A measuring method for micro force based on MEMS planar torsional spring

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Abstract

In order to measure the micro force in a micro-nano device, a new measuring method for micro force is introduced. In this paper, a measuring system based on micro-electro-mechanical systems (MEMS) planar torsional spring is presented, which contains a support block, MEMS planar torsional spring, a support arm, and a laser displacement detection system. The micro force has been obtained by measuring the moving distance of the light spot which is reflected by the MEMS planar torsional spring. The spring sample has been prepared with laser processing technology, and the stiffness is obtained by theoretical calculation, simulation, and calibration. The results show that the torsional stiffness of the MEMS planar torsional spring is 3.7181Nm/rad. The measurement system has a measuring range of ±159mN. The maximum error of mean in repeated measurement is 1.25 % of the reference value, and the repeatability standard deviation is a maximum 4.44 % of the reference value.

Keywords: MEMS planar torsional spring; the measurement for micro force; measurement accuracy; repeatability

1. Introduction

With the decreases of components size in MEMS, the actuator force becomes smaller and smaller, even less than 1 mN. For precision measuring instruments such as scanning probe microscopes and coordinate measuring instruments, the precision of the micro-force directly determines the measurement accuracy of the entire system. The main methods for measuring micro forces are by using capacitive sensors [1], piezoelectric sensors [2], and by resistive strain gages [3]. These methods are converted to micro forces by measuring changes in current or voltage under excitation, which have strict requirements on the sensor and its conversion circuit, and the processing performance of the intermediate signal restricts the measurement of micro forces.

MEMS spring is a typical microstructure, which not only provides elastic force but also transmits energy [4-5]. It is a key component of many micro-sensors [6] and actuators [7-8], and its performance determines the accuracy, output linearity of the device. Some researchers have tried to apply and measure the micro force with MEMS springs as driving sources. Miyamoto [9] *et al*. designed MEMS fold-beam springs and calibrated the stiffness under vertical load. Fukushige [10] designed a conical spring actuator array and described the calculation of the maximum output force and the driving voltage. Shi [11] carried out simulation and experimental verification on S-type and W-type planar micro-spring respectively and studied the influence of structural parameters on stiffness. Grech [12] presented a Quasi-Concertina spring, the spring constant and first mode resonant frequency of the spring was determined and verified. Nie [13] proposed a flexible stop structure of MEMS, the response characteristics of the switch in different stop modes were researched. Liu [14] *et al*. studied a support spring of a uniaxial micro-tensile system for testing micro-scale thin films. Kou [15] *et al*. developed a vibrating ring gyroscope with eight S-shaped symmetrical supporting springs to measure dynamic characteristics. All of these results verify that the MEMS spring has the ability to measure small loads by measuring the movement of components, however, their researches focus on the characteristics of the spring under vertical or radial loads.

In this paper, a micro force measuring system based on MEMS planar torsional spring is presented. The micro force has been obtained by measuring the moving distance of a light spot which is reflected by a MEMS planar torsional spring. The theoretical calculation and simulation of the MEMS planar torsional spring are carried out, and the torsional stiffness coefficient of the structure is calibrated by actual measurement. In order to ensure the accuracy and repeatability of the measurement system, the average and standard deviations also have been studied.

2. Working principle of the measurement system

The measuring system contains a support block, a MEMS planar torsional spring, a support arm, and a laser position detection system, as shown in figure 1. The laser is deflected through the triangular prism, the reflective lens, and then directed into the position detector. To meet the requirement of the position detector, the filter was used to reduce the laser intensity. Figure 2 shows the details of the composition of each part. The MEMS planar torsional spring and lower gasket are mounted on the support block. The middle gasket, support arm, and mirror support have been bolted to the middle rotating region of torsional spring. The triangular prism is adhesive directly above the mirror support.

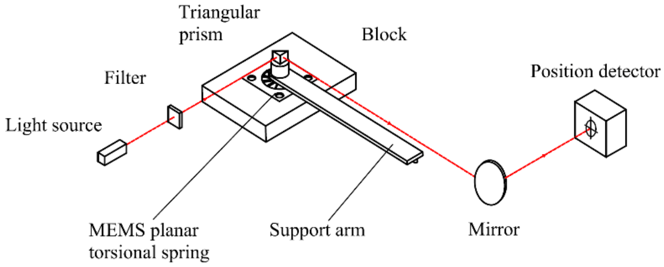

Figure 1. The schematic diagram for the micro torsional measurement system

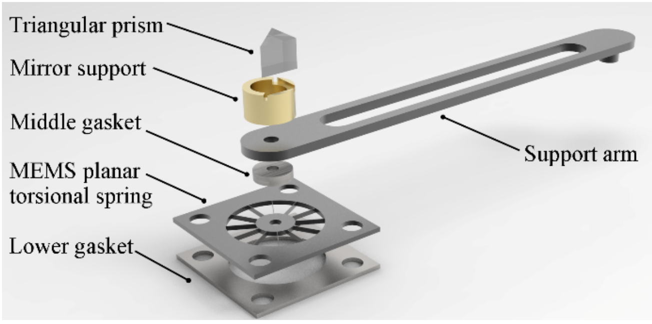

Figure 2. The composition of each part

The principle of micro force measurement is shown in figure 3. When the free end of the support arm gets a force F, a torque of T=F·L_1 will be generated for the center of the torsional spring (the cantilever length is L_1), and the central rotational region of the torsional spring will be deflected by the angle α (figure 3(a)). At this time, the triangular prism will also deflect the angle α, then the laser spot reflected by the prism will be offset by ΔL distance on the surface of the position detector (figure 3(b)).

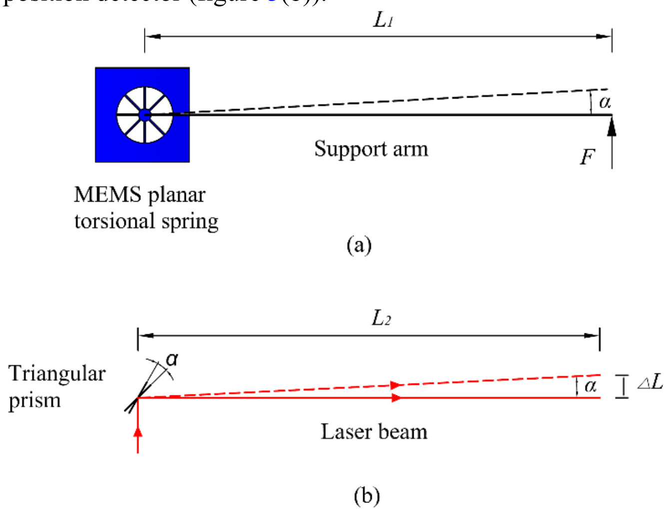

Figure 3. The schematic of measuring torque.

(a) The stress of support arm; (b) The laser path

If the laser path is much longer (L_2), the deflection angle α can be written as:

$$\sin(\alpha) \approx \alpha = \frac{\Delta L}{L_2} \tag{1}$$

The torsional stiffness coefficient of the planar torsional spring is k, and the torque T is:

$$T = k\alpha = k\frac{\Delta L}{L_2} \tag{2}$$

The force applied to the right end of the support arm is:

$$F = \frac{T}{L_1} = \frac{k\Delta L}{L_1 L_2} \tag{3}$$

where α is the planar torsional spring deflection angle (rad), $\triangle L$ is the distance of laser spot moving (mm), L_1 is the supported arm force point distance from the center of rotation (mm), L_2 is the path of laser (mm), T is the torque caused by force (Nm), k is the stiffness of the MEMS planar torsional spring (Nm/rad), and F is the applied force (N).

3. Design of MEMS planar torsional spring

The MEMS planar torsional spring is square, as shown in figure 4. The rotational region is connected to the fixed region by 12 single-arm beams which are evenly distributed. This size of the MEMS planar torsional spring is 15×15mm, the thickness is 500μm. The rotating region has a diameter of ⌀10 mm and a single-arm width of 250μm. This MEMS spring is made in monocrystalline Si (100), Young's modulus (E) of the material is 168 GPa, the Poisson's ratio (γ) is 0.28, and the material density (ρ) is 2.33×10^3 kg/m3. Figure 5 shows a MEMS planar torsional spring sample fabricated using laser processing technology (CO_2 laser tube, 250W). In this test, only 6 arms are kept to measure the micro force, which apart 60°.

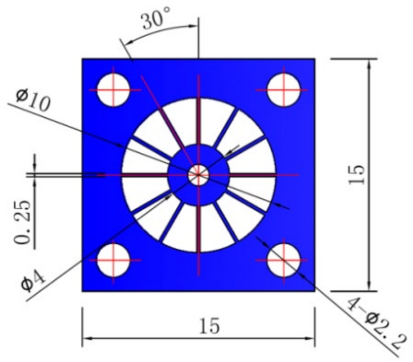

Figure 4. The structure of the planar torsional spring

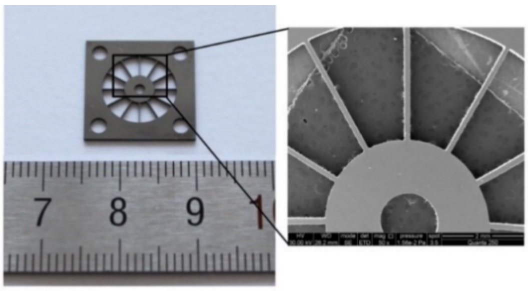

Figure 5. The photography of the planar torsional spring

4. Calculation and calibration for the spring stiffness

4.1 Theoretical analysis and simulation

The force model of the planar torsional spring is shown in figure 6(a). The rotational area, under the torque of T, will produce a deflection angle α.

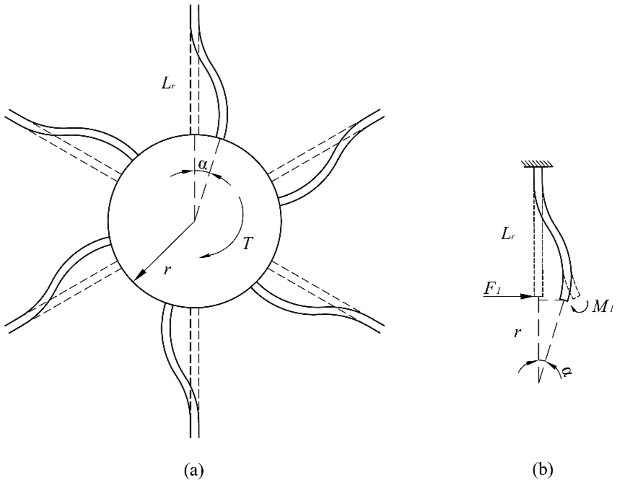

Figure 6. The deformation of the planar torsional spring

At this time, every single beam is deformed by a shear force F_1 and a torque M_1 (Fig. 6(b)), and the relationship between F_1 and M_1 can be written as:

$$\begin{cases} \dfrac{F_1 L_r^3}{3EI} - \dfrac{M_1 L_r^2}{2EI} = r\sin\alpha \approx r\alpha \\ \dfrac{M_1 L_r}{EI} - \dfrac{F_1 L_r^2}{2EI} = \alpha \end{cases} \quad (4)$$

Then,

$$\begin{cases} F_1 = (ar+b)\alpha \\ M_1 = (br+c)\alpha \end{cases} \quad (5)$$

where $a=\dfrac{12EI}{L_r^3}$, $b=\dfrac{6EI}{L_r^2}$, $c=\dfrac{4EI}{L_r}$, $I=\dfrac{bh^3}{12}$.

The torque T is generated by 6 torsional springs, and can be written as:

$$T = 6(F_1 r\cos\alpha + M_1) \approx 6(ar^2+2br+c)\alpha \quad (6)$$

The theoretical torsional stiffness k_1 of the system is given by:

$$k_1 = 6(ar^2+2br+c) \quad (7)$$

Where, r is the radius of the rotational region (2 mm), L_r is the length of a single beam (3 mm), b is the width of a single beam (0.25mm), h is the thickness a single beam (0.5mm). With Young's modulus (E) of 168 GPa, the theoretical stiffness k_1 is 15.17Nm/rad.

Concerns about the impact of the support arm weight, the axial deformation of the MEMS spring war analyzed. In this test, the support arm is made of aluminum alloy and weighs 2 (g). The simulation results show that the deformation of the support arm end along the direction of gravity is 0.01mm and the offset angle is 1.7e-4 (rad). Compared with the MEMS rotation angle, the difference is two orders of magnitude. The effect of the support arm gravity is ignored in this experiment.

The simulation of the planar torsional spring is shown in figure 7. In this model, the four faces of the cube are fully constrained, and a defined rotational torque is applied in the center hole. Then, the rotational area will rotate a certain angle α, which can be obtained by measuring the displacement of a point.

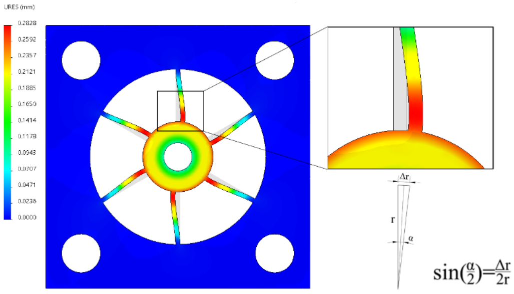

Figure 7. The simulation model of the spring beam

The simulation results of the rotational angle with the given torque are shown in figure 8. This figure shows that the relationship between the applied torque and the deflection angle is not linear. In this study, the elastic deformation of the spring is taken in a very small range because of the limitation of measurement accuracy. When the range of the angle change is within 0.01 rad in figure 8, the measurement accuracy is approaching a straight line, and the slope of the fitting curve equals the elastic stiffness of the planar torsional spring k_2, which is 3.3Nm/rad.

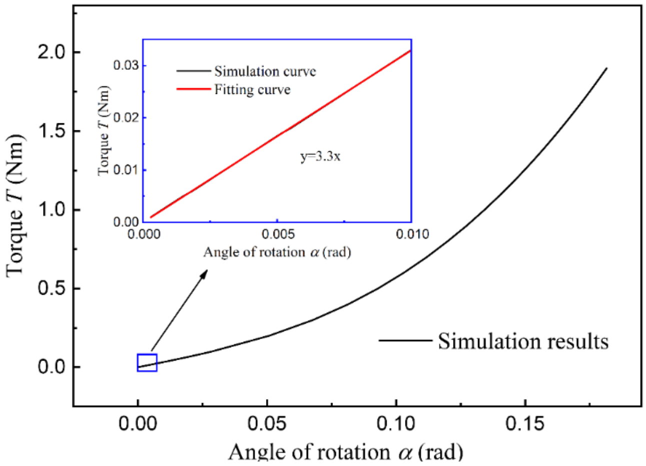

Figure 8. The simulation result of the spring beam

4.2 Calibration

The actual torsional stiffness of the planar torsional spring was calibrated by experimental methods. Figure 9 shows a photograph of the measurement system. All components are mounted on a 600 × 600 mm optical plate. The planar torsional spring is fixed by a three-axis platform and adjusted to a horizontal state. Light is reflected by a triangular prism which is placed upon the planar torsional spring and then detected by a position sensor after reflected by 4 mirrors. The red line marked in the figure is the light path.

Calibrated masses were connected to the end of the support arm by a string, and a small pulley was used to turn the gravitational force to horizontal direction.

When a given force is applied at the end of the support arm, the light spot will move on the surface of the position detector. The applied force and the moving distance are recorded for calibration of the planar torsional spring.

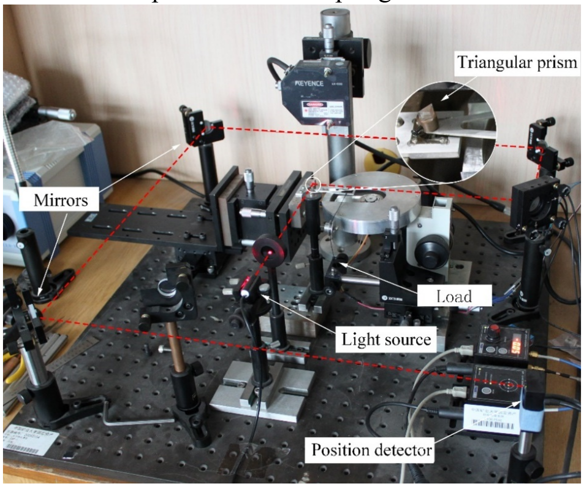

Figure 9. Photograph of the measurement system

The results of the calibration of the planar torsional spring are shown in figure 10. The abscissa and the ordinate show the applied force and the displacement of light spot moving. In this test, small masses are used to apply force in the range of 1g~10g, g is 9.8015 m/s^2. Each mass is measured 10 times, and the average is used as the standard value, the standard error is also marked in the figure.

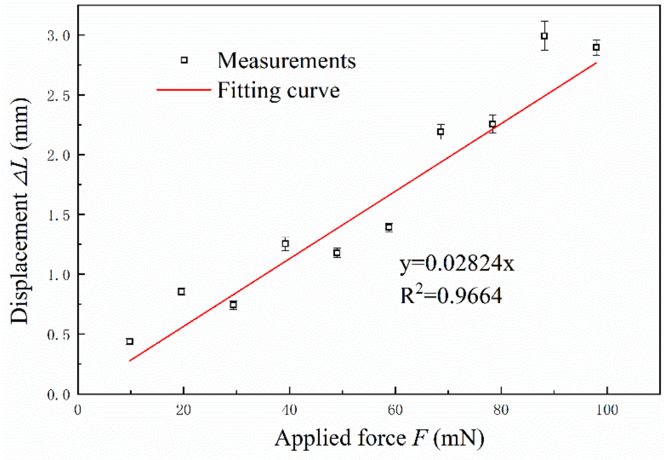

Figure 10. The calibration result of MEMS planar torsional spring

From the measurement results in the above figure, the slope of the fitted line can be obtained as 0.02824, and the planar torsional spring is calibrated to the torsional stiffness k_3 = $L_1 \cdot L_2 \cdot F/\Delta L$=3.7181Nm/rad, where the length of support beam L_1 is $50^{0}_{-0.0005}$ mm, and the laser path L_2 is $2100^{+0.021}_{0}$ mm.

The experimental calibration is used as the final planar torsional spring stiffness coefficient. Then, the designed MEMS planar torsional spring measures the micro force F based on the equation (8).

$$F = \frac{k_3\alpha}{L_1} = k_3\frac{\Delta L}{L_1L_2} = 35.41\Delta L(\mathrm{N}) \tag{8}$$

The position detector used in this experiment has a resolution of 0.75 μm and a measurement range of ±4.5 mm. Therefore, this measurement system has a theoretical resolution of 26.56 μN, and a range of ±159mN.

5. Characteristics of the measurement system

The accuracy and repeatability of this system were studied in the following experiment. Three small masses were measured by an electronic balance with a measurement uncertainty of 0.1 mg, which were used to define reference force. The calibrated torsional spring measurement system was used to measure the given reference force. Each force was measured 10 times. The deviation between the measurements and the reference standards are presented in figure 11.

It can be seen that the measured values are very close to the reference standards. In the case of 47.88 mN, the deviation of the mean is -0.60 mN, which equals -1.25% of the reference value. The repeatability standard deviation is 2.13 mN, which equals 4.44% of the reference value. By measuring 83.26 mN reference force, the mean deviation is -0.028 mN (0.03%) and the repeatability standard deviation is 3.31 mN (3.98%). For the largest reference force, 136.55 mN, the mean deviation is 0.34 mN (0.25%) and the repeatability standard deviation is 5.1 mN (3.75%).

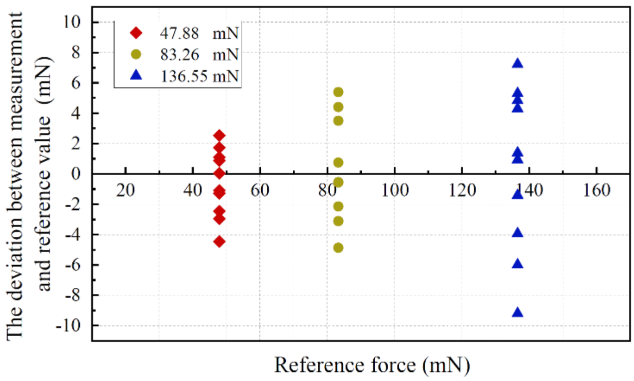

Figure 11. Measurements of reference standards with the torsional spring measurement system

6. Conclusion

In order to measure the micro force in the MEMS, a micro force measurement system based on a MEMS planar torsional spring is developed. By measuring the moving distance of the light spot which is reflected by a MEMS planar torsional spring, the micro force can be obtained. In this paper, a MEMS planar torsional spring is designed and the stiffness is obtained by theoretical calculation, simulation, and calibration. The results show that the torsional stiffness of the MEMS planar torsional spring is 3.7181Nm/rad. The measurement system has a resolution of 26.56 μN and a range of ±159mN. The accuracy and repeatability of this system were studied using the calibrated measurement system and an electronic balance. The three sets of results show that the measurement system has good accuracy and repeatability for micro force measurements.

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