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Resonance behavior of magnetostrictive micro/milli-cantilever and its application as a biosensor

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ABSTRACT

Magnetostrictive micro/milli-cantilever (MSMC) was recently introduced as a promised biosensor platform due to its high performance in liquid and wireless nature. To better understand the resonance behavior of the MSMC, unimorph-type MSMCs with thickness about 30 μm and different lengths and widths were fabricated, and their resonance behaviors were investigated in air and in different liquids. The influence of the driving magnetic fields and the surrounding media on their resonance behavior was also studied. It is found that the amplitude of the driving ac magnetic field has very weak influence on the resonance frequency. On the basis of the damping effect of different liquids on the resonance behavior of the MSMCs, it is found that the characteristic frequency of the MSMC is linearly dependent on the density of the liquid media, while the *Q* value is inversely proportional to the square root of the product of the density and viscosity of the liquid media. It is also found that the damping effect of liquid on the MSMC can be treated as a damping string of sphere and the effect radius of the oscillating sphere for an MSMC is a constant. The value of the effect radius for different MSMCs was experimentally determined. Additionally, the resonance frequency of the MSMC is very stable. Due to their wireless nature, MSMCs are suitable for the development of a cantilever array. It is experimentally demonstrated that the characterization of an MSMC array is as simple as a single MSMC. The detection of *Bacillus anthracis* spores in water was performed using MSMC biosensors in a real-time manner to demonstrate the *in situ* detection capability.

1. Introduction

Sensors using acoustic wave (AW) devices as platforms have great potentials to advance the bio/chemical-detection techniques due to their high sensitivity, simple structure, low cost, easiness to use, and capability to conduct real-time *in situ* detection [1–12]. AW sensors are operated as mechanical resonators with a characteristic resonance frequency. To form biosensors, bio-recognition elements, such as antibody and phage [13,14], are immobilized on the sensor surface to react with target species. The mass change due to the selective binding of the target species to the bio-recognition unit results in a change in the resonance frequency of the sensor. Therefore, by monitoring the resonance frequency of the sensor, the presence of the target species can be detected/monitored. On the basis of this principle, the performance of an AW device as a biosensor platform is characterized by two important parameters: mass sensitivity (S_m) and quality merit factor (*Q* value). The S_m is defined as the shift in the resonance frequency due to the attachment of a unit mass load on the surface of the AW device. A higher S_m means a larger shift in the resonance frequency for the same mass load. The *Q* value reflects the sharpness of the resonance peak in the plot of oscillation amplitude versus frequency. A larger *Q* value means a sharper resonance peak, which results in a higher resolution in determining resonance frequency. That is, an AW device with a higher *Q* value would have a capability to determine a smaller change in its resonance frequency. Therefore, an AW-based biosensor with a high S_m and a large *Q* value would be highly desirable for highly sensitive bio/chemical analysis [8,15,16].

In comparison with the traditional AW devices, MEMS-based microcantilevers (MCs) exhibit a much better performance in terms of the minimum detectable mass load, due to their small size and mass [6–8,17]. This feature is very attractive for developing ultra-sensitive analysis technologies and clinical diagnostic devices/systems. Therefore, a lot of efforts have been devoted to the development of MCs and MC-based biosensors [7,8,12,16–19]. In terms of operation technology, all the MCs can be classified into two types: passive and active [16,17]. The passive MCs, such as silicon-based MCs, require a separate system to actuate the device and usually use a separate optical system to measure/monitor the vibration of the device. On the other hand, the active MCs, such

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as piezoelectric-based MCs, can be easily actuated and sensed. For example, the piezoelectric MCs can be actuated by simply applying an electric field, and their resonance behavior can be easily determined using the impedance spectrum—the impedance versus frequency. However, due to the easiness and availability in the fabrication technology, silicon-based MCs are much more widely investigated than others. Additionally, silicon-based cantilevers exhibit a higher Q value and a higher S_m than piezoelectric-based cantilevers.

The main challenge facing current MCs is their performance in liquid due to the damping effect. It is well known that the damping effect makes the resonance frequency lower and the Q value smaller. That is why the ultra-high sensitivity of MCs in determining a small mass was demonstrated in vacuum [6–8]. Therefore, different approaches have been investigated to enhance the Q value of the MCs [8,20,21]. The damping effect of a surrounding media on an AW device is related to many factors including the properties of the surrounding media and the AW device itself. For example, both the density and viscosity of the surrounding media contribute to the damping effect, but have different influences on the resonance frequency and the Q value; the properties of the materials used to fabricate the device are directly related to the damping effect; the vibration mode and vibration frequency of the device are also related to the damping effect.

Recently, a magnetostrictive cantilever as an active MC was introduced as a high performance biosensor platform [19,22]. Utilizing the magnetostrictive material as the actuating material, the magnetostrictive cantilevers are actuated to mechanical oscillation using a time-varying magnetic field. This oscillation causes an emission of a magnetic flux from the device, which can be detected by a pickup coil. That is, the magnetostrictive cantilever can be wirelessly actuated and sensed. Additionally, the magnetostrictive cantilever exhibits a high Q value. For example, the Q value of a magnetostrictive milli/micro-cantilever (MSMC) reaches more than 500 in air and about 40 in water [19], while the Q value more than 10 is rarely observed in other rectangular MCs in liquid [17]. These advantages make the MSMC a great candidate for the development of high performance *in situ* biosensors. To fully develop the MSMC technology, a better understanding of its resonance behavior and the parameters that affect its oscillation is needed. In this paper, the fundamentals of the MSMC are discussed, and the technology to characterize the resonance behavior of the MSMC is presented. The influence of the media on the resonance frequency and the Q value is experimentally determined using MSMCs with different sizes and media with different densities and viscosities. The MSMC-based array is developed and its features are characterized. Finally, the *in situ* detection of *B. anthracis* spores in water was performed in a real-time manner.

2. Principle of MSMC

2.1. Configuration and operation principle of MSMC

The configuration of an MSMC is shown in Fig. 1(a). Similar to the piezoelectric unimorph, an MSMC consists of two layers: one is active (magnetostrictive), and the other is inactive. Due to the magnetostrictive effect, the length of the magnetostrictive layer changes under an external magnetic field. This dimension change is restricted by the inactive layer so that a bending motion in MSMC is induced. Since the magnetostrictive strain response (λ) is an even function of the driving magnetic field (H), as shown in Fig. 1(b), the MSMC is usually actuated using a small ac signal imposing on a large dc bias. As revealed in Fig. 1(b), if only a small ac magnetic signal is applied, the strain response in the material is in a quadratic function of the driving magnetic field. As a result, the strain response is

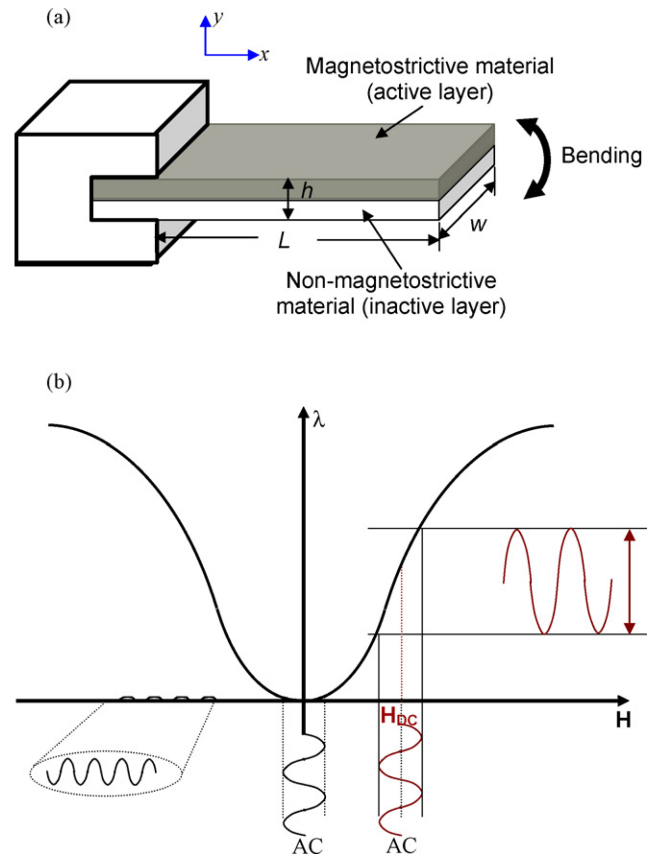

Fig. 1. (a) Structure of the MSMC, where L, W and h are the length, width and thickness of the MSMC beam. (b) Magnetostriction response of a magnetostrictive material under external magnetic field (H).

small and is at a frequency that is the double the frequency of the driving ac field. On the other hand, if the small ac field is imposed on a dc bias, a larger ac strain response is observed at the same frequency, and is proportional to, the ac driving field. Therefore, an MSMC is usually operated by imposing a small ac magnetic field on a dc bias.

As described in previous publications [19,22], due to the magnetic nature of the magnetostrictive material, the mechanical oscillation of the MSMC results in an emission of a magnetic flux, which can be detected/sensed using a pickup coil. To eliminate the background signal, such as the driving ac field, a pair of pickup coils is utilized to detect the oscillation of an MSMC. The pair of pickup coils consists of two same coils. However, they were wound in opposite directions and connected in series so that the signal picked up from the driving field is cancelled. The MSMC is placed in one of the pickup coils. Therefore, the outputs of the pickup coils only reflect the oscillation of the MSMC. When the frequency of driving magnetic field is the same as the characteristic resonance frequency of the MSMC, the MSMC undergoes the resonance oscillation, which results in a maximum in the vibration amplitude. Therefore, the spectrum, oscillation versus frequency, measured from the pickup coil can be used to determine the resonance behavior of an MSMC.

Wireless driving/sensing is the principal advantage of the MSMC over current MCs. Additionally, if the inactive layer is a magnetic material, the signal from the pickup coil can be enhanced and the dc field may not be needed. This is another advantage offered by MSMC, which would be important for small-size MSMCs. That is, for MSMCs with the same size, the signal strength can be enhanced over some range, which is a desired feature for real-time detection since the distance between the sensor and the inter-