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Weighing performances of a novel EMFC weighing cell with axis- symmetric structure

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Abstract

In our previous work, a novel electromagnetic force compensation weighing cell was proposed. The proposed weighing cell was developed as a unique force comparator for measuring difference between gravitational force and electromagnetic force in the KRISS Kibble balance. The proposed weighing cell is designed axial-symmetrically, unlike conventional precision weighing cells, with respect to the center of gravity axis using triple compound guide mechanisms and a tri-lever mechanism. The weighing cell employs three independent mass measurement units to measure the test mass by dividing it, improving weighing accuracy and structural stability. Moreover, it gives tilt information which enables correct alignment to the gravity axis. The repeatability of the weighing cell was 0.7 mg with respect to 1 kg test mass and improved to up to 0.2 mg when the zero-point drift was compensated in the air. Lastly, experimental result of ground-tilt response of the weighing cell suggested that a tilt angle can be estimated by observing the change in the compensating force of each mass measurement unit.

Metrology, Measuring instrument, Mechatronic, Force

1. Introduction

In our previous work [1-2], we designed a novel weighing instrument suitable for Kibble balance of Korea Institute of Standards and Science (KRISS). Proposed weighing cell serves as a force comparator in the KRISS Kibble balance by comparing between the gravitational force and electromagnetic force for a realization of the redefined 'kg' based on a Planck's constant [3].

The weighing cell follows an electromagnetic force compensation (EMFC) mass measurement principle, which is the most accurate and reliable mass measurement method. Unlike an asymmetric structure of conventional EMFC weighing cell, proposed weighing cell has been designed axis-symmetrically. By designing in this way, the proposed weighing cell secured structural identity with the KRISS Kibble balance. Moreover, asymmetric thermal expansion or parasitic motion from asymmetricity can be minimized.

As a core mechanism, a unique triple compound guide mechanism and a tri-lever mechanism are designed symmetrically with respect to the center of gravity axis. In addition, three independent mass measurement units are installed at each lever of the tri-lever mechanism.

In this work, weighing performances of the proposed weighing cell are evaluated, experimentally. First, repeatability of the weighing cell is evaluated with a 500 g and 1 kg prototype mass. Then, a ground-tilt response test is carried out, showing that the proposed weighing cell can estimate the ground-tilt angle by using a force change of each measurement unit.

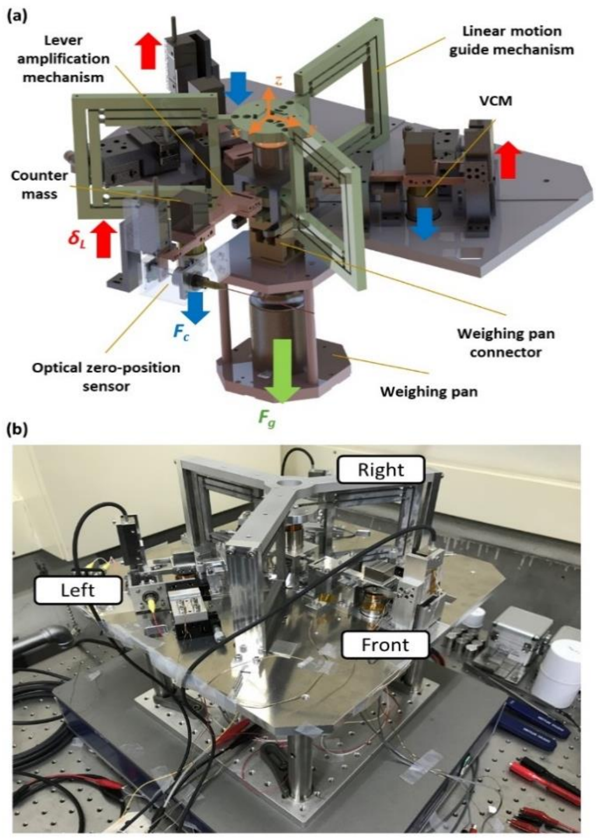

Figure 1. (a) Schematics of proposed weighing cell, (b) Photographs of the fabricated weighing cell.

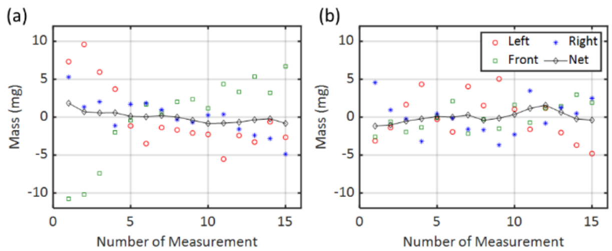

Figure 2. Repeatability of the weighing cell: (a) 500 g mass and (b) 1 kg mass.

2. System overview

Fig. 1-(a) and (b) describes a schematic of the proposed weighing cell and a photograph of the fabricated weighing cell. The weighing cell is composed of a flexure-based triple compound guide mechanism, tri-lever mechanism, and a weighing pan assembly. Each lever unit of the tri-lever mechanism functions as an independent mass measurement unit by installing an optical position sensor with 2 nm resolution, a voice coil motor (VCM), and a counter mass. When a test mass is applied to the weighing pan, the gravitational force of the test mass (F_g) is distributed to each measurement unit of the tri-lever mechanism while being guided by the triple compound guide mechanism. The lever position (δ_L) measured by each optical sensor is independently restored to the origin through the electromagnetic force (F_c) of the VCM generated by feedback control. The sum of the compensating forces measured at each lever unit represents the mass difference between the counter masses and the test mass. Weighing stiffness of the proposed weighing cell is 64.2 N/m, which is similar to that of conventional EMFC weighing cells, thanks to the highly sensitive flexure mechanism with a minimum thickness of about 0.2 mm. The system is also designed to have high parasitic stiffness that is thousands of times larger than a weighing stiffness.

3. Performance evaluations

3.1. Weighing test

Weighing test was performed for a calibrated 500 g and 1 kg F1 class standard masses. The masses were loaded onto and unloaded from the weighing pan automatically by the translation stage. Measured values were calculated from the average of 5000 data points measured for 5 s after settled (±2% criterion). Each mass was measured 15 times, and repeatability were derived from the mean and standard deviation of the data. At this time, a resolution of each measurement unit was 1 mg.

Figure 2 shows a repeatability of the weighing cell. Variations from 1.76 mg to 5.39 mg were observed for the repeatability of each individual measurement unit (units are shown in Figure 1-(b)). Nevertheless, the repeatability of the net mass achieved 0.7 mg in all test masses. When the deviation occurred in one lever, the other lever counteracted this by generating a force in the opposite direction at a similar level. Thus, a higher repeatability of net mass values was achievable. It can be estimated that precise force or mass measurement is possible with electromagnetic force compensation using additional lever mechanisms.

The net mass value showed a slight drift in overall linear shape during the measurement due to the thermal drift of the system. To predict the weighing performance in the absence of drift, the widely adopted ABA and ABBA calibration methods for comparative weighing were utilized [4]. Each method minimizes the effect of drift by differentiating the average of the first and last data from the intermediate data of the continuously measured data set. Calibrated repeatability was improved by 2.5 to 3.5 times compared with the original repeatability. The highest repeatability was 0.2 mg when the ABBA method was applied to the 1 kg mass measurement result; the other cases were at the level of 0.3 mg.

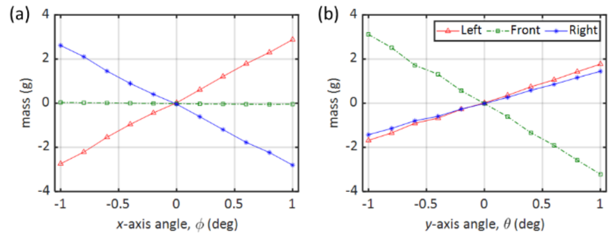

Figure 3. individual force changes of each measurement unit for (a) *x*-axis tilt and (b) *y*-axis tilt.

3.2. Ground-tilt response

In weighing instruments, ground-tilted state causes parasitic deformation of the compliant mechanism or changes the sensitivity of the actuator and position sensor, result in unignorable measurement errors. To evaluate the influence of the ground-tilt to the proposed weighing cell, the changes in the compensating force of each measurement unit were observed while the system was tilted with manual goniometer from −1° to 1° in 0.2° increment when the 1 kg mass was loaded. The test was performed with both tilts about the *x*-axis (ϕ) and tilts about the *y*-axis (θ) (coordinate is shown in figure.1-(a)).

Tilt sensitivity, angle-force relationship, of each measurement unit are different each other because each lever was positioned symmetrically with respect to the tilt axis. The tilt sensitivity of all levers was linear. Thus, tilt angles can be estimated by an equation of plane from three compensation force vectors. It can be obtained from the inner product of the nominal plane vector and tilted plane vector. Finally, the proposed weighing cell can be externally controlled to the zero-tilt angle state without any additional angle sensors. Though the error of each unit in tilted state was larger than that of the normal state, which is due to the increased stiffness caused by parasitic deformation induced from the tilt, the force change of the net mass value was reduced to 0.01 g/deg due to the force cancellation effect.

4. Conclusion

Weighing performance of the novel axis symmetric EMFC weighing cell was evaluated in this paper. In the weighing test with a 1 kg standard mass, the proposed weighing instrument achieved a relative uncertainty of 2×10^{-7}. The result suggests that the multi-EMFC configuration can be a candidate for high-precision mass measurements. Uncertainty of 10^{-8}, performance of a conventional weighing cell for KRISS Kibble balance, is expected to be achievable if room temperature is controlled or vacuum environment is secured [3]. In the ground-tilt test, it was shown that the ground-tilt angle can be obtained through the force change of each measurement unit, thereby adjusting the weighing cell to the zero-tilt angle state.

Acknowledgement

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