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A new sensitivity improving approach for mass sensors through integrated optimization of both cantilever surface profile and cross-section

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ABSTRACT

Sensitivity is of great importance for piezoelectric resonance mass sensors in the fields of material and particle analyzing. Different from the custom used methods such as geometric dimension reduction and configuration modification, a new sensitivity improving method was proposed by simultaneously modifying both the surface profile and the cross-section type of the cantilever to optimize its stiffness and mass distribution. Knowing the effects of the structural parameters on the resonance frequency, a novel piezoelectric resonant mass sensor was designed and fabricated by introducing the grooved trapezoidal cantilever with variable cross-section as the key elastic element. Through the cantilever vibration analysis by the finite element method, the sensitivity analyzing model for the grooved trapezoidal cantilever mass sensor was established, with which, the influence of the groove and profile parameters on the sensitivity improvement was systematically analyzed. The experimental and simulated sensitivities of the proposed sensor are 33.7×10^3 Hz/g and 38.0×10^3 Hz/g respectively, which are nearly 387.8% greater than that of the custom rectangular cantilever sensor of 9.8×10^3 Hz/g. More importantly, the proposed sensor also possesses the character of high sensitivity for distributed mass detection, which is 2.92 times that of the rectangular cantilever sensor. Finally, the feasibility and effectiveness of the newly proposed sensitivity improving method was validated.

1. Introduction

The piezoelectric resonance mass sensor mainly consists of an elastic substrate layer bonded with a layer of piezoelectric material, which can achieve quantitative analysis of material by analyzing the frequency change induced by the adsorbed analyte. With the elegance of integrating self-exciting and self-sensing functions and not requiring analyte labeling, such resonant cantilever sensors have been successfully applied in various application fields such as proteomics [1,2], genomics [3], gas sensing [4], food contamination [5], cancer detecting [6], chemical or fluidic detection [7,8].

The character of detecting sensitivity is of great importance in evaluating the performance of the piezoelectric mass sensor, which has attracted much attention in recent years. According to the operating principle of resonant sensors, the existed sensitivity improving methods can be mainly categorized into two main topics: geometrical dimension reduction [1–12], and configuration optimization [13–15]. Also, micro cantilevers achieved by MEMs or NEMs technology can make it easier to get high order mode vibration [9–12], thus resulting in high sensitivity and quality factor. However, the microsized sensor in a dynamic mode can be easily affected by the external interference, and special instrument and testing environment are required to ensure the measuring accuracy and stability.

Recently, to fulfill the requirement of portable applications, great efforts have been devoted to improving the sensitivity through configuration modification without largely reducing structural dimensions. For example, rectangular cantilevers or uniform rectangular cross-section cantilevers with constant weight per unit length have been used in mass detection sensors [13,14] at first. Then, to eliminate the negative influence of two bonding cantilevers of the same length on the sensitivity in fluid detection, two rectangular cantilevers of different lengths [15,16] were stuck together as the elastic elements, and the non-piezoelectric extension was used as the detection area with a sensitivity improvement of 36%. Furthermore, Fernando et al. [17] analyzed the influence of the cantilever profiles on the sensor sensitivity. Subramanian and Gupta [18] proposed an improvement in the shape of the V-shaped

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microcantilever by varying the width profile for sensing applications. Unlike the two layered cantilever, Sharma [19] reported an asymmetrically anchored piezoelectric cantilever sensor with single lead zirconate titanate (PZT) layer to measure the resonance shift. Tu et al. [20] proposed a resonant mass sensor with asymmetrically gapped cantilever, which utilized the structure asymmetry to significantly increase the displacement sensitivity, and thus the mass resolution. Additionally, Xu and Mutharasan et al. [21,22] proposed a equally effective alternate method for monitoring resonant cantilever response, which can significantly reduce the wait time and simplify the measurement system. Ansari and Cho [23] analyzed the frequency and stress characteristics of many microcantielvers with different profiles such rectangular, triangular, and step types for biosensors applications. Johnson and Mutharasan [24] proposed a new technique for measuring transverse mode node locations in cantilever sensors, which uses the relationship between the resonance frequency and the liquid immersion depth. The authors [25] proposed a sensitivity improving method by modifying the cross-section of the cantilever. Actually, according to the detecting principle of the resonant mass sensor, besides the cantilever's cross-section configuration, the surface profile also influences the sensitivity greatly by changing the ratio of the effective stiffness to the effective mass.

In this paper, a new sensitivity improving method was proposed through the integrated optimization of the effective stiffness and the mass distribution by simultaneously changing the cantilever profile and cross-section configuration. Then, different from the custom rectangular cantilever sensors, a novel piezoelectric resonant mass sensor was designed by employing grooved trapezoidal cantilever as the key elastic element. With the finite element method, the mathematical model of the mass sensor with varied cross-section grooved cantilever was established for analyzing the sensitivity, from which, the nonlinear relationship between the sensitivity and the structural parameters was obtained. For concentrated mass detection, the simulated sensitivity of the proposed sensor is 38.0×10^3 Hz/g, which is nearly 387.8% greater than that of the rectangular cantilever sensor of 9.8×10^3 Hz/g with the same geometric dimension. Influenced by the sticking layer between the piezoelectric layer and the elastic cantilever, the measured detecting sensitivity is 33.7×10^3 Hz/g with a deviation of 11.3% from the simulated results. More importantly, the sensitivity for distributed mass detection was also analyzed. And the proposed sensor possesses the character of high sensitivity for distributed mass detection, which is 2.92 times that of the rectangular cantilever sensor. Finally, the feasibility of the proposed sensitivity improving method was validated. To some extent, the proposed method provided an effective way for macro-size cantilever sensors to detect much tiny particles.

2. Structure of the cantilever sensor

From the sensitivity expression of the resonant cantilever sensor $\Delta f/\Delta m \propto v_n^2/(l^3 w)$ [16], it can be seen that the mass detection sensitivity is greatly influenced by the cantilever's profile and its geometrical dimension, where the ratio of $\Delta f/\Delta m$ represents the sensitivity, Δf the frequency shift induced by the added mass Δm, v_n^2 the nth-mode dimensionless eigenvalue, l the cantilever length, and w the cantilever width.

It is well known that the cantilever free end experiences the highest level of deflection from the equilibrium position. However, the cantilever free end makes less contribution toward the total stiffness than that of the other part, which means that reducing the size of the free end will result in a reduction ratio of the cantilever volume greater than that of the total stiffness [17,18,23]. For example, the resonance frequency of a triangular cantilever is much higher than that of the rectangular cantilever with the same length and thickness [23]. Then, the cantilever can be made narrower by removing the edge material at the free end, which will result in a trapezoidal profile. Consequently, the mass of the cantilever will be reduced, and the stiffness will decrease marginally and hence the resonant frequency will be increased and greater than the custom uniform rectangular cantilever. Besides, another effective way to increase the resonance frequency is to change the cantilever's mass and stiffness distributions by modifying the cross-section configuration. For example, the resonance frequency of the I shaped cross-section cantilever shown in Fig. 2(a) is much higher than that of the rectangular cantilever with the same size in Fig. 1. Actually, adding grooves along the cantilever longitudinal axis can reduce the mass by a greater factor than that of the spring constant, thus increasing the resonant frequency of the cantilever. Consequently, from the analysis above, a novel resonant mass sensor was proposed by using the symmetrical grooved trapezoidal cantilever as the key elastic element as shown in Fig. 2, which is different from the rectangular cantilever sensor in Fig. 1. In Fig. 2, l_1 and l_2 are the length of the piezoelectric layer and the extension respectively, l is the length of the grooved cantilever, w is the width of the rectangular beam; w_1 and w_2 are the width of the piezoelectric layer and the grooved cantilever at the free end, w_0 is the width of the grooved trapezoidal cantilever and the piezoelectric layer at the fixed end, w_m is the width of the web in trapezoidal cantilever; t_p and t_{np} are the thickness of the piezoelectric layer and the elastic trapezoidal cantilever, b is the height of the groove, $a(x)$ and $w(x)$ are the width of the groove and the cross-section width of trapezoidal cantilever at the position x.

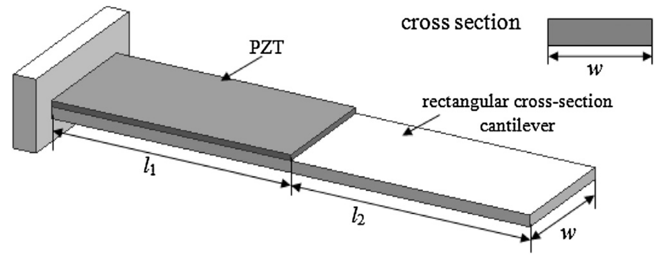

Fig. 1. The structure of rectangular cross-section cantilever sensor.

3. Analytical model of the sensitivity

The grooved cantilever can be treated as a complex structure composed of one up-layer shell, one middle beam with large thickness, and one down-layer shell. To determine the influence of the element type on the computing accuracy, the cantilever was modeled by solid, shell and beam elements in the mode analysis. By setting the results from the solid element model as the standard value, it can be found that the cantilever frequency obtained by beam theory is much similar to that of the solid elements with only 0.1% deviation. However, the deviation from the shell element model to the standard value can reach 2.66%, which is much greater than that of the beam element model. Therefore, the beam theory was introduced to analyze the sensor sensitivity. It is assumed that the piezoelectric layer is perfectly bonded to the elastic beam. And the free vibration differential equation of the cantilever can be obtained not considering the absorbed mass.

$$m\frac{\partial^2 h(x,t)}{\partial t^2} + \frac{\partial^2}{\partial x^2}\left(EI\frac{\partial^2 h(x,t)}{\partial x^2}\right) = 0 \quad (1)$$