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Magnetostrictive stress induced frequency shift in resonator for magnetic field sensor

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ABSTRACT

A static/quasi-static magnetic field sensor is developed by using a double ended trip-beam tuning fork (TBTF), a $Tb_xDy_{1\text{-}x}Fe_{2\text{-}y}$ plate and several piezoelectric $Pb(Zr_{1-x}Ti_x)O_3$ (PZT) plates. The TBTF is boned horizontally across two ceramic supports which are fixed on the ends of the $Tb_xDy_{1\text{-}x}Fe_{2\text{-}y}$ plate. The magnetostrictive stress induces an axial force in the TBTF, which causes the resonance frequency of the TBTF to increase. The theoretical analysis shows that the magnetostrictive stress increases approximately linearly with the increase of the external DC field, and so does the resonance frequency shift of the TBTF. The magnetostrictive stress can get to 32.65 MPa at the field of 1000 Oe, and the total frequency shift respectively achieves 2.97% and 16.67% under the assumption of 10% and 60% transmission efficiencies (as the sectional area of the magnetostrictive plate being 6mm × 1 mm). A Be-bronze TBTF based sensor was fabricated, and the frequency shift of 2.1% was obtained by applying a DC magnetic field in the range of 0–1000 Oe. The magneto-mechanical damping in the magnetostrictive plate has no influence on the quality factor of the TBTF which is found to be relatively constant after an initial increase. The results show the great potential to realize a high sensitivity magnetic sensor featuring high quality factor and digital frequency output.

1. Introduction

The magnetostrictive/piezoelectric laminate composites (MPLC) have generated a great deal of interest due to their potential applications for highly sensitive magnetic field sensors [1]. The magnetoelectric (ME) effect in MPLC was demonstrated to be feasible for detecting a low frequency(10^{-2}–10^3 Hz)magnetic field with the sensitivity of pico Tesla [2]. However, the ME voltage of the ME laminate has shown a roll-off characteristic with decreasing frequency due to the clamped capacitance of the piezoelectric layer [3]. In order to design a DC or quasi-static magnetic field sensor based on ME effect, a coil have been used to generate constant AC drive field [4].

Recently, Jahns et al. [5] presented a cantilever beam MEMS resonator with a stack composed of SiO_2/Pt/AlN/FeCoSiB, which can detect a low-frequency magnetic field by measuring the reactive current of the electromechanical resonator. The method provides a very low limit of detection of 6 nT. T.X. Nan et al. [6] demonstrated a 215 MHz magnetoelectric NEMS resonator based on an AlN/(FeGaB/Al_2O_3) heterostructure, the admittance of the NEMS resonator was very sensitive to DC magnetic fields at its electromechanical resonance. They considered that the variation of the admittance or the reactive current of the resonators to DC magnetic field are primarily resulted from the frequency shift of the resonators due to the ΔE effect of FeCoSiB or FeGaB [5,6].

We could not help thinking that it is more reasonable to detect magnetic fields through straightforward measuring frequency shift of a resonator. As the outputs of the sensors (e.g., in ref. [5,6]) are analogue signal with very small amplitudes, these sensors usually require conditioning circuits containing low-noise amplifiers, noise-reduction filters followed with A-D converters and digital signal processors. In general, the lock-in detecting scheme has to be applied in such cases. In contrast, the frequency shift of an oscillator can be readily acquired merely by a counter. Furthermore, the detection of frequency shift is inherently insensitive to noise. Kiser et al. [7] reported a doubly clamped Metglas resonator in which the field-induced resonance frequency shift was used for magnetic field sensing. The sensitivity was found to be 4.7 Hz/T at a DC bias

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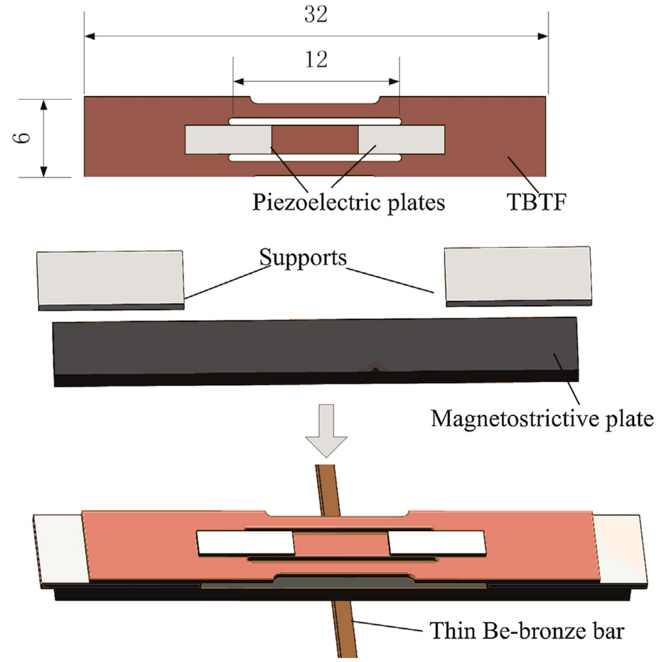

Fig. 1. The configuration of the resonant magnetic sensor.

of 700 μT. However, the quality factors (Q-factor) of the resonators based on Metglas is inevitably poor due to the low mechanical Q-factor of amorphous material [8,9]. We also note that the Q-factor of the composite resonators are restricted to low values (e.g., 260 for SiO_2/Pt/AlN/FeCoSiB [5], 250 for AlN/(FeGaB/Al_2O_3 @ 15 Oe [6]) due to the low mechanical Q-factor of magnetostrictive material. High Q-factor is a necessary condition for high resolution of frequency shift or the parameters to be measured. Actually, resonators (e.g. quartz tuning fork) with high Q-factor (10^4-10^5) have been widely used to design various sensors such as force [10], pressure [11], or micro-mass [12].

In this paper, a magnetic field sensor with frequency shift has been developed by using a tuning fork resonator, a magnetostrictive plate and several piezoelectric PZT [$Pb(Zr_{1-x}Ti_x)O_3$] plates. The principle, modeling, design and feasibility of the resonant magnetic sensor based on a resonator and magnetostrictive material was discussed. In the prototype, the tuning fork resonator is a double ended triple beam tuning fork (DE-TBTF) fabricated from beryllium bronze (Be-bronze) sheet. Two piezoelectric PZT8 elements are used to drive and detect the vibration of the TBTF. The magnetostrictive plate serves as an actuator which generates a longitudinal force along the axial of the TBTF. The longitudinal force causes the natural frequency of the TBTF to increase. Specially, the magnetomechanical damping (MMD) in magnetostrictive plate has no influence on the Q-factor of the resonator. In this manner, the resonant sensor can achieve a very high mechanical Q-factor.

2. Principle and design of the resonant magnetic field sensor

The resonant magnetic sensor consists of three parts, namely DE-TBTF, ceramic supports, and a magnetostricive plate, as shown in Fig. 1. The double ends of the TBTF are bonded to the supports which are bonded on the surface at each end of the magnetostrictive plate, allowing the magnetostrictive stress to be convened into longitudinal stress in the TBTF. The longitudinal stress causes the natural frequency of the TBTF to increase. The resonator can be maintained in continuous oscillation at resonance by an oscillator circuit and the frequency shift can be easily picked up through a frequency counter [13,14].

The TBTF is designed with symmetrical structure in which the central beam is twice the width of the two outer beams. Two piezoelectric films are bonded on the surface regions at each end of the central beam. One is used to excite the TBTF into vibration, while the other is used to pick-up the vibration. The TBTF is operated at an optimal mode, i.e., the central beam generates a flexural motion, and it moves anti-phase with the two outer beams. In this way, both of the bending moments and the shear forces at the common mounting zones are cancelled out. In this case, little vibrational energy is coupled into the supporting frame at either end [15].This phenomena will improve the Q-factor of the resonator. More information about the design of a TBTF can be found in [15].

For a single beam operating in flexural mode of vibration, the fundamental resonant frequencyf_r is dependent on the force F applied along its longitudinal direction. The expression is given by equation (1) [16]

$$f_r = f_0\sqrt{1+\gamma_n F\frac{l^2}{12E_b I}} \tag{1}$$

where

$$f_0 = \frac{\alpha_n^2}{2\pi l^2}\sqrt{\frac{E_b I}{\rho A}} \tag{2}$$

where,$A = bh$ and $I = bh^3/12$ are cross-section area and the second moment of inertia, respectively;l, h, b are the length, thickness and width of the beam, respectively; E_b is the Young's modulus of the beam, ρ is mass density, f_0 is the fundamental resonant frequency for zero applied longitudinal force. For the fundamental mode, the two constants α_0 and γ_0 are 4.730 and 0.295, respectively.

The expressions (1) and (2) define the fundamental frequency of a single beam under axial force. The equations can be modified for a TBTF by taking into account the three beams configuration, i.e., the cross-section area and the second moment of inertia are modified as the sum of the three beams. Equivalently, the width b is modified as the sum of the width of the three beams. A similar modification is shown in [17] for a double-ended tuning fork.

Thus, the frequency shift of the TBTF can be given by the expression as follow:

$$\Delta f = \frac{f_r - f_0}{f_0} = \sqrt{1+\gamma_n F\frac{l^2}{E_b h^3 b}} \tag{3}$$

When the magnetostrictive plate is subject to a magnetic field along its longitudinal direction, magnetostrictive stress is induced in the longitudinal direction. At a DC magnetic field or at a field with its frequency far below the natural frequency of the magnetostrictive plate, the distribution of the magnetostrictive strain is nearly uniform along its longitudinal direction [18]. In this manner, the magnetostrictive stress $\sigma_M$is

$$\sigma_M = E(H)\varepsilon(H) \tag{4}$$

where, $E(H)$ and $\varepsilon(H)$are the elastic modulus and magnetostrictive strain at external magnetic field H, respectively.Then, the longitudinal force F_M generated by the magnetostrictive plate is

$$F_M = A_M\sigma_M = A_M E(H)\varepsilon(H) \tag{5}$$

where, A_M is the cross-sectional area of the magnetostrictive plate.

Assuming a transmission efficiency $\beta\left(0<\beta<1\right)$, then the induced axial force F of the TBTF can be given by

$$F = \beta F_M = \beta A E(H)\varepsilon(H) \tag{6}$$

The magnetostrictive strain and elastic modulus can be calculated by a non-linear constitutive model. The constitutive model proposed by X. J. Zheng et al. [19] can accurately predict the curves