EM8

APSAEM 2018

Power-Saving Method of Linear Oscillatory Actuator for Mobile Haptic Device Using Mechanical Resonance

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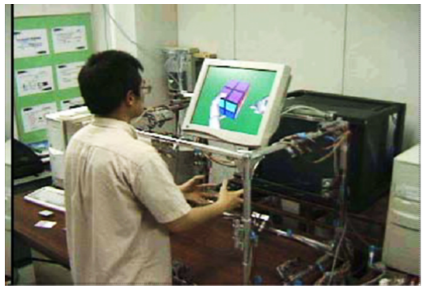
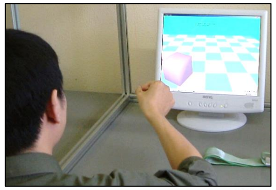
Contents

Background

What is Haptics?
- Tactile feedback technology that artificially reproduces the pulling or pushing sensation.



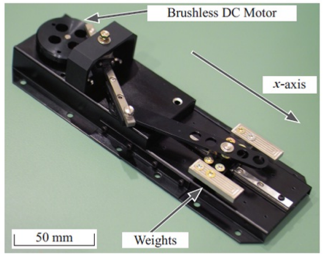
Grounded haptic device



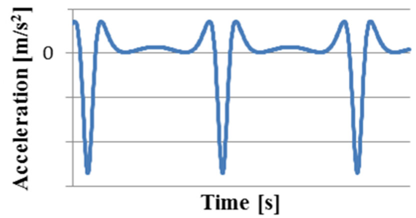
Computer game

Non-visual navigation

Mobile haptic device using slider-crank



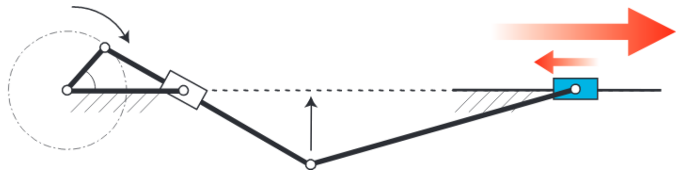
Slider-crank model (Amemiya, 2006)



Acceleration waveform

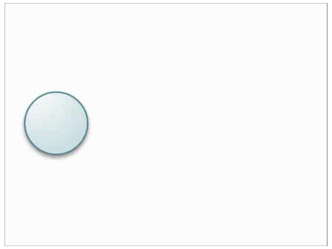
Input:
rotation at constant speed

Output:
asymmetric acceleration



Asymmetric acceleration is simply generated by slider-crank mechanism.

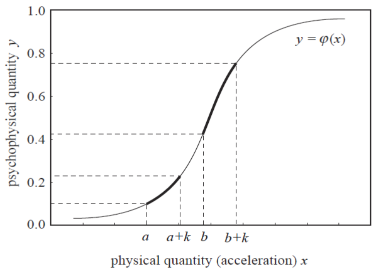
Asymmetric acceleration



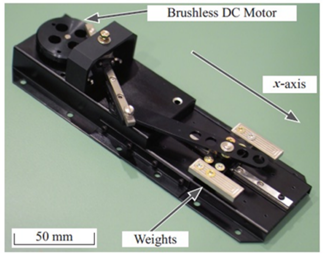
Symmetric acceleration
Feel both forces

Asymmetric acceleration
Feel only right force

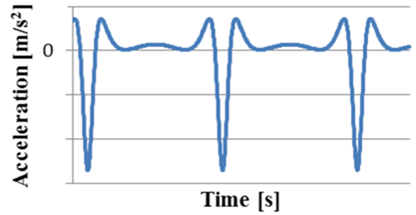
Human perception is not linear.
Only large acceleration can be perceived.



Disadvantage of slider-crank model



Slider-crank model

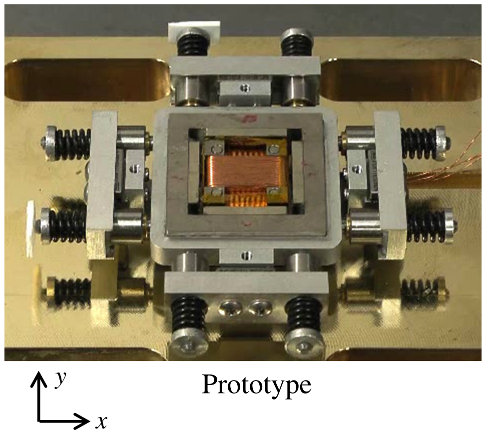


Acceleration waveform

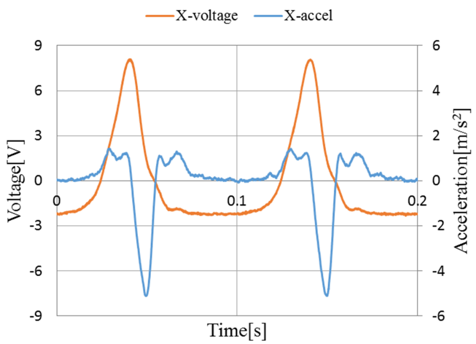
Disadvantage

- Large size for mobile application (70mm*200mm*48mm)
- One-DOF force

2-DOF oscillatory actuator



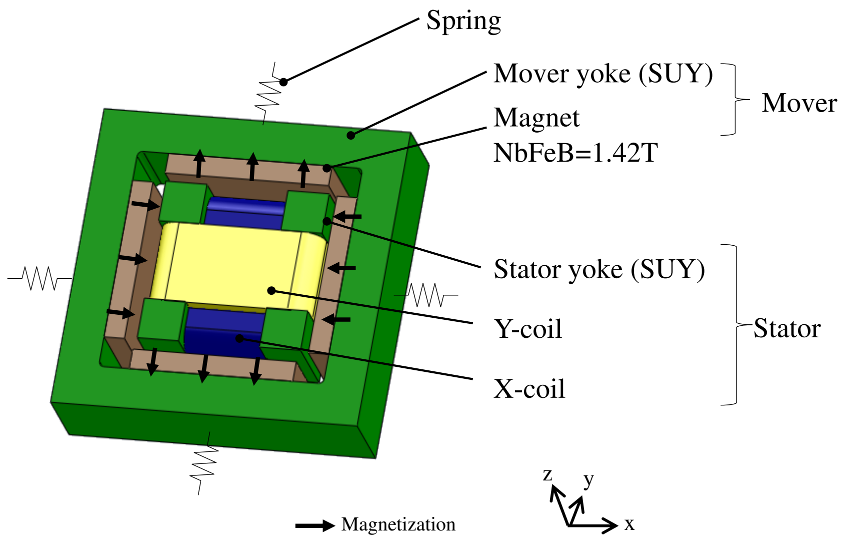
Prototype



Measured result
Power consumption: 1.7W
Acceleration peak: 5.1m/s²

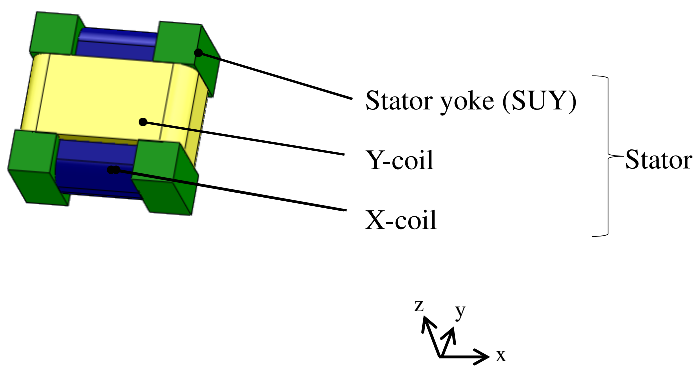
- Small size (80mm*80mm*15mm)
- Haptic perception in two direction
- Wide range of acceleration waveforms

Basic structure



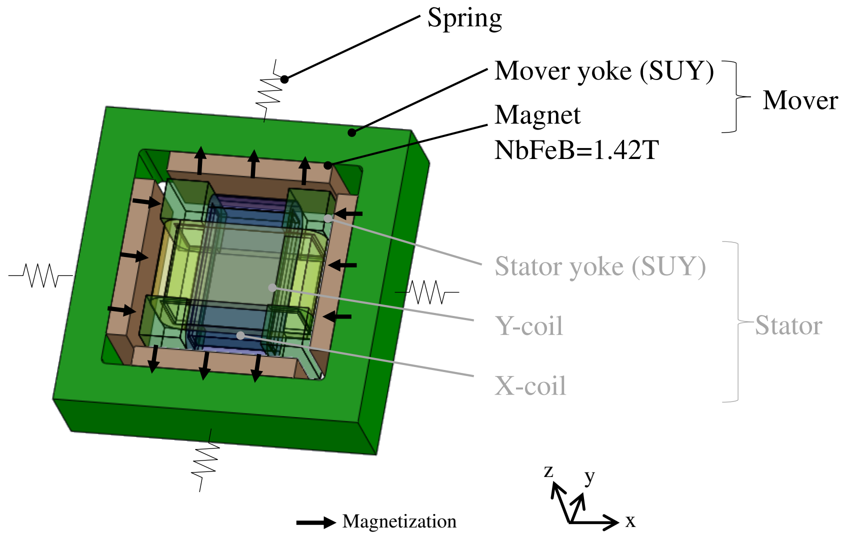
Cross section X-Y

Basic structure



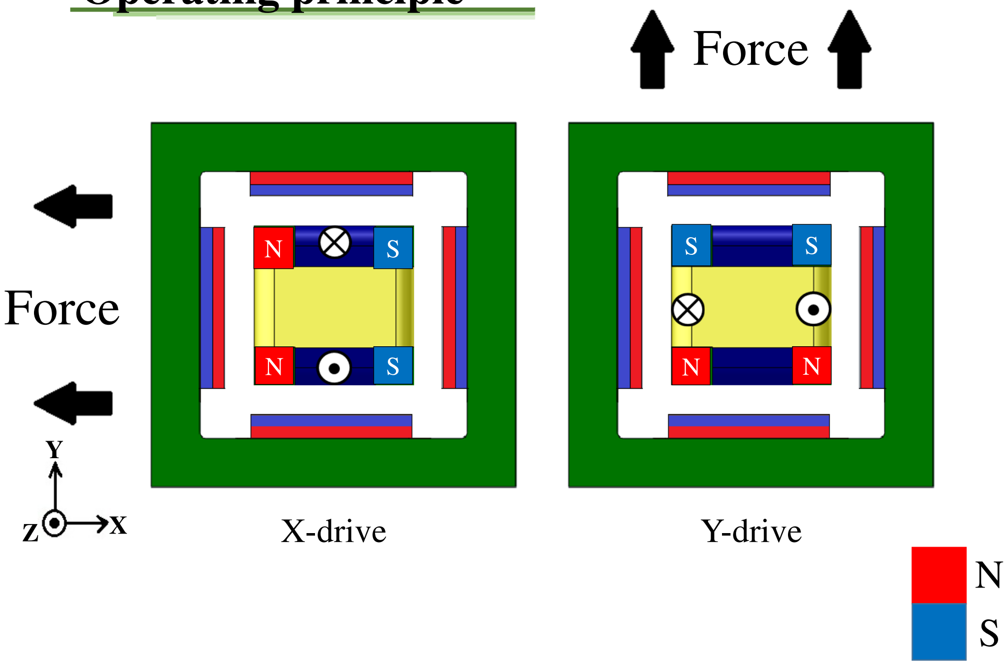
Cross section X-Y

Basic structure

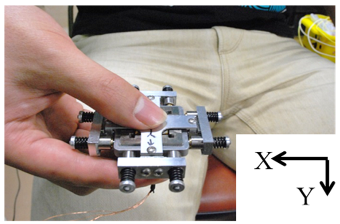


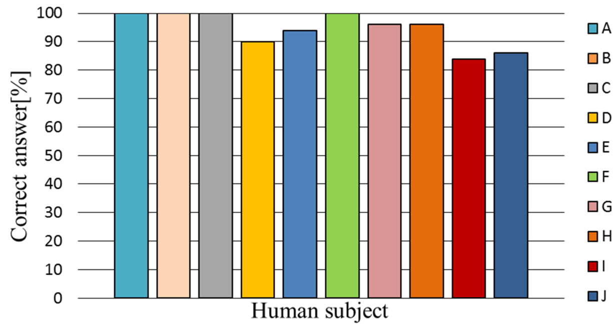
Cross section X-Y

Operating principle



Subject experiment





Procedure of experiment

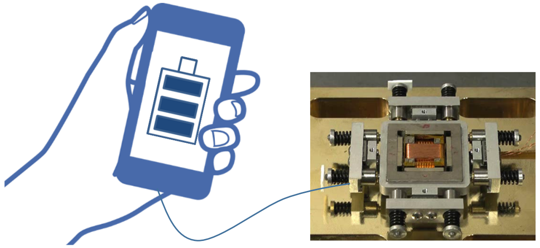
1. Subjects were blindfolded and covered their ears with headphones

2. I drove actuator in **four directions**, left, right, front and back, selected at random.

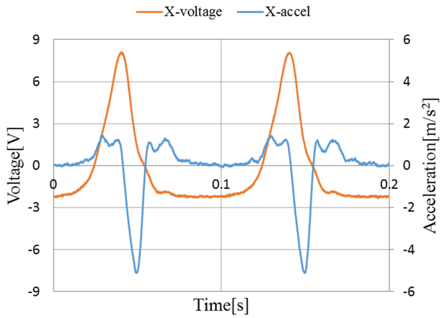
3. After each turn, they indicated the direction that they felt.

- Average correct answer: 94.6%
- Probability for random answer: 25%

For practical use



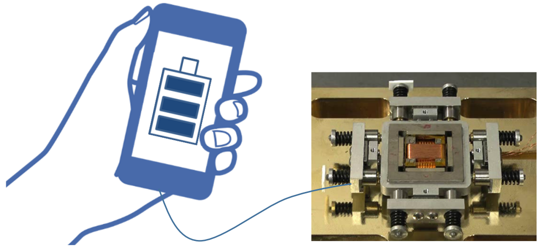
Supplied from a battery



Measured result
Power consumption: 1.7W
Acceleration peak: 5.1m/s^2

The continuous operating time was estimated to be about **5 hours** when we assumed that a certain battery supplied the power.
→It is not sufficient for using our actuator practically

Purpose and approach



Supplied from a battery

- Purpose

Proposal of power-saving method of 2-DOF oscillatory actuator for mobile haptic device

- Approach

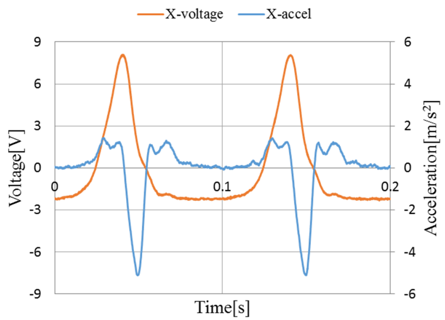
Use of mechanical resonance

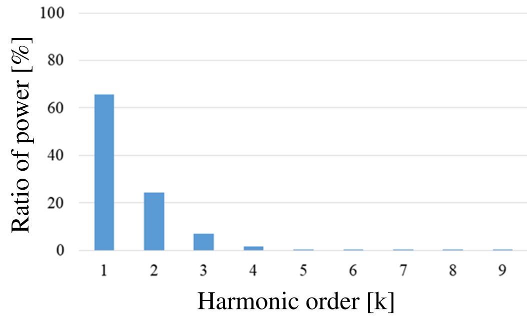
Contents

- Background and Purpose
- **Power-Saving Method Using Mechanical Resonance**
- Conclusion

Power consumption at each component

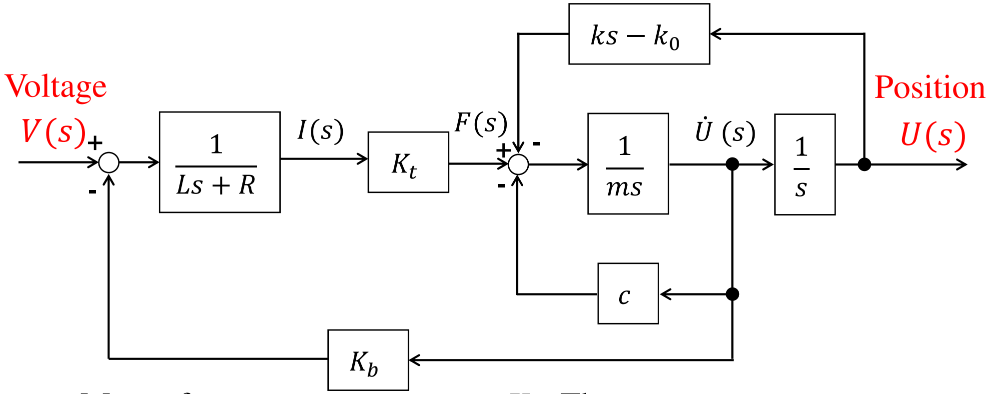
$$a(t) = \sum_{k=1}^{N} a_k \cos(2\pi f k t)$$





Effective power consumption at each component is investigated
→First-order component (10Hz) is dominant and the percentage is 65
→The power is saved significantly if our actuator resonates at 10Hz (Conventional: about 120Hz)

Block diagram of actuator



m: Mass of mover
c : Viscous damping coefficient
k_s : Mechanical spring constant
k_0 : Detent spring constant
K_t : Thrust constant
R: Coil resistance
L : Coil Inductance
K_b: back-EMF constant

We can determine a new spring constant value from transfer function

Transfer function

Circuit equation

$$V_i = R_i I_i + L_i \frac{dI_i}{dt} + K_{bi} \frac{dU_i}{dt}$$

Motion equation

$$k_{0i} U_i + K_{ti} I_i = m_i \frac{d^2 U_i}{dt^2} + c_i \frac{dU_i}{dt} + k_{si} U_i$$

Transfer function (s domain)

$$G_i(s) = \frac{U_i(s)}{V_i(s)} = \frac{K_{ti}}{A_1 s^3 + A_2 s^2 + A_3 s + A_4}$$

m: Mass of mover
c : Viscous damping coefficient
k_s : Mechanical spring constant
k_0 : Detent spring constant
K_t : Thrust constant
R: Coil resistance
L : Coil Inductance
K_b: Back-EMF constant
i: Operational direction (x and y)

$$A_1 = m_i L_i$$

$$A_2 = m_i R_i + c_i L_i$$

$$A_3 = c_i R_i + (k_{si} - k_{0i}) L_i + K_{ti} K_{bi}$$

$$A_4 = k_{si} - k_{0i}$$

Calculation of spring constant

$s = j\omega$

Transfer function (frequency domain)

$$U_i(\omega_i) = \frac{K_{ti}}{\sqrt{(A_4 R_i - A_2 \omega_i^2)^2 + (A_3 - A_1 \omega_i^2)^2 \omega_i^2}} V_i(\omega_i)$$

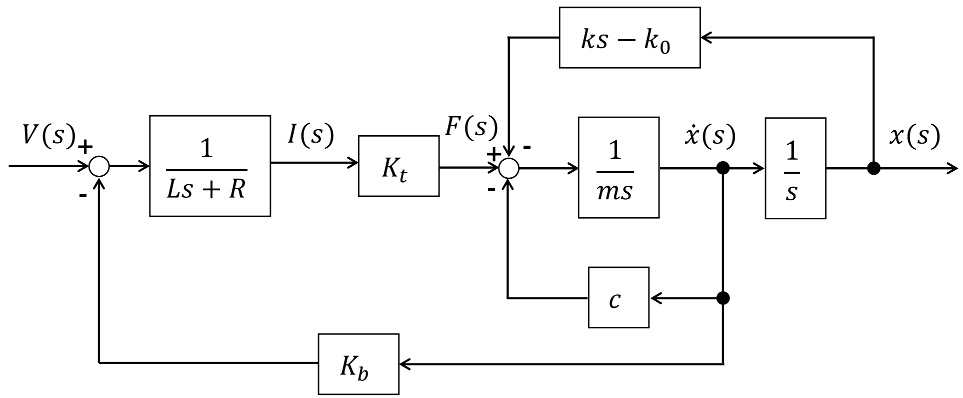
$$\varphi_i(\omega_i) = -\tan^{-1}\left(\frac{(A_3 - A_1 \omega_i^2)}{A_4 R_i - A_2 \omega_i^2} \omega_i\right)$$

Equation for obtaining resonant frequency ω_r

$$\frac{dU}{d\omega} = \begin{bmatrix} 6m^2 L^2 \\ 4(cL+mR)^2 - 8mL(cR+(k_s-k_0)L+K_t K_b) \\ 2(cR+(k_s-k_0)L+K_t K_b)^2 - 4R(cL+mR)(k_s-k_0) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \omega^4 \\ \omega^2 \\ \omega^0 \end{bmatrix} = 0$$

The spring constant is determined from this quartic equation

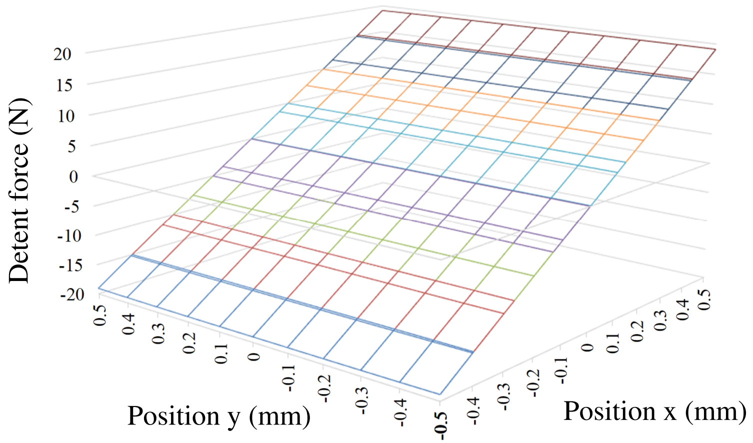
Block diagram of actuator

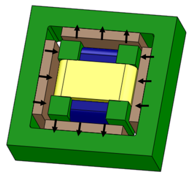


m: Mass of mover
c : Viscous damping coefficient
k_s : Mechanical spring constant
k_0 : Detent spring constant
K_t : Thrust constant
R: Coil resistance
L : Coil Inductance
K_b: back-EMF constant

These parameters must be obtained from finite element analysis

Computed results (Detent)

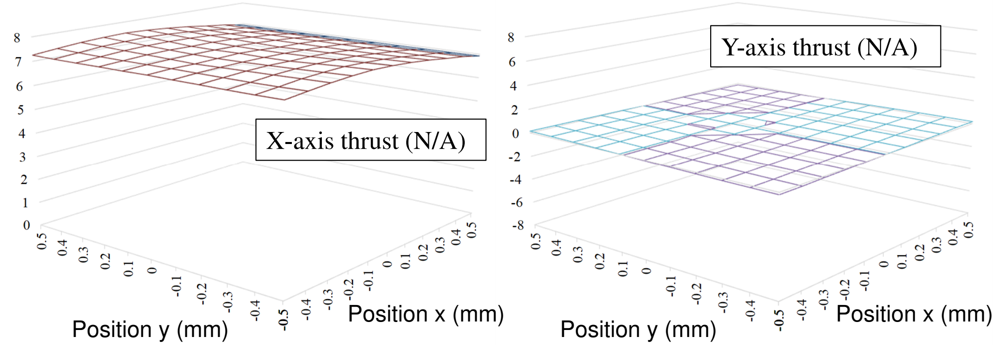




- proportional to x-axis displacement
- independent on y-axis displacement
- unstable at center position

$k_0 \simeq 38.0\text{N/mm}$

Computed results (Thrust constant)



$K_t \simeq 7.3\text{N/A}$

- almost constant with respect to x and y displacements
- little mutual thrust interference between x and y

Frequency response

Parameters

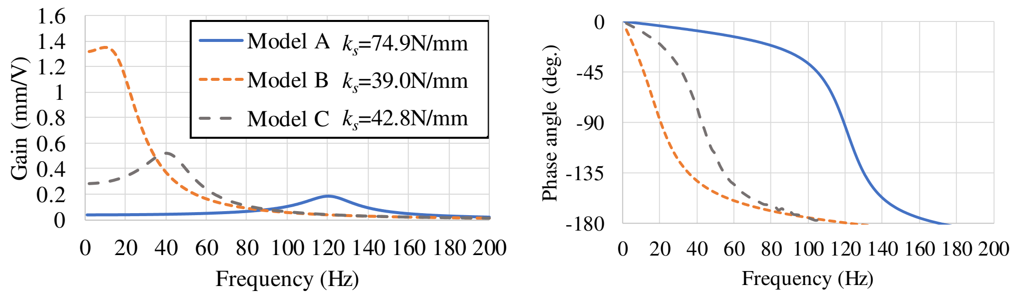
m	Mass of mover [g]	64.5
c	Viscous damping coefficient [Ns/m]	5
k_0	Detent spring constant [N/mm]	38
K_t	Thrust constant [N/A]	7.3
L	Coil inductance [mH]	1.3
K_b	Back-EMF constant [Vs/m]	3.6

Equation for obtaining resonant frequency ω_r

$$\begin{bmatrix} 6m^2L^2 \\ 4(cL+mR)^2 - 8mL(cR+(k_s-k_0)L+K_tK_b) \\ 2(cR+(k_s-k_0)L+K_tK_b)^2 - 4R(cL+mR)(k_s-k_0) \end{bmatrix}^T \begin{bmatrix} \omega_r^4 \\ \omega_r^2 \\ \omega_r^0 \end{bmatrix} = 0$$

New spring constant = 39.0 N/mm

Frequency characteristic



Resonant frequency

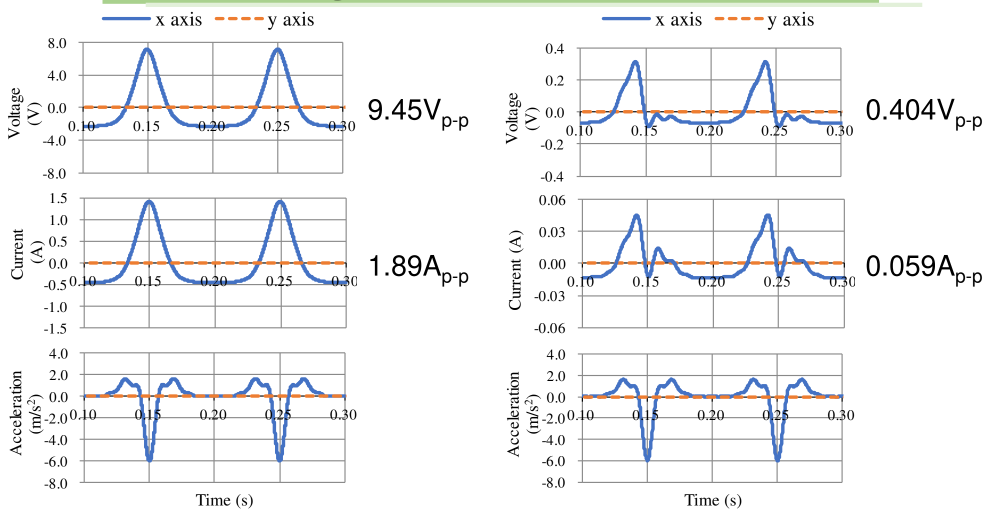
Model A (74.9N/mm) : about 120Hz

Model B (39.0N/mm) : about 10Hz (correspond to 1st component)

Model C (42.8N/mm) : about 40Hz (correspond to 4th component)

↑ to distinguish the effect of softer spring from resonance

Effect of using resonance

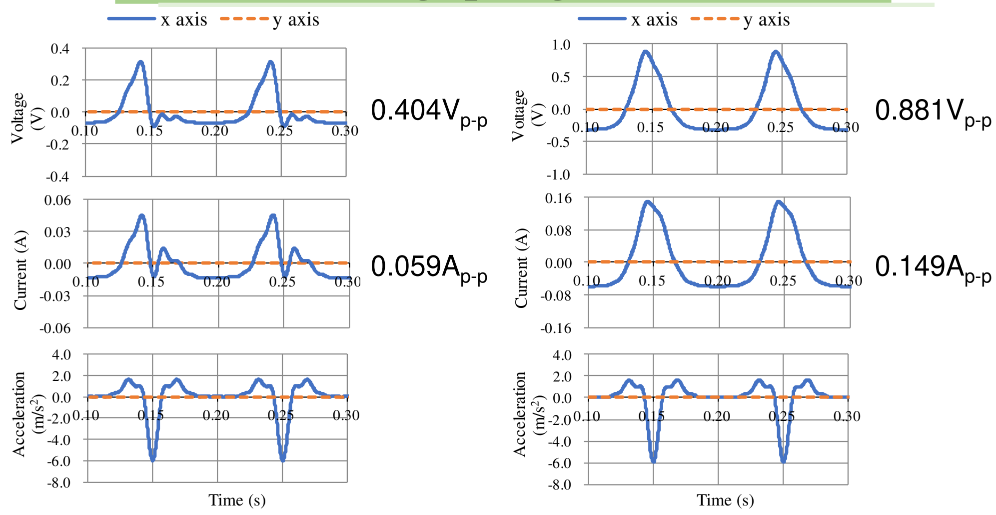


Model A (k_s=74.9N/mm) **Model B (k_s=39.0N/mm)**

Power consumption : 1.7W → 1.3mW

The effectiveness of the power-saving method is confirmed

Effect of softening spring

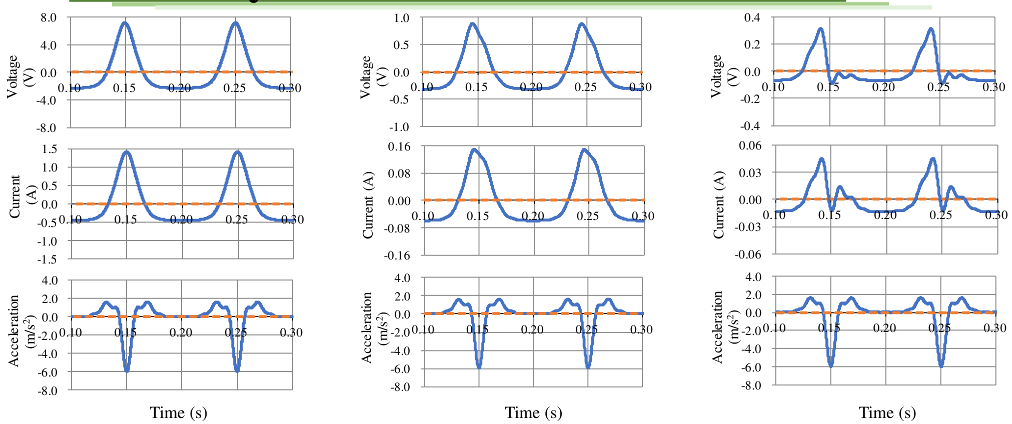


Model B (k_s=39.0N/mm) **Model C (k_s=42.8N/mm)**

Power consumption : 1.3mW → 25mW

Using resonance is more important than softening spring

Summary



Model A
(k_s=74.9N/mm)
Resonate at 120Hz
Power: **1.7W**

>

Model C
(k_s=42.8N/mm)
Resonate at 40Hz
Power: **25mW**

>

Model B
(k_s=39.0N/mm)
Resonate at **10Hz**
Power: **1.3mW**

Resonating at 1st order (10Hz) decreased power consumption by 99%

Conclusion

Purpose

- Proposal of power-saving method of 2-DOF oscillatory actuator

Approach

- Power consumption at each component was investigated
- The first-order component (10Hz) was dominant
- A new spring constant value was determined from a quartic equation based on a transfer function of the actuator

Achievement

- Using mechanical resonance at 10Hz contributed to reducing the power consumption (1.7W → 1.3mW)