

# Proposal of highly effective driving method for linear oscillatory actuator

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Linear oscillatory actuators (LOAs) have been widely used in linear compressors as a high-speed oscillatory driving device. Maximum efficiency is obtained at the resonance frequency determined from the spring constant and mass of the mover. However, there is a problem that the efficiency severely decreases when the driving frequency differs from the resonant frequency to change the output power. In this paper, we propose a highly effective driving method in which the thrust, which shows the characteristics of a spring, is generated by the LOA. In the proposed method, the resonance frequency always corresponds to the driving frequency. The efficiency can be improved in a wide range of driving frequency of 20-40 Hz. The efficiency is improved from 6.1 % to 52.2 % at the driving frequency of 40 Hz.

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## 1. Introduction

Linear oscillatory actuators (LOAs) have been widely used in linear compressors as high-speed oscillatory driving devices [1-4]. Linear compressors driven by LOAs are more efficient than current crank-driven compressors, because they have no rotation-linear movement conversion mechanism and are oscillated using the resonance of a spring [1,2]. To adjust the output of a compressor, the driving frequency of the LOA has to be changed. The maximum efficiency is obtained at the resonance frequency, which is determined from the spring constant and mass of the mover. However, there is a problem that the efficiency rapidly decreases when the driving frequency differs from the resonance frequency in the conventional method [5]. In this paper, we propose a highly effective driving method (proposed method) in which the thrust, which shows the characteristics of a spring, is generated by the LOA. In the proposed method, the resonance frequency always corresponds to the driving frequency. The following details are described.

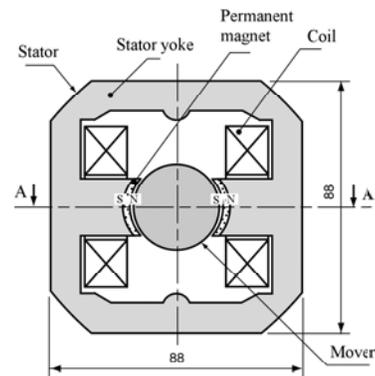
- (1) Highly effective driving method for LOA.
- (2) Improvement of LOA efficiency

## 2. High effective driving method for LOA

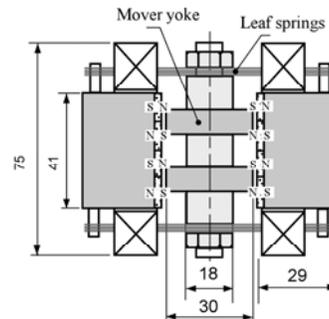
### 2.1 Structure of LOA

Fig. 1 shows the basic structure of the LOA in the form of a plane view and an A-A sectional view. The stator of the LOA is composed of a stator yoke and two coils. The coils are connected in series. Eight arc-shaped permanent magnets (PMs) are attached to the inside wall of the stator yoke. The mover of the LOA is composed of

two columnar mover yokes. The mover is supported by 8 leaf springs, as shown in Fig. 1 (b), which are also used as a resonator.



(a) Front figure



(b) A-A sectional view

Fig. 1. Basic structure of a LOA (unit: mm).

The thrust constant of the LOA is  $K_f = 37$  N/A and the maximum static thrust is  $F_{\max} = 111$  N at an exciting current of  $I = 3$  A. The rated stroke is 6 mm, the driving frequency range is 20-40 Hz and the yoke material is magnetic steel. The coil resistance is  $5.1 \Omega$  and the material of the PMs is Nd-Fe-B. The mass of the mover is 0.17 kg.

## 2.2 Principle of operation

In the proposed driving method, the resonance frequency can be change by controlling the spring constant. In this section, we give an explanation of the principle of operation of the proposed method, as shown in Fig. 2, for (a) the mechanical model of the LOA and (b) the characteristic of the thrust. The force  $F_s$  applied by the springs and the resonance frequency  $f_0$  of the LOA are given by

$$F_s = -K_s x \quad (\text{N}) \quad (1)$$

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{K_s}{M}} \quad (\text{Hz}) \quad (2)$$

where  $K_s$  is the spring constant (N/m) of the LOA,  $x$  is the displacement (m) of the mover and  $M$  is its mass (kg).

The electromagnetic thrust  $F_i$  generated by the LOA is given by

$$F_i = K_f I \quad (\text{N}) \quad (3)$$

where  $K_f$  is the thrust constant (N/A) of the LOA and  $I$  is the exciting current (A).

The thrust  $F$  of the LOA, which is the sum of the force  $F_s$  applied by the springs and the electromagnetic force  $F_i$ , can be described as

$$F = F_s + F_i = -K_s x + K_f I \quad (\text{N}) \quad (4)$$

In the proposed method, the exciting current  $I(x)$  is proportional to the displacement of the LOA and is given by

$$I(x) = -K_{si} x \quad (\text{A}) \quad (5)$$

where  $K_{si}$  is the changing gain (A/m).

Substituting Eq. (5) into Eq. (4), the thrust  $F$  of the LOA is expressed by Eq. (6). The spring constant becomes  $(K_s + K_f K_{si})$ , and the resonance frequency  $f_{0i}$  in the proposed method is given by Eq. (7). If  $K_{si}$  is adjusted, the resonance frequency  $f_{0i}$  can be changed.

$$F = -(K_s + K_f K_{si})x \quad (\text{N}) \quad (6)$$

$$f_{0i} = \frac{1}{2\pi} \sqrt{\frac{K_s + K_f K_{si}}{M}} \quad (\text{Hz}) \quad (7)$$

Fig. 3 shows a block diagram of the proposed method for driving the LOA. The rectangular area within the broken lines is the block diagram of the LOA. The other area within the broken lines is the control unit used in the

proposed method. The displacement  $x$  of the mover, measured using a displacement sensor, is multiplied by the changing gain  $K_{si}$ , and is feedback to the current instruction  $I^*$ .

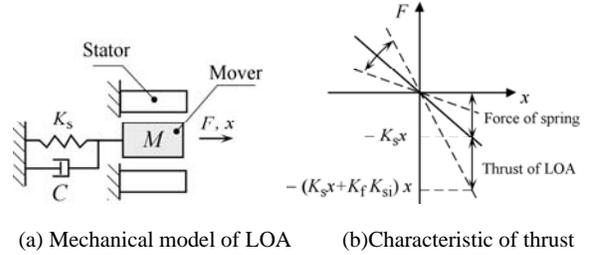


Fig. 2. Principle of operation of the proposed method.

The resonance frequency  $f_{0i}$  in the proposed method determined from the spring constant is given by Eq. (7).  $f_{0i}$  can be changed by changing  $K_{si}$ , which is adjusted so that  $f_{0i}$  always corresponds to the driving frequency  $f$  of the LOA. Thus, the efficiency can be improved over a wide range of driving frequencies in the proposed method.

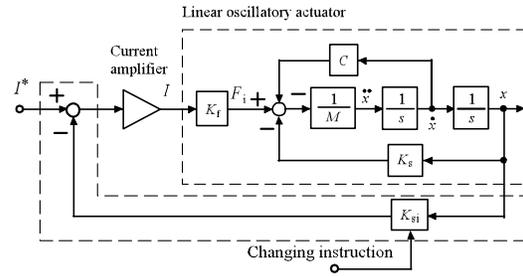


Fig. 3. Block diagram of a proposed method.

## 3. Method of measurement of efficiency

Fig. 4 shows the method of measurement efficiency of the LOA. The efficiency is measured using two identical LOAs, LOA-1 and LOA-2, connected to a load cell. The displacement  $x_2$  of LOA-2 is measured using a laser displacement sensor. The mechanical power of LOA-1 can be obtained from the displacement  $x_2$  of LOA-2 and output of the load cell [6].

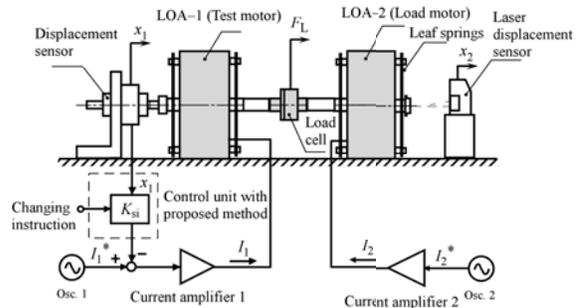


Fig. 4. Method of measurement of efficiency.

The input power  $P_i$ , mechanical power  $P_o$  and efficiency  $\eta$  of the LOA-1 can respectively be expressed

$$P_i = f \int_0^T v_1 i_1 dt \quad (W) \quad (9)$$

$$P_o = f \oint F_L dx_2 \quad (W) \quad (10)$$

$$\eta = \frac{P_o}{P_i} \times 100 \quad (\%) \quad (11)$$

where  $f$  is the driving frequency (Hz),  $T$  is the period of the cycle (s),  $v_1$  is the instantaneous value of the driving voltage (V) and  $i_1$  is the instantaneous value of exciting current in LOA-1.

$K_{si}$  can be adjust so that the resonance frequency  $f_{oi}$  always corresponds to the driving frequency to change the mechanical power when the LOA is driven at a different frequency from the resonance frequency.

#### 4. Improvement of LOA efficiency

We verify the feasibility of the proposed method by experiment using the apparatus shown in Fig. 4. The exciting current  $I_1^*$  in LOA-1, is 2 A under a constant-current mode. The amplitude  $A$  of the displacement of LOA-2 is keep constant at  $A = 3$  mm by adjusting the exciting current  $I_2^*$  in LOA-2.  $I_2^*$  is opposite in phase to  $I_1^*$ .

Fig. 5 shows waveforms of the voltage of LOA-1, the exciting current in LOA-1, exciting current in LOA-2, the displacement of LOA-2 and the output of the load cell. The exciting current in LOA-2 is adjusted to keep the amplitude of LOA-2 constant at 3 mm.

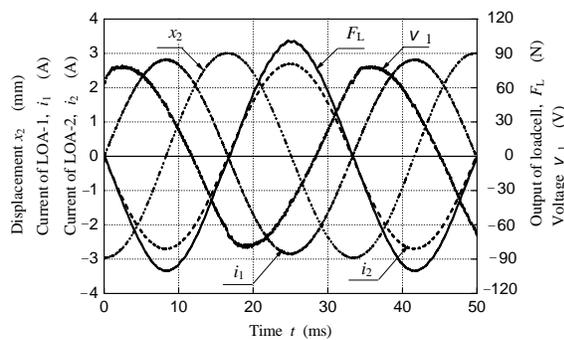


Fig. 5. Waveform of the measured values at  $f = 30.3$  Hz ( $I_1^* = 2$  A,  $I_2^* = 1.84$  A,  $A = 3$  mm).

Fig. 6 shows the mechanical power waveform of LOA-1 at  $f = 30.3$  Hz. The mechanical power of LOA-1 can be calculated by the area inside waveform by the output of the load cell  $F_L$  and the displacement  $x_2$  as Eq. (10). The input and mechanical power are  $P_i = 51.9$  W and  $P_o = 27.1$  W, respectively, and the maximum efficiency is 52.5% at the resonance frequency  $f_0 = 30.3$  Hz.

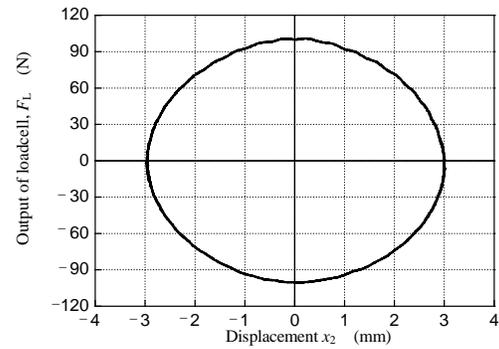


Fig. 6. Waveform of the output of the LOA at  $f = 30.3$  Hz ( $I_1^* = 2$  A,  $I_2^* = 1.84$  A,  $A = 3$  mm).

Fig. 7 shows the mechanical power waveform of LOA-1 at  $f = 20$  Hz. The waveform the conventional method is narrow. The input and mechanical power are  $P_i = 26.8$  W and  $P_o = 1.4$  W, respectively. The efficiency is  $\eta = 5.1\%$  at  $f = 20$  Hz. In the proposed method,  $K_{si}$  is adjusted to  $-390$  A/m, so that the resonance frequency  $f_{oi}$  agrees with the driving frequency of  $f = 20$  Hz. The input and mechanical power are  $P_i = 50.5$  W and  $P_o = 18.2$  W, respectively, and the efficiency is 36% for the proposed method. The efficiency increases by 7 times from 5.1% to 36%.

Fig. 8 shows the mechanical power waveform at  $f = 40$  Hz. The input and mechanical power are  $P_i = 28.6$  W and  $P_o = 1.7$  W, respectively. The efficiency is only 6.1 % for the conventional method. This is 1/8 of the efficiency at the resonance frequency (52.2%). In the proposed method,  $K_{si}$  is adjusted to 540 A/m, so that the resonance frequency  $f_{oi}$  agrees with the driving frequency of  $f = 40$  Hz. The input and mechanical power are  $P_i = 69.6$  W and  $P_o = 36.8$  W, respectively, and the efficiency is 52.6% for the proposed method. The efficiency increases by 8.6 times from 6.1% to 52.6%.

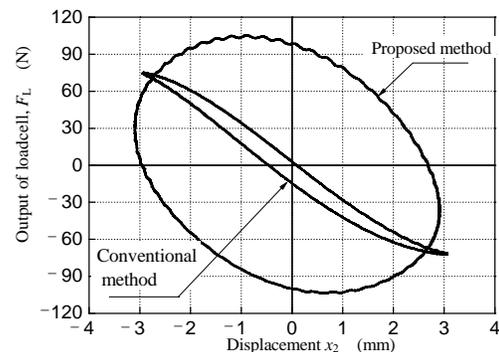


Fig. 7. Waveforms of the output of the LOA at  $f = 20$  Hz ( $I_1^* = 2$  A,  $A = 3$  mm).

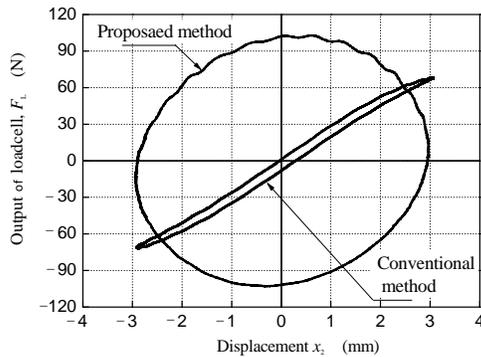
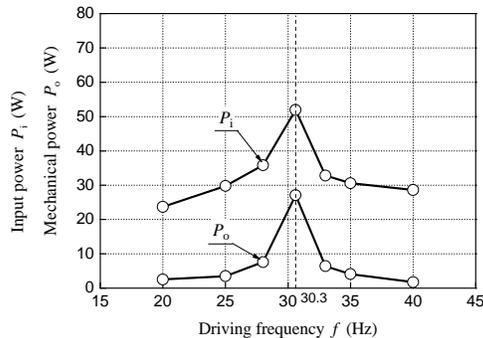
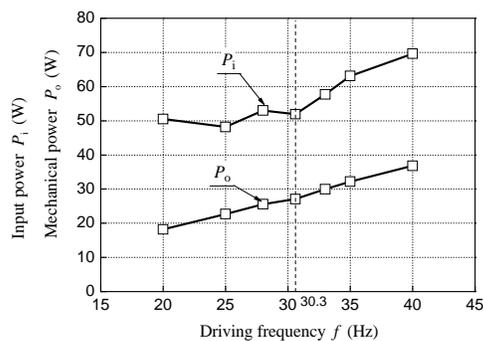


Fig. 8. Waveforms of the output of the LOA at  $f = 40$  Hz ( $I_1^* = 2$  A,  $A = 3$  mm).

Fig. 9 shows the input and mechanical power frequency characteristics of the LOA for the conventional and proposed methods. The input, mechanical power and efficiency of the LOA-1 are measured for the driving frequency range of 20-40 Hz and exciting current  $I_1^* = 2$  A. The input and mechanical power increases with driving frequency for the proposed method. The maximum mechanical power  $P_o$  of the conventional method as shown in Fig. 9 (a) is obtained at the resonance frequency of  $f = 30.3$  Hz.



(a) Conventional method



(b) With proposal method

Fig. 9. Input and output power vs. frequency characteristics of the LOA ( $I_1^* = 2$  A,  $A = 3$  mm).

However, as show in Fig. 9 (b), the mechanical power  $P_o$  of proposed method increase with increasing the driving frequency.

Fig. 10 shows the efficiency vs. frequency characteristics of the LOA. The maximum of the conventional method efficiency is obtained at the resonance frequency of  $f = 30.3$  Hz. The efficiency decreases away form the resonance frequency. The efficiency of the proposed method is improved in a wide driving frequency range of 20-40 Hz. The efficiencies of proposed method increase with increasing the driving frequency, because the  $P_o$  is increased.

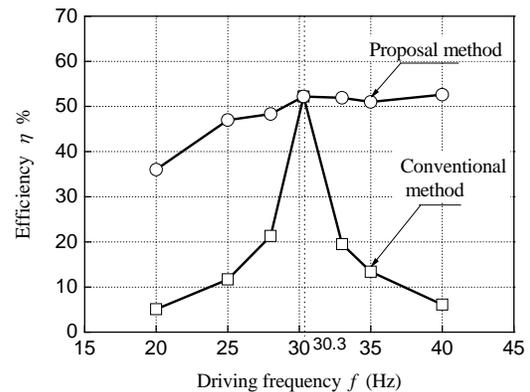


Fig. 10. Efficiency vs. frequency characteristics of the LOA ( $I_1^* = 2$  A,  $A = 3$  mm).

The efficiencies of the conventional and proposed methods are 6.1% and 52.6% at the driving frequency of  $f = 40$  Hz; the efficiency increases by 8.6 times. Thus, we have verified by measurement that our proposed driving method is highly effective.

### 5. Conclusions

In this paper, we demonstrated the following results for our proposed driving method for a LOA.

#### (1) Highly effective driving method

The changing gain  $K_{si}$  is adjusted so that the resonance frequency always corresponds to the driving frequency of the LOA. The efficiency can be improved over a wide range of driving frequencies by this method.

#### (2) Improvement of LOA efficiency

The efficiency was improved over a wide of driving frequency range of 20-40 Hz. The respective efficiencies of the conventional and proposed methods were 6.1% and 52.6% at the driving frequency of  $f = 40$  Hz; efficiency increases by 8.6 times. Thus, we verified the effectiveness of the proposed driving method by measurement.

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