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Design and analysis of compliant mechanism for EMFC weighing cell with axis-symmetric structure

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Abstract

In high-precision mass or force measurement, the electromagnetic force compensation (EMFC) weighing cell is utilized to achieve accuracy of sub-mg level. Conventional EMFC weighing cell consists of compliant flexure-based Roberval mechanism and lever amplification mechanism. In our previous work, we proposed a new type of EMFC weighing cell with an axis symmetric structure that three double parallelograms and lever mechanisms are arranged radially around the center of gravity axis. To investigate structural characteristics and design a proposed weighing cell, modelling and analysis of compliant mechanism was performed in this paper. The multi-body matrix method, which sets a mechanism as a multi-body mass-spring system and predicts static or dynamic characteristics through Lagrange equation, is adopted to model the proposed mechanism. We focused on the following three characteristics. First, we evaluated the stiffness in the weighing direction according to the dimensions of compliant mechanism, which should be minimized for high weighing sensitivity. Next, mode shapes and frequencies are evaluated depending on flexure dimensions to achieve control stability. Lastly, compensation force change from tilting of ground was observed to confirm the tilt sensitivity of the weighing cell.

Compliant mechanism, Flexure, Weighing cell, Electromagnetic force compensation (EMFC)

1. Introduction

Electromagnetic force compensation (EMFC) measurement principle has been widely utilized in various high-precision mass/force determination systems due to its high mechanical sensitivity from compliant mechanism and position sensors with nanometer level resolution. Among the applications, the EMFC weighing cell has been adopted in the Kibble balances, an instrument for realization of 'kg', to measure the force difference between gravitational force and electromagnetic force.

In a previous study, we proposed a weighing cell unit for KRISS (Korea Research Institute of Standards and Science) Kibble balance [1]. Since the balance was designed in a symmetrical structure, the design goal of the weighing cell was to build an axis symmetrical structure while adopting EMFC measurement principle. As a result, a new type of EMFC weighing cell was introduced that three double parallelograms and lever mechanisms are arranged radially around the center of gravity axis as shown in figure 1. gravitational force (F_g) from measuring weight is compensated by the electromagnetic force (F_c) of the actuator generated from position feedback control. The displacement (δ_L) of the lever is measured by high-precision sensor with 1 nanometer resolution.

The first prototype of proposed weighing cell had a 1.5 mg of repeatability in case of 10 g. A second prototype is currently being developed to increase weighing performance. In this paper, we introduce preliminary results of the structural analysis for system stiffness, modal characteristics, and tilt sensitivity.

2. Parametric analysis of compliant mechanism

2.1. Analytical model

The multi-body matrix method was utilized to build an analytical model of proposed system [2]. In this method, the system elements are classified into mass and spring elements, respectively. Then, each mass, inertia, and stiffness for the six degrees of freedom in the Cartesian coordinate system are matrixed. Based on the configured matrix and connection vector information between elements, static and dynamic characteristics of the system are predicted through the Lagrange equation.

2.2. Stiffness evaluation

The stiffness in weighing direction (F_c/δ_L) should be minimized to maximize mechanical sensitivity. Simulation results were obtained by changing the most sensitive dimensional parameters for determining system stiffness, i.e., thickness, the depth of guide, lever and coupler flexures as shown in figure 2-(a). Simulation results showed that minimizing the flexure thickness of the lever amplification mechanism is important to increase weighing performance.

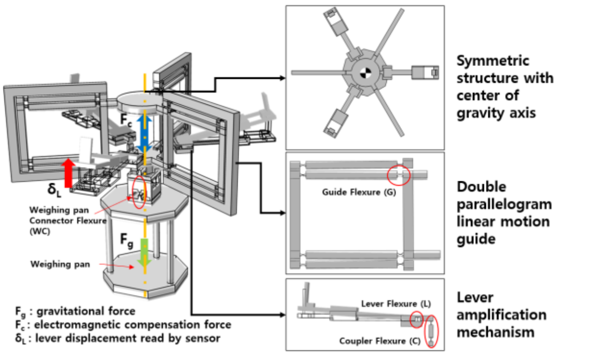

Figure 1. Compliant mechanism structure of proposed EMFC weighing cell.

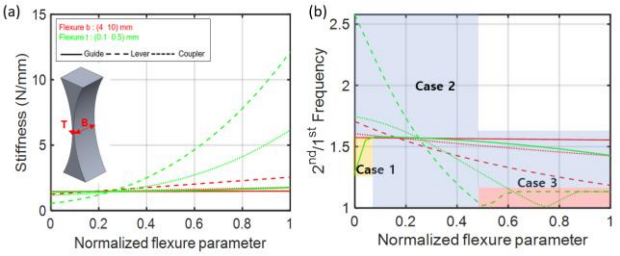

Figure 2. (a) system stiffness and (b) mode frequency ratio over flexure dimensions, parameter range is described in (a).

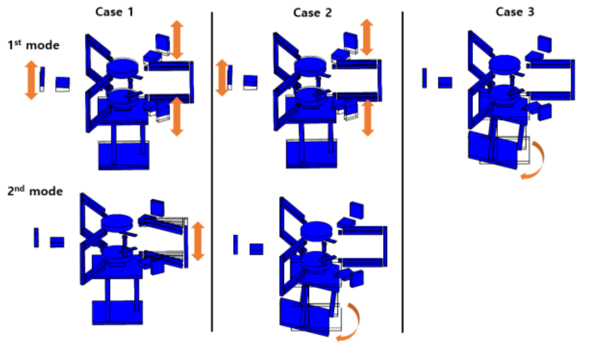

Figure 3. Graphical view of mode shapes obtained from analytical solution.

2.3. modal analysis

Since the EMFC weighing cell is driven through feedback control, dynamic characteristics represented by the natural frequencies and mode shapes are crucial for vibration suppression and stable weighing response. As shown in Fig. 2-(b) and 3, the first and second mode frequencies and shapes were investigated according to the flexure dimensions. As a result, three cases are observed depending on the mode shape. For case 1 and 2, the first mode shape was the shape in which the lever mechanism moves the largest in the vertical direction. Otherwise, the pendulum mode of weighing pan was set to the first mode shape for case 3.

Since the system can control only the lever displacement by the voice coil motor, the lever mode should be set as a 1st mode shape for stable control. Case 3 occurs when the lever and coupler flexure thicknesses are greater than about 0.3 mm, which is close to the thickness of weighing pan connector flexure (0.5 mm) designed so that parasitic moments of the weighing pan are not transmitted to the system. Therefore, it is necessary to ensure that the lever and coupler flexure thickness does not get close to the connector flexure thickness.

Cases 1 and 2 are classified by the difference in the shape of the 2nd mode. In the second mode of case 1, the linear motion guide resonates, and it occurs when the thickness of the guide flexure becomes much thinner than the thickness of the lever flexure. At this time, the second mode frequency becomes close to the first frequency as shown in figure 2-(b), so it would be difficult to increase the control bandwidth. Therefore, case 2 is preferable because the pendulum mode is insensitive to the flexure dimensions.

3. Tilt sensitivity analysis

When the ground is tilted in precision weighing, cosine deviation occurs in the weighing result, which directly acts as a measurement error. Therefore, system should be designed insensitive to ground tilt or be immune to the tilt. In case of the weighing cell installed on KRISS kibble balance, the tilt sensitivity characteristic is particularly important because the system is tilted by an external control to align the weighing cell in the direction of the gravity [3]. Thus, tilt sensitivity analysis conducted using the analytical model of weighing cell. The tilt angle range was set from -1 degree to 1 degree about the x- and y-axis angles.

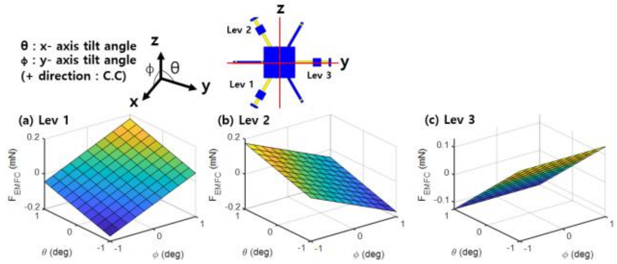

Figure 4. Compensation force distribution over x- and z- axis tilt angle when each lever was independently controlled.

In the proposed system, it is possible to independently control the displacement of each lever by installing sensors and actuators at the ends of all three lever amplification mechanisms. Therefore, the change in compensating force for the tilt angle was observed in each lever. The maximum change in force was about 0.2 to 0.4 mN when each lever was independently controlled as shown in figure 4-(a-c). In terms of tilt sensitivity, it was 0.2 mN/deg.

Since all displacements of lever end point can be measured, a plane can be determined from the vectors of these three non-collinear points. Finally, tilt angle θ and ϕ can be estimated by comparing between normal vector of the calculated plane and z-axis vector. Based on this result, it is expected that the ground tilt is removed through tilt angle adjustment procedure. We will investigate this proposed adjustment procedure through the model and experiments in the future.

4. Conclusion and future work

The compliant mechanism of the axis symmetric EMFC weighing cell for KRISS kibble balance was introduced and its structural characteristics were investigated by the multi-body matrix method. Parametric analysis confirmed that static stiffness and dynamic mode shapes are sensitive to flexure dimensions, especially its thickness Also, by observing the change of compensation force according to the tilt angle to the ground, we analysed how sensitive the system is to ground tilt.

Currently, the prototype is being designed based on the analysis result. To verify the analysis results obtained from the model, we will evaluate all the system characteristics analysed in this study through experiments in the future.

Acknowledgement

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