[GT-17]

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A Disturbance Compensation Control for Linear Resonant Actuator Based on the Law of Energy Conservation

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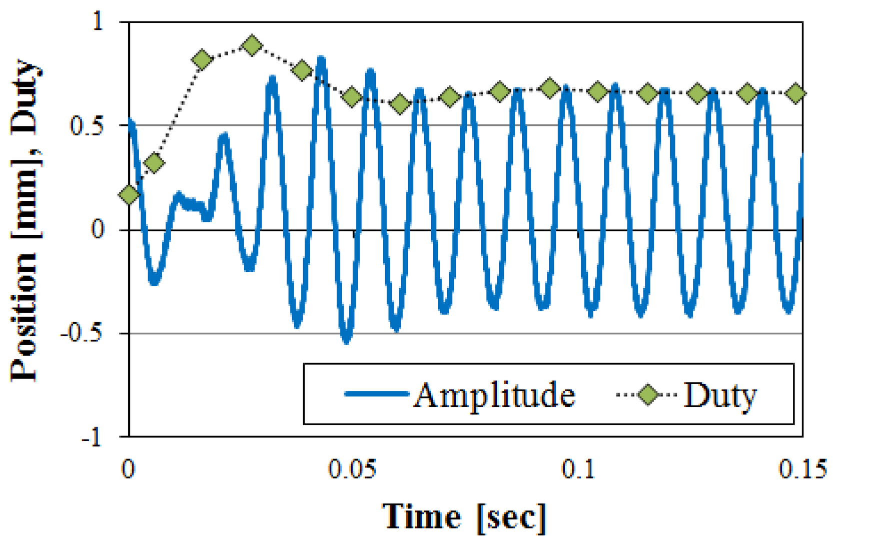
Introduction

Linear Resonant Actuator (LRAs) are actuators that reciprocate by alternating currents excitation.

○Simple structure, easy control, direct drive

◆ Problem

- ➢ It takes much time until the amplitude of the LRA becomes steady state after it decreases once by external load.
- ➢ Compensating the load disturbance is desirable without a load sensor.

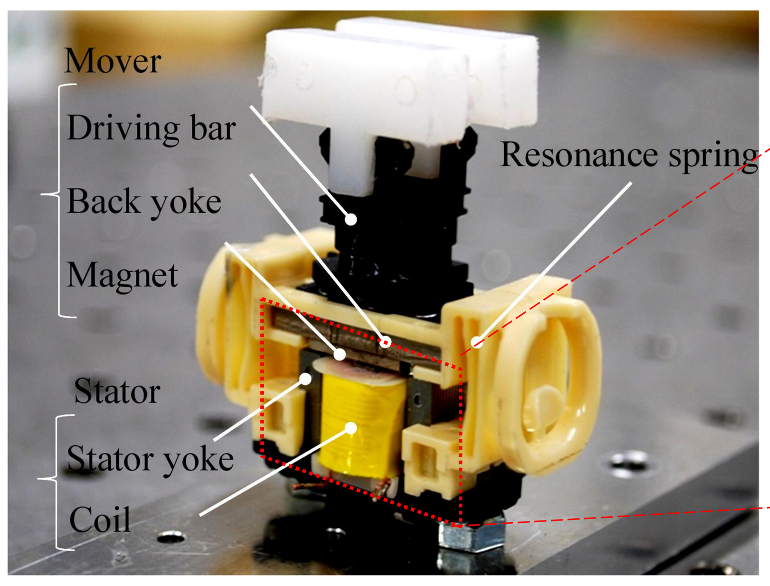


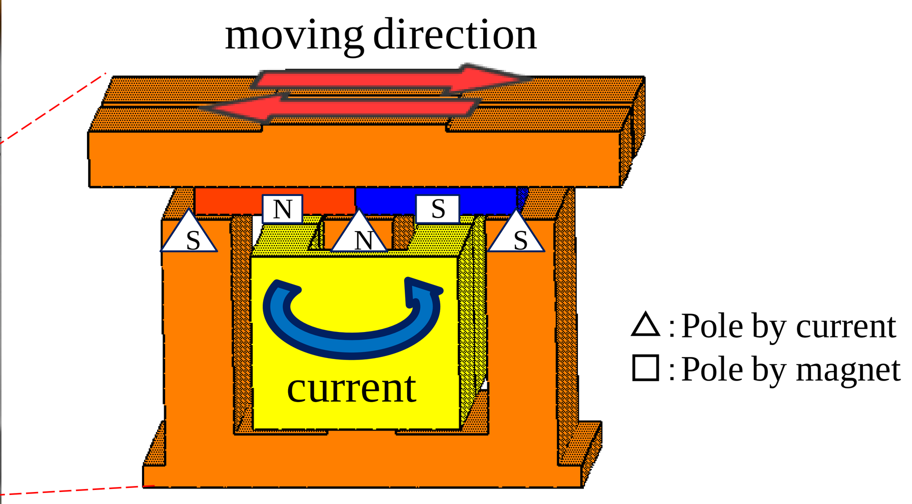
Transient response when load is suddenly applied at 0s

◆ Aim of this study

- ➢ Propose a load estimation method based on the law of energy conservation
- ➢ Build a disturbance compensation control system using the estimated load

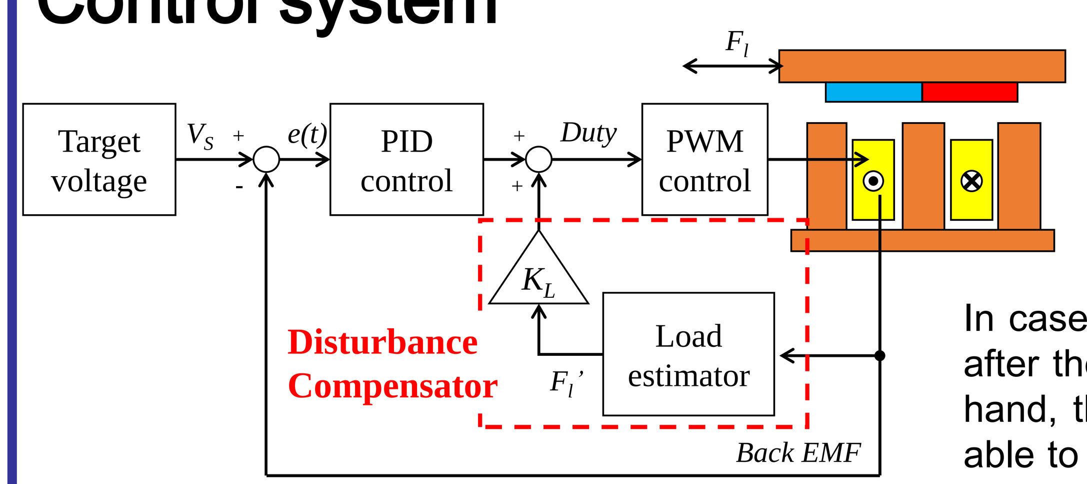
Basic Structure and Operational Principle





Disturbance Compensation Control

Control system



$$Duty = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} + K_L \Delta F_l$$

PID control — Compensation

$$e(t) = V_S - V_2$$

In case of only PID control, the duty increases after the deviation e(t) increases. On the other hand, the disturbance compensation control is able to respond rapidly to the sudden load due to the compensation term.

Load estimation method

Equation of motion

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = F_x + F_l \operatorname{sgn}\left(\frac{dx}{dt}\right)$$

⇩

Energy conservation

$$F_l = \frac{1}{x_2 + x_1}\int_0^{\frac{1}{2f}} F_x \frac{dx}{dt}dt - \frac{1}{2}k(x_2 - x_1) - \frac{1}{4}c\pi^2 f(x_2 + x_1)$$

Assumption: Average thrust is a linear function of x1, x2, and duty.

⇩

Amplitude-based function

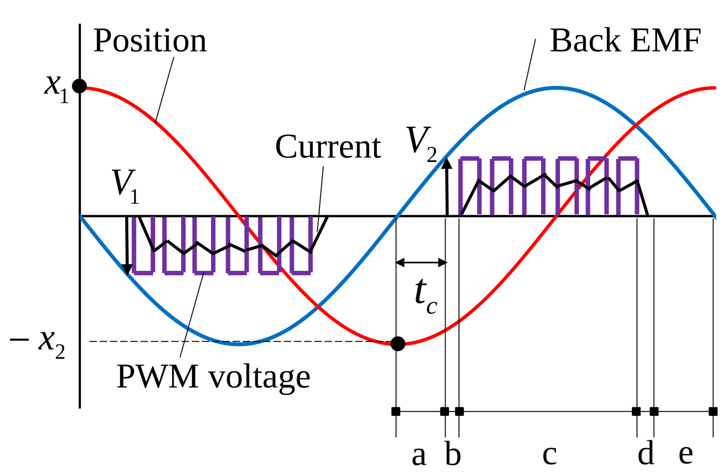
$$F_l = a_1 Duty + a_2 x_1 + a_3 x_2 + a_4 - \frac{1}{2}k(x_2 - x_1) - \frac{1}{4}c\pi^2 f(x_2 + x_1)$$

⇩

Convert to back-EMF

$$x_1 = -\frac{v_1}{\omega_n \exp(-\xi\omega_n t_c)\sin(\omega_n t_c)} + \frac{F_l}{k} = -\frac{K_v V_1}{\omega_n \exp(-\xi\omega_n t_c)\sin(\omega_n t_c)} + \frac{F_l}{k} = g(V_1) + \frac{F_l}{k}$$

⇩



Schematic diagram of feedback control

Estimation function

$$\hat{F}_l = \alpha Duty + \beta g(V_1) + \gamma g(V_2) + \delta$$

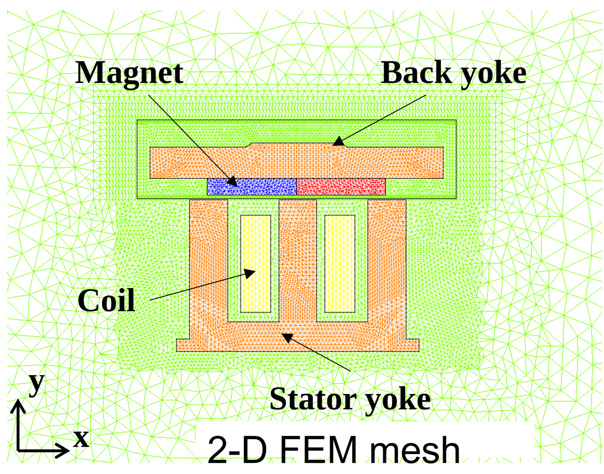
$$\alpha = a_1 \Big/ \left(1 - \frac{a_2 + a_3}{k} + \frac{\pi\xi}{2}\right) \qquad \gamma = \left(\frac{k}{2} - a_3 + \frac{\pi^2 cf}{4}\right) \Big/ \left(1 - \frac{a_2 + a_3}{k} + \frac{\pi\xi}{2}\right)$$

$$\beta = \left(\frac{k}{2} + a_2 - \frac{\pi^2 cf}{4}\right) \Big/ \left(1 - \frac{a_2 + a_3}{k} + \frac{\pi\xi}{2}\right) \qquad \delta = a_4 \Big/ \left(1 - \frac{a_2 + a_3}{k} + \frac{\pi\xi}{2}\right)$$

$\hat{F}_l$: estimated load
ξ : damping ratio
f : resonant frequency
$g(\ )$: Approximation function

Load estimation function is formulated on the basis of the law of energy conservation.
This function uses two back-EMF signals V_1, V_2 and duty ratio in PWM control.

Analysis Model and Condition



Gain parameters

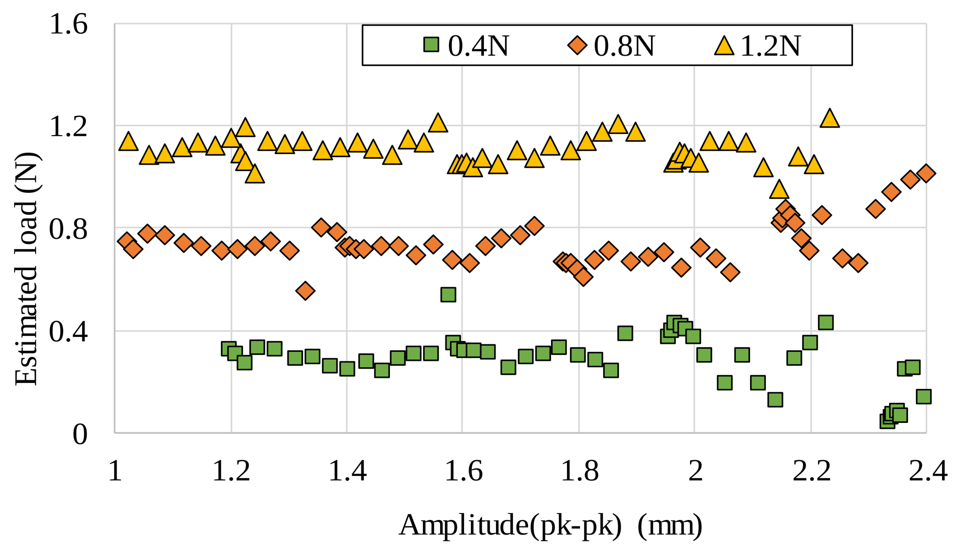
Parameters	Only PID control	With disturbance compensation control
Proportional gain K_P	1.0	1.0
Integral gain K_I	0.034	0.034
Derivative gain K_D	0.5	0.5
Compensation gain K_L		0.6

Dynamic analysis condition

Quantity	Value
Remanence of magnets (T)	1.42
Mass of mover (g)	6.95
Spring constant (N/mm)	13.36
Viscous damping coefficient (N·s/m)	0.14
Thickness of stator and mover (mm)	10.25
Detecting time t_c (μs)	250
Length of interval c (μs)	1500
Coil resistance (on) (mΩ)	320
Coil resistance (off) (mΩ)	290
Input voltage (V)	3.6

Analysis Results

Load estimation results



Average thrust (approximation)

$$\frac{1}{x_2 + x_1}\int_0^{\frac{1}{2f}} F_x \frac{dx}{dt}dt = 4.56Duty - 0.91x_1 - 0.91x_2 - 0.42$$

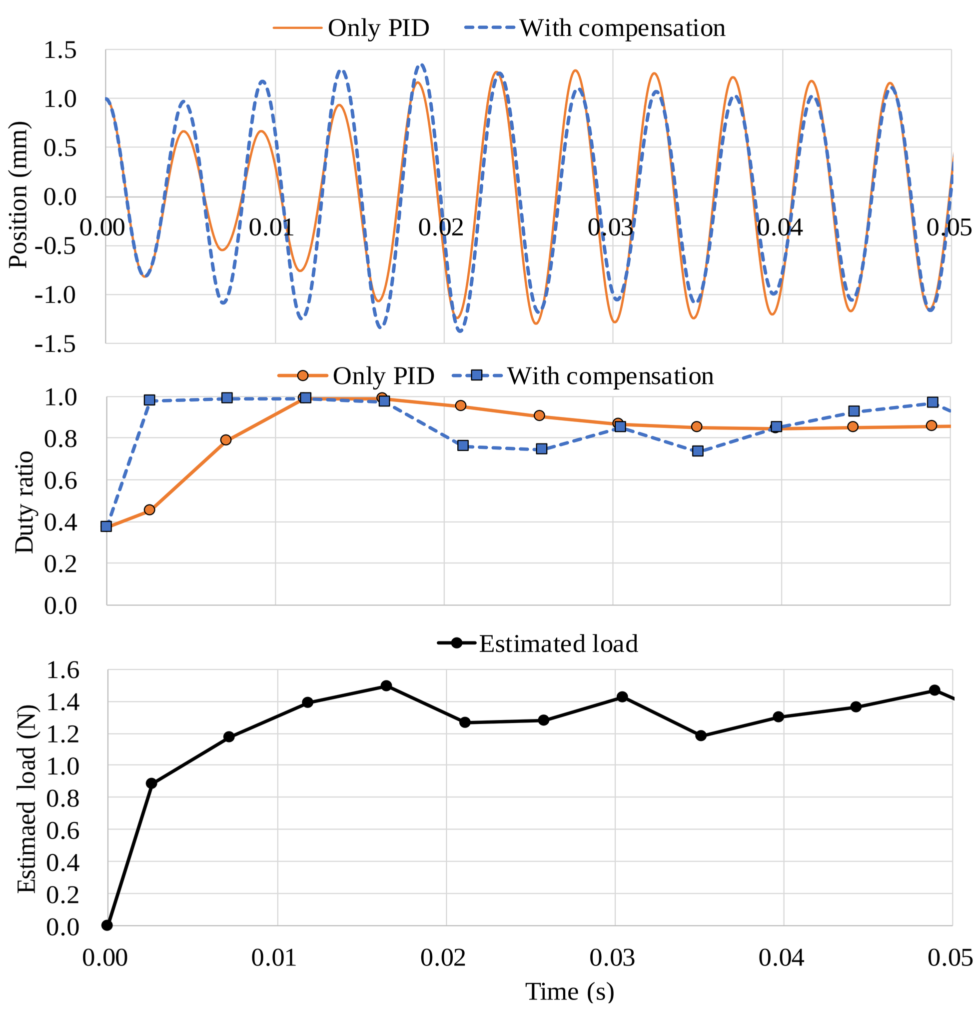
Correction function

$$g(V_i) = 3.41V_i^3 - 3.65V_i^2 + 2.90V_i - 0.17 \ (i = 1, 2)$$

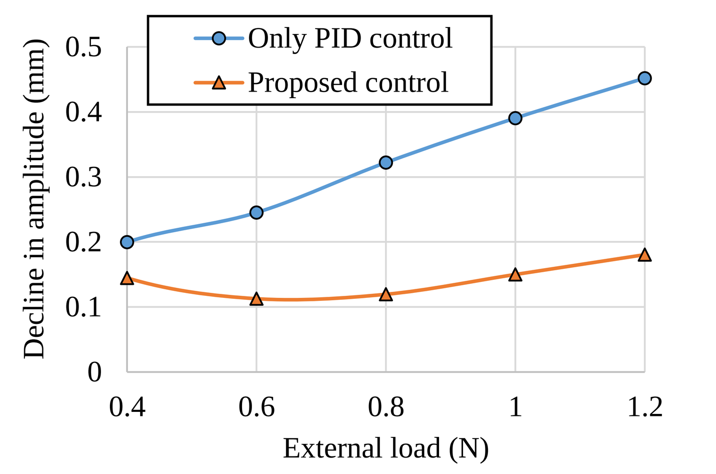
The loads were largely estimated and the theoretical validity of the proposed estimation function was confirmed.
Average estimation errors at 0.4, 0.8, 1.2 N were 32, 11, 7.5 %, respectively.

Effectiveness of the proposed compensation control

Transient responses under with and without compensation



Maximum amount of decline in amplitude



The effect of compensation was remarkable particularly when a large load was suddenly applied.

The load of 1.2 N was suddenly applied at the time of 0 sec.
The duty ratio increased quickly under the disturbance compensation control. As a result, the maximum decline in amplitude was 0.18 mm at a half cycle.
When only PID control was employed to determined the duty ratio, the maximum decline was 0.45 mm at one and a half cycle.
The proposed control was able to improve a transient amplitude response significantly.

Conclusion

- We proposed a load estimation method on the basis of the law of energy conservation.
- Additionally, we built a load compensation control system in which the duty ratio is determined by PID element and compensation term calculated from the estimated load.
- The proposed compensation control is able to improve a transient amplitude response significantly particularly at large load.