PROPOSAL OF FORCE MEASUREMENT USING A ZERO-COMPLIANCE MECHANISM

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Abstract − Zero-compliance mechanism is applied to force measurement. The force to be measured acts on a target body suspended by a zero-compliance mechanism consisting of two suspensions connected in series through a detection point. One of the suspensions is operated to cancel the displacement of the other. The force can be estimated from the displacement of the detection point. An instrument was fabricated which used double series magnetic suspension as a zero-compliance mechanism. The effectiveness of the proposed measurement method was demonstrated experimentally.

Keywords: force measurement, zero compliance, infinite stiffness, servomechanism, magnetic suspension

1. INTRODUCTION

Force is an important physical quantity in many industries and scientific fields. There are various methods of force measurement [1]. They can be classified in a number of different ways. One classification is based on the structure of measurement system. One category is measurement by an *open-loop system* that is referred to as *deflection method*. The other is measurement by a closed-loop system that is referred to as *null method* [2].

Most of the measurement devices belong to the former category. A typical example is load cell. In such devices, higher resolution can be achieved as the stiffness of the mechanical conversion part is made lower. However, such low-stiffness mechanism causes several problems. The measurement conditions such as the distance between the force source and the point of action may change in measurement. In addition, the measurement bandwidth tends to be narrow.

The first problem can be avoided by using a measurement system with servomechanism, which is categorized into the null method. To widen the bandwidth of the closed-loop system, higher feedback gains are usually necessary. However, such high-gain system tend to suffer from noise generated in the control signal, which will worsen the resolution of measurement because the force is estimated from the control signal.

In this work, a novel method of force measurement is proposed to overcome the above-mentioned problems. It is characterized by using a zero-compliance mechanism.
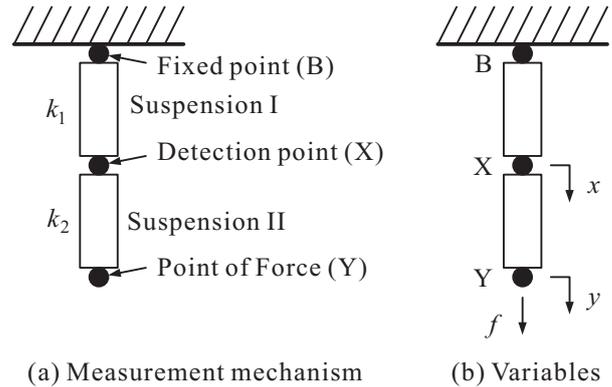

(a) Measurement mechanism   (b) Variables

Fig.1 Schematic drawing of measurement mechanism

2. PRINCIPLES OF MEASUREMENT

2.1. Zero-compliance Mechanism

Figure 1 shows a zero-compliance mechanism for force measurement. The point of force Y is suspended by a series-connected suspensions; the connection point becomes the detection point X. The stiffness of the connected suspensions, denoted by k_c, is given by

$$k_c = \frac{k_1 k_2}{k_1 + k_2},$$ (1)

where k_i: stiffness of each suspension. This equation shows that the total stiffness becomes lower than that of each suspension when normal springs are connected. However, if one of the suspensions has negative stiffness that satisfies

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

the resultant stiffness becomes infinite, that is

$$|k_c| = \infty.$$ (3)

It indicates that the point of force does not move even if force acting on this point as if measured by the null method. In contrast, the detection point displaces proportionally to the force acting on the body as

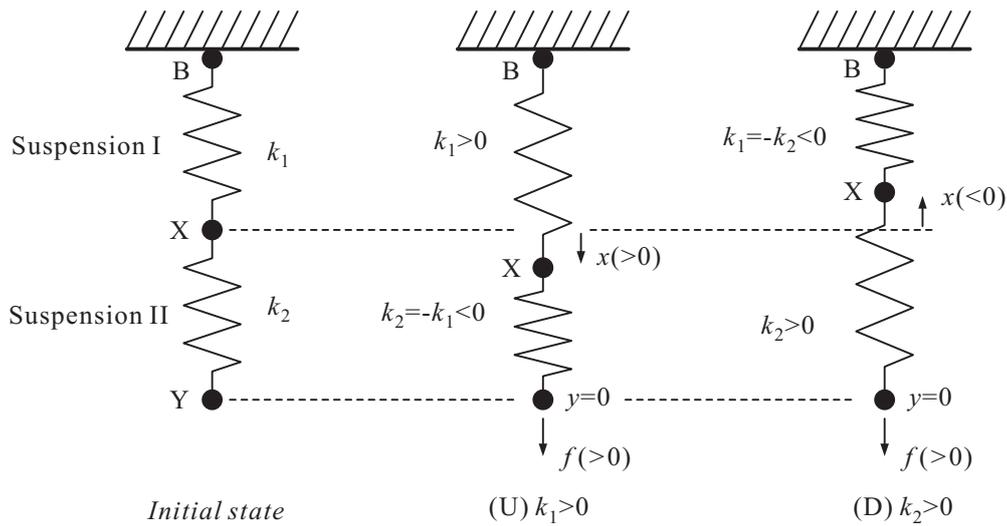$$x = \frac{f}{k_1} = -\frac{f}{k_2}$$ (4)

Fig.2 Operation to applied force

Therefore, the force can be estimated from the displacement as if measured by the deflection method. It is noted that high resolution is expected when low-stiffness suspensions are used.

2.2. Classification

The proposed force measurement systems can be classified according to
- location of active element
- location of positive-stiffness element

Practically, active control is necessary to achieve the zero-compliance characteristic without losing stability [3]. Therefore, at least one of the suspensions must be active. There are three ways of locating such active element:

(a) Suspension I
(b) Suspension II
(c) Both suspensions

The last one is most flexible but highest in cost.

Another criterion of classification is the location of positive-stiffness element. There are two ways:

(U) Suspension I
(D) Suspension II

The operation of mechanism in each case is illustrated by Fig.2. The detection point displaces in the same direction as the applied force in the case of (U) while opposite in the case of (D).

3. DOUBLE SERIES MAGNETIC SUSPENSION

A typical example of zero-compliance mechanism is series magnetic suspension [4]. It is classified to (a) and (U). In double series magnetic suspension system, two floators are suspended by a single electromagnet as shown in Fig.3. The force of the electromagnet directly acts on the first floator made of permanent magnet. The force of the permanent magnet acts on the second floator. The position of the first floator is controlled by the current flowing the coil of the electromagnet. The attractive force acting on the second floator varies when the gap between the first and second floator varies so that the position of the second floator is
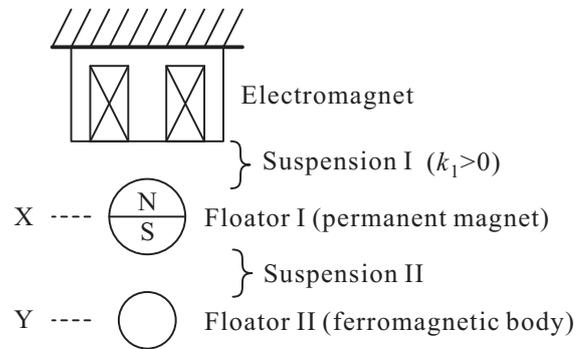

Fig.3 Double series magnetic suspension

indirectly controlled by the coil current. Thus, this system is controllable and can be stabilized by feedback control.

In the proposed measurement system, the second floator is operated as the point of force and the first floator becomes the detection point. The second floator is controlled to maintain the original position at least in the steady states even if an external force acts on the second floator. The first floator displaces to increase or decrease the attractive force between the floators to cancel the external force. Therefore, the force can be estimated for the displacement of the first floator.

3. EXPERIMENT

3.1. Apparatus

For basic studies, a conventional-size apparatus is fabricated to examine the measurement principle. Figures 4 and 5 show a schematic drawing and a photo of the fabricated apparatus, respectively. An electromagnet is installed on the top of the frame. A permanent magnet is installed at the bottom of the second floator. Each floator is supported by four leaf springs to constrain the motion of the floator solely to the vertical translation. A voice coil motor (VCM) is installed below the second floator to generate an external force on the second floator.

3.2.M mathematical Model

The equations of motion in the neighbourhood of the equilibrium states are given by [5]

$$m_1 \ddot{x}(t) = -(h_1 - k_s)x + k_m(x - y) - k_i i, \qquad (5)$$

$$m_2 \ddot{y}(t) = -h_2 y - k_m(x - y) + f(t), \qquad (6)$$

where m_1 : mass of the first floator, m_2 : mass of the second floator, h_1 stiffness of the leaf springs supporting the first floator, h_2 : stiffness of the leaf springs supporting the second, k_s : gap-force factor of the electromagnet, k_i : current-force factor of the electromagnet, k_m : gap-force factor of the permanent magnet, x : displacement of the first floator, y : displacement of the second floator, i : control current, f : external force acting on the second floator.

3.3. Control System

In the proposed system, the force acting on the second floator is estimated from the displacement of the first floator when the second floator is maintained at the original position. To achieve such condition, we apply PID control to the second floator. In addition, the total system must be made stable so that PD control to the first floator is added. Assuming that the coil current of the electromagnet is supplied by an amplifier with current output, the coil current is treated as control input. The control input is represented as

$$I(s) = (p_d + p_v s)X(s) + (q_d + q_v s + \frac{q_I}{s})Y(s) \qquad (5)$$

where p_d and p_v are the proportional and derivative gains of the PD controller for the first floator, and q_d, q_v and q_I are the proportional, derivative and integral gains of the PID controller for the second floator.

Figure 6 shows a block diagram of the control system.

3.3. Static Force Measurement

Figure 7 shows the displacement of each floator when static force is added to the second floator. In this figure, downward (positive) displacement is plotted to the downward direction for intuitive understanding. The static force was produced by adding weights to the second floator one by one from 0 to 10 [N]. One weight corresponds to 1 [N]. After all the weights were attached, weights were removed one by one to the initial state. It is confirmed from this result that the second floator maintains the original position and instead the

first floator displaces in proportion to the force. In addition, a slight difference was observed between in decreasing and increasing. This is due to magnetic hysteresis.
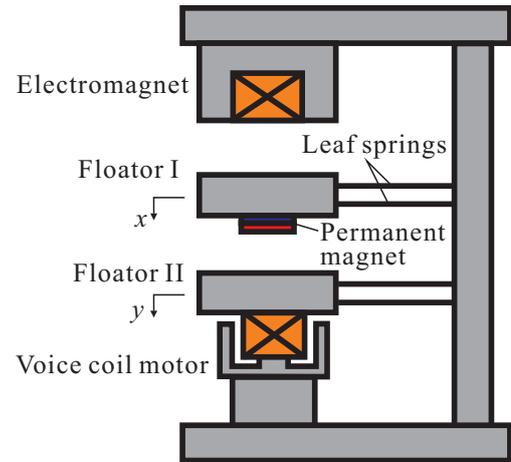

Fig.4 Photograph of the apparatus

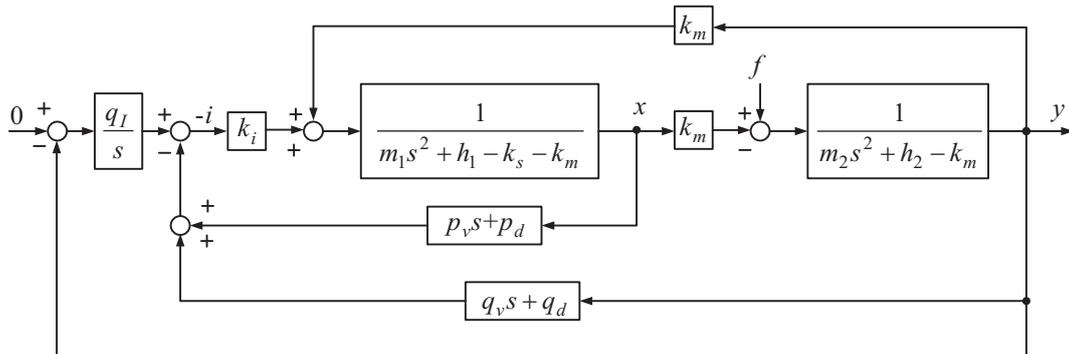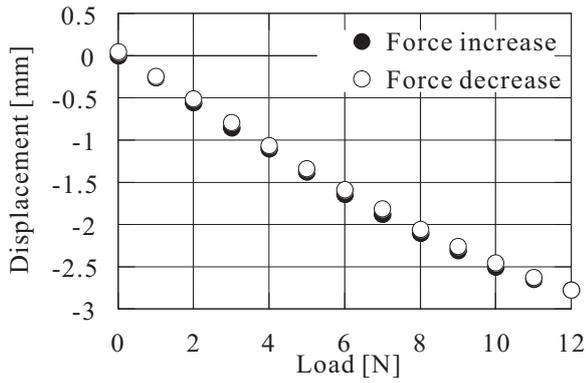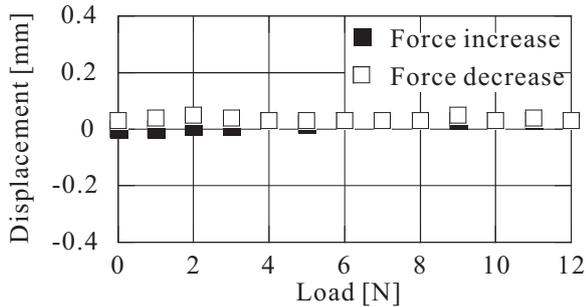Fig.5 Schematic drawing of the appratus

Fig.6 Block diagram of the control system

(a) Displacement of the detection point

(b) Displacement of the point of force

Fig.7 Displacement of each floator when static force is added to the second floator
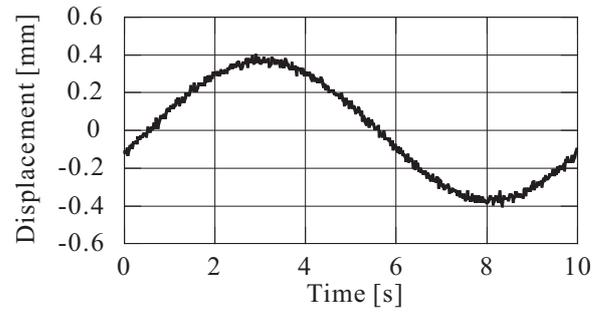

(a) Displacement of the detection point

(b) Displacement of the point of force

(c) Force

Fig.8 Responses when a dynamic force acting on the second floator.

3.3. Dynamic Force Measurement

Figure 8 shows the displacement of each floator when an harmonic force with a frequency of 0.1 [Hz] and an amplitude of 1 [N] added to the second floator. It is found that the first floator maintains the original position and instead the first floator displaces in proportion to the force for such dynamic force. It demonstrates the possibility of dynamic force measurement by the propose method.
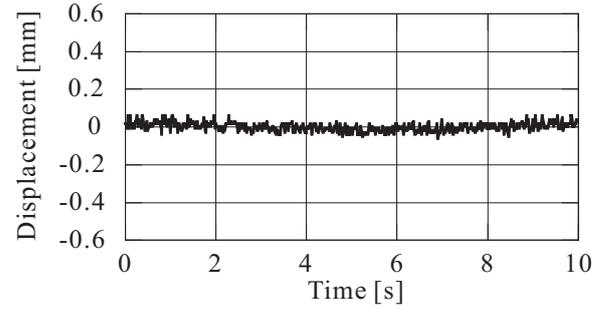
4. CONCLUSIONS

Force measurement using double series magnetic suspension was proposed. In the proposed measurement method, the force acting on the second floator was transformed to the displacement of the first floator by the feedback control including integral action. An apparatus was fabricated for experimental study on the proposed measurement method. It was confirmed experimentally that the first floator displaced proportionally to external force acting on the second floator. In addition, the measurement of a dynamical force was carried out by the developed apparatus.
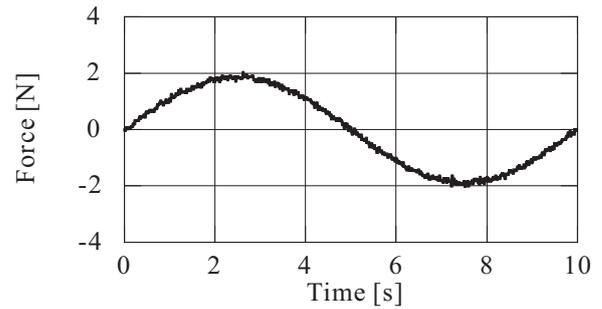
ACKNOWLEDGMENTS

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