Self-powered active vibration control

Introduction

Active vibration control
Merit:
Better suppression performance and ride quality.
Drawback:
Power consumption.

Proposed system

We proposed a self-powered active vibration control, which regenerates energy from vibration, accumulate it, and use it for active control to suppress the vibration. This system can carry out the active control without a power source.

Power consumption

Force produced by the actuator $f$ when the power source whose voltage is $e$ is connected is written as

$$f = \phi \frac{e - \phi \dot{z}}{r}.$$  

To obtain the desired force $f^*$, the voltage $e$ should be

$$e = \frac{r f^*}{\phi} + \phi \dot{z}.$$  

Then the power consumption $E_c$ is given by

$$E_c = e i = \left( \frac{1}{c_{el}} f^2 + f \dot{z} \right).$$

It is transformed into a quadric form:

$$E_c = c_{el} \dot{z}^2 \gamma (\gamma - 1), \text{ where } \gamma = \frac{f}{-c_{el} \dot{z}}.$$  

Flow of the energy

Electromagnetic actuator

The following picture shows one of prototypes of an electromagnetic actuator, which can be installed inside suspensions of automobiles.

Induced voltage $= -\phi \dot{z}$.  
Output force $= \phi i$.  

Electrical damping coefficient: $c_{el} = \frac{\phi^2}{r}$  
$r$: resistance

K.Nakano Lab, Institute of Industrial Science, University of Tokyo
Energy Balance

Modeling
We examine feasibility of the proposed control when we apply it to two-degree-of-freedom system. The equation of motion is derived as follows:
\[
\ddot{x}_1 + 2 \cdot \omega_1 \cdot \zeta_1 \cdot \dot{x}_1 + \omega_1^2 \cdot x_1 = \mu \cdot \omega_2^2 \cdot z_a - f_a + \frac{f_0}{m_1} + \frac{f_0}{m_1}
\]
\[
\ddot{z}_a + \omega_2^2 \cdot z_a = \frac{f_a}{m_2}
\]
where
\[
z_a = x_2 - x_1 \cdot \omega_1 = \sqrt{k_1 \cdot m_1}
\]
\[
\omega_2 = \sqrt{k_2 \cdot m_2}
\]
\[
\zeta_1 = \frac{c_1}{2 \cdot \sqrt{k_1 \cdot m_1}}
\]
\[
\mu = \frac{m_2}{m_1}
\]

Skyhook control
Skyhook control is carried out by the actuator, that is, the force produced by the actuator is given by
\[
f_a = -c_{sky} \cdot \ddot{x}_2
\]
\[
= -2m_2 \omega_2 \zeta_{sky} \ddot{x}_2
\]
where
\[
\zeta_{sky} = \frac{c_{sky}}{2 \cdot \sqrt{k_2 \cdot m_2}}
\]

Consumed power
The mean value of the power consumed by the actuator is obtained by
\[
\bar{E}_c = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^\tau \left( \frac{1}{c_{el}} \cdot f_a^2 + f_a \cdot \dot{z}_a \right) dt
\]
\[
= \frac{1}{\tau} \int_{-\infty}^{\infty} \varepsilon_c(\omega) \cdot P_0(\omega) \, d\omega
\]
\[
\varepsilon_c(\omega) = \left( \frac{1}{c_{el}} \cdot G_{f_0}(\omega) + G_{f_0}(\omega) \cdot G_{z_a}(\omega) \cdot \cos(\Phi_{f_0}(\omega) - \Phi_{z_a}(\omega)) \right)
\]
when we define \( \dot{\omega} = \frac{\omega}{\omega_2}, \)
\( n = \frac{c_{sky}}{c_{ela}}, \)
\( \varepsilon_c \) is written as
\[
\varepsilon_c(\omega) = 2 \cdot m_2 \cdot \omega_2 \cdot \zeta_{sky} \cdot G_{s_2/f_0}(\omega) \cdot \left(n - \dot{\omega}^2\right)
\]

Experimental setup
Upper and lower mass: 1.6 kg
Damping ratio of the upper and the lower suspension: 0.3, 0.0
Electric damping ratio of the actuator: 0.23

Result: Power consumptions
Left and right graph show the power consumption when \( n=1 \) (mean is -0.5mW) and power provided by the input force \( f_0 \) (mean is 68.0mW) to the suspension, respectively.

Contour plot
Lateral and vertical axes represent the equivalent damping ratio of the actuator and feedback gain ratio \( n \), respectively. Values written in the figure indicate the non-dimensional power consumption, which is obtained by dividing the consumed power by the power provided by the input force \( f_0 \). The area where the power consumption becomes negative indicates the condition where the self-powered active control is feasible.
Realization of SP control

Electric circuit

Regenerative Mode (a)

Regenerative Mode (b)

Brake Mode

Drive Mode

(a) induced voltage > capacitor voltage

(b) induced voltage < capacitor voltage

Experimental results

When $n=0.8$

Control input

Conclusion

Through numerical calculations and experiments, it is found the self-powered active control is feasible and its performance is similar to a typical active control using an external power source.
Self-powered active control using a piezoelectric actuator

**Background**
A piezoelectric transducer has become a popular actuator to control a structural vibration. Using the piezoelectric transducer, we can make a distributed actuator system, which is effective for the vibration suppression, however it needs power sources. Then we propose to solve the problem with self-powered active control.

**Objectives**
1. To derive governing equations expressing dynamics of mechanical and electrical systems and an equation to estimate the power balance between the consumed and the generated power.
2. To examine the suppression performance and the power balance of the active controller.
3. To examine the feasibility of the self-powered active control system achieved by the piezoelectric transducer.

**Plant and active controller**
Assuming the point force is disturbance, we consider a simply supported beam where the piezoelectric transducer is installed to suppress the lateral vibration.

The moment produced by the transducer is

\[ M(y) = -f_i \frac{H(y - p_i) - H(y - p_i - L_i)}{2} \]

where \( H(y) = \begin{cases} 1, & y > 0; \\ 0, & y < 0. \end{cases} \)

The active controller is obtained using optimal control scheme.

**Self-powered active control**
The power consumption of the transducer is obtained by the product of the electric current and the voltage of the power source. This fluctuates and can become less than zero, which means the control system generates power. In the self-powered system, it generates and accumulates energy when the power consumption is negative, while consumes energy when the power consumption is positive. When the average power consumption is less than 0, the active control without the supplied power is feasible.

\[
\bar{P} = \lim_{T \to \infty} \frac{1}{T} \int_0^T i u \, dt \\
= \int_0^\infty G_i(\omega) G_u(\omega) \cos[\Phi(\omega)] \, d\omega
\]

where \( G_i(\omega) \), \( G_u(\omega) \) and \( \Phi(\omega) \) are the gains of the electric current, the control input, that is the supplied voltage, and the phase difference between \( i \) and \( u \), respectively.

**Numerical analysis**
The frequency response of the maximum beam deflection of the third mode is illustrated on the left figure. The active control system has better suppression performance than the system without control and the optimally tuned shunt system. The mean values of the power consumed for the several normalized frequencies are shown on the right figure. The consumed power becomes less than zero in all frequency range near the third natural frequency.

**Experiment**
The photograph of the experimental setup is shown below:

The following figure on the left shows the normalized lateral accelerations when we input the impulse force. The normalized accelerations were obtained by dividing the measured acceleration by the amplitude of the input force. The active control system has better suppression performance.

The following figure on the right shows the consumed power. It is clear the average power consumption becomes less than zero. The total energy consumed during the period is -0.34 mJ, which shows the self-powered active control is feasible.

**Conclusion**
1. Through the numerical simulation and the experiment in 3rd mode, it is found that the active controller can achieve better suppression performance than a passive system under condition where the amount of the generated power exceeds that consumed.
2. These results indicate the proposed system is feasible from the perspective of the power balance.