Newly Designed Three-degree-of-freedom Zero-compliance Mechanism for Precise Force Measurement Using Cantilever*

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Abstract— The concept of force measurement using zerocompliance mechanism was extended to measurement with cantilever. To achieve the zero-compliance states of the tip of the cantilever (point of action) in measuring force, a three-degree-offreedom zero-compliance mechanism was developed. It had a triangle whose sides were variable in length. However, the developed device consisted of approximately fifty components, and there were interactions among the motions. For improvement, another three-degree-of-freedom zero-compliance mechanism is newly designed and manufactured. Because the three motions (two translations and one rotation) of the detection point are quasiseparated, there are less interactions among the motions, which is better for precise measurement. In this article, numerical analyses are carried out to predict the displacements and the attitude of the point of action without control and those of the detection point in the zero-compliance states. In the experiment, static force is applied to the tip of the cantilever. The experimental results demonstrate that the manufactured device operates as expected.

I. INTRODUCTION

Force has been a fundamental physical quantity since ancient times. The measurement of fine force is one of the critical technologies in various fields. To measure force precisely, a variety of methods and devices have been proposed and developed [1]. They are classified in a number of different ways. One classification is according to the system structure: open-loop system or closed-loop system. The former corresponds to the *deflection method* [2, 3] while the latter corresponds to the *null method* [2-4].

A common atomic force microscope (AFM) uses a cantilever to detect force sensitively [5-7]. The cantilever deflects when force acts on the tip of the cantilever. The value of force is calculated from the amount of this deflection. Thereby, it belongs to the former type (*deflection method*). To detect fine force, the stiffness of the cantilever is usually set to be sufficiently low because the softer is the cantilever, the larger is the deflection. It causes the point of action (the tip of the cantilever) to move from the original position when force to be measured acts on the point of action. Owing to such movements, conditions in measuring force may change. For instance, the force usually becomes larger when the distance between the source of force and the point of action becomes smaller. It indicates that the movement of the point of action may lead to measurement error. This problem can be overcome by applying the *null method*. In this method, however, high-gain feedback is usually implemented to ensure against phase lag in measurement [8]. It often makes the control signal noisy, which may result in significant degradation of measurement resolution because the force is estimated from the control signal.

The authors have proposed force measurement with zerocompliance mechanism [9]. According to the original concept, this mechanism is a series connection of a spring with positive stiffness (positive spring) and another spring with negative stiffness (negative spring); the amplitude of stiffness is set to be identical. Force to be measured acts on one of the ends of the connected springs (point of action). Nevertheless, this point of action does not move because the deflections of the springs cancel each other. It indicates that this method belongs to the latter type (*null method*). In contrast, the connection point (detection point) displaces in proportion to the applied force. The force is estimated from the deflection of the detection point like by the *deflection method* and not from the control signal.

The concept of force measurement with zero-compliance mechanism was extended to measurement with cantilever. A three-degree-of-freedom zero-compliance mechanism was designed and manufactured [10]. It had a triangle whose sides are variable in length. It enables the mechanism to maintain the positions and attitude of the tip of the cantilever (point of action) to be invariant even when force acts on the point of action. However, the manufactured device consisted of approximately fifty components, and had some interactions among the motions, which caused errors in measuring force.

In this work, another three-degree-of-freedom zerocompliance mechanism is newly designed and fabricated. Because the three motions (two translations and one rotation) of the detection point are quasi-separated, there are less interactions among the motions, which is better for precise measurement.

In this article, numerical analyses are conducted to predict the position and attitude of the root of the cantilever (detection point) in the zero-compliance states. In the experiment, static force is applied to the tip of the cantilever. The experimental results demonstrate that the fabricated device operates as expected.

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Figure 1. Force measurement using zero-compliance mechanism.

II. PRINCIPLES OF MEASUREMENT

A. Zero-compliance mechanism

The principle of force measurement with zero-compliance mechanism is illustrated by Fig.1. Suspension I is connected in series with Suspension II. The connection point is denoted by "D", which becomes the detection point. Target force acts on the other end of Suspension II that is denoted by "A". This point is called as the point of action. The stiffness of the connected suspensions, denoted by k_c , is given by

$$k_c = \frac{k_1 k_2}{k_1 + k_2} \tag{1}$$

where k_i : stiffness of each suspension. This equation indicates that the resultant stiffness becomes lower than each stiffness if normal springs are used ($k_i > 0$). Nevertheless, such a situation changes if one of the suspensions is allowed to have negative stiffness. Especially, when

$$k_1 = -k_2, \qquad (2)$$

is satisfied, the resultant stiffness becomes infinite as

$$\left|k_{c}\right| = \left|\frac{k_{1}k_{2}}{k_{1}+k_{2}}\right| = \infty \tag{3}$$

It means that the point of application is invariant (no deflection), which is just a characteristic of measurement by the *null method*. Meanwhile, the detection point moves from the original position proportionally to the force as

$$z_1 = \frac{f}{k_1} = -\frac{f}{k_2}$$
(4)

where z_1 : displacement of detection point and f: force acting on the point of action (Fig.1 (a) and (b)). It indicates that the force



(a) Movement of cantilever when force is applied.



(b) Target state

Figure 2. Movement of cantilever

can be estimated from the displacement of the detection point. Therefore, this is categorized into measurement by the *deflection method*. Equation (4) indicates that each suspension should have low stiffness for high resolution in measurement.

B. Force measurement with cantilever

In measuring force with high sensitivity, a cantilever is often used [5-7]. The amplitude of force is estimated from the deflection of the cantilever. It is assumed that force is applied to a tip at the end of the cantilever in the vertical direction. The movement of the cantilever is shown in Fig.2 (a). The tip naturally displaces in the vertical direction. In addition, the tip displaces also in the horizon direction that is perpendicular to the direction of the applied force. Moreover, the attitude of the tip also varies according to the applied force. Measurement error or uncertainty can be induced by such deflections of cantilever because the states of the point of action change from the original ones where force just acts on the tip. Ideally, the states should be maintained to be original even force acts on the tip as shown by Fig.2 (b). Such measurement is the target of this research.

C. Prediction of displacements and attitude of each point

A special cantilever shown in Fig.3 will be used in the experiment demonstrating the feasibility of the proposed method of force measurement. The shape is selected to be a slender triangle to restrict the movements of the point of action in the vertical (z) and horizontal (x) directions and the rotation (θ) in this (x-z) plane.

Fig.4 shows the calculated displacements and the attitude of the point of action (the tip of the cantilever) when force is applied to this point and the detection point is fixed at the original states. The longitudinal elastic modulus of the lever is assumed to be 105 GPa. Then the positions and attitude of the detection point are calculated according to inverse kinematics when those of the point of action are regulated (kept zero). The results are shown by Fig.5, which predict the movements of the detection point when the zero-compliance mechanism are operating well.



Figure 3. Cantilever used in the experiment.

III. THREE-DEGREE-OF-FREEDOM ZERO-COMPLIANCE MECHANISM

A. First 3-DoF zero-compliance mechanism

To regulate the positions and attitude of the point of action, a three-degree-of-freedom (3-DoF) mechanism is necessary. Fig.6 shows a conceptual drawing of the originally manufactured mechanism [10]. This mechanism has a three-link hinge, three variable-length links (Link 1 to Link 3) and two fixed-length links. The former three links comprise a triangle whose inner angles are variable. Link 1 and the passive links comprise another triangle whose inner angles are also variable. A cantilever is fixed at the vertex opposite to Link 1. This vertex becomes the detection point in measuring force. The position and the attitude of the detection point are adjusted by varying the lengths of the former links.

Fig.7 shows a drawing of the manufactured mechanism [10]. A variable-length link consists of a voice coil motor (VCM) and a leaf spring that are installed in parallel. The leaf spring restricts the motion of the link to a single-degree-of-freedom motion in the normal direction. The length of the link is varied by the VCM. A rotational spring is placed at the vertex of the triangle, which enables the inner angle to vary.

Although the device was carefully designed, it had approximately fifty components, and had some interactions among the motions, which caused errors in measuring force [10].

B. Newly designed 3-DoF zero-compliance mechanism

Fig.8 shows a schematic drawing of the newly designed mechanism. It has a center block supported by two leaf springs. The springs restrict the movement of the block to three degrees of freedom of motion: two (vertical and horizontal) translations and one rotation (pitching). Three voice coil motors (VCMs) are used to control the three motions. Two of them (VCM1 and VCM2) are installed below the block and operated in phase to



Figure 4. Displacements and attitude of the point of action when the detection point is fixed.



Linear springs

Figure 7. Fabricated 3-Dof zero-compliance mechanism.

control the vertical translation and in opposite phase to control the rotation. The other VCM (VCM3) is installed beside the block to control the horizontal translation. It is expected from the structure that three motions are controlled individually.

A slender-triangle cantilever whose shape is shown by Fig.3 is attached to the block that corresponds to the detection point. This special shape is selected to restricting the movement of the tip to the three degrees of freedom of motion.



Figure 8. Newly designed 3-DoF mechanism.



Figure 9. Arrangement of sensors in the newly designed 3-DoF mechanism



Figure 10. Picture of force measurement device

Fig.9 shows the arrangement of sensors. The horizontal and vertical displacements of the tip are detected by two optical sensors (L1 and L2). The angle of the tip is detected by an optical lever consisting of a Laser source and a position sensitive detector (PSD). The vertical displacement and the angular displacement of the block are measured with two optical displacement sensors (L3 and L4). The horizontal displacement of the block is detected by an optical sensor (L5). Each optical

sensor consists of a sensor head (KEYENCE IL-S025) and an amplifier (KEYENCE IL-1000). The resolution is 1 $\mu m.$

A picture of the fabricated force measurement device is shown by Fig.10. The size is $W330 \times H170 \times D140$ mm . All the components mentioned above are installed in this device.



Figure 11. Measurement results

IV. MEASUREMENT RESULT

Weights are added on the tip of the cantilever for static force measurement. The vertical displacement z_A , horizontal displacement x_A and the angular displacement θ_A of the point of action, and the vertical displacement z_D , horizontal displacement x_D and the angular displacement θ_D of the detection point are measured. The measurement results are presented by Fig.11 in which the average and standard deviation of five-time measurements are shown. They indicate that the position and attitude of the point of action are kept zero and the vertical displacement of the detection point is clearly proportional to the applied force. The angular displacement of the detection point is also proportional to the applied force. These results indicate that the force can be measured from the vertical displacement and/or the angular displacement of the detection point when the position and attitude of the point of action are regulated.

Meanwhile, the horizontal displacement of the detection point increases as the force increases, but the linearity is not good. It is because the displacement is approximately one-tenth that of the vertical translation, and the signal-to noise ratio becomes low.

V. CONCLUSION

The principle of the zero-compliance force measurement with cantilever was presented. Numerical analyses were carried out to predict the displacements and the attitude of the point of action without control and those of the detection point in the zero-compliance states. A new three-degree-of-freedom zerocompliance mechanism was designed and manufactured. The experimental results demonstrate that the fabricated device operates as expected.

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