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Mass value correction method for weighing cell based on digital PID state-locking control

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Summary:
The weighing cells with electromagnetic force compensation are frequently employed for high-precision mass measurement. Digital control enables more comprehensive monitoring and facilitates the implementation of flexible control algorithms. However, due to the limited resolution of the digital-to-analog converter, small-step impacts exist in the electromagnetic force control process, adversely affecting the balancing process of the highly sensitive mechanical elastomer. The lever exhibits a discernible amplitude of vibration even in its stable stage, thereby inducing repetitive deformation in each flexible hinge and resulting in significant fluctuations of the measured values. A digital PID state-locking measurement method was proposed to reduce the influence of lever vibration on measurement results by fixing the states of input, output, and integration of the PID controller during stable stages, which disconnects the PID controller and the displacement of the mechanical elastomer. Additionally, mass values calculated using coil current are corrected by lever end displacement, leveraging the low stiffness coefficients exhibited by flexible hinges. Experimental results demonstrate that the proposed method effectively reduces fluctuation amplitudes in mass values during balance stages, thereby enhancing quality measurement accuracy.

Keywords: electromagnetic force compensation, weighing cell, digital PID control, mass correction.

Introduction

Weighing cells with electromagnetic force compensation is frequently used in high-precision mass measurement [1,2]. With the development of metrology digital transformation [3] and real-time control technology, digital control enables more comprehensive monitoring and flexible control algorithms for the weighing cells. However, due to the limited resolution of digital-to-analog converters (DAC), there is a small step shock in coil current control, resulting in excessive fluctuation. Additionally, the low natural frequency of highly sensitive mechanical elastomers makes feedback control of coil current susceptible to external signals, such as vibrations caused by lever movement during balance positioning. The adoption of digital control amplifies this vibration amplitude, which negatively impacts the measurement accuracy of the weighing unit. To mitigate mass measurement value fluctuations during steady stages, the displacement of the lever end is utilized to correct the mass value calculated by coil current.

Method

The weighing unit utilizes the lever balance principle to convert force signals into electrical signals for high-precision measurements. When balanced at the pivot hinge point, as shown in Fig. 1, the equilibrium equation can be expressed as eq. (1).

$$m_t g L_t = B I_{coil} L_{coil} L_l + k_{eq} \varphi \qquad (1)$$

Where m_t is the mass value of the tested weight, L_t is the force arm of the tested weight relative to the fulcrum hinge, k_{eq} is the equivalent rotational stiffness coefficient of elastomer, φ is the rotation angle of the balance, B indicates magnetic induction intensity, L_{coil} refers to effective length of coil within magnetic field, I_{coil} is the coil current, and L_l is the equivalent lever of the lorentz force.

The tested mass can be expressed as eq. (2).

$$m_t = k_I I_{coil} + k_s s_{tail} \qquad (2)$$

Where k_I is related to elastomeric link size, magnetic steel structure, permanent magnet strength, coil length and local gravity acceleration; while k_s is related to elastomeric link size, flexible hinge stiffness coefficient and local gravity acceleration among other parameters.

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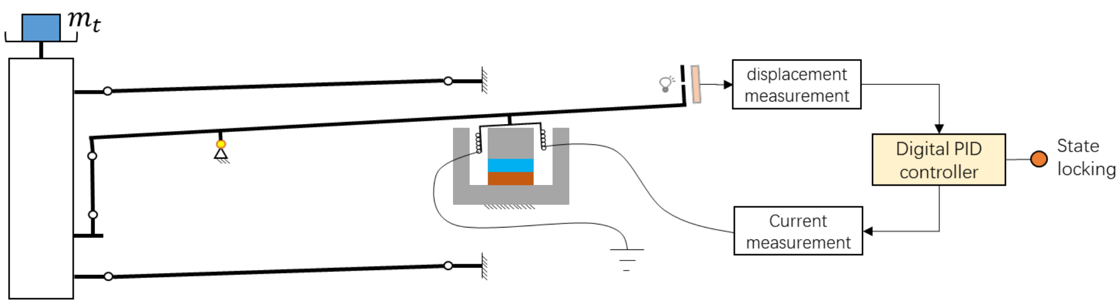

Fig. 1. Digital PID state locking measurement method of weighing cell.

The unbalance of the lever, as indicated by eq. (2), introduces a certain error in the calculated mass solely based on the coil current. However, this error can be corrected by the displacement at the end of the lever.

Therefore, the zero-order holder is utilized to lock states of the PID controller during the lever stabilization stage, as shown in Fig. 1. As a result, the negative feedback control channel of the electromagnetic force is interrupted, allowing the elastomer lever to freely balance under the tested weight and the electromagnetic force. Due to the mechanical properties of the elastomer and torque stiffness of the flexure hinge, a slight amplitude vibration eventually occurs at a specific position on the lever. The mass value calculated by coil current can be corrected based on Eq. (2) using the balance position of lever displacement vibration and the low stiffness coefficient to reduce the fluctuation of the steady-state stage of the weighing module under digital control. The stationary stage of the lever can be determined by whether or not its end displacement peak-to-peak value remains below a threshold value for a certain period.

Results

A weighing cell controlled by a digital PID controller was set up based on the TwinCAT development platform. The real-time control period was set to 2ms. Lever end displacement was measured by a photodiode and division amplifier circuit. The voltage and current acquisition cards were selected with 24-bit resolution, while the voltage DAC was selected with 16-bit resolution.

The experiment was carried out with a weight of 2g. Fluctuations in mass measurement results within the 60s during the stable stage were compared between analog circuit PID control, traditional digital PID control, and digital PID lock control, as shown in Table 1. The fluctuation error of traditional digital PID continuous control was the largest because of the resolution limitation of the voltage DAC. The results of the digital PID state-locking method exhibit the most minor fluctuation error, reduced by about 53% compared to traditional digital PID control and about 24% compared to analog PID control.

Tab. 1: The fluctuation results of the mass value in the stable stage during the mass measurement

Control Method	peak-to-peak value (μg)	standard deviation (μg)
Analog PID control	21.5	3.7
Traditional digital PID control	35.9	6.3
Digital PID state-locking control	16.9	2.8

Summary and Outlook

In conclusion, the proposed method of digital PID locking control and lever end displacement correction effectively reduces the amplitude of measurement result fluctuations and enhances the measuring accuracy of the digitally controlled weighing cells.

The future holds the potential for enhanced measurement accuracy of weighing units through real-time digital monitoring and control, enabling the integration of additional sensing capabilities such as ambient temperature and magnetic steel temperature, which will facilitate the establishment of digital twin models for weighing cells.

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