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An in-pipe wireless swimming microrobot driven by giant magnetostrictive thin film

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ABSTRACT

In this work, the nonlinear vibration characteristics of bimorph giant magnetostrictive thin film (GMF), TbDyFe/PI/SmFe, are measured and analyzed, firstly. Thereafter, by employing the primary resonance and superharmonic resonance performance of GMF cantilever, and simulating the ostraciiform locomotion of boxfish, an in-pipe wireless swimming microrobot is developed, whose caudal fin is fabricated by GMF microactuator. On the basis of the equivalent load model of magnetostrictive effect of GMF, the governing equations for swimming microrobot are established and solved by the method of multiple scales. Experiments on the swimming characteristics of this GMF microrobot in gasoline pipe show that the microrobot can swim at a mean speed of 4.67 mm/s with the external magnetic field driving frequency of 4.7 Hz, which is close to the first primary resonance frequency in gasoline. Besides, the mean swimming speed can reach 2.8 mm/s with the external magnetic field driving frequency of 2.4 Hz, which is close to the superharmonic resonance frequency of order two of GMF cantilever actuator in gasoline.

1. Introduction

In medical and industrial applications, a fish-like microrobot has attracted more attention due to its compact structure, high driving efficiency, noiseless motion, and great maneuverability, which make it possible for micropipe inspection and microsurgery of blood vessels.

Recently, many micro-swimming robots have been developed, by simulating the propulsion mechanism of fish or aquatic animal. Most reported micro-swimming robots are driven by shape memory alloy actuators (SMA) [1], ionic exchange polymer metal composites actuators (IPMC) [2,3], ion-exchange membrane metal composites (IEMMC) [4], or piezoelectric actuators (PZT) [5]. For instance, the IPMC actuated microrobot like carangiform fish, which was 45 mm in length and 0.76 g in weight, reached a speed of 5.21 mm/s at 1 Hz [2]. Guo et al. developed a jellyfish type of multi-DOF microrobot (4.81 g in weight), driven by SMA actuator and IPMC actuator, which could get a peak speed of 5 mm/s at 0.6 Hz [6]. Mojarrad and Shahinpoor proposed a biomimetic fish-like robot using polyelectrolyte ion-exchange membrane metal composites (IEMMC) for propulsion, which could reach a speed of 18.8 mm/s at 5 Hz [4]. Deng and Avadhanula designed a micro-underwater vehicle like a boxfish controlled by PZT bimorph actuators [5]. These micro-fish-like robots exhibit good swimming performances for underwater operations.

However, there are some problems for above microrobots, such as leaking electric current, safety in water, especially driving with long cables or batteries, which will result in some difficulties in further application of microoperation in small and complex space. Thus, wireless driving mode is a better solution to this problem. Honda presented the fin type of micro-swimming robot, driven by a NdFeB permanent magnet, which got a speed of 70 cm/s at 65 Hz [7]. Thereafter, Mei et al. designed a swimming microrobot actuated by two ferromagnetic polymer (FMP) fins, which could reach the speed of 40–45 mm/s at 20 Hz and 15 mT magnetic field [8]. Therefore, the micro-swimming robots driven by external magnetic field show the better potential for local work and operation with high flexibility in a very small space.

As a new magnetic functional material, giant magnetostrictive thin film (GMF) has exhibited large magnetostrictive strains and wireless driving power at low magnetic fields, and been employed to make the microsensors or microactuators such as traveling machine [9], microvalve, micropump and linear ultrasonic motor [10], which indicates the power of fabricating micro-swimming robot with GMF.

Thus, this paper focuses on the nonlinear vibration characteristics of GMF cantilever at low frequency magnetic field. Then, we present an in-pipe wireless swimming microrobot driven by GMF actuator, by simulating the propulsion mechanism of boxfish. The motion mechanism of microrobot is analyzed. Finally, the swim-

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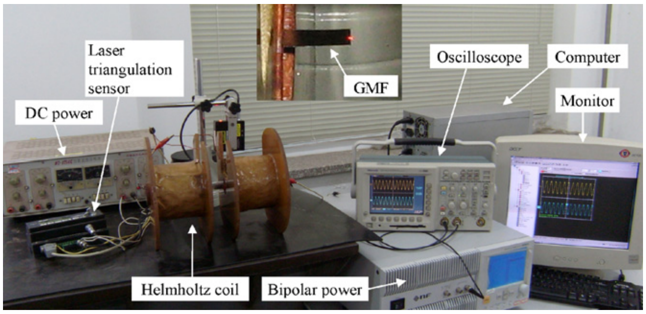

Fig. 1. Vibration measurement system for GMF actuator.

ming experiments of micro-swimming robot are reported in this paper.

2. Vibration characteristics of GMF cantilever actuator

A kind of bimorph GMF, TbDyFe/PI/SmFe, is made of 1 μm-thick TbDyFe and SmFe films deposited on both surface of 80 μm-thick polyimide (PI) substrate, with IBS method. A bimorph GMF cantilever actuator, with a length of 40 mm and a width of 5 mm, is developed, as shown in Fig. 1. When a magnetic field is applied along the longitudinal direction, the positive giant magnetostrictive thin film (TbDyFe) expands, and the negative magnetostrictive thin film (SmFe) contracts. Thus, the bimorph GMF actuator enables larger deflections and forces than single layer giant magnetostrictive thin film.

In order to detect the driving power of bimorph GMF cantilever actuator, vibration characteristics of the actuators are measured with the experimental system as shown in Fig. 1. The dynamic deflections of GMF cantilever are measured by laser triangulation sensor (MTI Instruments Inc.). The external magnetic field is provided by the Helmholtz coil driven by the bipolar power (NF Corporation).

Fig. 2(a) shows the primary resonance of bimorph GMF cantilever actuator in air, at the bias magnetic field of 17.2 mT and the amplitude of alternative magnetic field of 15.48 mT, where the peak-to-peak value of vibration of GMF actuator reaches 1.24 mm. With the bias magnetic field of 17.2 mT and the amplitude of alternative magnetic field of 21.5 mT, the GMF cantilever exhibits the properties of superharmonic resonance of order two, three and four, as shown in Fig. 2(b), (c), and (d), respectively, where the peak-to-peak values of superharmonic resonance of GMF cantilever reach to 0.182 mm, 0.116 mm, and 0.116 mm. Moreover, the efficiency of superharmonic resonance of order two, three and four can be comparable with that of the primary resonance, which exhibits the power of low frequency driving with superharmonic resonance of TbDyFe/PI/SmFe cantilever. Thus, we can fabricate some microactuators by employing resonance characteristics of GMF under low frequency magnetic field, which allows the simple driving magnetic field design and fabrication for engineering applications.

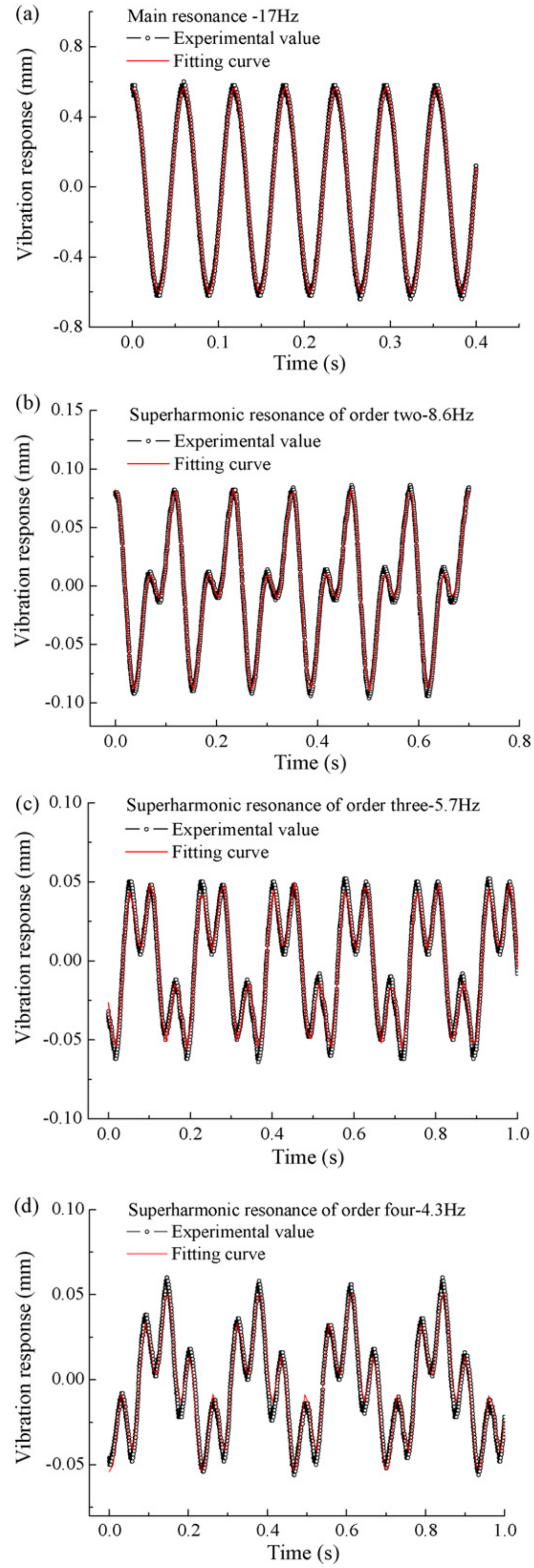

Fig. 2. Primary resonance (a) and superharmonic resonances of order two (b), three (c), and four (d) for bimorph GMF cantilever actuator.

3. Fabrication of swimming microrobot

In order to develop an in-pipe swimming microrobot driven by GMF actuator with low driving frequency, it is necessary to select an applicable swimming mode of fish. Boxfish are known for their ability to swim smoothly through turbulent waters of coral reefs and their excellent maneuverability. Ostraciiform locomotion of boxfish is characterized by the pendulum-like oscillation of the caudal fin (tail fin), which plays the principal role in forward propulsion of boxfish, while the body remains essentially rigid [11], as shown in Fig. 3(a). Then, ostraciiform locomotion exhibits the relative simple propulsion mechanism for mechanical design and swimming motion control, and, the swimming performance can be optimized by changing the flapping frequency and amplitude of the caudal fin. Therefore, ostraciiform propulsion mode is