System modeling and identification of a balance type checkweigher compensated by voice coil actuator

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Abstract
The aim of this article is to investigate the characteristics of checkweigher which consists of two parts: electrical part (voice coil actuator) and mechanical part (lever-pivot mechanism). Its integrated weighing system simplified \( m, c, \) and \( k \) model, and system identification is performed through comparison of experimental results and simulated results by Simulink. \( m \) and \( k \) are attributed to the mechanical part and \( c \) is mainly due to the electromagnetic damping of voice coil actuator. Even with a determined voice coil actuator, the damping effect can be adjusted by the relocation of voice coil actuator to improve the performance of checkweigher. The validity of the simplified model is verified by comparing simulation and experimental results.

Keywords
Checkweigher, balance type, system identification, magnetic damping, voice coil actuator

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Introduction
Weighing technology has been essential for manufacturing of standardized packed products in the electronic, food, and pharmacy industry. Since the industrial era, there have been new ways to measure mass which started from spring scales to electronic systems for more accurate and faster performance. A checkweigher is a system weighing items as they pass through a production line, additionally classifying objects by preset weight zones, and ejecting or sorting things based on classification. Because the in-motion products must be measured during a short time while they are traveling over the weighing spot, many troubles are caused due to vibration and inconsistent measuring timing. Along with increasing application of checkweighers, dynamic weighing technology was adopted to improve its performance of productivity and accuracy.

Generally, two types of measurement system associated with checkweigher are deflection and balancing type. In the load cell system based on deflection type, the relationship of elastic deformation and spring constant is used to measure a wide range of mass. The deflection type is simple in mechanism and fast in speed but less accurate. On the contrary, the balancing type in which an actuator generates a counter force to keep a pivoted lever balanced against a loaded mass has the advantage of high accuracy but less speed. Voice coil...
Actuators (VCAs) are used due to its fast response and linear motion. VCAs are used due to its fast response and linear motion. Through measurement of current flow in the VCA, both compensation force and the weight force are determined.

Many research efforts have been devoted to the estimation of weight and studied about removing noise and modeling spring, mass, and damper on dynamic weighing. The effect of the sensor in different locations on the ability of dynamic weighing was investigated.

This research focuses on developing an integrated model of mechanical part and electrical part and simplifying it as an n, c, and k model. To improve its performance, it is necessary to identify the system parameters and based on the system model, the effect of each parameter is examined.

**Structure of a balanced type checkweigher**

**Configuration of measurement system**

Figure 1 shows a scheme of a balanced type checkweigher which is composed of the lever mechanism, VCA, laser displacement sensor, conveyor, and balancing compensation controller. The lever mechanism includes such elaborate parts as hinge and pivot to make a large displacement even for a tiny mass loaded on the weighing pan. The VCA is controlled to compensate a gap from the balanced position caused by a mass.

**Measuring principle**

A mass loaded on the weighing pan causes a small clockwise rotation of the lever around the pivot, which results in a large displacement of the measuring spot, measured by a laser displacement sensor. Then the VCA is controlled to compensate the displacement so that the lever returns to the balanced position with zero displacement. During compensation, a current depending on the displacement is flown through the coil of VCA to generate a corresponding Lorentz force, which is proportionally related to the weight of the mass. Finally, an unknown mass can be estimated from the current which is detected by a resistor sensor. The important things are how fast and how accurately it is measured. They are the fundamental characteristics for the performance of evaluating weighing systems.

**System modeling and simulation model**

**System modeling**

The checkweigher system needs to be modeled and identified to investigate the performance. It is composed of two units: one is a mechanical unit by which displacement is generated and amplified responding to a loaded mass and the other is an electrical unit of VCA which compensates a gap displacement. Its dynamic model is simplified as shown in Figure 2 where a hinge is modeled as a spring (K), electromagnetic damping (c), and Lorentz force (F_{VCA}) are generated by the VCA.

**Electrical modeling of VCA.** The electric model of VCA can be expressed as equation (1)

\[ V = L \frac{di}{dt} + Ri + k_b \dot{x} \]
Here $k_b\dot{x}$ is back electromotive force, which is dependent on the bobbin velocity, and $L$, $R$, and $k_b$ are inductance, coil resistance, and back electromotive force constant, respectively. Figure 3(a) shows an equivalent circuit of VCA composed of inductor and resistor.

**Force–current relationship of VCA.** To investigate the relationship between current and force of the VCA, $F_{VCA} = k_f \cdot i$, $F_{VCA}$ is measured through load cell as five levels of current (mA) are input to the VCA. The experimental results are shown in Figure 4.

From the linear regression analysis, $F_{VCA}$ has a linear relationship with current where $k_f = 28.5$ N/A.

$F_{VCA}$ is different according to the position of bobbin from the center of coil length even under the same current. Figure 5 shows the experiment results of $F_{VCA}$ depending on the location of bobbin. It means that the proper operating region is limited to $\pm 0.5$ mm from the center.

**Mechanical modeling of lever motion.** The lever mechanism is initially condition with $x = 0$, $m = 0$, and $F_{VCA} = 0$, $M_0L_2 = M_cL_1$, where $M_c$ is conveyor mass and $M_0$ is a required counter mass including lever mass. Setting $M_c = 4.0$ kg, $L_1 = 3.5$ mm, $L_2 = 97.7$ mm, then $M_0$ is calculated as 0.15 kg.

As an object ($m$) is loaded on the weighing pan, a balancing control starts. The force and moment equilibrium are expressed in equations (2) and (3) based on the free body diagram depicted in Figure 2(b)

\[
F_P = (m + M_c + M_0)g + kx + c\dot{x} + F_{VCA} \quad (2)
\]

\[
M_P = mg \cdot L_1 - (c\dot{x} + kx + F_{VCA})L_2 \quad (3)
\]

The rotational motion of lever is described as follows

\[
M_P = I \cdot \ddot{\theta} \quad (4)
\]

where the inertia of lever $I = (m + M_c)L_1^2 + M_0L_2^2$ is due to object, conveyor, and lever.

Substituting $M_P$ and $I$ in equation (4)

\[
-(kx + c\dot{x} + F_{VCA})L_2 + mgL_1 = \{ (m + M_c)L_1^2 + M_0L_2^2 \} \ddot{\theta} \quad (5)
\]

Since the rotation of movement of lever is too small, $x = L_2 \sin \theta = L_2 \theta$ (for $\theta \ll 1$). The equation of motion (equation (5)) is converted into the form of rectilinear motion

\[
-(kx + c\dot{x} + F_{VCA})L_2 + mgL_1 = \{ (m + M_c)L_1^2 + M_0L_2^2 \} \frac{\dot{x}}{L_2} \quad (6)
\]

Thus, as depicted in Figure 2(c)

\[
M_c\dot{x} + c\dot{x} + kx = mg \frac{L_1}{L_2} + F_{VCA} \quad (7)
\]
where \( M_e = \{ ( m + M_c) \frac{L_1}{L_2}^2 + M_0 \} \) is the equivalent mass in the rectilinear equation.

**Simulation model**

To investigate characteristics and performance of the weighing system, its dynamic properties of \( M_e, c, \) and \( k \) as depicted in Figure 2(c) should be identified through comparison of simulation and experimental results. Thus, each simulation model is induced through the Laplace transform of the governing equation of electrical and mechanical models.

**VCA actuation model.** Equation (1) is transformed into equation (8)

\[
V(s) = I(s) \cdot R + L \cdot sI(s) + k_b \cdot x(s) \quad (8)
\]

Electrical specification about VCA is \( L = 0.0245 \, \text{H}, \) \( R = 28.9 \, \Omega, \) \( k_f = 28.5 \, \text{N/A,} \) and \( k_b = 28.5 \, \text{V/s/m.} \)

**Lever motion model.** Equation (7) is transformed into equation (9)

\[
M_e x^2 \cdot x(s) + cs \cdot x(s) + k \cdot x(s) = mg \frac{L_1}{L_2} + F_{VCA} \quad (9)
\]

**Simulink model.** Combining equations (8) and (9), a simulation model of the weighing system is represented by a Simulink program, as shown in Figure 6.
Experiment setup

Figure 7 shows a photograph of the measurement system setup. A laser displacement sensor is used to detect lever movement. A VCA is used to compensate a deflection gap generated by lever movement. The current through VCA coil generating Lorentz force is measured by a resistor sensor. NI VirtualBench is used to generate step input current.

Estimation of spring constant

To investigate the spring constant \( (K) \), experiments are conducted to obtain displacement with respect to five different weights. The force of each weight loaded on the weighing pan is converted into equivalent force at \( P_A \). The displacement at \( P_A \) is measured by laser displacement sensor. Based on the experimental results listed in Table 1, a linear relationship is shown in Figure 8 and \( K \) is calculated as 1453 N/m through regression analysis.

Effect of back electromotive force of VCA

The effect of back electromotive force (BEMF) \( k_b \) in Simulink model needs to be examined. Figure 9 shows how fast the current flows through the VCA coil as a voltage is applied to VCA by considering \( k_b \) as 28.5 and \( k_b \) as 0. \( k_b \) tends to hinder the current flow resulting in slow response.

Estimation of damping coefficient

Setting \( m = 0 \) in equation (9), a step value of \( F_{VCA} \) is applied to get a step response because a step voltage can be easily and precisely input to VCA through NI Virtual Bench by LabVIEW algorithm. \( M_e \) is already determined as 0.155 kg in section “Mechanical modeling of lever motion.”

With the previously identified parameters, \( M_e = 0.155 \text{ kg} \) and \( K = 1453 \text{ N/m} \), the damping coefficient can be identified through comparison between the simulated response to a step \( F_{VCA} \) and the corresponding experimental response. With a step input of 3 mA to VCA, the measured step response seems quite overdamped, as shown in Figure 10. In order to identify the damping coefficient, simulations are repeated with several values of 16.5, 26.5, and 36.5 and the results are
displayed together in Figure 10. From comparison with the experimental data, the best estimated damping coefficient is 26.5 N s/mm, which corresponds to damping ratio of 0.89.

Figure 11 shows an improper step response which goes beyond the proper operating region (±0.5 mm) of VCA and the real damping effect lessens. Thus, considering less step input of 3 mA has good similarity with the simulation results.

**Effect of relocation of VCA**

Under the condition of a determined VCA, relocation of VCA could be an available way to reduce the damping coefficient of the overdamped system as described in section “Estimation of damping coefficient.” To examine the effect of VCA relocation (from $L_2$ to $L_3$), simulation is carried out for two locations, $L_3 = 71.8$ and 89.8 mm (Figure 12). As shown in Figure 13, both simulation results correspond to the less damping ratios, that is, 0.68 and 0.78, respectively, compared to the actual response at $L_2 = 97.7$ mm.

**Conclusion**

For a balanced type weighing system by VCA, system modeling and identification are presented and validated with simulation and experiment. The rotational motion of lever is converted into the rectilinear motion with
Based on this model, system identification of checkweigher can be carried out at an early stage of development. The new findings are as follows:

1. The system parameters are identified as $M_e = 0.155 \text{ kg}$, $K = 1453 \text{ N/m}$, and $c = 26.5 \text{ N s/mm}$ (or damping ratio = 0.89) resulting in an over-damped system.

2. Even in the case of VCA given, adjusting the position of VCA from the pivot can keep the system under proper damping. The closer to the pivot is the position of VCA, the less is the damping.

3. The stable operating range of VCA used in this research is ± 0.5 mm beyond which experimental and simulated results show no conformity.

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