Study of Sensorless Load Estimation Method for Disturbance Compensation Control of Linear Resonant Actuator

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This paper proposes a feedback control method for a Linear Resonant Actuator (LRA), in which an external load can be estimated using two signals of the back-EMF. Using this estimated load, it becomes possible to reduce the decrease in amplitude of LRAs when the external load suddenly increased. The effectiveness of this method was verified through FEM analysis and measurements.

Keywords: Linear resonant actuator, External load estimation, PWM control, Finite element method, Disturbance compensation control.

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1. Introduction

Recently, linear resonant actuators (LRA) have been used in a wide range of applications [1-4] because of their many advantages: high efficiency, simple structure, easy control etc. However, the amplitude of the mover severely decreases when an external load is applied. To prevent this from happening, we proposed a PWM feedback control method to keep the amplitude constant regardless of the external load, in which the back-EMF of the coil is detected and is used to determine the current duty by PID control [5]. However, under the proposed control technique, the decrease in the amplitude was large when the external load was suddenly increased. To solve this, it is necessary to correct the PWM duty according to the external load. Also, external load estimation has to be done without any extra sensors so as not to increase the size of the actuator's system.

In this paper, we propose an external load estimation method for a LRA using two signals of the back-EMF. Moreover, we propose a disturbance compensation control method which reduces the decrease in the amplitude of the LRA when a disturbance occurs in the system. The effectiveness of this method is verified through the FEM analysis in [6-10], in which the magnetic field equation was coupled with the electric circuit equation, control method, and motion equation. Measurements were performed to verify the effectiveness of this new control method.

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3.1 Load Estimation Method

Under unipolar PWM feedback control, it is difficult to estimate the external load using only the maximum back-EMF \( V_j \). Therefore, the load estimation method that we propose uses two signals of the back-EMF, \( V_j \) and \( V_s \). \( V_j \) is the value when a constant time \( t_b (500\mu s) \) passes after the back-EMF has crossed zero.

The external load is estimated using the motion equation shown in (1).

\[
F' = K_s \{ V_j \exp(-\xi \pi) - K_v V_s \} K \frac{2}{\exp(-\xi \pi) + 1}
\]

(1)

\[
K_v = \exp\left\{ -\xi \frac{\pi}{2} \left[ 1 - \frac{2}{\sqrt{1 - \epsilon^2}} - \omega_n t_b \right] \right\} \sin(\sqrt{1 - \epsilon^2} \omega_n t_b)
\]

(2)

\[
\xi = \frac{C}{2 \sqrt{MK}}
\]

(3)

\[
\omega_n = \sqrt{\frac{K}{M}}
\]

(4)

where \( F' \) is the estimated load, \( K_s \) and \( K_v \) are constants, \( \xi \) is the damping ratio, \( C \) is the damping viscous coefficient, \( M \) is the mass of the mover, \( K \) is the spring constant, and \( \omega_n \) is the angular frequency.

3.2 Disturbance Compensation Control Method

The coil is excited under PWM control according to the duty determined by PID control using the back-EMF \( V_j \) and disturbance compensation control using the estimated load. The block diagram of the feedback control method is shown in Fig.2. In PID control, the duty is changed only after the amplitude decreases due to a change in the external load and the detected value deviates from the target value. However, when disturbance compensation control is added, the control system can respond to the change in the external load faster because the change in the external load is detected and the value estimated before the amplitude of the mover starts to decrease. The duty is defined by equations (5) and (6).

\[
Duty = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} + K_c F'
\]

(5)

\[
e(t) = V'_s - V_1
\]

(6)

where \( K_p \) is the proportional gain, \( K_i \) is the integral gain, \( K_d \) is the differential gain, \( e(t) \) is the deviation, \( K_c \) is the disturbance compensation control gain.

3.2 Load Estimation PWM Feedback Control

Fig. 3 shows the load estimation PWM feedback control outline of this actuator. The coil is used for inputting the voltage and detecting the back EMF. First, in interval (a), the coil detects the maximum value of the back-EMF \( V_j \) after the back-EMF crosses zero. In interval (b), the coil detects the back-EMF \( V_s \) when a constant time \( t_b \) (500 \( \mu \)s) has passed after the back-EMF crosses zero again. In interval (c), there is a short delay (50 \( \mu \)s) where the actuator calculates the external load value. In interval (d), the coil is excited under PWM control according to the duty determined by PID control and disturbance compensation control. The circuit diagram of this operating mode is shown in Fig. 4(a). In interval (e), current circulates through a diode as shown in Fig. 4(b). Finally, in interval (f), the circuit is opened as shown in Fig. 4(c). It is highly effective to drive the actuator under advanced PWM control, in which a multi-square wave input voltage is applied so that the actuator can be operated under low electric power because the current does not decrease immediately even if the input voltage is turned off.
4. Analysis Method

4.1 Magnetic Field Analysis

The equations of the magnetic field and the electric circuit, which are given by the magnetic vector potential $A$ and the excitation current $I_0$, are coupled in FEM, and are given as follows:

$$\text{rot}(\text{rot} A) = J_0 + \nu_0 \text{rot} M$$

$$E = V_0 - R I_0 - \frac{d\Psi}{dt} = 0$$

$$J_0 = \frac{n}{S_c} I_0 n_s$$

where $\nu$ is the reluctivity, $J_0$ is the excitation current density, $\nu_0$ is the reluctivity of vacuum, $M$ is the magnetization of the permanent magnet, $V_0$ is the applied voltage, $R$ is the resistance, $\Psi$ is the interlinkage flux of the excitation coil, $n_c$ is the number of turns, $S_c$ is the cross-sectional area of the coil and $n_s$ is the unit vector along the direction of the excitation current.

4.2 Coupled Analysis with Motion Equation

The motion equation is given as follows:

$$M \frac{d^2x}{dt^2} + C \frac{dx}{dt} + K x \pm F = F_x$$

where $M$ is the mass of mover, $x$ is the displacement of the mover, $F_x$ is the thrust, $K$ is the spring constant, $F$ is the load and $C$ is the viscous damping coefficient.

The thrust of the mover is calculated using the Maxwell stress tensor method, and is substituted into equation (10). The position of the mover is calculated at each time step. Load estimation PWM feedback control is taken into consideration in this analysis.

5. Dynamic Analysis under Proposed Control

5.1 Analyzed Model and Condition

Fig. 5 shows the FEM model. The number of elements is about 19,000, and unknown variables are about 9,400. Table 1 shows the analysis conditions. The total resistances of the coil and FET during excitation mode and during circulation mode were respectively calculated. The number of steps is 20,000, time division is 10μs, and total CPU time is about 2 hours. The following optimized gain values $K_p = 0.5$, $K_i = 0.05$, $K_o = 0.1$, $K_l = 0.2$, were obtained from the analysis.

5.2 Analysis Results of Estimated Load

Fig. 6 shows the analysis results of the relationship between $V_1$, $V_2$, and the external load. From this result, it can be seen that because the bias of the relationship between $V_i$ and $V_2$ changes with the external load, the external load can be estimated. The detent characteristic of this actuator is nonlinear. So the resonance frequency changes according to the amplitude. This causes an error in the load estimation. Therefore, it is necessary to correct $K_v$ according to the amplitude, or $V_i$ in Figs. 7 and 8, since it is proportional to the amplitude.

Fig. 9 shows the relationship between $V_i$ and the estimated load after correction. From this result, it is shown that the external load is able to be estimated correctly.

5.3 Dynamic Characteristic

Fig. 10 shows the analysis results of the transient characteristics of the mover’s position under only PID control and Fig.11 shows the analysis results with disturbance compensation control. In this analysis, the external load (0.8N and 1.6N) was applied at 0 seconds, after reaching a steady state. From these results, it can be seen that the decrease in the amplitude was successfully reduced by the disturbance compensation control because the duty was increased before the deviation in the amplitude occurred.
Fig. 6. Relationship of $V_1$, $V_2$, and the external load

Fig. 7. Relationship between $V_1$ and frequency

Fig. 8. Correction of $K_v$

Fig. 9. Relationship between $V_1$ and the estimated load after correction

Fig. 10. Only PID control

Fig. 11. With disturbance compensation control

6. Experiment under Proposed Control

6.1 Measuring System

Measurements were performed to verify the effectiveness of this new control method. Fig. 12 shows an overview of the experimental setup of the dynamic characteristics measurement system. The microcomputer obtains the back-EMF value using an A/D converter and it estimates the external load and determines the...
duty. A direct voltage of 3.6V supplied from a stabilized power supply was converted into the PWM voltage with the control circuit also controlled by the microcomputer, and is applied to the coil.

Fig. 13 shows the load device. In this experiment, the external load was applied by a voice coil motor (VCM) which was controlled to synchronize with the LRA’s motion.

6.2 Experimental Results of Estimated Load

Fig. 14 shows the measurement results of the relationship between \( V_1 \) and \( V_2 \) when the external load was changed. It was confirmed in the measurements that the bias of the relationship between \( V_1 \) and \( V_2 \) changes with the external load. The measured results for the 2.0N load are incomplete because the duty ratio became 100% halfway through the experiment.

Fig. 15 shows the measurement results of the estimated load. From this result, it is shown that the external load was estimated correctly and the effectiveness of proposed load estimation method was proven.

6.3 Experimental Results of Dynamic Characteristic

Fig.16 shows the measurement results of the transient characteristics of the mover’s position under only PID control and Fig.17 shows the measurement results with disturbance compensation control. The external load (0.8N and 1.6N) was applied at 0 seconds, after reaching a steady state. From these results, it can be seen that the decrease in the amplitude was successfully reduced by the disturbance compensation control because the duty was increased before the deviation in the amplitude occurred. Therefore, the effectiveness of the proposed disturbance compensation control was confirmed.
7. Conclusion

This paper presented a sensorless load estimation method for our LRA using two back-EMF values. A disturbance compensation control method which reduces the decrease in the amplitude of the LRA when the external load was increased was also presented. The effectiveness of this control method was verified through FEM analysis, in which the magnetic field equation was coupled with the electric circuit equation, control method, and motion equation.

Measurements were performed to verify the effectiveness of this new control method. From the measurement results, it was shown that the proposed method was able to estimate external load correctly. In addition, it was also shown that the decrease in the amplitude was successfully reduced by the disturbance compensation control.

References


