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An experimental study on characteristics of a magnetostrictive vibrator

Jiang Guo[a,*], Sze Keat Chee[b]

[a] Ultrahigh Precision Optics Technology Team, RIKEN Center for Advanced Photonics (RAP), RIKEN, Wako, Saitama 351-0198, Japan
[b] Mechano Transformer Corp., Tokyo, 101-0044, Japan

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ABSTRACT

The paper presents an experimental study on the key characteristics of a magnetostrictive vibrator being developed for polishing application. Firstly, the actuation principle is systematically illustrated by a general model and experimentally verified by measuring magnetic fluxes flowing in the legs of the vibrator. Then the vibration mode is analyzed by finite element method and proved by node position test. It is found that the experiment result shows good consistent with that of simulation. After that, the effect of external stress on vibration amplitude is tested and the result indicates that under the stress of 0–1 N, the vibration amplitude shows in a rough proportion relationship to the stress. However, when the stress is less than 100 mN, vibration amplitude is almost not changed. Finally, the heat generation of the vibrator is evaluated, and a cooling device is developed for effectively decreasing the operating temperature.

1. Introduction

Vibrators which can generate micro-vibration are increasing, especially in the field of vibration-assisted machining (VAM) where micrometer order vibration is combined with precision machining processes to improve surface quality [1]. To meet this requirement, some new types of vibrators have been developed to assist the precision machining processes such as cutting, grinding and polishing, and some good results have been reported [2–4].

However, most of them are made by piezoelectric material owing to their good performance and high control stability. Recently, with the rapid improvement of material properties, particularly in magnetostriction, the giant magnetostrictive materials (GMM) have been paid more attention and application-oriented researches are increasing [5–9]. For instance, Kim et al. devised a low-power linear magnetostrictive actuator by using Terfenol-D (Tb–Dy–Fe alloy) which has a giant magnetostriction more than 2000 ppm [10]. Ueno et al. developed a miniature spherical motor and a micro-magnetostrictive vibrator by using Galfenol (Fe–Ga alloy) in terms of magnetostriction over 200 ppm and Young's modulus of 70 GPa [11,12]. Compared to piezoelectric actuators, magnetostrictive actuators can be miniaturized, manufactured to complex structures, and shaped without pre-stressing while piezoelectric actuators suffer from low mechanical strength due to their brittle nature. After machining, magnetostrictive material can maintain effective magnetostriction and is robust against external bending and tensile forces. It is driven by an electric current which is the same with motors, so the mature technology used for driving motors can be applied to magnetostrictive actuators whereas piezoelectric material requires high voltage supply [13,14]. Additionally, a preloading mechanism is not necessary for actuating GMMs. From another aspect, preloading will improve the magnetostrictive property of material. Furthermore, as a metal alloy, GMMs are environmental friendly and can be recycled unlike PZT, a piezoelectric material which contains lead.

We proposed a magnetostrictive vibrator made of Permendur (Fe–Co alloy). On behalf of its smart design, it can generate lateral, circular or elliptical vibration traces which have been applied in the ultra-precision finishing of micro-optic mold [15–17]. Permendur, with the advantages such as Young's modulus of 170 GPa, magnetostriction exceeding 70 ppm, high relative permeability of 4500 and good machinabilty, shows great potential for use in developing actuators. Compared with Terfenol-D and Galfenol, the cost of the material is much lower. Besides that, it is easier to be machined into small components especially with complex structures. Although the magnetostriction is low, the high permeability enables the driven electromagnet to be constructed with lower current and fewer coil turns. However, to well control the vibrating

* Corresponding author.
E-mail address: guojiang3302@gmail.com (J. Guo).

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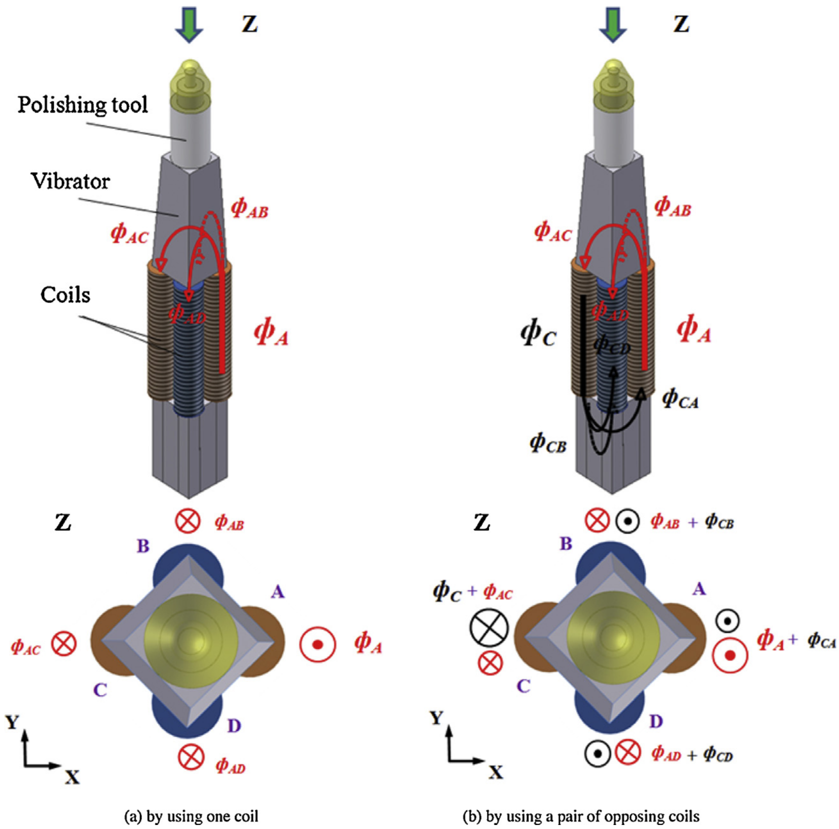

Fig. 1. Magnetic flux flow in the legs of the vibrator.

performance, further research becomes necessary on investigating the actuation principle and key characteristics of the vibrator. Therefore, this paper focuses on the necessary scope including analysis and verification of actuation principle, vibration mode analysis, effect of stress on vibration amplitude as well as evaluation of heat generation which will be systematically analyzed and discussed in the following sections.

2. Analysis and verification of actuation principle

The proposed magnetostrictive vibrator has four-symmetrical-legs around which coils are wound as shown in Fig. 1. For polishing application, a polishing tool is mounted on top of the vibrator. The vibration is generated by coupled magnetic fields through alternatively exciting the four-symmetrical-legs while the magnetic field used to strain the legs are induced by the wound coils.

Due to the compact structure of the vibrator, the magnetic circuits are complex. To illustrate the actuation principle, a general model is proposed. The input currents of wound coils for the four-symmetrical-legs named *A*, *B*, *C* and *D* are defined as I_A, I_B, I_C and I_D, respectively. They are expressed by Eqs. (1)–(4).

$$I_A = i_0 + i_A \sin(2\pi f_0 t + \varphi_A) \quad (1)$$

$$I_B = i_0 + i_B \sin(2\pi f_0 t + \varphi_B) \quad (2)$$

$$I_C = i_0 + i_C \sin(2\pi f_0 t + \varphi_C) \quad (3)$$

$$I_D = i_0 + i_D \sin(2\pi f_0 t + \varphi_D) \quad (4)$$

where f_0 denotes the frequency of the sinusoidal wave which decides the vibration frequency of the vibrator. i_0 is the bias current which is used to induce bias magnetostriction in each leg so that the legs of the magnetostrictive vibrator can be expanded and contracted under a linear motion. i_A, i_B, i_C, and i_D are the amplitudes of input signals which affect the vibration amplitude. $\varphi_A, \varphi_B, \varphi_C$, and φ_D show the phase of input signals. The magnetic flux induced by each coil can be described by Eqs. (5)–(8).

$$\phi_A = \phi_{AB} + \phi_{AC} + \phi_{AD} \quad (5)$$

$$\phi_B = \phi_{BA} + \phi_{BC} + \phi_{BD} \quad (6)$$

$$\phi_C = \phi_{CA} + \phi_{CB} + \phi_{CD} \quad (7)$$

$$\phi_D = \phi_{DA} + \phi_{DB} + \phi_{DC} \quad (8)$$

Then through combining the magnetic fluxes induced by the four coils, a general model which describes the magnetic flux flowing through each leg of the vibrator is obtained by Eqs. (9)–(12).

$$\gamma_A = \phi_A + \phi_{BA} + \phi_{CA} + \phi_{DA} \quad (9)$$

$$\gamma_B = \phi_B + \phi_{AB} + \phi_{CB} + \phi_{DB} \quad (10)$$

$$\gamma_C = \phi_C + \phi_{AC} + \phi_{BC} + \phi_{DC} \quad (11)$$

$$\gamma_D = \phi_D + \phi_{AD} + \phi_{BD} + \phi_{CD} \quad (12)$$

For ease of explanation, the magnetic flux generated by bias magnetostriction is not taken into account. As the four-symmetrical-legs are in the same size, the magnetic flux generated in one leg which is induced by the wound coil will be divided into three equivalent flows of flux into other three legs (Fig. 1(a)). So Eqs. (9)–(12) are rewritten as follows:

$$\gamma_A = \phi_A + \frac{1}{3}\phi_B + \frac{1}{3}\phi_C + \frac{1}{3}\phi_D \quad (13)$$

$$\gamma_B = \phi_B + \frac{1}{3}\phi_A + \frac{1}{3}\phi_C + \frac{1}{3}\phi_D \quad (14)$$

$$\gamma_C = \phi_C + \frac{1}{3}\phi_A + \frac{1}{3}\phi_B + \frac{1}{3}\phi_D \quad (15)$$

$$\gamma_D = \phi_D + \frac{1}{3}\phi_A + \frac{1}{3}\phi_B + \frac{1}{3}\phi_C \quad (16)$$