Available online at www.sciencedirect.com
ScienceDirect
IFAC-PapersOnLine 49-21 (2016) 536–540

Fabrication of a Three-dimensional Force Measurement System Using Double Series Magnetic Suspension

Takeshi MIZUNO*, Yuji ISHINO, Masaya TAKASAKI

Saitama University, Shimo-Okubo 255, Sakura-ku, Saitama 338-8570, JAPAN
(Tel: +81-48-858-3455; e-mail: mizar@mech.saitama-u.ac.jp).

Abstract: Double series magnetic suspension is applied to force measurement. In a double series magnetic suspension system, two floators are suspended with a single electromagnet. When the position of the second floator is regulated, for example by PID control, the second floator is maintained at the original position against an external force acting on it whereas the first floator displaces in proportional to the force. Therefore, the force acting on the second floator can be estimated for the displacement of the first floator. This principle of force measurement was applied to single-dimensional force measurement. In this work, an apparatus for three-dimensional force measurement is designed and fabricated. An individual three-axis control is applied to the apparatus to achieve noncontact suspension. Then, three-dimensional force measurements are carried out to study the performances of the fabricated apparatus.

Keywords: Magnetic suspension, Measuring transducers, Force balance, Servomechanisms, Magnetic bearing, Cancellation, PID control, Zero compliance.

1. INTRODUCTION

Magnetic suspension using controlled electromagnets can realize various functions that are impossible for conventional mechanical suspension. For example, in a wind-tunnel system, magnetic suspension is used to measure aerodynamic forces acting on the test body where the force is estimated from the control signal of magnetic suspension system that is operated to maintain the positions of the body against wind (Boyden et al., 1985; Sawada et al., 1994; Mizuno et al., 2010).

In many industries and scientific fields, such force measurement is quite important because it is one of the fundamental physical quantities. There are various methods of force measurement (Stefanescu, 2011). We have proposed to apply double series magnetic suspension to force measurement (Mizuno et al., 2012, 2015). In the double series magnetic suspension system, two objects, which are referred to as floators in the following, are suspended with a single electromagnet (Mizuno et al., 2011). The force of the electromagnet directly acts on the first floator equipped with a permanent magnet. The force of the permanent magnet acts on the second floator. It means that the second floator is indirectly suspended by the electromagnet (Yamamoto et al., 2008). When PID control is applied to the motion control of the second floator, the first floator displaces in proportion to the force applied to the second floator whereas the position of the second floator is maintained to be original. Therefore, the force can be estimated for the displacement of the first floator. The proposed method has an advantage over conventional methods; the distance between the operating point of force (second floator) and the source of force is kept invariant.

In this work, an apparatus using double series magnetic suspension for measuring three-dimensional forces is designed and fabricated. The control system for three-dimensional suspension is designed and implemented. In addition, three-dimensional force measurements are carried out based on the proposed principle of force measurement.

2. PRINCIPLES OF MEASUREMENT

2.1 Zero-Compliance Mechanism

Figure 1 shows a zero-compliance mechanism for force measurement (Mizuno et al., 2015). The point of force A is suspended by a series-connected suspensions; the connection point becomes the detection point P. 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 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

$$k_1 = -k_2, \tag{2}$$

the resultant stiffness becomes infinite, that is

$$|k_c| = \infty. \tag{3}$$

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

2405-8963 © 2016, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.657

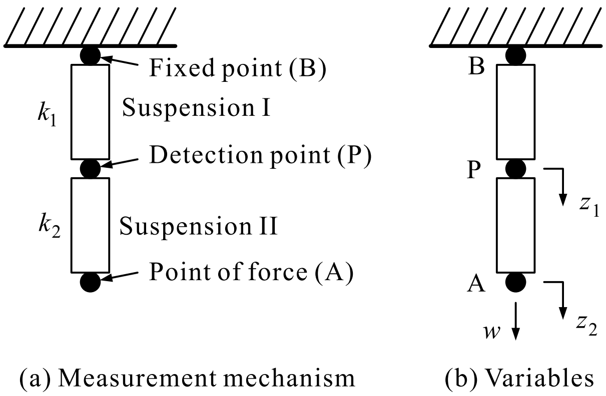

Fig.1 Schematic drawing of measurement mechanism

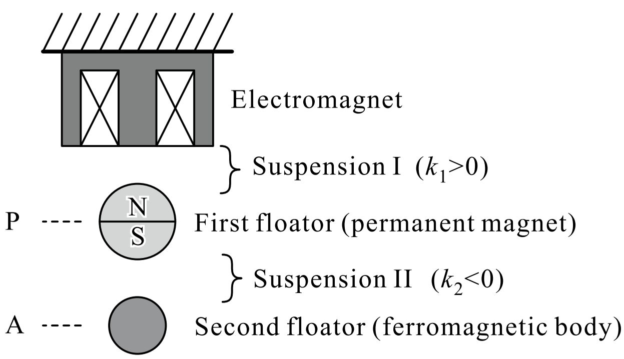

Fig.2 Double series magnetic suspension system

$$z_1 = \frac{w}{k_1} = -\frac{w}{k_2} \tag{4}$$

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 Double Series Magnetic Suspension

The above-mentioned zero-compliance mechanism can be actualized by double series magnetic suspension (Mizuno et al., 2015). In basic magnetic suspension system using attractive force of electromagnet, one or more electromagnets are used to suspend a floator. In double series magnetic suspension system, two floators are suspended by a single electromagnet as shown in Fig.2. 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 indirectly controlled by the coil current. Thus, this system is controllable and can be stabilized by feedback control.

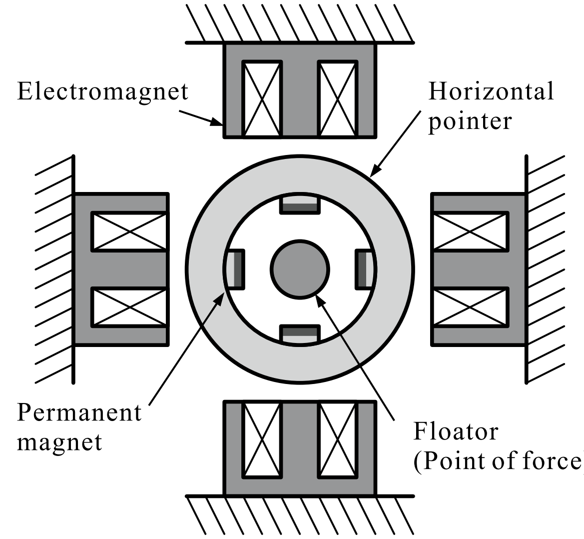

Fig.3 Horizontal suspension system

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

2.3 Three-Dimensional Force Measurement

The proposed measurement system using double series magnetic suspension is extended for the measurement of three-dimensional forces in this work. As to the vertical force, the configuration shown by Fig.2 is applied. To measure horizontal two-dimensional forces by the same principle, the horizontal motions of the detection point must be controlled with a similar mechanism. Figure 3 shows a model of horizontal suspension for this purpose. The detection point for horizontal forces is shaped into a ring and four permanent magnets are attached at every right angle to produce bi-directional horizontal forces. It is referred to as “horizontal pointer” in the following. Four electromagnets are also placed on the stator to surround the horizontal pointer to control the two-dimensional positions of the detection point. A feature of this system is that the detection point is commonly used to measure horizontal forces.

3. EXPERIMENTAL APPARATUS

3.1 Structure and Components

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