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Proposition for sensorless self-excitation by a piezoelectric device

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ABSTRACT

In this paper, we propose a method to realize self-excitation in an oscillator actuated by a piezoelectric device without a sensor. In general, the positive feedback associated with the oscillator velocity causes the self-excitation. Instead of measuring the velocity with a sensor, we utilize the electro-mechanical coupling effect in the oscillator and piezoelectric device. We drive the piezoelectric device with a current proportional to the linear combination of the voltage across the terminals of the piezoelectric device and its differential voltage signal. Then, the oscillator with the piezoelectric device behaves like a third-order system, which has three eigenvalues. The self-excitation can be realized because appropriate feedback gains can set two of the eigenvalues to be conjugate complex roots with a positive real part and the other eigenvalue to be a negative real root. To confirm the validity of the proposed method, we experimentally demonstrated the sensorless self-excitation and, as an application example, carried out mass sensing in a sensorless self-excited macrocantilever.

1. Introduction

In recent years, vibrations have been employed to enhance the performance of some machines. One example is resonant sensors, which measure mechanical properties (e.g., mass, stiffness, and surface shape) of objects from the natural frequency shift of an oscillator [1–5]. Vibrationally assisted cutting devices and transport devices utilize the resonant energy of the oscillator to improve energy efficiency [6–8]. External excitation has been widely employed as an excitation method in vibrationally assisted machines. In the resonant sensor, the natural frequency shift is estimated from the shift of an experimentally obtained frequency response curve. It is impossible to accurately measure the shift of the resonance peak in a high-viscosity environment because it is ambiguous or does not exist. Vibrationally assisted cutting devices and transport devices based on external excitation require operation at the resonant condition in which the excitation frequency is set at a value that approximates the natural frequency of the whole system. Hence, if the contact load between the device and the object (workpiece or cargo) varies, tuning of the excitation frequency of the oscillator is required to maintain the resonant state continuously.

To overcome the drawbacks of external excitation, the application of self-excitation to maintain the resonant state independent of a measuring environment or contact load has attracted a lot of attention. Okajima et al. [9] proposed a self-excitation method for atomic force microscopy, which is superior to others in that it can be used in high-viscosity environments, such as in liquids. Yabuno et al. [10] developed a viscometer for high-viscosity sensing by employing a self-excited disk oscillator. Babitsky et al. [11] proposed a self-excitation method for an ultrasonically assisted cutting device that can maintain the resonant state

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under variable conditions. Batako et al. [12] developed a percussive-rotary drill that utilizes the self-excitation caused by the friction between the drill bit and the bore hole.

In general, positive feedback with respect to the velocity of the oscillator, which is measured by an optical or piezoelectric sensor, is required for producing self-excitation [13,14]. Therefore, a vibrationally assisted machine based on self-excitation is complicated compared to one based on external excitation. When the self-excitation system is down-sized for application to nano sensing and machining, sensor adjustment becomes very difficult, so a self-excitation method not relying on any sensor is desirable. A self-sensing method that combines the actuator and sensor into a single piezoelectric device may be suitable for this purpose. Hagood et al. [15] proposed a sensorless damping method utilizing self-sensing of the piezoelectric device, which is shunted by passive electrical circuits. Kuiper et al. [16] proposed a sensorless damping method in a piezoelectric tube scanner for atomic force microscopy. Many of these studies proposed a sensorless damping method utilizing self-sensing for the piezoelectric device. Suresh et al. [17] developed a resonant mass sensor based on self-sensing in a piezoelectric device, but the mass sensor employed external excitation. To the best of our knowledge, no existing self-sensing piezoelectric device can produce sensorless self-excitation, although for an electromagnetic device, Mori et al. [18] proposed a sensorless self-excitation method; however, this method cannot be applied to piezoelectric devices because the governing equation of the electromagnetic system is different from that of the piezoelectric system, despite each having a duality.

In this paper, we theoretically propose a sensorless self-excitation method to produce self-excited oscillation in a cantilever using self-sensing in a piezoelectric device. Then, we fabricate a sensorless self-excitation system for a macrocantilever based on the proposed method and conduct experiments to assess the proposal's validity. Furthermore, to illustrate a potential application, we demonstrate mass sensing by a sensorless self-excited macrocantilever.

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

2.1. Dynamic analysis of cantilever with bimorph piezoelectric device

To clarify the sensorless self-excitation method proposed in Section 2.2, we first review the equation of motion of the cantilever with a bimorph piezoelectric device and the circuit equation in the piezoelectric device in accordance with [19]. Fig. 1 shows our analytical model for the cantilever with the bimorph piezoelectric device; the x and z axes are defined as the horizontal and vertical directions of the cantilever, respectively. The origin O of the x and z axes is defined as the neutral surface of the cantilever at the fixed end. The length, width, and thickness of the cantilever are defined as l, b, and $2h_2$, respectively. The width and the thickness of the piezoelectric device are defined as b and h_p, respectively. The piezoelectric device is attached between points s_1 and s_2 on the cantilever. The distance between the neutral surfaces of the cantilever and the piezoelectric device is expressed as z_m. The constitutive equations of the bimorph piezoelectric device are expressed as follows [19]:

$$D = e_{31}S + \epsilon^T(1 - k^2)E, \tag{1}$$

$$T = c^E S - e_{31}E, \tag{2}$$

where D is the electric displacement, E is the electric field, T is the stress, and S is the strain of the piezoelectric device. The coefficients of each term in Eqs. (1) and (2) are

$$e_{31} = \frac{d_{31}}{s^E}, \quad c^E = \frac{1}{s^E}, \quad k^2 = \frac{d_{31}^2}{s^E \epsilon^T}, \tag{3}$$

where ϵ^T is the dielectric constant of the piezoelectric device under constant stress, s^E is the compliance of the piezoelectric device when the electric field is constant, and d_{31} is the piezoelectric constant of the piezoelectric device. The flexure of the cantilever is expressed as the function $w(t, x)$ in terms of time t and the horizontal position of the cantilever x. By utilizing the distance between the neutral surfaces of the cantilever and the piezoelectric device z_m and the curvature of the cantilever w'', the strain of the piezoelectric device S is expressed as

$$S = -z_m w''. \tag{4}$$

Hereafter, the prime symbol denotes the derivative with respect to the horizontal position of the cantilever x. By substituting Eq. (4) into Eq. (1) and integrating the result with respect to the electrode area of the piezoelectric device, the electric charge in

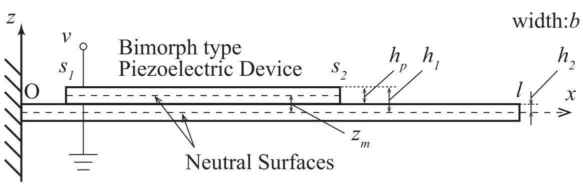

Fig. 1. Analytical model of cantilever with bimorph piezoelectric device.