MASS SENSING UTILIZING SENSORLESS SELF-EXCITATION OF PIEZOELECTRIC DEVICE

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Abstract

We propose a method to produce the self-excitation in an oscillator actuated by a piezoelectric devise without sensor. In general, the positive feedback with respect to the velocity of an oscillator, which is a cantilever in this study, can produce the self-excitation. Considering the electrical dynamics of the piezoelectric device for the self-excitation, the entire system can be regarded as a third order system. Then, utilizing a coupling effect between the mechanical and electrical systems through the piezoelectric effect, we can produce the self-excitation without the velocity information of the oscillator, namely, by sensorless. We drive the piezoelectric device by the current consisting of the proportional to the linear combination of the voltage across the terminals of the piezoelectric device and its differential voltage signal: the coefficients of the linear coupled signal correspond to the feedback gains. Appropriate feedback gains can locate the eigenvalues at the set of one negative real root and a pair of conjugate complex roots with a positive real part, and the self-excitation can be produced. To confirm the validity of the proposed method, we demonstrated experiments of the sensorless self-excitation and showed the efficiency on the mass sensing using a macrocantilever with the piezoelectric device.

Key words

Self-excitation, Sensorless, Piezoelectric device, Cantilever, Mass sensing

1 Introduction

Many sensors and actuators utilizing the external excitation have been developed in recent years. Vibrational sensors measure the mechanical properties (mass, stiffness, surface shape, etc.) of measurement objects from the natural frequency shift of an oscillator [Wang, Chatani, Ikehara, and Maeda, 2012]. A cantilever to which a piezoelectric device is attached is widely utilized as the oscillator in the vibrational sensor. On the other hand, many vibrational actuators utilizing the resonant energy of the oscillator have been developed [Dei, Kasagawa, Ashida, Yabuno, Fujisawa and Kuroda, 2015]. However, in the vibrational sensor utilizing the external excitation, the sensing precision is degraded under a high viscosity environment (such as in a liquid), whereas in the vibrational actuator utilizing it, the actuating efficiency is degraded because the resonant state can not be maintained due to the natural frequency shift depending on the contact with an actuated object. In contrast, the application of the self-excitation which can always maintain the resonant state in the natural frequency has attracted a lot of attention [Batako, Babitsky and Halliwell, 2003].

In general, the application of the positive feedback with respect to the velocity of the oscillator, which is derived by an optical sensor, is required for producing the self-excitation [Malas and Chatterjee, 2014]. When the self-excitation system is down-sized for the application to the nano sensing and actuating, since the irradiation adjustment of the optical sensor is very severe, the conventional self-excitation method utilizing the sensor feedback is not suitable for the nano sensing and actuating. A self-sensing method which serves the actuator and the sensor in the single piezoelectric device is useful for such purposes. However, to the best of our knowledge, there does not exist the self-sensing method for the piezoelectric device to produce the sensorless self-excitation. For an electromagnetic device, a sensnorless self-excitation method has been proposed [Mori, Kurita and Matsumura, 2001]. However, this method cannot be applicable directly in the self-excitation of the piezoelectric device because a governing equation of the electromagnetic system is different from that of the piezoelectric system and there is a duality in each of them [Preumont, 2006].

In the present paper, we theoretically propose a sensorless self-excitation method to produce the self-excited oscillation in the cantilever. Moreover, we manufacture the sensorless self-excitation system for a macrocantilever based on the proposed method, and perform a experiment to assess the validity of the proposed method. Finally, as an example of applications, we show that the proposed method is useful for the mass sensing.

2 Analytical proposition of sensorless self-excitation method of cantilever with piezoelectric device

We product the sensorless self-excitation by utilizing the voltage across the terminals of the piezoelectric device instead of the velocity information of the cantilever. The equation of motion of the cantilever and the circuit equation of the current in the piezoelectric device are derived as

$$
\begin{aligned}
&m\ddot{a}_1 + c\dot{a}_1 + ka_1 = -\psi V,\\
&C_p\dot{V} = \psi\dot{a}_1 + i,
\end{aligned}
\tag{1}
$$

where a_1 is the 1^{st} modal amplitude of the cantilever, V the voltage across the terminals of the piezoelectric device and i the current caused to flow to the piezoelectric device. m, c and k are the mass, the viscous damping, and the stiffness of the cantilever with piezoelectric device under the assumption that the cantilever oscillates in the 1^{st} mode, respectively. C_p is the capacitance of the piezoelectric device and ψ the electromechanical coupling coefficient between the cantilever and the piezoelectric device. Equation (1) constitutes the third order coupled system consisting of the mechanical system of the cantilever and the electrical system of the piezoelectric device. In order to realize the sensorless self-excitation, we input the feedback current

$$
i = \alpha V + \beta\dot{V},
\tag{2}
$$

to the terminal of the piezoelectric device (α and β are the feedback gains assigned arbitrarily). Then, setting the feedback gains α and β appropriately, we can change the dynamics of the third order coupled system to produce the self-excitation without sensors. Substituting Eq. (2) into Eq. (1) and nondimensionalizing it by utilizing the represent time $T = \sqrt{m/k}$, we derive

$$
\frac{d}{dt}\begin{bmatrix} a_1^* \\ \dot{a}_1^* \\ V^* \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & -\gamma & \tilde{\psi} \\ 0 & \tilde{K_a} & \tilde{\alpha} \end{bmatrix}\begin{bmatrix} a_1^* \\ \dot{a}_1^* \\ V^* \end{bmatrix},
\tag{3}
$$

where

$$
\begin{aligned}
&\gamma = \frac{c}{\sqrt{mk}}, \quad \tilde{\psi} = -\frac{\psi}{k},\\
&\tilde{\alpha} = \frac{\alpha}{C_p - \beta}\sqrt{\frac{m}{k}}, \quad \tilde{K_a} = \frac{\psi}{C_p - \beta}.
\end{aligned}
\tag{4}
$$

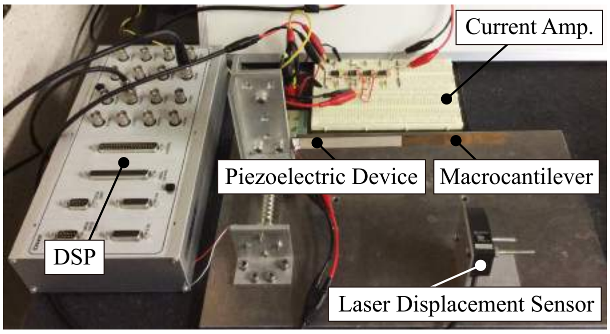

Figure 1. Picture of the experimental setup based on the theoretically proposed method

The eigenvalues of Eq. (3) governing the dynamics of the sensorless self-excitation system can be changed to produce the self-excitation by suitably setting the feedback gains α and β. For producing the self-excitation in the third order system, three eigenvalues must be one negative root and one pair of conjugate complex roots with the positive real part. In this study, utilizing the eigenvalue analysis such as the root locus method and Routh stability criterion, the conditions when this third order coupled system has such eigenvalues are derived as follows:

$$
\begin{aligned}
&\tilde{\alpha} < 0,\\
&1 - \frac{\gamma^2}{4} > \tilde{K_a}\tilde{\psi} > \gamma(2-\gamma),\\
&(-\tilde{\alpha} + \gamma)(1 - \tilde{\alpha}\gamma - \tilde{K_a}\tilde{\psi}) + \tilde{\alpha} < 0.
\end{aligned}
\tag{5}
$$

In other words, we showed theoretically that the sensorless self-excitation can be produced by setting the feedback gains α and β so that the self-excitation conditions (5) are satisfied.

3 Experiments

In order to verify the theoretically proposed method, we performed experiments by employing the macrocantilever with the piezoelectric device. Figure 1 shows a picture of the experimental setup. The experimental setup consists of the macrocantilever with the piezoelectric device, a DSP (Digital Signal Processor) and a current amplifier. The voltage across the terminals of the piezoelectric device V is transferred to the DSP. The DSP produces the linear combination of the voltage across the terminals of the piezoelectric device and its differential voltage signal. The current amplifier produces the current proportional to the preceding linear combination Eq. (2). Then, inputting the current to the terminal of the piezoelectric device, we realize the sensorless self-excitation in Fig 1. Note that a laser displacement sensor was not utilized for the production of the self-excitation, but for the observation of the oscillation.

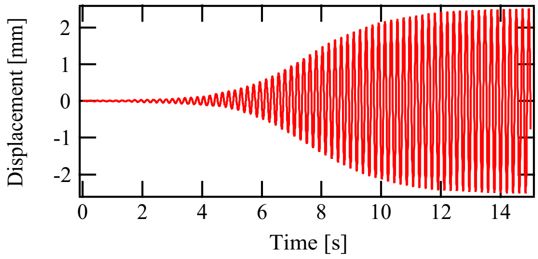

Figure 2. Time history of the displacement of the macrocantilever in the verification experiment

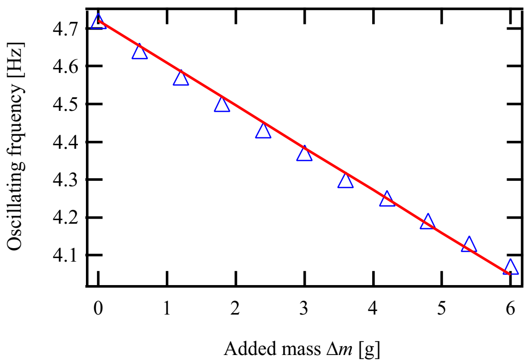

Figure 3. Relationship between the added mass and the oscillating frequency

Figure 2 shows the time history of the displacement of the macrocantilever in the case of setting the feedback gains α and β so that the self-excitation conditions Eq. (5) were satisfied. Then, the horizontal axes of Fig. 2 indicate time elapsed since the current feedback was inputted to the terminal of the piezoelectric device. This result shows that the sensorless self-excitation can be realized by setting the appropriate feedback gains which satisfy Eq. (5).

4 Mass sensing utilizing sensorless self-excitation

We assessed the usefulness of the proposed method as the vibrational sensor by adopting the vibrational mass sensor as one of an application example and performing the mass sensing by means of the sensorless self-excitation. In this experiment, we employed permanent magnets with the mass $0.3\mathrm{g}$ as the measurement object. 20 permanent magnets in total were added two by two so as to sandwich the macrocantilever from both sides. Then, we measured the oscillating frequency to the added mass. Figure 3 shows the relationship between the added mass and the oscillating frequency. The plots and the line in Fig. 3 show the experimental results and the regression line based on the least squares method to them. The slope of the regression line corresponds to the ratio of the natural frequency shift to the added mass, which is called the frequency sensitivity. In this experiment, we derived the frequency sensitivity as $-1.12 \times 10^2 \mathrm{Hz/kg}$. The sensorless self-excitation is useful for mass seining because the oscillating frequency monotonically varied as the added mass increased.

5 Conclusion

In the present paper, we propose the sensorless self-excitation method of the cantilever without sensor by utilizing the self-sensing method of the piezoelectric device. At first, we derived the sensorless self-excitation conditions theoretically by utilizing the eigenvalue analysis based on the root locus method and Routh stability criterion. In order to confirm the validity of the proposed method, we performed experiments of the sensorless self-excitation for the macrocantilever with the piezoelectric device. Moreover, we indicated that the proposed method is useful as the vibrational mass sensor by making a mass sensing experiment.

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