# Turning Performance of Fish-Type Microrobot Driven by External Magnetic Field

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**A new turning method based on hydrodynamics was applied for a magnetically driven fish-type microrobot. The swimming propulsor of the robot consists of a magnet and a cantilever with a caudal fin, and can be driven by external alternating magnetic fields. In order to realize a fish-like turning, the fin motion was controlled by the waveform of the external magnetic fields. Two waveform patterns of the magnetic fields were designed for the turning by the caudal fin. As a result of the water tank test, the microrobot showed good turning performance under both waveform patterns.**

***Index Terms*—External magnetic field, fin oscillation, microrobot, permanent magnet, turning performance.**

## I. Introduction

SINCE a microactuator, including a permanent magnet, can be remotely driven by external magnetic fields, it is suitable for a mobile microrobot working in a closed space. Several attempts have been made on the microrobots for pipeline inspection and treatment inside a human body [1], [2].

In addition to such industrial and biomedical applications, we would like to propose a new type of magnetically driven microrobots for amusement and educational use. In order to explore the possibilities, we have constructed a fish-type microrobot that can propel itself using a caudal fin. However, the basic characteristics such as the mechanical properties of the propulsor and the maneuverability have never been examined. In this study, therefore, we began with the examination of the static and dynamic mechanical properties of the swimming propulsor. Next, in order to realize a fish-like turning, we attempted to control the fin motion by changing waveforms of the magnetic fields. This paper describes the design of the waveform patterns for two turning modes and the results of the turning performance test.

## II. Structure and Actuation Principle

Fig. 1 shows a photograph of a fish-type microrobot. It consists of a rigid body balanced with a float and a weight, and a propulsive mechanism including an angular oscillator and a bending part. Fig. 2 shows the structure of the propulsive mechanism. The oscillator is composed of a cylindrical NdFeB magnet, 5 mm in diameter and 3 mm in length, with a rotary axis and a pair of arms. The bending part is composed of a 75-$\mu$m-thick polyimide cantilever and a 100-$\mu$m-thick polyethylene caudal fin. The size of each part is as shown in Fig. 2. The arms of the magnet and the both sides of the caudal peduncle are linked by means of two polyester wires.

Fig. 3 shows the actuation principle of the propulsive mechanism. When a magnetic field is applied perpendicular to water surface, the magnet rotates due to magnetic torque and then one side of the arms pulls the wire, which causes the cantilever to bend to one side. Under alternating magnetic fields, therefore, the magnet oscillates angularly and two arms pull the wires alternatively. As a result, the caudal fin oscillates from side to side and can produce a thrust. It should be noted that the magnetic

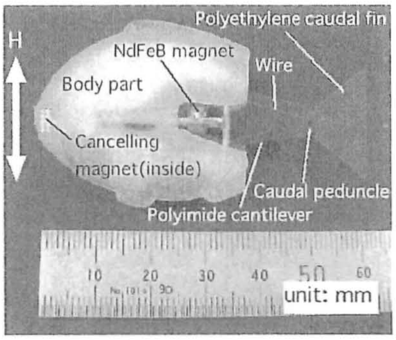


Fig. 1. Photograph of fish-type microrobot.

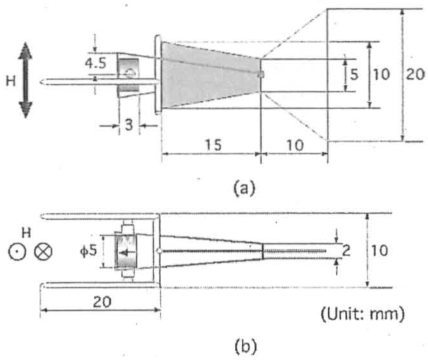


Fig. 2. Structure of swimming propulsor. (a) Side view. (b) Top view.

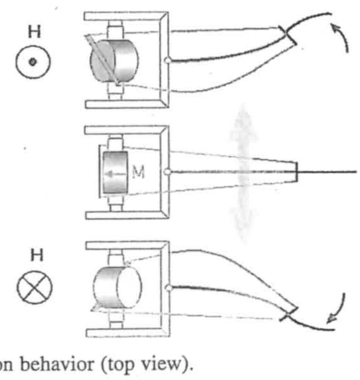


Fig. 3. Actuation behavior (top view).

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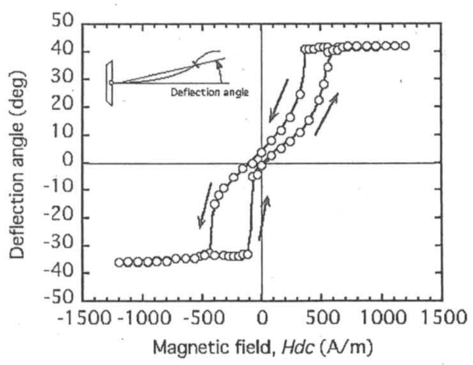


Fig. 4. Static deflection curve of cantilever.

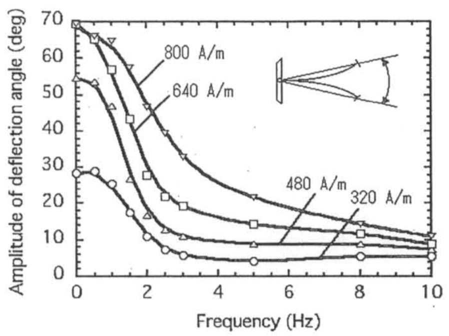


Fig. 5. Amplitude of deflection angle of cantilever in water.

torque causes pitching (the body oscillation about the horizontal transverse axis), as well as the fin oscillation when the microrobot swims freely. In order to reduce the pitching moment, the canceling NdFeB magnet, 3 mm in diameter and 1.5 mm in length, magnetized in the opposite direction to the oscillating magnet, is placed inside the head of the body part.

## III. Mechanical Properties of Propulsive Mechanism

At first, the mechanical properties of the propulsive mechanism were investigated. Fig. 4 shows the static deflection angle of the polyimide cantilever as a function of dc magnetic field $H_{dc}$. The deflection showed strong nonlinearity including a jump and a large hysteresis, which was mainly caused by buckling (sudden deformation induced by bending moment acting on the free end) of the cantilever. Also, asymmetry of the deflection to both sides was observed. This may be due to that the polyimide film used here has a slight bend at the initial product condition. Such deflection properties should be improved for precise control of the fin motion, but we are not concerned here with this problem.

Fig. 5 shows the frequency dependence of the amplitude of the deflection angle for the cantilever, measured in water. The amplitude decreased rapidly at low frequencies below 5 Hz. Furthermore, a mechanical resonance peak was not observed at all. These results mean that viscous force is dominant for the propulsive mechanism.

## IV. Turning Performance

According to a report about a large-size robot fish, there are three fundamental modes for turning by caudal fin [3]. In this study, we focused on two turning modes (modes A and B) and designed the waveform of the magnetic field suitable for each turning. The definition of each turning mode is given below.

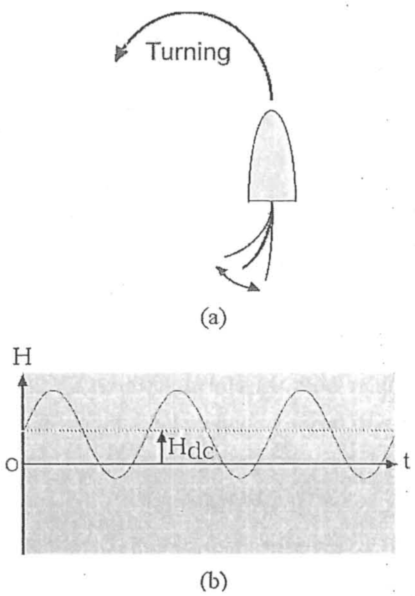


Fig. 6. Concept of turning mode A. (a) Turning in mode A. (b) Waveform for mode A.

Before moving on to the turning test, we have to decide the standard condition of alternating magnetic fields. As seen in Fig. 5, the amplitude of the fin oscillation beyond 5 Hz was too small to control the motion of the caudal fin. In addition, from the straight swimming performance test, the maximum swimming speed over 20 mm/s was obtained when $H_{ac}$ of more than 640 A/m was applied around 3–5 Hz. Considering these results, we used $H_{ac}$ of 640 A/m at 3 Hz as the standard in the following experiment. The turning test was performed in a cylindrical water tank with a diameter of 236 mm, which was wound with a coil ($\mathrm{N} = 375$ turns), 240 mm in diameter and 150 mm in height.

Fig. 6(a) shows the conceptual figure of the turning mode A. The microrobot oscillates the caudal fin biased to the left side during turning and then turns to left side. The mode A can be realized by applying the alternating magnetic field biased with a direct current (dc) magnetic field $H_{dc}$, as shown in Fig. 6(b).

In order to confirm the effect of $H_{dc}$, first of all, we fixed the body part in water and observed the fin motion by changing $H_{dc}$ from $-160$ to 160 A/m. The bias of the fin oscillation increased rapidly with $H_{dc}$ of 80 A/m or less due to buckling of the cantilever and then was almost saturated at $H_{dc}$ ranging 80–160 A/m. Fig. 7 shows the deflection angle of the cantilever for $H_{dc} = -120, 0, 120$ A/m as a function of time. Although a slight asymmetry due to the initial condition of the cantilever was observed, the $H_{dc}$ largely biased the fin oscillation to each side.

Next, we performed a turning test without fixture in the water tank. At $H_{dc}$ ranging 80–160 A/m, the microrobot could swim in a circular orbit as expected in Fig. 6(a). The turning radius was almost a constant value of 35–40 mm for both directions. On the other hand, we could hardly keep the turning radius constant at $H_{dc}$ below 80 A/m. In this study, therefore, we used $H_{dc}$ ranging 80–160 A/m for the turning mode A.

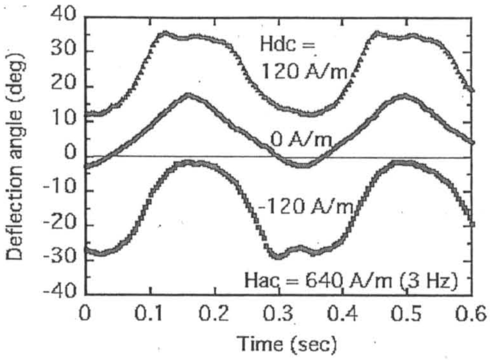


Fig. 7. Deflection angle as a function of time.

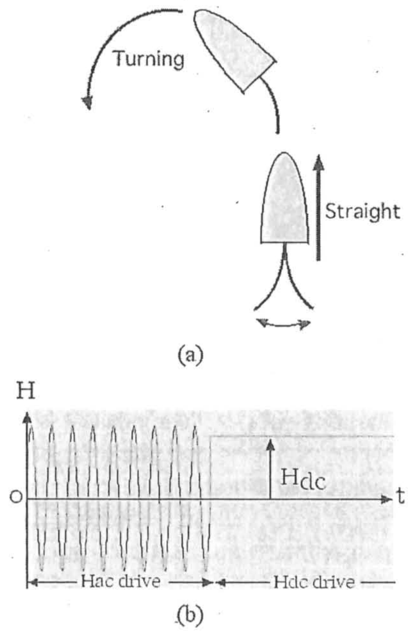


Fig. 8. Concept of turning mode B. (a) Turning in mode B. (b) Waveform for mode B.

Fig. 8(a) shows the conceptual figure of the turning mode B. At first, the microrobot swims straight and obtains kinetic energy. Next, it stops the oscillation and keeps the posture biased to one side. Then, the microrobot can turn by hydrodynamic force until swimming speed reduces to zero. The turning mode B can be realized by applying the waveform pattern of the magnetic field, as shown in Fig. 8(b).

Fig. 9 shows the heading angle and the swimming speed for the turning mode B as a function of time after switching from the $H_{ac}$ drive to the $H_{dc}$ one. $H_{dc}$ applied during turning was 480 A/m. The heading angle increased with time and reached approximately 100° after 3 s. On the other hand, the swimming speed showed a little increase just after switching to the $H_{dc}$ drive, and after that gradually became slower.

Fig. 10 shows sequence photographs of the typical turning behavior for two turning modes. In the case of mode A, the microrobot could successfully swim tracing an eight-figure by

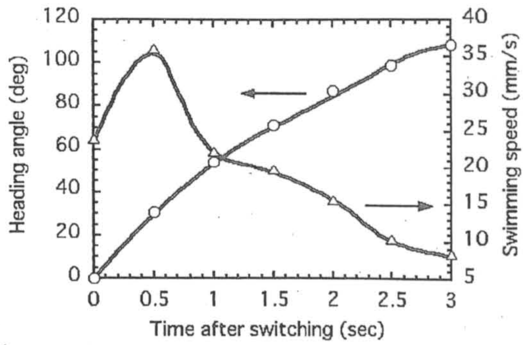


Fig. 9. Heading angle and swimming speed as a function of time.

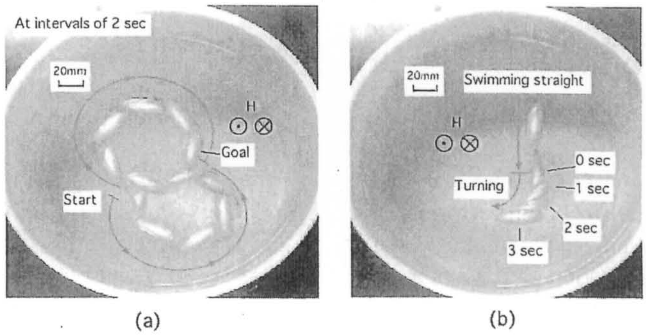


Fig. 10. Sequence photographs of turning modes A and B. (a) Mode A. (b) Mode B.

switching $H_{dc}$ from −160 to 160 A/m at fixed intervals. The turning radius for both turning directions was approximately 40 mm. In the case of mode B, although the swimming speed reduced to zero after about 3 s, the turning radius was half as large as that of the mode A, which means that the turning mode B is advantageous for a short area turning.

## V. Conclusion

The magnetically driven fish-like microrobot that can propel itself using a caudal fin was constructed to study the turning performance. Two magnetic field waveform patterns including a dc field were designed for turning by the caudal fin. As a result of the tank test, the microrobot could successfully turn in a small radius under both waveform patterns.

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