Research on Self-Sensing and Self-Actuated Cantilever for Atomic Force Microscopy Probe*

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Abstract

Recently, considerable attention of material scientists and mechanical engineers has been devoted to measurement based on atomic force microscopy (AFM). Self-excitation is known to be an effective excitation method for AFM probe to measure the surface of a biological molecule in liquid. For practical use of a probe in liquid, we must realize a self-sensing and self-actuating AFM probe using PZT instead of using a conventional optical lever method. However, frequency characteristics of the PZT are very complex in applications for probe behavior measurement. For detecting sensor characteristics, the dynamics of the cantilever to which the PZT is attached are extracted from the PZT sensor output signal. To this end, we examine the frequency response of the PZT output signal in the case where the cantilever is excited with constant response amplitude using a PZT actuator. Then, we establish a method to process the signal so that the frequency characteristic of the PZT sensor has no high gain for the frequency range other than the first natural frequency. Finally, we conduct experiments to verify that the resultant signal is suitable to generate van der Pol-type self-excited oscillation.

Key words : Self-Excited Oscillation, Van der Pol, Self-Actuation, Self-Sensing, PZT Sensor, AFM, Cantilever Probe

1. Introduction

An AFM is an apparatus that observes the surface shape of a small object based on variations of the natural frequency and the amplitude using a micro cantilever probe. To date, AFM has been used mainly to measure the atomic arrangement of metal and semiconductor samples. In fact, AFM has become an indispensable technology to observe and evaluate various materials on a nanoscale⁽¹⁾. The application of AFM to observation of biological samples is especially anticipated. For example, AFM would be extremely useful to measure the structural and dynamical characteristics of protein and the stiffness of DNA⁽²⁾.

It is necessary to use the cantilever in a liquid for observation of biological samples in a nanoscale under physiological conditions. In such cases, when we measure a cantilever vibration, conventional optical measurement methods⁽²⁾ are difficult to use because of the reflection and refraction of the laser optical path. We propose a self-sensing cantilever that

Fig. 1 Experiment specimen

uses piezo-electric ceramics to overcome defects of conventional optical measurement methods in liquid⁽²⁾. In early studies of such a self-sensing and self-actuated cantilevers, Wan and Sanghun clarified that the self-sensing cantilever is applicable to a viscometer and a mass meter⁽³⁾⁽⁴⁾.

In those studies, the shift in the natural frequency is measured from the change in the position of the notch in the graph of the phase characteristic in the frequency response curve under the condition that the cantilever is excited externally⁽³⁾⁽⁴⁾. On the other hand, in the present study, AFM is presumed to be used in a liquid environment. Therefore, under the external excitation method described above, it is difficult to measure the natural frequency with high accuracy because the notch in the graph of the phase characteristic becomes shallow as a result of the high-viscosity effect. To overcome that difficulty, we propose application of the self-excited oscillation method to the self-sensing cantilever. The method simplifies measurements of the natural frequency, even under a high viscosity. However, an important characteristic is that the output signal from the self-sensing cantilever has a high gain in the frequency range apart from the natural frequency. We must process the output signal because the self-sensing methods used by Wan and Sanghun can not be used directly to obtain an output from the sensor that is suitable for self-excited oscillation.

On the other hand, in general, the amplitude of the self-excited oscillation increases with time. In such cases, the cantilever contacts with the sample, which can destroy the sample. The use of a van der Pol-type self-excited oscillation⁽⁵⁾ is proposed to overcome this problem. Van der Pol-type self-excited oscillation is well known to have a limit cycle and to oscillate with finite amplitude. In this study, we combine the self-sensing cantilever and the van der Pol-type self-excited oscillation. Subsequently, we develop a filter that specializes in the measurement of the self-excited oscillation. Finally, we confirm, experimentally, the occurrence of the van der Pol-type self-excited oscillation in the proposed self-sensing and self-actuated type cantilever. We then realize the steady-state small amplitude so that we can estimate the cantilever's natural frequency.

2. PZT sensor properties

2.1. Experiment specimen

For this study, the micro-cantilever is substituted with a macro beam to investigate basic characteristics of the self-sensing cantilever. Figure 1 portrays the macro beam structure. Two sets of piezo-electric ceramics (PZT) with a bimorph-type element are attached on the top and bottom of the macro beam, which is made from phosphor bronze. The macro beam dimensions are 80 mm length and 20 mm width, with 0.8 mm thickness; other characteristics are $E = 1.16 \times 10^{11} \text{ Pa}$ as the Young's modulus, and $\rho = 8890 \text{ kg/m}^3$ as its density. The piezo-electric ceramics (C-6; Fuji Ceramics Corp.) are 70 mm long, 20 mm wide, and 0.45 mm thick; also, $E_a = 5.80 \times 10^{10} \text{ Pa}$ is its Young's modulus, $d_{31} = 210 \times 10^{-12} \text{ m/V}$ is its piezo-electric constant. These piezo-electric ceramics, ranging from 5 mm to 80 mm, are attached from the fixed end on both sides of the macro beam. We use PZT on the top as an actuator, and measure the behavior of the beam by PZT on the bottom.

Fig. 2 Experimental setup

Fig. 3 Frequency response curve (input voltage amplitude, 91 V)

2.2. Preliminary experiment: a method of external excitation

Figure 2 shows the experimental setup. A sine wave is output from the function generator (FS-2201; TOA). A PZT driver (HJPZ-0.15B; Matsusada Precision Inc.) amplifies the input signal. A PZT actuator (C-6; Fuji Ceramics Corp.) is attached to the macro beam; the driver output signal is applied to the PZT actuator. Consequently, the macro beam is excited by the external force. A PZT sensor is attached to the macro beam, and the PZT sensor outputs the signal of the beam vibration. This output signal is analyzed using an FFT analyzer (DS-2100; Ono Sokki Co. Ltd.). Moreover, as a reference of the actual displacement, the displacement is measured simultaneously at the position of 45 mm from the fixed end of the macro beam using the laser displacement sensor (measurement accuracy, $0.02 \mu\text{m}$, LC-2430; Keyence Co.).

In addition, we describe (A) and (B) later because (A) is a part for a digital filter for signal processing and (B) is a part for the self-excited oscillation.

2.3. PZT sensor properties

First, to compare the output signal from the PZT sensor with the output signal from the laser displacement sensor; using a PZT actuator, we measured the cantilever behavior

Fig. 4 Block diagram from the actuator PZT to the sensor PZT

(a) Response amplitude of PZT sensor

(b) Phase difference between PZT sensor and displacement sensor

Fig. 5 Frequency response of the PZT sensor depending on the natural frequency of the beam (○, $\Delta m = 0$ g (natural frequency, 63 Hz); Δ , $\Delta m = 0.6$ g (natural frequency, 60 Hz))

(a) Response amplitude of PZT sensor

(b) Phase difference between PZT sensor and displacement sensor

Fig. 6 Frequency response of the PZT sensor in a higher frequency range

under external excitation. Figures 3(a) and 3(b) respectively show the response of the laser displacement sensor and that of the PZT sensor. The phase difference in Figs. 3(a) and 3(b) are those with respect to the input-signal for the external excitation. Furthermore, V_{laser} is the output amplitude of the laser displacement sensor; V_{PZT} is the PZT sensor output amplitude. The frequency response curve of the cantilever, shown in Fig. 3(a), is the usual resonance characteristic of a second-order system with one degree of freedom. On the other hand, the output from PZT sensor shown in Fig. 3(b) is different from that in Fig. 3(a) because the output signal from the PZT sensor includes the dynamics of the macro beam, the PZT actuator, and the PZT sensor in the case of the self-sensing and self-actuating cantilever, as shown in Fig. 1. Here, the only characteristics to measure are the PZT sensor dynamics, which are independent of the macro beam dynamics.

Let us consider a method of removing the effects of the dynamics of the macro beam and the PZT actuator using Fig. 4. In that equation, the following variables represent these values: V_{in} is the signal for external excitation; V_{laser} is the output signal from the laser displacement sensor; V'_{PZT} and V_{PZT} are the output signals from the PZT sensor; $G(s)$ represents the PZT actuator and the macro beam dynamics; and $F(s)$ represents the PZT sensor dynamics. Let us consider how to pick up the dynamics of $F(s)$. The output signal V_{PZT} from the PZT sensor includes the dynamics of $G(s)$. Therefore, the effect of $G(s)$ must be removed. Consequently, by multiplying with $1/G(s)$, the signal V'_{PZT} can be derived as a signal corresponding to $F(s)$.

Fig. 7 Frequency response of the PZT sensor properties after filtering
(o, $\Delta m = 0$ g; Δ , $\Delta m = 0.6$ g)

To this end, a sine wave is input into the PZT actuator from the function generator shown in Fig. 2 using the sine-sweep method. The excitation amplitude is adjusted so that the response amplitude from the laser displacement sensor is kept constant; then the output from the PZT sensor is measured. Figures 5 and 6 respectively depict experimental results in cases where the excitation frequency is near the first natural frequency and in the case when the excitation frequency is in a wider range. Here, V_{PZT} is the output amplitude of the PZT sensor. The phase difference is that of the PZT sensor to the laser displacement sensor. Figure 5 shows that the output from the PZT sensor takes a local minimum near the first natural frequency of the macro beam. The phase of the output from the PZT sensor advances to that of the laser displacement sensor. The output from the PZT sensor has a phase-lead of 90° to the output from the laser displacement sensor at the first natural frequency.

Moreover, experiments are carried out to investigate the characteristic in the case in which the natural frequency changes. In the experiments, by attaching the weight of $\Delta m = 0.6$ g to the tip of the macro beam, the natural frequency of the macro beam is shifted. Figure 5(a) shows that the lowest sensitivity point shifts according to the change of the natural frequency. In addition, the output from the PZT sensor has a phase lead of 90° to the output from the laser displacement sensor at the natural frequency as well as the case of $\Delta m = 0$ g. These results show that the PZT sensor output has a phase lead of 90° to the output from the laser displacement sensor at the position of the natural frequency, irrespective of the value of the natural frequency. The gain of the output from the PZT sensor has lowest sensitivity at the natural frequency, irrespective of the value of the natural frequency. However, it is possible to induce self-excited oscillation using the signal from the PZT sensor because the PZT sensor outputs a small but finite magnitude signal at the natural frequency. Figure 6 shows that the output from the PZT sensor has a peak near 200 Hz, but this frequency does not correspond to any natural frequency of the macro beam. Because of this peak, the self-excited oscillation at the first natural frequency fails. Therefore, to generate self-excited oscillation at the first natural frequency⁽⁵⁾, it is necessary to shape the frequency response of the PZT sensor to reduce the sensitivity of the PZT sensor at the peak near 200 Hz.

3. Filter design

A low-pass filter and a phase shifter are designed to generate self-excited oscillation with the cantilever at the first natural frequency. Figure 2 portrays the experimental setup

Fig. 8 Analytical model

used to evaluate the designed low-pass filter in panel (A). The analog output-signal from the PZT sensor is converted into a digital signal by the AD converter; then the digital signal is processed using a digital filter. The resultant digital signal is converted into an analog signal using the DA converter; then the analog signal is output. The frequency response characteristics of the output signal from the PZT sensor after filtering are presented in Fig. 7; the cutoff frequency is set to $f_c=70$ Hz and at least 500 dB attenuation is obtainable at $f_s=80$ Hz. On the other hand, the phase shifter is designed so that the phase shift becomes 0° at the first natural frequency of the cantilever. The digital filter is implemented with RTLinx on a personal computer. Figure 7(a) shows that the amplitude is reduced to a greater degree in the frequency range that is higher than the first natural frequency. The peak near 200 Hz becomes very small, which is not shown in Fig. 7(a); then the possibility of the occurrence of the self-excited oscillation in the high-frequency range can be removed.

Moreover, being independent of the value of the first natural frequency, the phase difference between the output from the PZT-sensor and the output from the laser displacement sensor is 0° at the first natural frequency. Therefore, the output signal from the PZT sensor is useful to generate self-excited oscillation with the cantilever.

Next, the characteristics of the PZT sensor output processed with the filter are examined corresponding to the change in the first natural frequency of the cantilever. To investigate whether the frequency shift is detectable or not, identical experiments are carried out in which a weight of 0.6 g is attached to the macro beam tip. As a result, the response amplitude takes the minimum value at the first natural frequency. Even if the first natural frequency shifts, the phase difference between the output from the PZT sensor and the output from the laser displacement sensor is retained at 0° . Eventually, the first-order derivative with respect to time of the output from the PZT sensor is equivalent to the velocity signal, independent of the shift in the first natural frequency. Therefore, using the positive feedback of this signal to the self-sensing and self-actuated cantilever, the cantilever will be able to generate self-excited oscillation.

4. Van der Pol-type self-excitation of a self-sensing and self-actuating cantilever

4.1. Van der Pol-type self-excited cantilever beam

In this section, van der Pol-type self-excited oscillation is achieved using the macro cantilever with a self-sensing function to reduce the response amplitude and thereby prevent the cantilever's contact with the sample. This method is proposed by Yabuno⁽⁵⁾.

The effects of viscous damping and nonlinear damping in the van der Pol-type self-excited oscillation are realized by applying linear positive feedback and nonlinear negative feedback. First, the analytical model of the beam is shown in Fig. 8. A Cartesian coordinate system using $x-y$ is introduced: the origin O is located on the centerline at the left end (fixed end) of the macro beam. The arc-length from the fixed end to the position of a certain point on the centerline of the macro beam is denoted as s . The displacement at this point in the y direction is v , and the displacement at this point in the x direction is u . Piezo-electric ceramic

Fig. 9 Feedback circuit

is attached in the range from s_1 to s_2 from the left end (fixed end) of the macro beam. Here, the PZT actuator applies the bending moment to the macro beam based on the feedback control. By taking account of the dimensionless linear viscous damping term $\mu\dot{v}$ and the dimensionless nonlinear viscous damping term $\mu_n v^2\dot{v}$ in the measurement environment, the dimensionless equation of motion and the boundary conditions are described as follows⁽⁸⁾⁽⁹⁾:

$$\begin{aligned} & \ddot{v}^* + (v^{*''''} + v^{*''''} v^{*2} + 4v^{*'} v^{*''} v^{*'''} + v^{*''3}) + v^{*'} \int_1^{s^*} \int_0^{s^*} (\dot{v}^{*2} + v^{*'} \dot{v}^{*'}) ds^* ds^* \\ & + v^{*'} \int_1^{s^*} (\dot{v}^{*2} + v^{*'} \ddot{v}^{*'}) ds^* + \mu \dot{v}^* + \mu_n v^{*2} \dot{v}^* \\ & = \{K_{lin}^* \dot{v}^*|_{s=1} - K_{non}^* v^{*2}|_{s=1} \dot{v}^*|_{s=1}\} \times [h(s^* - s_1^*) - h(s^* - s_2^*)]'' \\ & v^*|_{s=0} = v^{*'}|_{s=0} = v^{*''}|_{s=1} = v^{*'''}|_{s=1} = 0, \end{aligned} \quad (1)$$

$$v^*|_{s=0} = v^{*'}|_{s=0} = v^{*''}|_{s=1} = v^{*'''}|_{s=1} = 0, \quad (2)$$

where K_{lin}^* is the linear feedback gain and K_{non}^* is the nonlinear feedback gain. The output signal from the PZT sensor has the frequency response characteristics presented in Fig. 7; the magnitude of the signal is not equivalent to the magnitude of the cantilever deflection. However, when the cantilever vibrates at the first natural frequency, the phase of the output signal from the PZT sensor is equal to the phase of the first natural frequency component of the cantilever. Therefore, the linear feedback signal and the nonlinear feedback signal are producible by the output signal from the PZT sensor.

4.2. Experimental setup for van der Pol-type self-excited oscillation

Figure 2 shows the experimental setup for the van der Pol-type self-excited oscillator; in part (B), the feedback control is carried out. The digital filter explained in section 3 not only decreases the gain in the higher frequency range than the first natural frequency, but also performs the phase shift to obtain a signal that is equivalent to the deflection of the cantilever. In addition, by making the first-order temporal-derivative of the output signal from the PZT sensor, $\dot{x}$ and $\dot{x}x^2$, which are necessary for van der Pol-type self-excited oscillation, are calculated using a personal computer and are output as an analog signal. The analog signal output from the personal computer is fed back to the PZT driver through the feedback circuit mentioned later. After being amplified to 15 times by the PZT driver, the resultant signal is applied to the PZT actuator. Figure 9 shows details of the feedback circuit in Fig. 2. In Fig. 9(a), the linear feedback signal $K_{lin}\dot{x}$ is output, which feedback gain can be adjusted from 0 to 100 times. In Fig. 9(b), the nonlinear feedback signal $-K_{non}\dot{x}x^2$ is output, by which feedback gain can be adjusted from 0 to 100 times. Through the processes described above, the control signal is output from the feedback circuit; it is then input into the PZT driver. All operational amplifiers used in this study are identical (LF356N; Toshiba Corp.).

Fig. 10 Time history and power spectrum of a van der Pol-type self-excited cantilever ($K_{lin}=6.8$, $K_{non}=3.3$)

Fig. 11 Time history and power spectrum of a van der Pol-type self-excited cantilever (without filter, $K_{lin}=6.8$, $K_{non}=3.3$)

4.3. Experimental result for van der Pol-type self-excited oscillation

4.3.1. Effect of the filter on self-excited oscillation Figure 10 shows a time-history waveform of the PZT sensor output and the power spectrum when the van der Pol-type self-excited oscillation is generated in practice using a displacement signal from the PZT sensor. Here, the output signal from the PZT sensor is used for the feedback. The response frequency contains only the single frequency component that corresponds to the cantilever's first natural frequency because of self-excited oscillation. For comparison, we try to generate the self-excited oscillation using only the phase compensation, namely, without the proposed filter to decrease the gain in the higher frequency range than the first natural frequency. Figure 11 shows the result. Figure 11 shows that the cantilever does not oscillate at the first natural frequency merely by the phase compensation. If it does oscillate, the cantilever oscillates at a high frequency. We can not estimate the first natural frequency of the cantilever from the waveform because the response frequency deviates from the first natural frequency. The reason why such an oscillation takes place might be that the gain of the response amplitude of the output from the PZT sensor rises near 200 Hz, as shown in Fig. 6. However, to clarify the reason why the response frequency of the self-excited oscillation becomes near 110 Hz remains as a subject for future work. Consequently, it is concluded that the filter designed in the section 3 is necessary to generate van der Pol-type self-excited oscillation with the self-sensing and self-actuated cantilever.

4.3.2. Nonlinear characteristics of self-excited oscillation Under the condition that the ratio of the input-output voltage, K_{non} , in panel (b) of Fig. 9 is kept constant, and the ratio of the input-output voltage, K_{lin} , in panel (a) of Fig. 9 is varied, bifurcation diagrams are obtainable as Figs. 12 and 13, where $\times$, $\blacktriangle$ and $\bullet$ respectively denote the cases of K_{non} is 0, 10 and 50. Figure 12(a) shows the bifurcation diagram using the laser displacement sensor. Figure 12(b) shows the change in the response frequency with respect to the linear feedback gain. On the other hand, Fig. 13(a) shows the bifurcation diagram of the system using the PZT sensor. Figure 13(b) shows the change in the response frequency with respect to the linear feedback gain. Figures 12(a) and 13(a) show that the critical value of the linear feedback gain K_{lin} is 5–5.5, at which the system undergoes Hopf bifurcation. The cantilever amplitude increases with the value of K_{lin} . On the other hand, the amplitude of the van der Pol-type self-excited cantilever decreases as the nonlinear feedback gain becomes large. Moreover, we obtained experimental results in which the bifurcation point is delayed with respect to

Fig. 12 Relationship between amplitude and frequency of self-excited oscillation by laser displacement sensor
($\times$, $K_{non}=0$; Δ , $K_{non}=10$; $\bullet$, $K_{non}=50$)

Fig. 13 Relationship between amplitude and frequency of self-excited oscillation by PZT sensor
($\times$, $K_{non}=0$; Δ , $K_{non}=10$; $\bullet$, $K_{non}=50$)

Fig. 14 Frequency-shift of self-excited oscillation by PZT sensor
($\circ$, $K_{non}=0$; $\square$, $K_{non}=10$; Δ , $K_{non}=50$)

the value of the linear feedback gain caused by adding the nonlinear feedback. We can not theoretically explain the cause of this delay at present.

It is confirmed that the response frequency shown in Fig. 13(b) corresponds with the response frequency shown in Fig. 12(b), in which the cantilever vibration is measured simultaneously. Additionally, the oscillation frequency of the cantilever is constant, with about 60 Hz. In addition, comparing Fig. 12 to Fig. 13, the inclination of the amplitude curve of the output from the PZT sensor and the PZT sensor output values from with respect to the magnitudes of K_{lin} and K_{non} are qualitatively identical to those of the output from the laser displacement sensor. Therefore, self-excited oscillation can be generated using the self-sensing and self-actuated cantilever, which has similar characteristics to those obtained when using the laser displacement sensor.

4.3.3. Measurement possibility of the natural frequency variation Furthermore, when the first natural frequency is changed, it was investigated whether the response frequency shift can be detected in the self-excited oscillation with the self-sensing and self-actuated cantilever. Figure 14 shows the shift in the response frequency of the self-excited cantilever by measurement with the PZT sensor. The horizontal axis is the mass attached to the macro beam tip; the vertical axis is the response frequency. Figure 14 confirms that the response frequency of the self-excited cantilever changes according to the change in the first natural

frequency depending on the attached mass. Results of this study show that the self-sensing and self-excited cantilever with the proposed signal processing is useful to measure the change in the first natural frequency of the cantilever.

5. Conclusion

In this research, toward the development of the AFM probe to measure biological molecules, we achieved generation of self-excited oscillation with a self-sensing and self-actuated cantilever. Using the self-sensing and self-actuated macro cantilever, we propose the signal processing method for the output signal from the PZT sensor to generate self-excited oscillation with the cantilever by the output signal. Using this apparatus, we can generate the velocity feedback signal and the nonlinear feedback signal from the processed output signal from the PZT sensor. Consequently, by feeding back their signals, van der Pol-type self-excited oscillation can be induced in the self-sensing and self-actuated cantilever. Furthermore, we demonstrate that the variation of the first natural frequency of the cantilever can be detected by measuring the response frequency of the self-sensing and self-excited cantilever. From the results described above, finally, it is expected that the self-sensing and self-actuated cantilever is applicable to the AFM cantilever in liquids where optical sensors are difficult to use. Therefore, we will apply the self-sensing and self-excited oscillation method proposed in this paper to an actual AFM using downsizing of the van der Pol-type self-excited cantilever⁽¹⁰⁾. We will develop an atomic force microscope to observe biological molecules.

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