DYNAMIC BEHAVIOR OF CHECKWEIGHER WITH ELECTROMAGNETIC FORCE COMPENSATION (2ND REPORT)

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Abstract − This paper describes the dynamic behaviors of a high speed mass measurement system with conveyor belt (a checkweigher). The objective in this study is to propose the model of the measurement system. The checkweigher with electromagnetic force compensation can be approximated by the combined spring-mass-damper systems as the physical model, and the equations of motion are derived. The model parameters can be obtained from the experimental data. Finally, the validity of the proposed model can be confirmed by comparison of the simulation results with the realistic responses. The dynamic model obtained offers practical and useful information to examine control scheme.

Keywords: mass measurement, electro-magnetic force compensation system, dynamic behavior

1. INTRODUCTION

In recently, a highly accurate mass measurement system of packages moving the conveyor belt operated at high speed, so-called the checkweigher, has been getting more important in the food and logistics industries etc. To achieve the high speed (continuous) measurement, packages should be moved in sequence. It means that the measuring time for one package is very short. In the near future, the continuous mass measurement for 300 products per minute will be required.

In general, there are two types of the measurement system of the checkweigher, such as a load cell type and an electromagnetic force compensation (EMFC) type. In the load cell system, the mass of an object can be measured by the deformation of Roberval mechanism when the mass to be measured is put on the weighing pan. Although this type is applicable to the wide range of mass, it makes this type difficult to achieve high accuracy. On the other hand, the EMFC system keeps a balance with the displacement of the lever linked Roberval mechanism with electromagnetic force. Then, the mass of the object can be measured by the driving (or feedback) current for electromagnetic force. This type can be achievable for high accuracy by null method, but the wide range of measurement cannot be desirable.

For the dynamic behavior of the load cell system, Ono, W. G. Lee, and Kameoka have already cleared in detail [1]-[4]. But the dynamic behavior of the EMFC system has not still been presented. Our aim is that the performance of the checkweigher can be improved for high-speed and high-accuracy. To do this, it is highly necessary to develop the control scheme of the EMFC. Thus, we proposed the dynamic model of the checkweigher with EMFC in the previous paper [5]. However, the validity of the model for the closed-loop system cannot be confirmed. Namely, the model of the measurement system will be improved in this paper. Then, the validity of this model will be confirmed by comparison between the simulation and experimental results.

2. MEASUREMENT SYSTEM

Fig. 1(a) shows the figure of the checkweigher. Only a measuring conveyor appears in the photograph, actually, the feed conveyor is located in the left of the measuring conveyor and the sorter is located in the right. The products are moved by the feed conveyor, the mass of product measured by measuring conveyor and the product out of the measurable range is removed by a sorter.

The enlarged photograph of the mass measurement mechanism in the checkweigher is shown in Fig. 1(b). The mass measurement system consists of weighing platform, the Roberval mechanism, the lever linked Roberval mechanism, the counter weight, the electromagnetic force actuator and the displacement sensor. By applying the Roberval mechanism to the measurement mechanism, the mass of the product can be measured even if the product locates in everywhere over the weighing platform.

The mass of the product is estimated from the current of the electromagnetic force actuator to control the lever displacement.

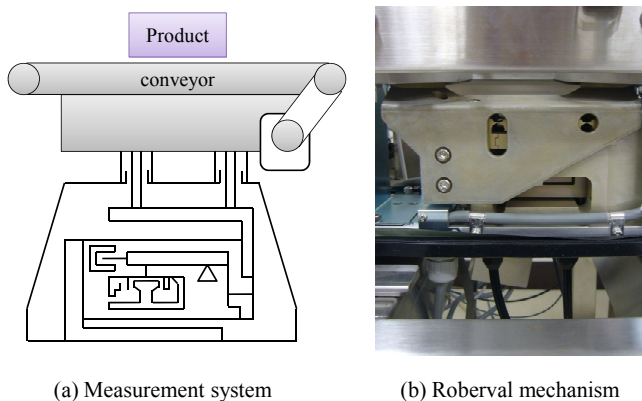(a) Measurement system   (b) Roberval mechanism
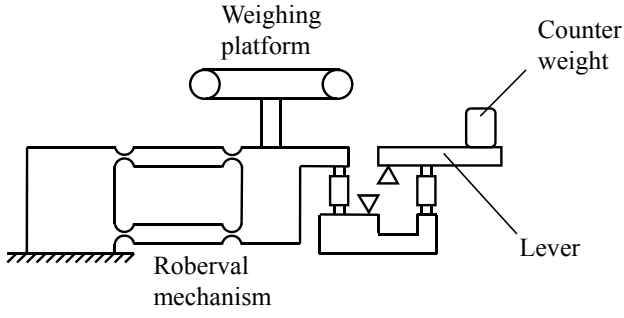
Fig. 1. Photographs of checkweigher
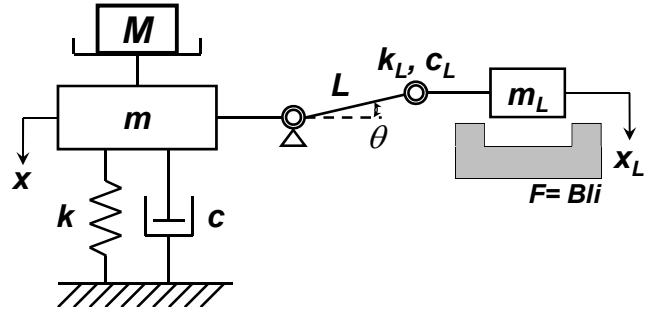
Fig. 2. Image of Roberval mechanism

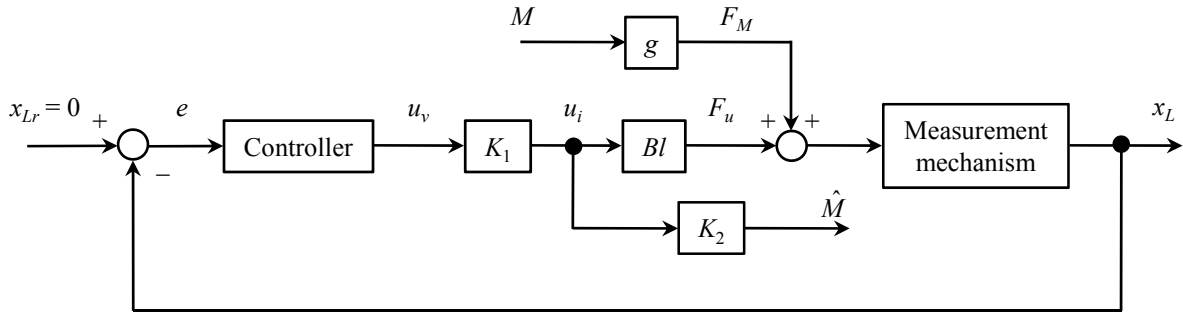Fig. 3. Physical model of measurement system

Fig. 4. Block diagram of the model

3. MODELING

Fig. 2 and Fig. 3 show the illustrations of the Roverval mechanism and the physical model of the measurement system including the Roverval mechanism, respectively. The measuring method of mass can be explained as follows: First, when the product of the mass M is put on the measurement system, the displacement of the Roberval mechanism is caused. Then, the displacement of the Roberval mechanism is magnified twenty times by the lever. And, the magnified displacement can be measured by the displacement sensor. Secondly, the current is controlled so that the displacement of the lever can be maintained at zero. Finally, the current is measured and the current is converted to the estimated mass $\hat{M}$ by using the linear function.

Considering the physical model as shown in Fig. 3, the equations of motion about mass m and mass m_L can be obtained as follows:

$$\begin{cases} (M+m)\ddot{x} + c\dot{x} + kx + c_L(\dot{x} + \frac{1}{L}\dot{x}_L) + k_L(x + \frac{1}{L}x_L) = Mg \\ m_L\ddot{x}_L + \frac{1}{L^2}c_L\dot{x}_L + \frac{1}{L^2}k_Lx_L = F_u + \frac{1}{L}c_L\dot{x} + \frac{1}{L}k_Lx \end{cases} \quad (1)$$

where, m is mass of the Roberval mechanism, M mass of an product to be measured, c a damping coefficient, k a spring constant, g the acceleration of gravity, L (= 20 m/m) the lever ratio, and x the displacement of mass m. And, m_L mass of the lever, c_L a damping coefficient, k_L a spring constant, x_L the displacement of mass m_L, and F (= Bli, where B is a density of magnetic flux, l a length of the coil, and i a current.) an electromagnetic force which means the control

input to control the position x_L of the mass m_L. Finally, Fig. 4 depicts the block diagram of these systems.

Considering the steady state of the second equation in (1) for $F_u = 0$ (open-loop system), the following equation can be obtained,

$$x_L = -Lx . \quad (2)$$

Substituting (2) into the first equation in (1), the steady state of the Roberval mechanism becomes

$$x = \frac{Mg}{k} . \quad (3)$$

When the mass of the target is 0.1 kg on the basis that $x_L = 0.24 \times 10^{-3}$ m, and $x = 0.012 \times 10^{-3}$ m are measured, thus we can obtain as

$$k = \frac{0.1 \times 9.8}{0.012 \times 10^{-3}} = 81.7 \times 10^3 \quad (4)$$

From the second equation in (1), the natural frequency of the lever is

$$f_L = \frac{1}{2\pi L}\sqrt{\frac{k_L}{m_L}} . \quad (5)$$

From the experimental result, the natural frequency of the lever is 5 Hz and the damping ratio is 0.08. Substituting $f_L = 5$ Hz and $m_L = 0.215$ kg into the above equation, the spring constant of the lever can be given as follows:

$$k_L = (2\pi \times 5 \times 20)^2 \times 0.215 = 84.9 \times 10^3 . \quad (6)$$
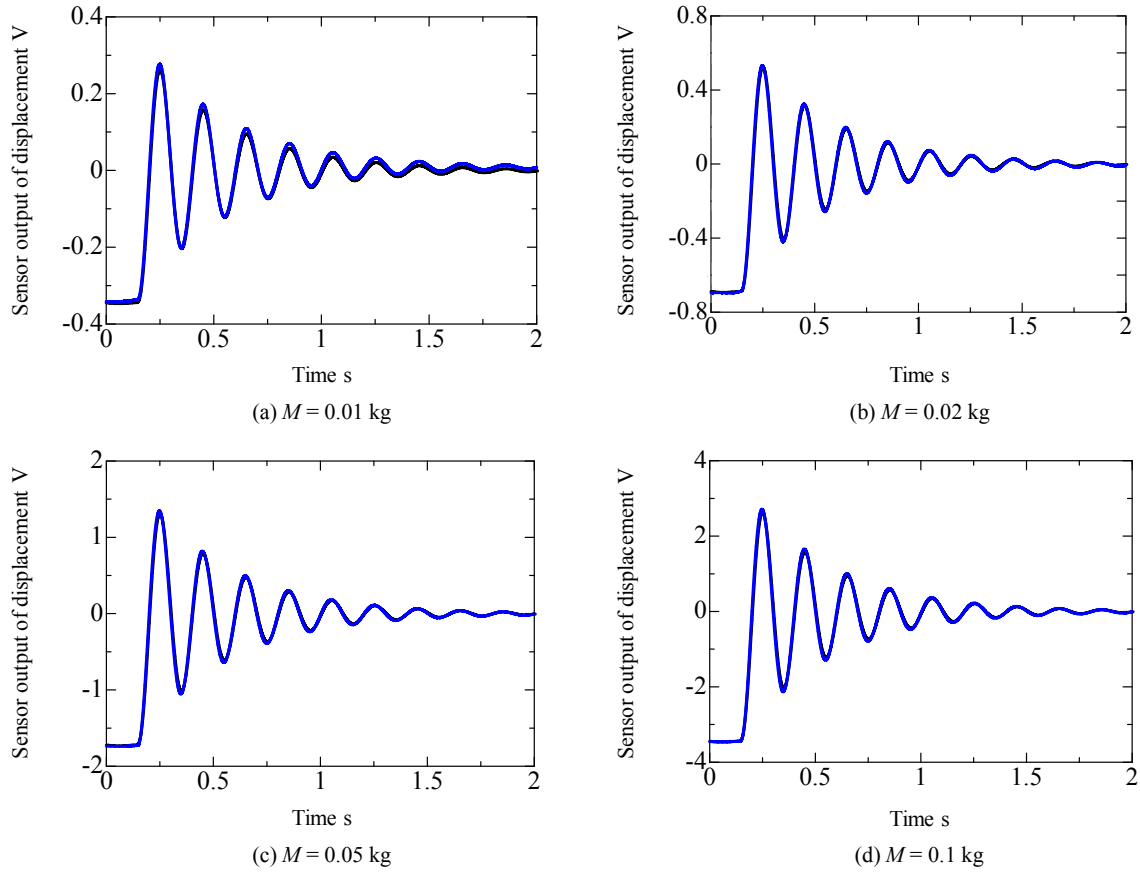
(a) $M = 0.01$ kg

(b) $M = 0.02$ kg

(c) $M = 0.05$ kg

(d) $M = 0.1$ kg

Fig. 5. Comparison between experimental result and simulation result (open loop)

4. EXPERIMENTAL AND SIMULATION RESUTLS

In this section, the validity of the proposed model is confirmed with comparison between the simulation result and the experimental result. In section 4.1, the comparison for open-loop system is performed. Moreover, the comparison for closed-loop system is discussed in section 4.2.

Fig. 4 shows the block diagram of the proposed model. When the electromagnetic force F_u is equal to zero, the measurement system is open-loop system. On the other hand, when the force F_u acts to the measurement mechanism, the closed-loop system is constructed.

4.1. Open-loop system

The validity of the proposed model is examined with comparison between the simulation result and the experimental result for the open-loop system.

Fig. 5 depicts the experimental and simulation results for $M = 0.01$, 0.02, 0.05 and 0.1 kg. The start-up operation is the time when the product of the mass M is put on the measurement system. Then, when the time is 0.2 s, the product of the mass M is removed. At the same time, the displacement x_L is measured by the displacement sensor. In Fig. 5, the vertical axis shows the displacement sensor output of the lever displacement.

It can be seen from these figures that the responses of the simulation made a good agreement with the experimental results perfectly. Thus, the validity of the proposed model is

confirmed for the open-loop system. Although the amplifier of the response is changed depending on the mass, the convergence time is not changed. Thus, this measurement system can be assumed to be the linear system. Namely, even if the controller is added to the measurement system, the response does not depend on the mass.

In the next section, the validity of the proposed model for the closed-loop system will be confirmed.

4.2. Closed-loop system

This section explains the experimental and simulation results with EMFC. The electromagnetic force is controlled by proportional-integral-differential (PID) control scheme. Taking the actual circuit of the D action into account, the ideal D action cannot be implemented. So, it is assumed that the D action is the approximated differential action. Namely, the transfer function of the PID controller $C(s)$ can be described by,

$$C(s) = k_p + \frac{k_i}{s} + \frac{k_{dn}s}{k_{dd}s + 1} \qquad (7)$$

where, k_p is the proportional gain. k_i is the integral gain. k_{dn} and k_{dd} are the numerator and denominator coefficients of the differential gains, respectively. And, the control voltage $U_v(s)$ (Laplace transform of $u_v(t)$) can be adjusted as follows.

$$U_v(s) = C(s)E(s) \qquad (8)$$

where, $E(s)$ is Laplace transform of $e(t)$ and $e(t)$ $(=x_{Lr} - x_L)$ is the error between the reference x_{Lr} and the displacement
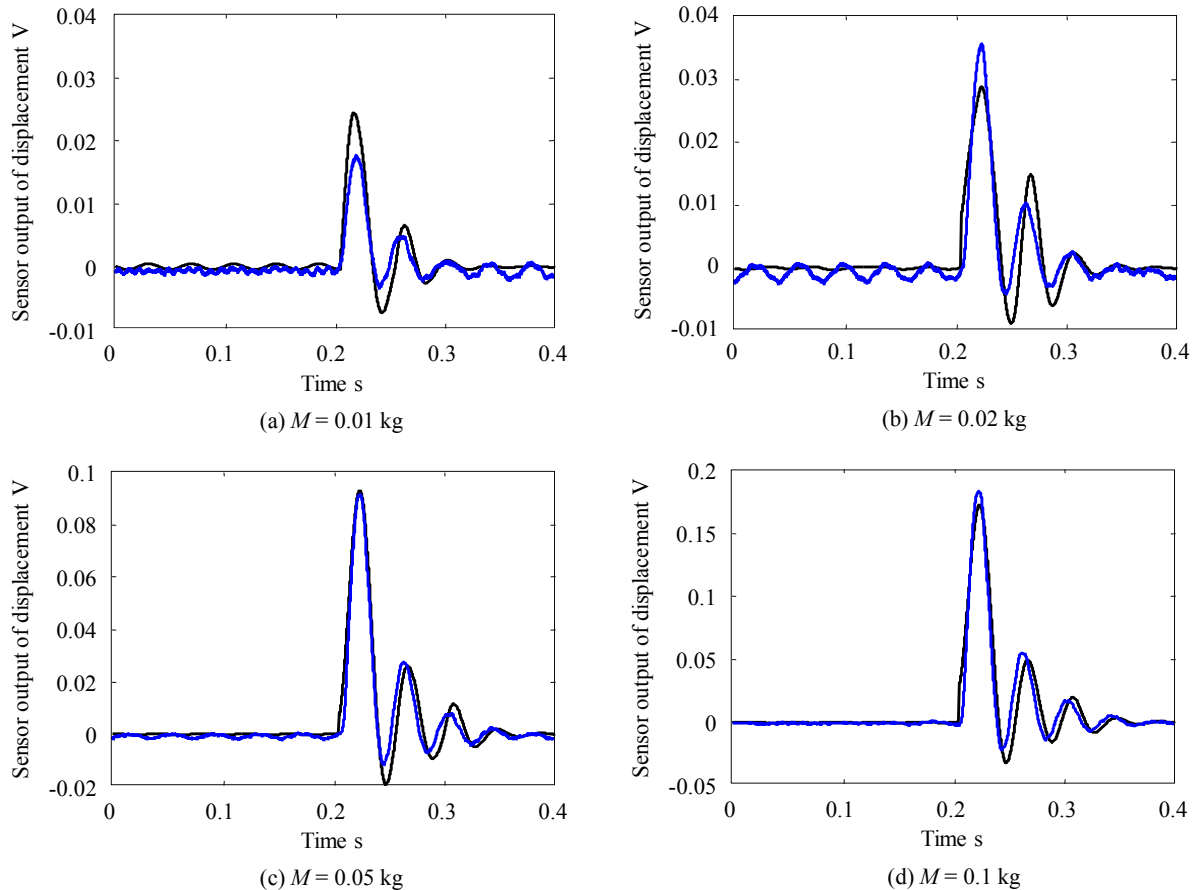
Fig. 6. Comparison between experimental result and simulation result (closed loop)

sensor output of the lever x_L. The PID control can be performed by FPGA (Field Programmable Gate Array) every 0.1 ms.

Fig. 6 depicts the experimental and simulation results for M = 0.01, 0.02, 0.05 and 0.1 kg. The blue line and the black line mean the experimental result and the simulation result, respectively. The simulation and experimental conditions are the same as the open-loop.

The peak values of the simulation results for M = 0.01 and 0.02 kg are different on those of the experimental results. Moreover, the first least value and the second peak value between both responses are slight different. However, the convergence time, the rise time and the settling time between the simulation and experimental results are almost the same. Thus, the validity of the proposed EMFC model is confirmed. We consider that the reasons of modelling error are the friction force in small displacement and the magnification mechanism of the lever.

5. CONCLUSIONS

In this paper, the dynamic model of the electromagnetic force compensation (EMFC) system is constructed. The measurement system is composed of the Roberval mechanism and the lever. Thus, the model consists of the dynamics of the Roberval mechanism and the lever. Each model is approximated by a spring-mass-damper system. The model parameters are identified by the experimental data for open-loop response.

Then, the validation of the proposed model is examined for the open-loop system and the closed-loop system. As a result, the validity of the proposed EMFC model can be confirmed. In particular, the responses between the simulation and experimental results for the open-loop system are the exactly same. And, both responses for the closed-loop system are the almost same. However, there exist a few differences of the responses for the closed-loop system. Thus, this problem should be solved and will be improved.

In the future, an entirely new control scheme for the electromagnetic force compensation will be proposed by using the proposed model. Then, the high-speed and high-accuracy mass measurement system will be applicable to many industrial fields.

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