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Comparison and Dynamic Behavior of Moving-Coil Linear Oscillatory Actuator with/without Mechanical Spring driven by Rectangular Voltage Source

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Abstract – This paper deals with the comparison and dynamic behavior of a moving-coil linear oscillatory actuator (MCLOA) with/without a mechanical spring. On the basis of a dynamic simulation model, the dynamic characteristics such as a current and a stroke of the MCLOA without the spring are predicted for various values of frequency. And then, dynamic test results are given to confirm the dynamic simulations. Finally, this paper describes the influence of the spring on the dynamic behavior of the MCLOA from the dynamic experiments of the MCLOA with/without the spring.

Keywords: Moving-coil linear oscillatory actuator, Dynamic simulation model

1. Introduction

With its simple structure, the linear oscillatory actuator is used as an actuator for small displacement round-trip motion. It has been applied to various fields such as: vibrators, air pumps, and compressors, and more recently, artificial hearts [1]. Since the specifications required mainly in design of the LOA are maximum stroke, operating frequency and efficiency, the prediction of the dynamic behavior in the actual operation state is very important. And, it is desirable to employ simple drives due to cost limitations. Of the various driving methods, sinusoidal current drives require a complicated electronic circuit structure, whereas rectangular voltage drives has a simple electronic circuit [2].

Therefore, on the basis of control parameters calculated in the previous work [3] and dynamic simulation algorithm obtained from a motion and a voltage equation, this paper predicts the dynamic performance of the MCLOA without the spring driven by a rectangular voltage source for various values of frequency. The simulation results are shown in good agreement with experimental results. In particular, by presenting the dynamic test results of the MCLOA with the spring, this paper describes the influence of the mechanical spring on the dynamic performance of the MCLOA.

2. The Structures of Drive Systems

Fig. 1 shows the schematic of drive system for the rectangular voltage drive of the MCLOA. As shown in Fig. 1, the drive system consists of sensing parts for measurement of current waveform, a position sensor for measurement of displacement, a gate driver which amplifies two control signals, and a single-phase inverter for generating a single-phase rectangular voltage from a DC power supply.

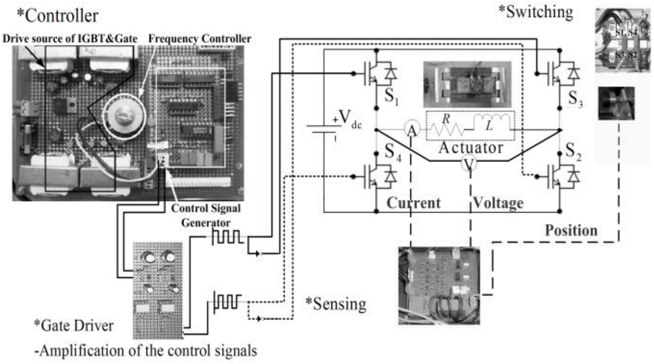

Fig. 1. The schematic of the drive system for rectangular voltage drive.

The control signals amplified by the gate driver are applied to a gate of each switch and make switches have the switching state as follows:

$$\begin{cases} S_1 + S_4 = 1 \\ S_2 + S_3 = 1 \end{cases} \tag{1}$$

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It can be observed from (1) that two paired switches (S_1 and S_4 or S_2 and S_3) are complementary to each other. However, when the switching state changes from one state to the other state between the two paired switches, both switches must be on the OFF states for a short time. This is to avoid the possibility of short-circuiting in the transient state in which the two switches can be simultaneously closing [4].

3. State Variable Equations

The mechanical motion equation for the MCLOA is given by [5]

$$M\frac{d^2x}{dt^2} = K_T i - kx - C_d\frac{dx}{dt} \tag{2}$$

where M and dx/dt are mass and velocity of the mover, respectively. k and C_d are the coefficient of elasticity for spring and the coefficient of friction, respectively.

The equivalent electrical circuit for the MCLOA can be represented by the following equation:

$$e = Ri + L\frac{di}{dt} + K_E\frac{dx}{dt} \tag{3}$$

where e is the voltage supplied to actuator. R and L are the resistance and the inductance of stator windings, respectively. In (3), the right-hand-side first, second and third term are the Ohmic drop, the induced voltage due to inductance of the stator coil and back-emf, respectively. The value of coefficients used in (2) and (3) are reported fully in Table 1.

From a motion equation and a voltage equation, the state and the output equations for the MCLOA can be obtained by

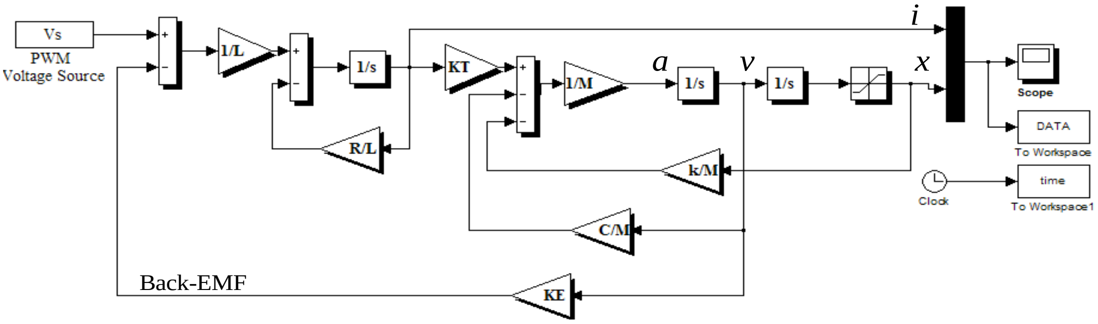
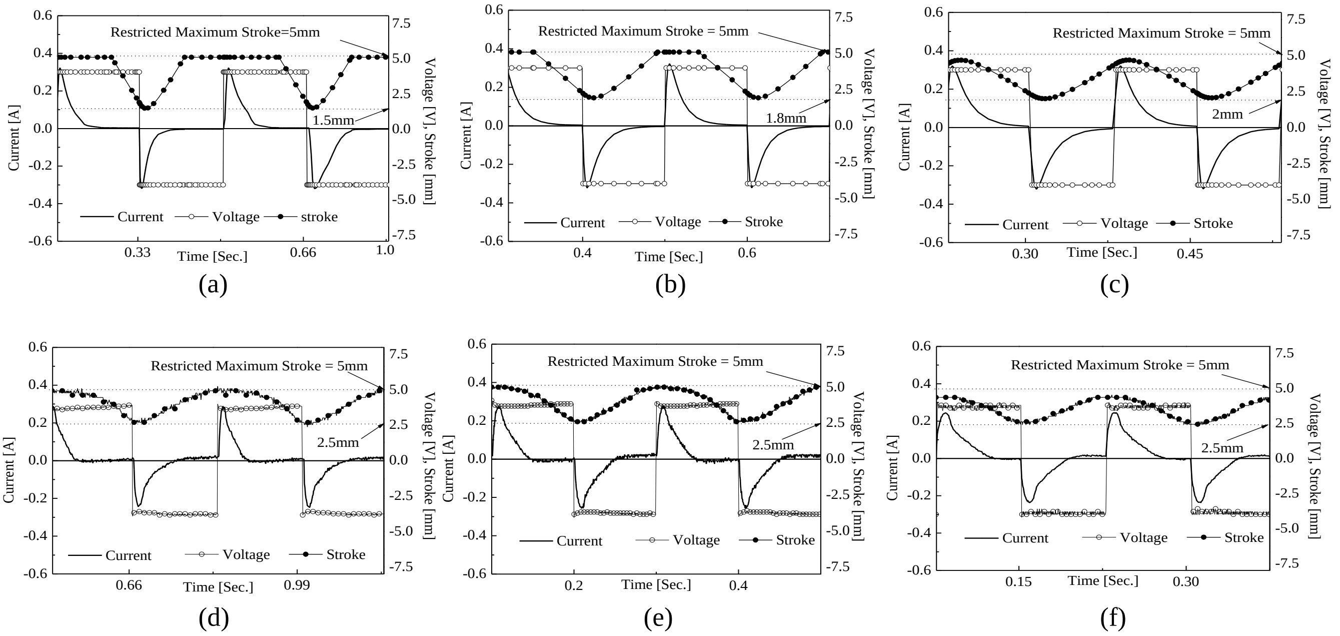


Fig. 2. Dynamic simulation algorithms for the MCLOA with mechanical spring.



(a) (b) (c)

(d) (e) (f)

Fig. 3. The comparison of simulations and measurements for dynamic performance of the MCLOA without the mechanical spring: simulations [(a) 3Hz, (b) 5Hz and (c) 6.57Hz] and measurements [(d) 3Hz, (e) 5Hz and (f) 6.57Hz].

Table 1. Estimated Control Parameters of MCLOA

Coefficients [Unit]	Value
Thrust constant K_T [N/A]	32.5
Back-emf constant K_E [V·s/m]	32.5
Inductance L [mH]	71.2
Resistance R [Ω]	17.8
Moving Mass [kg]	0.3
Spring Coefficients [N/m]	2000

$$\begin{bmatrix} x' \\ x'' \\ i' \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{k}{M} & -\frac{C_d}{M} & \frac{K_T}{M} \\ 0 & \frac{K_E}{L} & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x \\ x' \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} e$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ x' \\ i \end{bmatrix} \qquad (4)$$

where state variables are the displacement and the current. (4) offers the dynamic simulation algorithm shown in Fig. 2. For the case when the MCLOA does not have the spring, a spring coefficient k shown in Fig. 2 should be set 0.

4. Dynamic Simulation Results and Discussion

Fig. 4 shows the testing apparatus for measurements of dynamic performance of the MCLOA with/without the spring.

4.1 MCLOA without Spring

Fig. 3 shows the comparison of predictions with measured results for dynamic performance of the MCLOA without the spring for various values of frequency. It can be seen that as the frequency is increased, the stroke decreases and the rms (root mean square) value of the current increases. This result suggests that since the driving voltage is constant for various values of frequency, the power dissipated in the MCLOA will increases as the frequency is increased. It is noted that restricted maximum stroke is due to the difference between pole width of mover and stator.

The simulation results for various values of frequency are shown in good agreement with experimental results.

4.2 MCLOA with spring

Fig. 5 shows the experimental results for dynamic perfor mance of the MCLOA with the spring for various values of frequency.

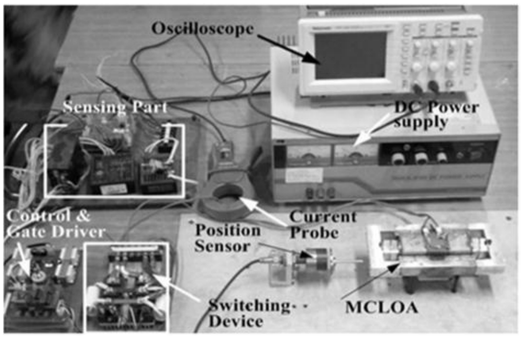


Fig. 4. The testing apparatus for measurements of dynamic performance of the MCLOA with/without the spring.

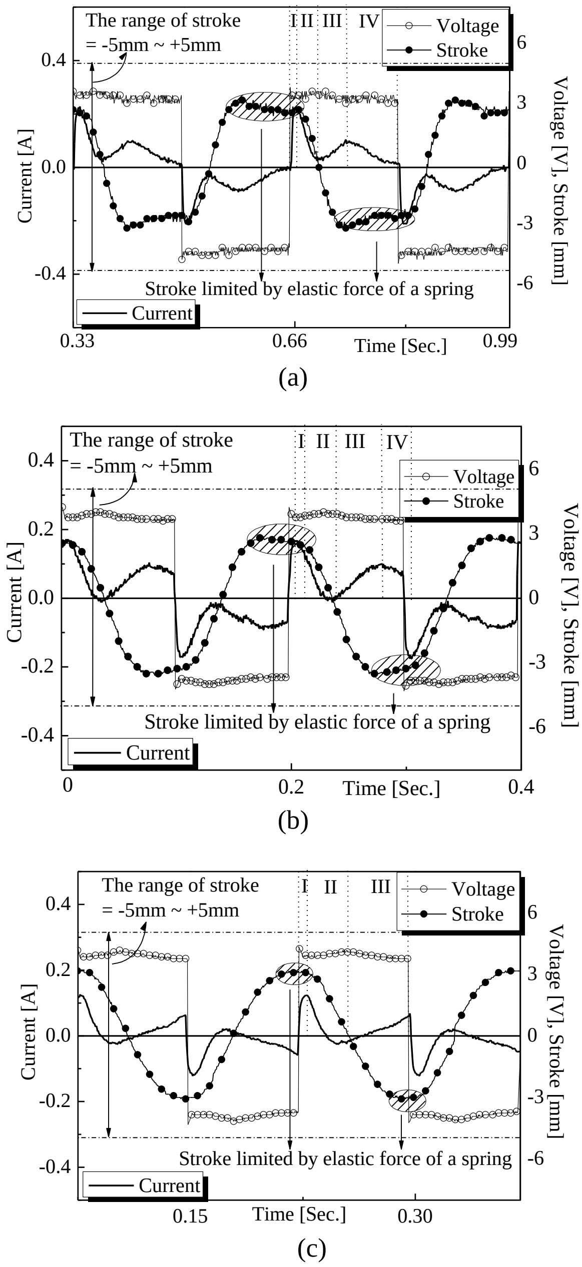
The current waveform in each region represented as I~IV shown in Fig. 5 can be described using Fig. 6. For the case when the mover's position is the same as Fig. 6 (a), the driving voltage changes (–) into (+). So, the current quite increases in order to move (x-direction) the mover with the inertia in the direction of –x, as shown in region I of Fig. 5.

Once the mover starts to move in the direction of x, the current decreases with aid of the spring until the mover is reached in the position shown in Fig. 6(b), as shown in region II of Fig. 5. And then, when the mover moves from the position shown in Fig. 6(b) to that shown in Fig. 6(c), the current increases again due to the elastic force of a right spring, as shown in region III of Fig. 5. Finally, for the case when a operating frequency is low, since the mover which reaches the position shown in Fig. 6(c) does not move until the driving voltage is changed, the current decreases, as shown in region IV of Fig. 5(a) and (b). However, as shown in Fig. 5(c), the region IV is nonexistent in case of a higher frequency.

Although the mover's initial position of both the MCLOA with and without the spring is x=0mm, it can be observed from Fig. 3 and Fig. 5 that the stroke of the MCLOA without the spring is +2.5mm~+5mm, whilst that with the spring is -3mm~+3mm. It can be predicted from these results that the spring makes the mover oscillate in the range between negative and positive position.

5. Conclusion

Comparison and dynamic behavior of the MCLOA with/without mechanical spring driven by rectangular voltage source have been developed. This paper has predicted the dynamic performance of the MCLOA without the spring driven by a rectangular voltage source for various values of frequency, using dynamic simulation algorithm obtained from motion and voltage equation. The



(a)

(b)

(c)

Fig. 5. The measurements for dynamic performance of the MCLOA with the mechanical spring: (a) 3Hz, (b) 5Hz and (c) 6.57Hz.

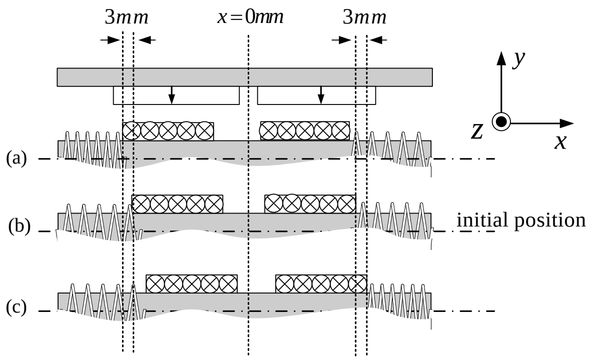


Fig. 6. The schematic for the explanation of the relation between current waveform and mover position.

simulation results such as current and stroke are shown in good agreement with experimental results. In particular, by presenting the dynamic test results of the MCLOA with the spring, the influence of the mechanical spring on the dynamic performance of the MCLOA has been described in terms of the variation of current dissipated in the MCLOA according to mover position and elastic force of the spring. Finally, analysis results presented in this paper are very useful for the design of the MCLOA.

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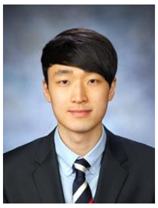

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