Evaluation of Multi-Dimensional Force Measurement Apparatus using Zero-Compliance Principle in Microforce Measurement

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Abstract. Measuring microforce is inevitable in the current technical world of micro-assembly and micromanipulation. Zero-compliance principle is implemented in measuring microforce. There are two floaters suspended in series to achieve zero-compliance in force measurement. The first floater is denoted as detection point and the second floater is denoted as point of force. If external force is applied at the point of force, the detection point displaces to balance the force and in result, the point of force maintains its position. The amount of the applied force is estimated from the displacement of the detection point. A novel multi-dimensional force measurement apparatus is designed and developed based on the zero-compliance principle to measure microforce. Evaluation of the apparatus in microforce measurement is demonstrated in this paper by using vertical direction force measurement results.

1. Introduction
In the last few decades, micro-assembly and micromanipulation have drawn significant attention due to the progressive trend of miniaturization of devices. Therefore, precise measurement of microforce is indispensable for proper micro-assembly and micromanipulation in the modern field of material science, biomedical application, medical application, and so on.

There are several researches focused on developing systems for sensing microforces based on strain gauge-force sensors, piezoelectric actuators, MEMs sensors and optical force sensors [1]. Amongst all, atomic force microscope (AFM) cantilever is the mostly used instrument for measuring microforces in diversified areas like material sciences to biological researches [2, 3]. Including AFM, most of the current methods estimate force from the deflection of the point of force and that causes the point of force to be displaced form the source of force. Force can be measured from the control current of the magnetic suspension balance without deflecting the point of force, but the resolution of measurement is degraded in case of measuring microforce because of high noise-signal ratio.

To address these issues, force measurement using zero-compliance principle has been proposed [4]. This method assures high sensitivity in force measurement and maintains high stiffness at the point of force. Several devices have already been developed for zero-compliance force measurement using double series magnetic suspension. In the double series magnetic suspension, a single electromagnet levitates two floaters. The control current of the electromagnet directly controls the movement of the first floator. A permanent magnet is installed with this floator. The attractive force of the permanent magnet regulates the motion of the second floator. Thus, this floator is indirectly controlled by the electromagnet.

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A novel multi-dimensional force measurement apparatus is developed to measure microforce based on the principle of zero-compliance. To avoid fluctuation in lateral directions of the previously developed tri-axial force measurement instrument [5], leaf springs are used to suspend both of the floators and restricts their motion in translation. High-resolution laser sensors and leaf springs with softer stiffness are installed to make the apparatus capable of measuring micro-newton force in comparison with the previously developed one dimensional device that can measure force up to milli-newton range [4]. The competency of the apparatus in measuring microforce is evaluated by the experimental results of vertical direction force measurement.

2. Measurement Principle

2.1. Zero-compliance principle

Basic principle of estimating force using zero-compliance mechanism is shown by Fig. 1. Suspension I \((k_1)\) and suspension II \((k_2)\) are connected in series. The free end, B is denoted as the point of force and the connection point, A of the two suspensions is mentioned as the detection point. The stiffness of the complete suspension \((k_c)\) can be represented as

\[
k_c = \frac{k_1 k_2}{k_1 + k_2},
\]

Equation (1) mentions that the combined stiffness is smaller than that of individual stiffness when normal springs are connected. If the stiffness of the suspensions is set as shown by Fig. 1,

\[
\begin{align*}
(b) \quad & k_1 > 0 \quad \text{and} \quad k_2 = -k_1 < 0 \\
(c) \quad & k_1 < 0 \quad \text{and} \quad k_2 = -k_1 > 0,
\end{align*}
\]

the combined stiffness becomes infinite.

\[
|k_c| = \left| \frac{k_1 (-k_1)}{k_1 - k_1} \right| = \infty,
\]

Equation (3) confirms that even force is applied, the point of force maintains its position. In contrast, Eq. (4) shows that the detection point displaces in proportion to the force either in the same direction or in the opposite direction.

\[
\begin{align*}
(b) \quad & z_1 = \frac{f}{k_1} = -\frac{f}{k_2} > 0 \\
(c) \quad & z_1 = \frac{f}{k_1} = -\frac{f}{k_2} < 0,
\end{align*}
\]

The zero-compliance principle is implemented in force measurement using double series magnetic suspension [4]. An electromagnet controls the motion of the detection point and the point of force. The applied force can be estimated from the displacement of the detection point by maintaining the position of the point of force.

2.2. Multi-dimensional force measurement

Multi-dimensional force measurement is achieved by expanding the zero-compliance principle of

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![Figure 1. Zero-compliance principle.](image1.png)

![Figure 2. Vertical direction force measurement.](image2.png)
single axis. Similar to double series magnetic suspension system, an electromagnet is affixed at the top to control the movement of the point of force and the detection point in vertical axis as shown by Fig. 2. Figure 3 presents the schematic diagram of the structure. Four voice coil motors (two in each direction) are arranged to regulate the motion in the x and y directions. In every direction, both the detection point and the point of force are suspended through leaf springs from the base frame to restricts their motion in translation. In lateral directions, voice coil motors are used to reduce the nonlinearity effect of the permanent magnet and to avoid excessive structural complexity, electromagnet and permanent magnet are used in the vertical direction only.

3. Experimental setup

3.1. Apparatus

A conventional size multi-dimensional force measurement apparatus has been developed based on the principle of zero-compliance mechanism [6]. Figure 4 presents the photograph of the device. As shown by Fig. 2, the vertical direction motion is controlled by the electromagnet fixed at the top frame and the permanent magnet attached under the detection point. A voice coil motor is affixed with the bottom frame and its bobbin is connected to the point of force to add disturbance. Two laser sensors are used to detect the displacement of the detection point and the point of force.

3.2. Mathematical model and control system

The equations of the z-direction motion can be represented by

\[ m_1^{(z)} \ddot{z}_1(t) = -\left(h_1^{(z)} - k_s^{(z)}\right)z_1 + k_m^{(z)}(z_1 - z_2) - k_i^{(z)}i, \]  
\[ m_2^{(z)} \ddot{z}_2(t) = h_2^{(z)}z_2 - k_m^{(z)}(z_1 - z_2) + f^{(z)}i, \]  

where \( m_1^{(z)} \) and \( m_2^{(z)} \): mass of the detection point (z) and the point of force (z); \( h_1^{(z)} \) and \( h_2^{(z)} \): stiffness of the leaf springs connected with the detection point (z) and the point of force (z); \( k_s^{(z)} \) and \( k_i^{(z)} \): gap force factor and current force factor of the electromagnet; \( k_m^{(z)} \): gap force factor of permanent magnet; \( z_1 \) and \( z_2 \): displacement of the detection point (z) and the point of force (z); \( f^{(z)} \): external force and \( i \): control current of the electromagnet.

To accomplish zero-compliance at the point of force, PID control is applied to the point of force and PD control to the detection point to make the system stable.

The control current for the z-direction force measurement can be given by

\[ i^{(z)}(s) = \left(p_d^{(z)} + sp_v^{(z)}\right)Z_1(s) - \left(q_d^{(z)} + sq_v^{(z)} + \frac{q_i}{s}\right)Z_2(s), \]  

(7)
where \( p_d(z) \) and \( p_v(z) \): proportional gain and derivative gain of the PD controller of the detection point (z); and \( q_d(z), q_v(z), \) and \( q_i(z) \): proportional gain, derivative gain and integral gain of PID controller of the point of force (z).

4. Experimental result

Microforce measurement experiment is done in vertical direction only. Force is applied at the point of force by using the bottom VCM. The results of the static and dynamic force measurement are shown by Fig. 5 and Fig. 6, respectively. Figure 5 shows that the detection point displaces linearly with the addition of static force in micro-newton range and stable zero-compliance is achieved at the point of force. This result demonstrates that the apparatus is capable of measuring force more than thousand times smaller than the single axis force measurement device [4] and similar amount of force with better linearity compared to three-dimensional force measurement system [5]. Figure 6 confirms that the apparatus can also measure dynamic force by maintaining the position of the point of force.

![Figure 5](image1.png) **Figure 5.** Displacement of the detection point and the point of force with addition of static force.

![Figure 6](image2.png) **Figure 6.** Dynamic force measurement result.

5. Conclusion

Multi-dimensional force measurement apparatus using zero-compliance principle was evaluated for measuring micro force both in static and dynamic condition. Stable zero-compliance was achieved at the point of force without any rotation or fluctuation. The force was measured from the displacement of the detection point and the linear displacement indicates the high accuracy in the measurement result. The error in the vertical direction microforce measurement result was 10-15\%, which is less than 5\% when the measurement range was in milli-newton. Horizontal direction force measurement in milli-newton range is demonstrated in [7] and further work is going on for measuring microforce.

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