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3-D Finite Element Analysis of Linear Resonance Actuator under PID Control

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Introduction

Linear resonant actuators (LRA) have been used in a wide range of applications,

Advantages;
High efficiency, simple structure, easy control, and so on.

Problem;
The amplitude severely decreases in response to an external load.

To control this, we proposed PWM feedback control.
However, the amplitude measurably decreased against an external load under the control.

The more effective feedback control is investigated using PID control in PWM feedback control to keep the amplitude constant against an external load.

We propose a numerical method to analyze dynamic characteristics of the LRA under PID control in PWM feedback control by the back-EMF detecting from a coil employing 3-D FEM.

Analysis Method

The equations of the magnetic field and the electric circuit are coupled using the 3-D FEM, which are given by the magnetic vector potential $\boldsymbol{A}$ and the exciting current I_0 as follows:

$$\mathrm{rot}(\nu\,\mathrm{rot}\,\boldsymbol{A}) = \boldsymbol{J}_0 + \nu_0\,\mathrm{rot}\,\boldsymbol{M}$$

ν : the reluctivity
$\boldsymbol{J}_0$: the exciting current density
ν_0 : the reluctivity of the vacuum
$\boldsymbol{M}$: the magnetization of permanent magnet

$$E = V_0 - RI_0 - \frac{d\Psi}{dt} = 0$$

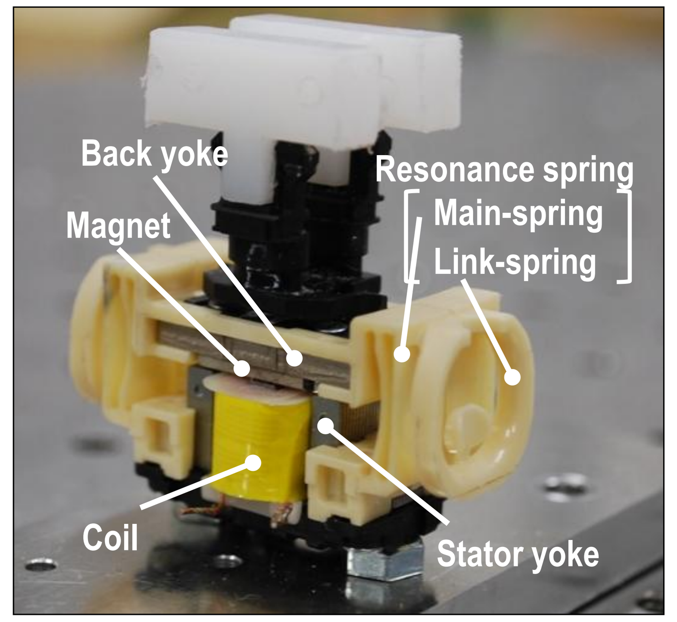
V_0 : the applied voltage
R : the resistance
ψ : the interlinkage flux of exciting coil

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

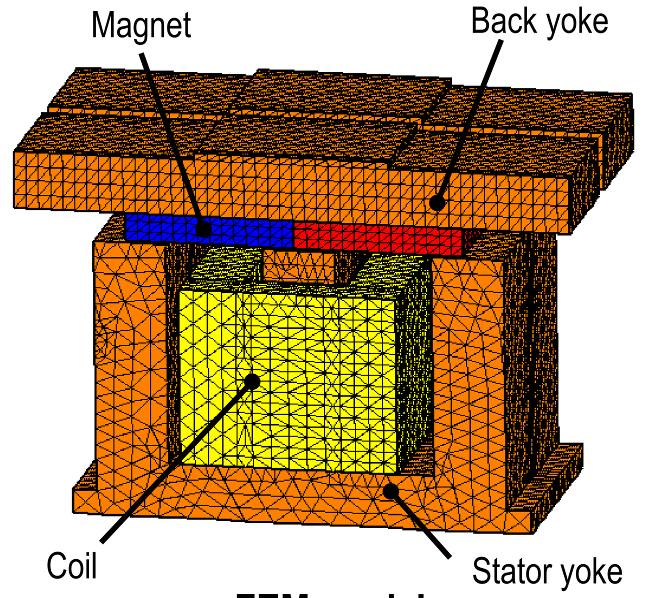
M : The mass of movers
x : The displacement of movers
F_x : Trust
F_k : Spring force
C : Viscous damping coefficient

The thrust of each mover is calculated using the Maxwell stress tensor method.

Analyzed Model and Condition



Basic structure of the LRA

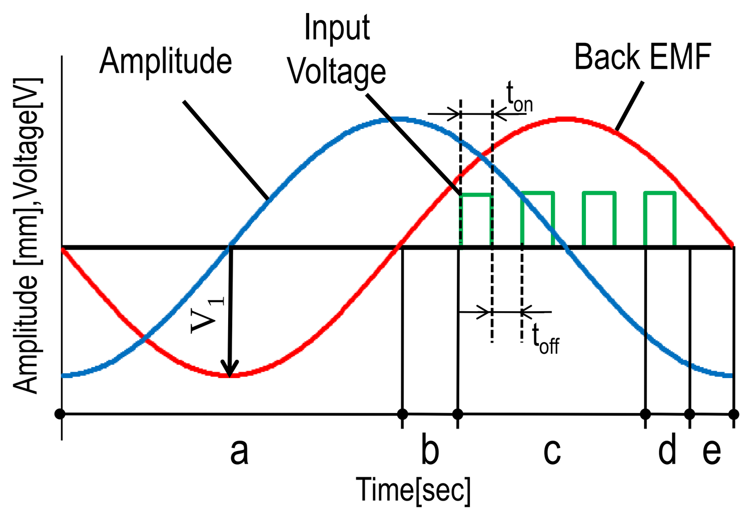


FEM model

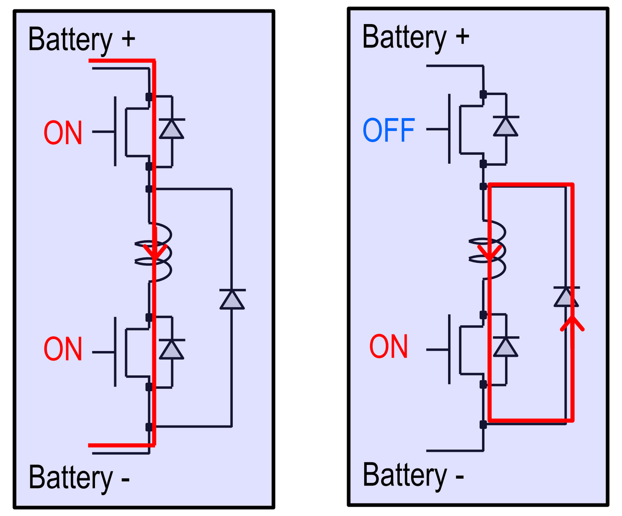
Discretization date and CPU time

Number of elements	668,934
Number of edges	792,175
Number of unknown variables	768,815
Number of steps	1,300
Time division [μsec]	10
CPU time [h]	300
Computer used : Core2 Duo 3.0GHz PC	

PWM Feedback Control



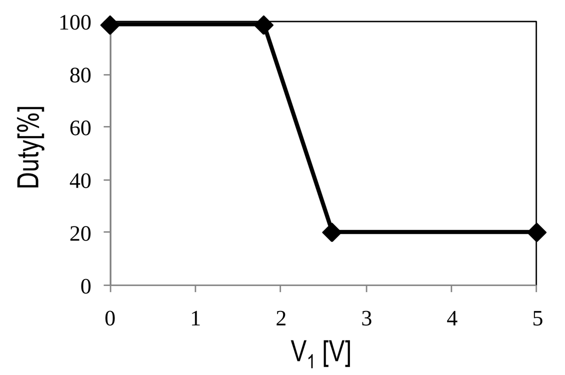
PWM feedback control



c: Excitation mode d: Circulation mode

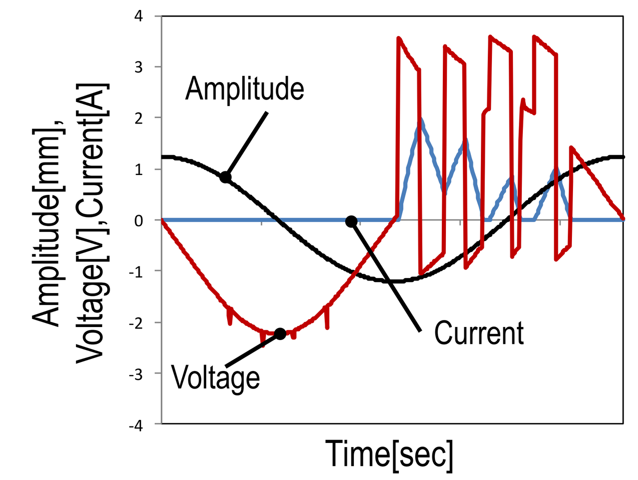
a: Voltage sensing mode
The coil detects the maximum value of back EMF V_1 after the back EMF is reduced to zero.
b: Delay mode
The coil is excited with a delayed time.
c: Excitation mode
The coil is exited under PWM control.
d: Circulation mode
Current circulates through a diode.
e: Circuit opening mode

The duty is determined by control function using the back EMF V_1.

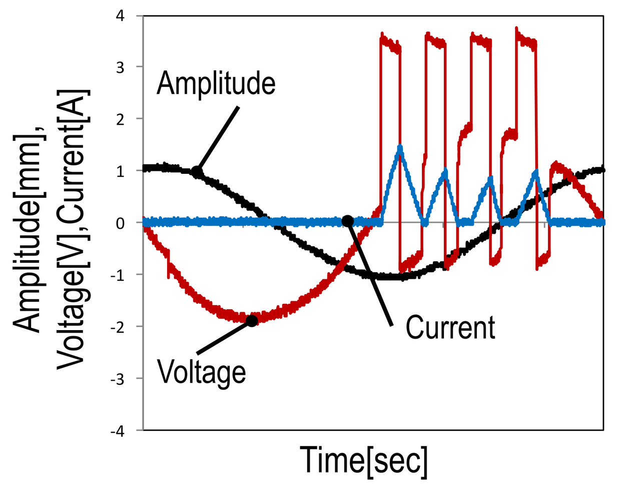


Control function

Analyzed Results

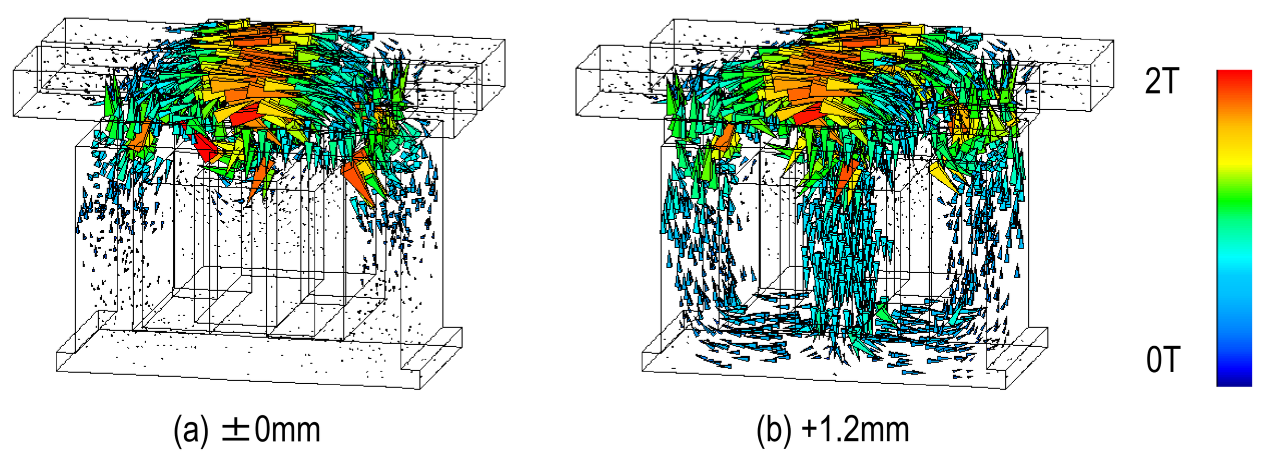


Computed results



Measured results

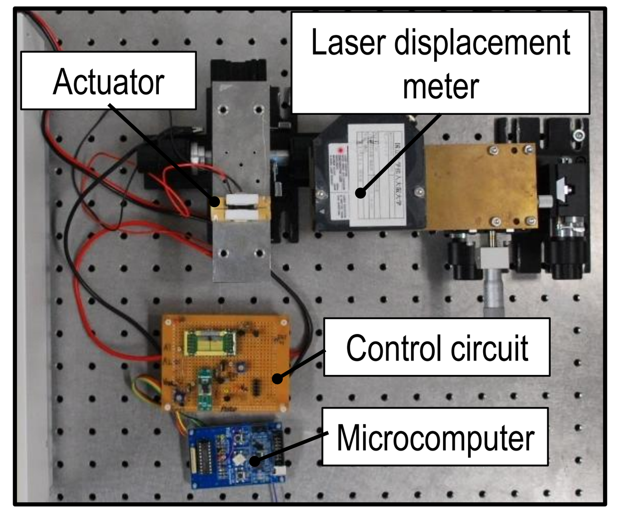
⇒Both results are well in good agreement.



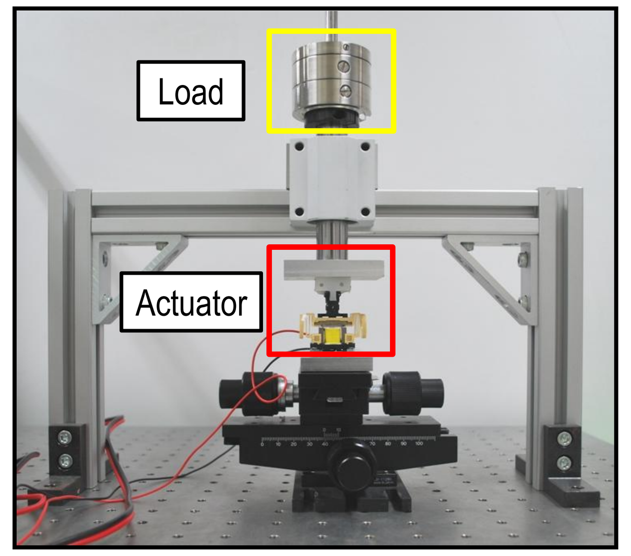
(a) ±0mm (b) +1.2mm

Distributions of magnetic flux density vectors

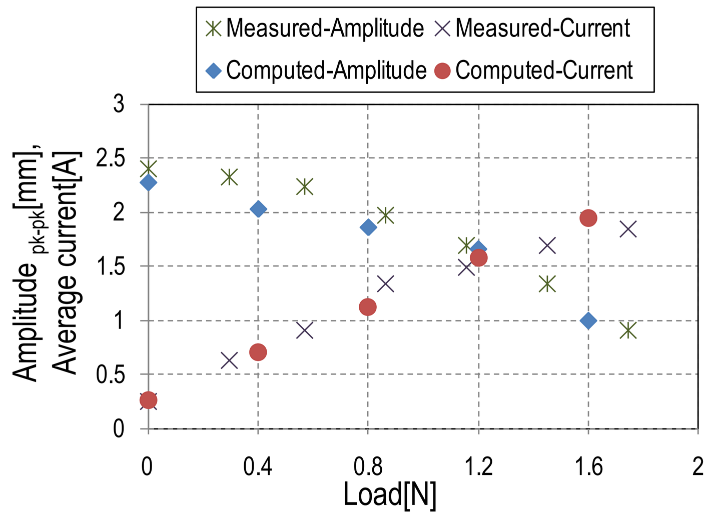
Load characteristics



Experimental setup



Load device



Load characteristics

⇒Both results are well in good agreement.
➢However, the amplitude measurably decreased against an external load under the control.

The more effective feedback control is investigated using PID control in PWM feedback control to keep the amplitude constant against an external load.

PID control

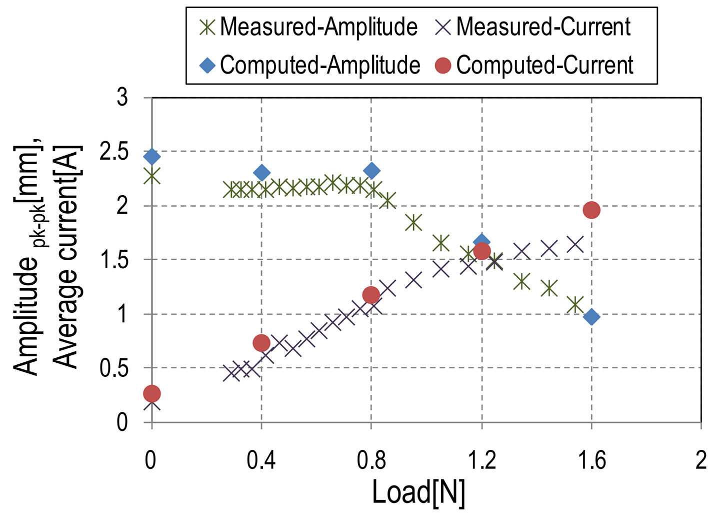
Under PWM feedback control, the coil is exited in interval (c) according to the duty. Here, the duty is determined by PID control using the back EMF V_1.

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

$$e(t) = V_S - V_1$$

K_P : The proportional gain
K_I : The integral gain
K_D : The differential gain
$e(t)$: The deviation
V_S : The target voltage

Each gain is decided by the analysis. $K_P = 1$, $K_I = 0.05$, $K_D = 0.5$



Load characteristic under PID control

⇒Both results are well in good agreement.
➢The amplitude is kept constant under the load of less than 0.8N by PID control.
➢Over the load of 0.8N, the amplitude decreases because its duty becomes nearly 100%.

Conclusion

➢A dynamic analysis method of the LRA under PID control in PWM feedback control by the back-EMF detecting from a coil was proposed employing the 3-D FEM.

➢The effectiveness of this method was shown by the comparison with the measured results of a prototype.

➢The effectiveness of the feedback control using PID control was clarified.