulsion\(^\text{19}\).

As shown in Table 1, several types of oscillating fins were tested by varying the elastic modulus of the flexible part and shape.

<table>
<thead>
<tr>
<th>Type</th>
<th>Configuration (mm)</th>
<th>Modulus of elasticity of the flexible part (mm/N)</th>
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<th>Configuration (mm)</th>
<th>Modulus of elasticity of the flexible part (mm/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>200 200</td>
<td></td>
<td>D</td>
<td>125 75</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Rigid part</td>
<td></td>
<td></td>
<td>Flexible part</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>75 125</td>
<td>7.3</td>
<td>E</td>
<td>75 125</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>Flexible part</td>
<td></td>
<td></td>
<td>Rigid part</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>25 75</td>
<td>10.3</td>
<td>F</td>
<td>75 125</td>
<td>9.7</td>
</tr>
<tr>
<td></td>
<td>Flexible part</td>
<td></td>
<td></td>
<td>Flexible part</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>250 200</td>
<td>6.3</td>
<td></td>
<td>Flexible part</td>
<td></td>
</tr>
</tbody>
</table>

\(^{19}\) Mitsubishi Heavy Industries, Ltd.
Table 2 shows the power and efficiency for the different types of oscillating fins shown in Table 1.

6. Tank test using a model ship

The oscillating fin propulsion device was loaded onto a model ship and the tank cruising test was carried out. The purpose of the tank test was to grasp the propulsion characteristics as a ship's actuator and self-cruising capability using only the neural network.

Fig. 4 shows the model ship with the oscillating fin propulsion device. During the cruising test by using the command generator the cruising test learning data for the neural network control is accumulated and the weights in the neural network are determined by back propagation. Then the oscillating fin driving command signal is given by the forward operation in the neural network based on the target value command and then the model ship cruises.

![Fig. 4 Ship model with oscillating fin propulsion device](image)

The ship model with the oscillating fin propulsion device developed as an applied product is shown.

The results of the cruising test can be summarized as follows.

(1) Based on the results of the independent oscillating fin test, the average thrust force generated from the oscillating fin generates the maximum positive thrust force around a phase difference of 90 degrees of sway and yaw motion and generates the maximum negative thrust force around −90 degrees. Thrust force changes like a sine curve with respect to the phase angle. In this example, the sway amplitude is 100 mm and the yaw amplitude is 20 degrees. The average thrust force using the type A oscillating fin in Table 1 increases in proportion to the oscillating frequency and the sway amplitude.

(2) As shown in Fig. 5, a positive ship speed of 0.5 m/s around a phase angle of 90 degrees and negative ship speed of 0.3 m/s around a phase angle of −90 degrees were obtained. Under these conditions, ship speed increases in proportion to the oscillating frequency. For example, the ship speed reaches 0.8 m/s at an oscillating frequency of 1.2 Hz.

(3) As a result of the self-cruising test with a neural network, it was found that it was possible to determine the control command signal by a function of the interpolation toward
any target setting signal after the learning signal had been acquired.

Fig. 6 shows the results of the self-cruising test by a neural network. The neural network is effective for the identification of a ship model for a vehicle equipped with the oscillating fin. Its application for any ship type has been conducted and the effectiveness was confirmed. The generality of its application to vehicles can be widened by the neural network.

(4) The transition of the thrust force from a positive to a negative direction can be conducted smoothly only by changing the phase angle of the sway motion and yaw motion. Therefore, it was found that the transition of the thrust force from progress to reverse of the vehicle can be conducted smoothly.

(5) As the test data in Table 2 show, propulsive thrust and efficiency can be improved by using a flexible part in part of the oscillating fin. The characteristics can be further improved by improving the fin shape.

(6) Gyration can be conducted by changing the central angle of the fin in one oscillating fin propulsion system. Therefore, this system has a function of gyration while propulsion is conducted by one actuator.

(7) A mathematical model of vehicle equipped with the oscillating fin was architected and it was found that it matched the test results.

7. Development toward artificial fish

Based on the basic technical research of the flexible oscillating fin propulsion system, artificial fish have been developed as an applied product of this system. Fig. 7 shows a sea-bream type artificial fish (weight: 2.6 kg, length: 60 cm) and Fig. 8 shows a coelacanth type artificial fish (weight: 40 kg, length: 1.2 m).

Batteries and a buoyancy control device are built into the artificial fish and 3-dimensional movement of the artificial fish is possible by remote control using underwater wireless information communication. The computer wireless maneuvering control device and non-contact submerged charging equipment as peripheral equipment have been developed and continuous swimming can be conducted for hours.

As an example is shown in Fig. 9, very realistic and lifelike swimming method can be realized by the flexible oscillating fin propulsion and its application to an aquarium event hall and various amusement systems is possible.

8. Conclusion

The advantages of the oscillating fin propulsion system can be summarized as follows.

(1) A safe actuator can be created for avoiding dangerous rolling generated by screw.

(2) Identification of vehicles with various oscillating fins by the neural network becomes possible. The generality of the system's application is then improved.

(3) The transition from positive/negative to negative/positive thrust force can be conducted easily by the phase angle control of the oscillating fin motion. The hovering characteristics of vehicles are therefore improved.

(4) One fin can control both the thrust force and its direction simultaneously. Then, a compact actuator can be constructed.

(5) The fin's flexibility can be utilized actively. It is therefore possible to improve the propulsion performance.

(6) Multi-joint fin structure has possibilities for further improvement of the propulsion performance and a quiet and calm motion by a large fin is promising in the future by setting up widely the actuator operating area.

(7) Realistic movement becomes possible by making the most of the oscillating fin propulsion system for artificial fish, etc.

Fig. 7 Sea-bream type artificial fish
An artificial fish capable of three-dimensional movement without any tether is shown.

Fig. 8 Coelacanth type artificial fish
Another type artificial fish is shown.

Fig. 9 Artificial fish swimming view
The view of an artificial fish movement in a water tank is shown.
As a result of the research, it was found that oscillating fin propulsion device is especially effective for actuators in a muddy or sludgy water cruising area, a quiet cruising demand area, a slow speed cruising area and a hovering area, and actuators of artificial fish for amusement at aquariums, etc. In this research the test was conducted by the oscillating fin propulsion device using sway and yaw motion. Propulsion is possible by the same theory even by a method of using heave and pitch motion.

The research outcomes can be widely applied to the propulsion system of various vehicles such as ships, underwater vehicles, artificial fish, leisure equipment and underwater monitoring robots, and some of the products have been realized.

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