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Self-Sensing Vibration Suppression of Piezoelectric Cantilever Beam Based on Improved Mirror Circuit

BIN JU[1,2], ZHIHUA GUO[1], YONGBIN LIU[1,2], GANG QIAN[1], LANBING XU[1], AND GUOLI LI[1,2]
[1]College of Electrical Engineering and Automation, Anhui University, Hefei 230601, China
[2]National Engineering Laboratory of Energy-Saving Motor and Control Technology, Anhui University, Hefei 230601, China

Corresponding author: Yongbin Liu (lyb@ustc.edu.cn)

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ABSTRACT The self-sensing technique allows a single piece of piezoelectric element to function simultaneously as an actuator and a sensor in a closed-loop system. This study proposes an improved vibration suppression system using the piezoelectric self-sensing technique whose usefulness is experimentally verified in a cantilever beam. A single piezoelectric element is bonded to the root of the beam and functions as an actuator and a sensor simultaneously. A mirror circuit constructed with two charge driver circuits is used to pick up the sensing signal from the driving voltage signal. Then, a closed-loop control strategy based on the proportion integration differentiation (PID) algorithm can adjust the sensing signal precisely to suppress the vibration of the cantilever beam quickly. The first mode of vibration is suppressed, and the amplitude of the vibration is actively dampened by a factor exceeding 96.4%. Moreover, the frequency sweep experiments demonstrate that with the PID feedback control circuit connected to the piezoelectric cantilever beam, the Q value of the system is greatly reduced, and the loss factor is increased from 0.053 to 0.288. The improved mirror circuit with PID control has a good suppression effect in the frequency range near the first order mode of the cantilever beam.

INDEX TERMS Self-sensing actuator, piezoelectric cantilever beam, mirror circuit, PID algorithm, vibration suppression.

I. INTRODUCTION

Piezoelectric materials have been increasingly used as sensors and actuators for vibration control in many situations [1]. Compared with other materials, piezoelectric smart materials have many obvious advantages, such as rapid reaction, easy control, small volume and absence of electromagnetic interference. Hence, many studies have been conducted using piezoelectric materials for the intelligent control of vibration [2], [3].

Numerous studies are based on separate applications of piezoelectric sensors and actuators [4], [5]. However, these applications have limitations in several aspects. For example, many application areas usually require the same numbers of sensors and actuators, and placing the sensors and actuators in a symmetrical position is difficult in practice. Moreover, these sensors and actuators should be attached at locations where the strain varies significantly. Such requirement is difficult to fulfill in separate applications of piezoelectric sensors and actuators.

Great progress has been made in this respect since the concept of self-sensing actuator was first developed by Dosch *et al.* [6] . In a self-sensing actuator, a single piezoelectric ceramic can function as a sensor and an actuator simultaneously [7], [9]–[11]. Using this method can solve the aforementioned problems. Therefore, the self-sensing actuator structure has several desirable properties and is widely employed in vibration and control applications [12]–[15]. However, separating sensing and control signals is a key point during the utilization of the

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self-sensing actuator. Bridge circuit is a classical approach and is widely used in solving such problems [16]. The control signal is usually mixed with the sensing signal due to the mechanical response in a piezo-based self-sensing actuation configuration. The bridge circuit can extract the sensing signal from the piezoelectric self-sensing driver, but the key is the balance of the capacitance bridge [17]. On the basis of the static capacitance of a piezoelectric actuator, bridge balance is easy to obtain on the static work point. However, the capacitance values must be constantly adjusted in the feedback control process to extract the sensing signals. To confirm the feedthrough capacitance of a piezoelectric element, Cole and Clark [18] and Vipperman and Clark [19] proposed an adaptive filter algorithm to digitally compensate for the parameter changes in self-sensing circuits. Tzou and Hollkamp [20] achieved effective control of structural vibration by studying the use of self-sensing orthogonal modal actuators. Dong and Sun [21] designed a simple controller consisting of proportional control and phase lag compensation for an unbalanced bridge. Garnett *et al.* [22] analytically and experimentally quantified the variations of piezoelectric capacitance in terms of the performance in vibration testing and control against the effects of an unbalanced bridge circuit. Nevertheless, other issues must be considered. Piezoelectric actuators mainly work near resonance. The value of the equivalent capacitance varies dramatically due to environmental temperature, applied electric field, driving frequency, and boundary conditions. Therefore, the balance of the bridge circuit during operation is difficult to maintain. Balance implementation is a process that requires dynamic adjustment, and researchers attempt to find ways to automatically track the changes in piezoelectric capacitance. Although theoretical analysis is feasible, the real-time changes of piezoelectric capacitors are difficult to track in experiments.

Only when the impedance property of a piezoelectric element is continuously collected under different vibration conditions [14] is the impedance property database of this piezoelectric element established [23]. Then, according to the vibration information, the equivalent capacitance is compensated to obtain the balance of the bridge circuit in real time. Only in this way can we completely track the changes. However, the information of different piezoelectric elements is not the same under different vibration conditions [24], [25]. The real time processing of the impedance data of different piezo-elements will be rather complicated. The theoretical analysis of this method is feasible but difficult to achieve in practical applications.

The purpose of a vibration suppression device is to suppress vibration quickly and effectively. Achieving this goal from an application perspective does not require the precise separation of sensing and driving signals in self-sensing drives. By extracting the vibration signal and setting the target function for proper feedback, the control signal can be quickly adjusted, and the vibration suppression will be realized. Liu *et al.* [26] proposed a mirror charge driver circuit to separate sensing signals from a piezoelectric self-sensing drive. The problem of nonlinearity and balance adjustment in bridge circuits is avoided. The piezoelectric element is driven by a charge pump circuit, which can reduce nonlinearity and hysteresis. In addition, a mirror reference circuit is used to separate sensing signals. However, the reference capacitance of the mirror reference circuit in this method must be consistent with the dynamic equivalent capacitance of the piezoelectric actuator during operation to achieve vibration suppression effectively. Therefore, the reference capacitance value must be manually adjusted in the process of experiment to achieve the desired result, which is of poor precision and complicated in operation.

The current work is based on the mirror charge driving circuit method. However, the capacitance in the reference circuit is kept equal to the static capacitance of the piezoelectric element, and does not need to be dynamically adjusted during operation. A differential circuit is used to extract the sensing signal of the self-sensing piezoelectric actuator. A closed-loop control strategy with a proportion integration differentiation (PID) algorithm is used to control the sensing signal. Theoretical analysis proves that, as long as the PID control parameters are reasonably adjusted, and the transfer function of this link and the magnification of the mirror circuit meet a certain relationship, the external vibration of the cantilever beam can be suppressed even without the precise separation of sensing and driving signals in self-sensing drives. Then, the target value of vibration suppression is set. The signal acquisition circuit collects the sensing signal from the mirror circuit, adjusts it to the target value through the PID algorithm, and feeds it back to the mirror circuit to control the piezoelectric element. This method can quickly stabilize to the target value automatically and achieve vibration suppression. Experiments show that the closed-loop control strategy with the PID algorithm can precisely suppress the vibration of a cantilever beam in the first-order mode quickly. The amplitude of the vibration is actively suppressed by 96%. Meanwhile, the vibration control of the method on different vibration displacements (from 0.05 mm to 0.58 mm) in the frequency range from 16.5 Hz to 30.5 Hz was tested, and the suppression performance was very stable. The corresponding Q values and loss factors are also calculated before and after the vibration suppression. Experimental results demonstrate that this method is simple and effective practically. It does not require the precise separation of sensing signals for self-sensing and does not require the manual adjustment of the reference capacitance.

II. MIRROR CIRCUIT BASED ON PID ALGORITHM

The proposed vibration suppression circuit system for a piezoelectric structure is mainly composed of a mirror circuit and a signal acquisition and processing circuit (Fig. 1). The mirror circuit consists of two symmetrical charge driver circuits and a differential amplifier and is used to preliminarily extract the vibration signal of the structure. The signal acquisition and processing circuit is composed of a signal

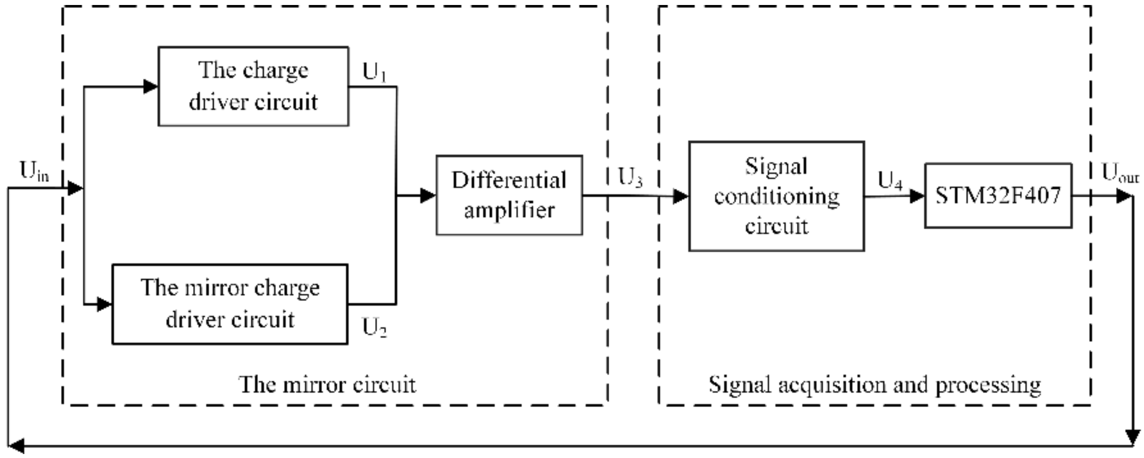

FIGURE 1. Diagram of the piezoelectric self-sensing control system.

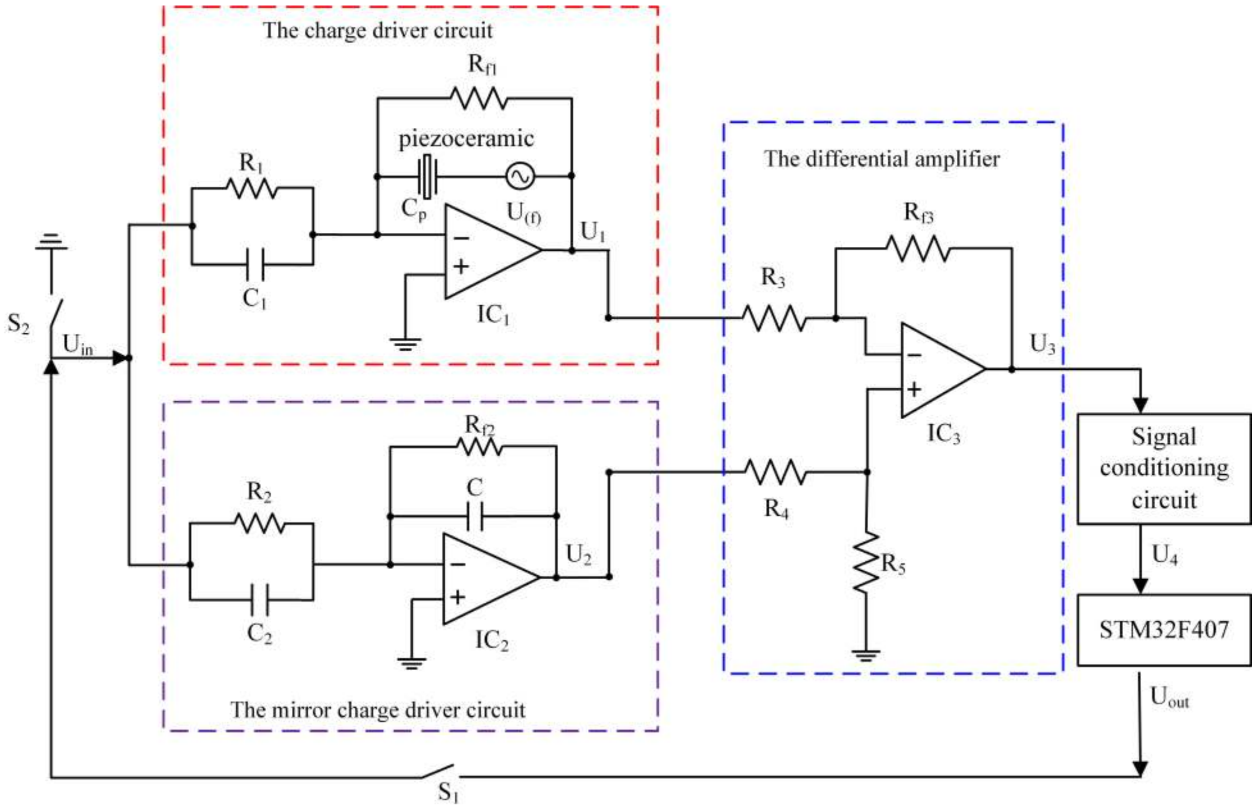

FIGURE 2. Circuit of vibration suppression system for piezoelectric structure.

conditioning circuit and a microprocessor (STM32F407). The signal conditioning circuit converts the sensing signal from the mirror circuit into an input signal suitable for the analog-to-digital converter of STM32F407, which is a 32-bit high-speed processor that controls the sensing signal and feeds it back to the input of the mirror circuit to effectively and rapidly suppress the vibration of the structure.

A. OPERATION PRINCIPLE OF THE MIRROR CIRCUIT

The mirror circuit used to extract the vibration signal of a piezoelectric structure is shown in Fig. 2. R_1, C_1, R_{f1}, and IC_1 establish the charge driver circuit for the piezoelectric element. As shown in Fig. 2, the self-sensing piezoelectric patch is equivalent to a dynamic voltage source $U_{(f)}$ in series with a static capacitor of C_p. The static capacitor of C_p participates in the normal operation of the charge driver circuit just like ordinary capacitors. The dynamic voltage source $U_{(f)}$ consists of two parts. One is the voltage produced by the constant external excitation, which should be suppressed by the system, and the other is the voltage generated by the mirror circuit system and used to suppress the external vibrations. Hence, the value of $U_{(f)}$ reflects the dynamic suppression of the external vibration. When the external vibration is completely suppressed by the system, the voltage $U_{(f)}$ should be controlled to zero.

The mirror charge driver circuit for obtaining the compensation voltage comprises R_2, C_2, R_{f2}, C, and IC_2. The differential amplifier is constructed by R_3, R_4, R_5, R_{f3}, and IC_3 and utilized to extract and amplify the vibration sensing signal. According to [26], the mirror capacitance (C) in the mirror charge driver circuit should be adjusted to obtain $C = C_p$. Regard the capacitors, the resistors and operational amplifiers in the circuit as ideal components and set them as follows: $R_1 = R_2, R_{f1} = R_{f2}, C_1 = C_2$. Then the following equations can be obtained:

$$U_1(j\omega) = k_1 U_{in}(j\omega) + U_{(f)}(j\omega) \tag{1}$$

$$U_2(j\omega) = k_2 U_{in}(j\omega) \tag{2}$$

$$U_3(j\omega) = k(U_1(j\omega) - U_2(j\omega)) \tag{3}$$

where U_1 is the output voltage of the charge driver circuit, U_2 is the output voltage of the mirror charge driver circuit, and U_3 is the output voltage of the differential amplifier circuit and contains the separated sensing vibration signal. k_1 and k_2 are the amplification factors of the charge driver circuits in Fig. 2, which are decided by the values of C_1, C_p, C_2 *and* C. When the resistances R_1, R_2, R_{f1} and R_{f2} are large enough, $k_1 = C_1/C_p$, and $k_2 = C_2/C$. k is the gain of the differential amplifier, and ω is the operation angular frequency. Since the capacitances $C = C_p$, and $C_1 = C_2$, the amplification factor k_1 is equal to k_2. Hence, the voltage U_3 can be expressed as:

$$U_3(j\omega) = kU_{(f)}(j\omega) \tag{4}$$

If no external vibration is excited on the structure, the $U_{(f)}$ is zero, and the output voltage U_3 is also zero. At this point, the mirror circuit is balanced regardless of the input voltage (U_{in}). However, when an external vibration is excited on the structure, the stresses produced by the structure act on the self-sensing piezoelectric element. Simultaneously, the external exciting source breaks the balance of the mirror circuit. Output voltages U_1 and U_2 of the charge driver circuits are no longer equal. The differential amplifier circuit amplifies the difference between U_1 and U_2, and output voltage U_3 is not equal to zero. Analysis shows that output voltage U_3 is generated only when external force is applied and is proportional to the force. Hence, this voltage can be used as a sensing signal to reflect the external vibration excited on the piezoelectric element. To extract the vibration sensing signal perfectly using the mirror circuit, the two charge driver circuits must be completely symmetrical. Ensuring that $C = C_p$ is an essential part among other circuit parameters. However, the equivalent capacitance of a piezoelectric element varies significantly between the quasi-static and resonant states. A piezoelectric component can even exhibit an inductive characteristic in the resonance state [23]. Moreover, occasions requiring vibration suppression often occur near the resonance of the structure where a small external disturbance causes a large structure vibration. Therefore, selecting an appropriate capacitance (C) to satisfy the equilibrium condition of the mirror circuit in the resonance state is difficult. To extract the sensing signal effectively, the capacitance (C) in the mirror charge driver circuit must be continuously adjusted manually such that it matches the changing piezoelectric equivalent capacitance. The dynamic adjustment of capacitance C and the real-time tracking of the non-linear variation of piezoelectric element parameters make the vibration suppression system complicated and difficult to realize [27]. To solve this problem, we add a PID controller to the mirror circuit as shown in Figs. 2 and 3(a).

In Fig. 2, suppose the transfer function from the output voltage U_3 of the differential amplifier circuit to the feedback voltage U_{out} is $G(j\omega)$. Then the following equation can be obtained:

$$U_{out}(j\omega) = G(j\omega)U_3(j\omega) \tag{5}$$

Since the voltage U_{out} is the feedback voltage in the closed loop, it is equal to the input voltage U_{in}, namely

$$U_{out}(j\omega) = U_{in}(j\omega) \tag{6}$$

Combined the equations (1), (2), (3), (5) and (6), the relationship between the input voltage U_{in} and the dynamic voltage $U_{(f)}$ can be obtained as follows:

$$U_{in}(j\omega) = U_{out}(j\omega) = \frac{kG(j\omega)}{k\,(k_1 - k_2)\,G(j\omega) - 1} U_{(f)}(j\omega) \tag{7}$$

When the external vibration of the cantilever beam is suppressed by the control system, the value of the mixed voltage $U_{(f)}$ on the piezoelectric element should be zero, and simultaneously, the output feedback voltage of PID should also be a voltage signal close to zero.

If the reference capacitance C can be dynamically adjusted and consistent with the equivalent capacitance C_p of the piezoelectric element, the amplification factor k_1 is equal to k_2, and the equation (7) will be simplified as

$$U_{in}(j\omega) = U_{out}(j\omega) = -kG(j\omega)U_{(f)}(j\omega) \tag{8}$$

However, as is mentioned above, it is rather difficult to realize the dynamic adjustment of capacitance C and the real-time tracking of the non-linear variation of piezoelectric element parameters. Hence, k_1 is basically not equal to k_2 in practice, and to separate the sensing signal accurately is almost impossible. Nevertheless, as long as we adjust the PID control parameters reasonably, and keep the output feedback voltage U_{out} of this link meeting the relationship given in equation (7), the external vibration of the cantilever beam can still be suppressed even without the precise separation of sensing and driving signals in self-sensing drives. In this way, we effectively compensate for the drawback of ensuring the equality of capacitance C and C_p in real time.

B. SIGNAL CONDITIONING AND CONTROL CIRCUIT

As shown in Fig. 1, the PID strategy is realized by the microcontroller STM32F407. Given the special need of the input signal for the microcontroller, a signal conditioning

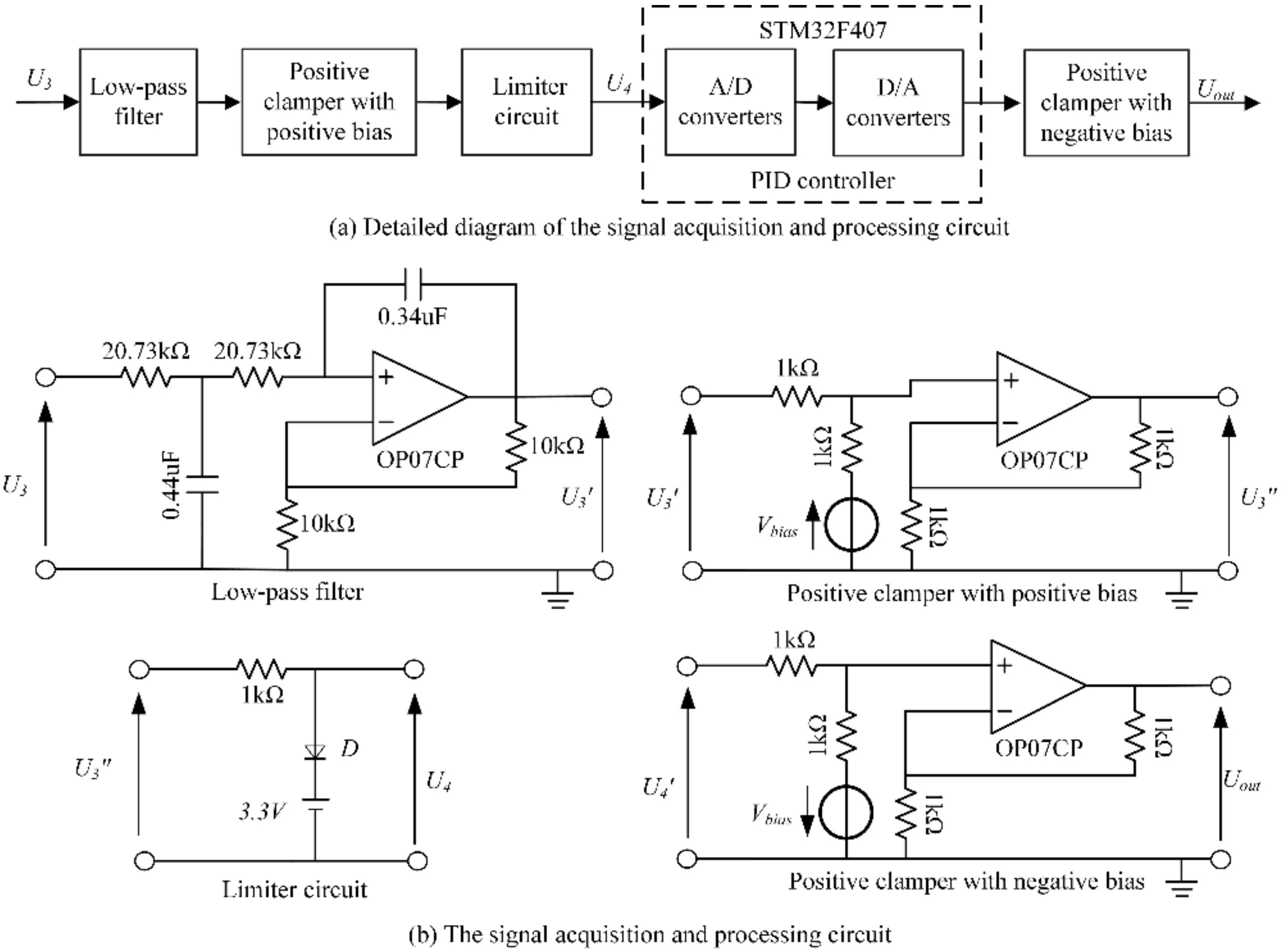

FIGURE 3. The signal conditioning circuit.

circuit is necessary to ensure the integrity of the sensing signal preliminarily separated from the mirror circuit. The detailed circuit modules of the signal acquisition and processing unit are shown in Fig. 3. These modules include a low-pass filter, a positive clamper with a positive bias, a limiter circuit, A/D converters, and a positive clamper with a negative bias.

Due to the hardware limitation of STM32F407, only a voltage between 0 and 3.3 V can be identified by the port of the ADC. The voltage signal from the mirror circuit has not only positive voltages but also negative voltages. But the port of STM32F407 does not receive negative voltage signal. So U_3 cannot be directly inputted to STM32F407. In order to ensure that the negative voltage signal of U_3 can be biased to positive voltage signal, the clamp voltage is set to 1 V after many experimental tests. This bias voltage also has an influence on the reference value setting of the following PID target. In addition, the maximum input voltage is 3.3V for the ADC port. Hence, it is necessary to use a limiter circuit to ensure that the input voltage amplitude cannot exceed 3.3V, otherwise STM32F407 will burn out. Since the output voltage of the D/A port only contains positive values, the direct-current bias voltage added by the upstream circuit should be eliminated. A positive clamper with negative bias is designed, which is the same as the positive clamper with a positive bias to simplify the design and eliminate errors. Hence, to obtain the effective sensing signal, the signal processing should involve a positive clamper with positive bias, a positive clamper with negative bias, and a limiter circuit.

C. THE PID CONTROL STRATEGY

The vibration sensing signals separated from the above-mentioned mirror circuit can be processed to suppress the vibration of the structure through feedback control. However, the suppression result is affected by the dynamic capacitance of piezoelectric ceramics. On the premise that the reference capacitor C cannot track C_p in real time, the result of vibration suppression is not ideal. To avoid manually adjusting the capacitance value, the PID control strategy is introduced to compensate for the segregation errors caused by $C \neq C_p$ and suppress the vibration of the structure.

The PID controller (in Fig. 4) consists of three parts, namely, the proportional, integral, and differential elements [28]. After the signal conditioning circuit, the preliminary vibration sensing signal U_3 is regulated into the

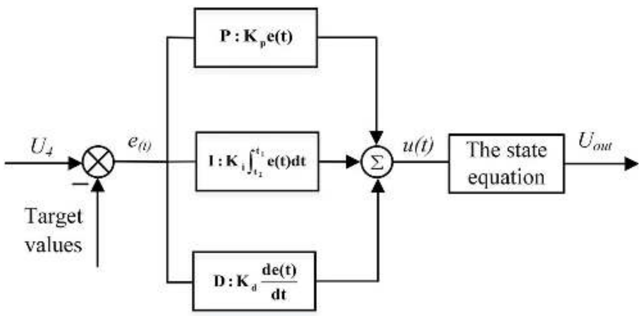

FIGURE 4. PID control loop.

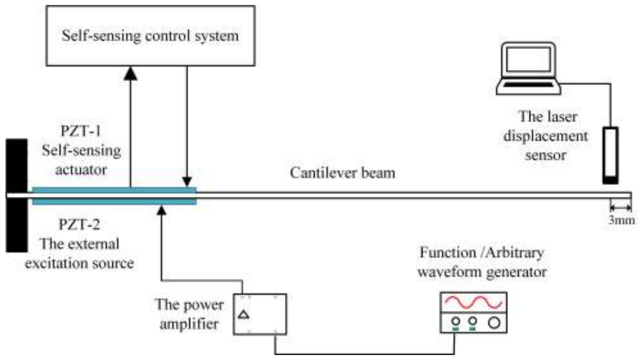

FIGURE 5. Schematic diagram of the experimental system.

voltage U_4. U_{out} represents the voltage that is eventually fed back to the piezoelectric element for vibration control through the signal conditioning circuit. $e(t)$ is the error value between the output voltage of the signal conditioning circuit and the preset target value. $u(t)$ is the dynamically adjusted vibration suppression voltage. According to the PID control strategy, the state equation input ($u(t)$) can be expressed as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{9}$$

where K_p is the proportional parameter, K_i is the integral parameter, and K_d is the differential parameter [29], [30].

When the vibration of the piezoelectric structure is suppressed effectively with the external excitation continually acting on it, the vibration displacement at the end of the cantilever beam is very small. In this case the stress exerted by the cantilever beam on the piezoelectric ceramic is also very small, approaching to zero. Ideally, the abovementioned voltage $U_{(f)}$ is close to zero since this signal is induced by the stress. Hence, according to the operation principle of the mirror circuit and equation (4), the output voltage of the differential amplifier circuit U_3 is zero. After signal conditioning circuit processing, the voltage U_3 is exported to the PID part for feedback control. However, due to the existence of the clamp circuit the whole voltage of U_3 has an increase of 1V. Therefore, in order to realize PID feedback control for the vibration suppression, the target voltage value of the PID controller is set to 1V. During the process of the vibration suppression, the PID controller adjusts the three key parameters (K_p, K_i and K_d), re-regulate the error of U_4 and the target value and feedback the signal U_{out} to the charge driver circuit. The vibration of the cantilever beam will be controlled to achieve an objective state quickly and stably.

Therefore, on the basis of the original mirror circuit, the problem of needing continuous adjustment for the compensation capacitance is solved by adding a PID controller to the vibration suppressing process. As shown in Fig. 2, when the switch S_1 is disconnected and the switch S_2 is closed, the circuit is in an open-loop state. C and C_p in the mirror circuit are set to be approximately equal. Then, set the target value of the PID as 1 V. Finally, switch the circuit system to the closed-loop state by closing S_1 and disconnecting S_2. The PID controller automatically adjusts the feedback input voltage according to the target value and eventually suppresses the vibration of the cantilever beam. The final performance of the improved mirror circuit in self-sensing vibration suppression will be displayed in the following.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. EXPERIMENTAL SETUP

The suppression effectiveness of the piezoelectric self-sensing control system based on the mirror circuit and the PID algorithm is verified through an experiment on a piezoelectric cantilever beam. The schematic of the experimental system is shown in Fig. 5. The experimental setup consists of a cantilever beam, an external excitation source, a power amplifier, a self-sensing control system, and a laser displacement sensor.

The beam is made of cold-rolled carbon structural steel sheet. Under the premise that the vibration of the first order mode can be suppressed, the vibration suppression of the higher order mode mainly depends not on the control method, but on the control structure. Fig. 6 shows the stress distributions of the first, second and third order bending modes of the cantilever beam in the manuscript. For the higher order modes, the stress distributions are completely different from that of the first order mode. It is difficult to control the vibration only with a single piece of piezoelectric ceramic. However, by changing the control structure, additional piezoelectric ceramics can be attached to the positions where the maximum or sub-maximum stresses of the beam locate at for vibration control [5], [31]–[35]. Hence, only the first-order vibration mode is chosen for the suppression experiment in the paper.

According to the first-order mode stress distribution of the beam shown in Fig. 6, the excitation and self-sensing piezoelectric elements are bonded to the root of the beam to achieve a satisfactory excitation and suppression effect [36], [37]. The two piezoelectric elements are placed in opposite positions on the upper and lower sides, as shown in Fig. 5. The prototype and the size marking of the cantilever beam are shown in Fig. 7. The upper piezoelectric element (PZT-1) acts as a self-sensing actuator, which integrates the sensor and actuator functions. The piezoelectric element on the lower

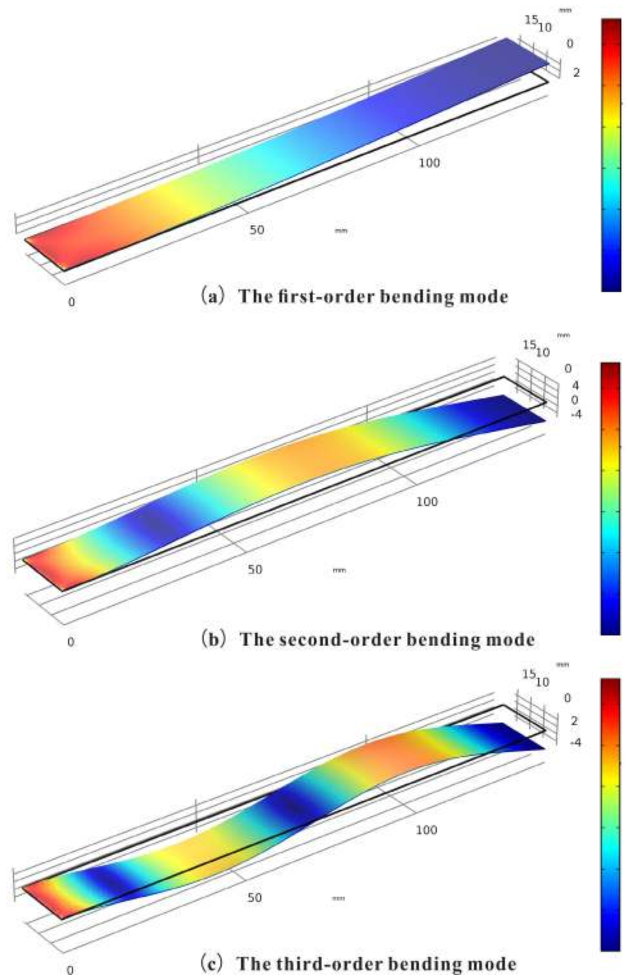

FIGURE 6. Stress distribution of the first three-orders bending modes of the cantilever beam.

surface (PZT-2) is collocated as an excitation source and continuously provides excitation during the experiment. The properties and dimensions of the PZT and the beam are provided in Table I and Table II.

As shown in Fig. 5, an arbitrary waveform generator (Rigol DG 1200U) is utilized to generate the external excitation signal, which is amplified via a power amplifier and then actuates PZT-2. The displacement of the free end of the cantilever beam is used to characterize the vibration of the beam and is measured using a high-resolution laser displacement sensor (ILD1402-10, Micro-epsilon, Germany). The sensor, which is 3 mm away from the free end of the beam, is connected to a computer, and the displacement of the beam can be collected and exhibited in real time by software (ILD1402 Tool V3.1.1).

The operational amplifiers, IC_1 and IC_2, select the OPA541 in the charge driver circuits of the mirror circuit system. OPA541 is a power amplifier with an extremely low bias current (4 pA typically) and a large peak output current of 10 A. With OPA541, the charge driver circuit can drive the piezoelectric plate with ±30 V and satisfy the specification well. Capacitance C equals the equivalent

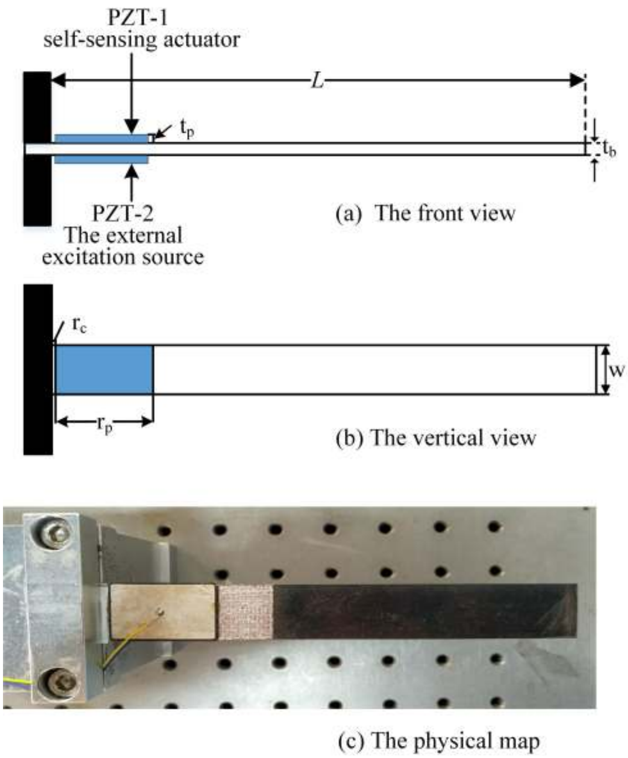

FIGURE 7. Outline drawing of the piezoelectric cantilever beam.

TABLE 1. Size parameters of the beam and PZT ceramic.

Parameter	Value	unit
Cantilever beam length (L)	140	mm
Cantilever beam width (w)	16	mm
Cantilever beam thickness (t_b)	0.3	mm
PZT length (r_p)	30	mm
PZT width (w)	15	mm
PZT thickness (t_p)	0.2	mm
Clearance (r_c)	3	mm

capacitance of PZT-1 in the first-order resonant mode of the cantilever beam with a driving voltage of 580 mV, which is 24.87 nF in the experiment. The signal acquisition and processing circuit, as mentioned in Section II, is mainly composed of STM32F407. STM32F407 has a 32-bit high performance microcontroller and a 12-bit ADC. The sampling frequency is 10 kHz, which satisfies the requirements of signal acquisition.

B. EXPERIMENT AND ANALYSIS

In this study, the first-order vibration mode of a cantilever beam is taken as the experimental subject to conduct the piezoelectric self-sensing vibration suppression experiment. The experimental setup is shown in Fig. 8.

TABLE 2. Material properties of the beam and PZT ceramic.

	properties	Value	unit
PZT-4	s^E_{33}	15.5×10^{-12}	m^2/N
	ε^T_{33}	1.15×10^{-8}	F/m
	c^E_{33}	11.5×10^{10}	N/m^2
	d_{33}	289×10^{-12}	C/N
	ρ	7500	kg/m^3
Cantilever beam	Young's modulus	1.97×10^5	MPa
	Poisson's ratio	0.247	
	ρ	7.81×10^3	kg/m^3

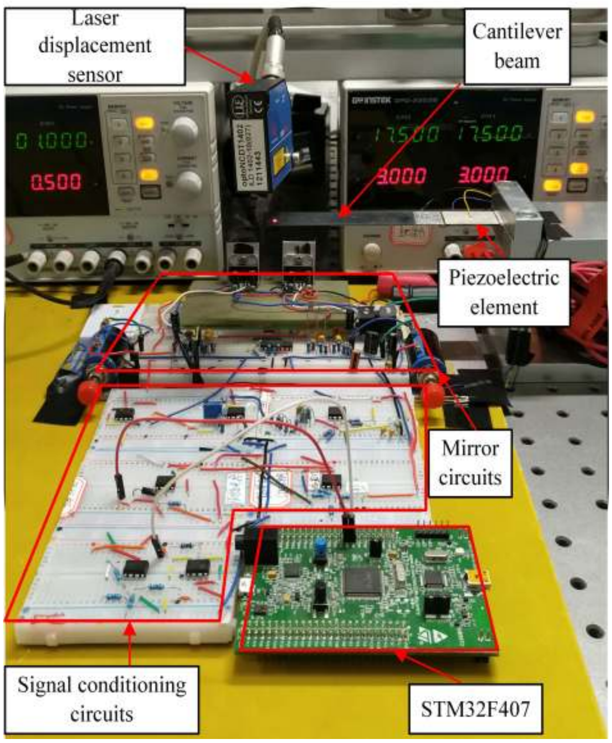

FIGURE 8. Experimental setup of the vibration suppression system.

The first-order vibration mode of the cantilever beam is excited by the external excitation source of PZT-2, and the vibration frequency is 24.26 Hz. First, switch S1 is turned off and switch S2 is turned on, as shown in Fig. 2. Then, the system is working in an open loop. The input of the mirror circuit is grounded, and U_{in} is equal to zero. The beam is only energized by the excitation source to vibrate at its resonance frequency. Voltage signal $U_{(f)}$ is generated by the deformation of PZT-1 due to the bending of the beam. The analysis of the mirror circuit in Fig. 2 indicates that $U_{(f)}$ is amplified to U_1 by the charge driver circuit constructed by IC_1. Given that the input voltage of the mirror compensation charge driver

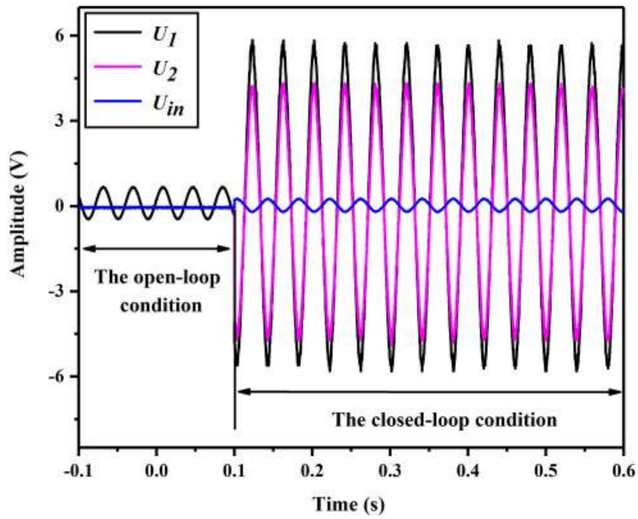

FIGURE 9. Waveforms of output voltages U_1, U_2, and U_{in} from open loop to closed loop.

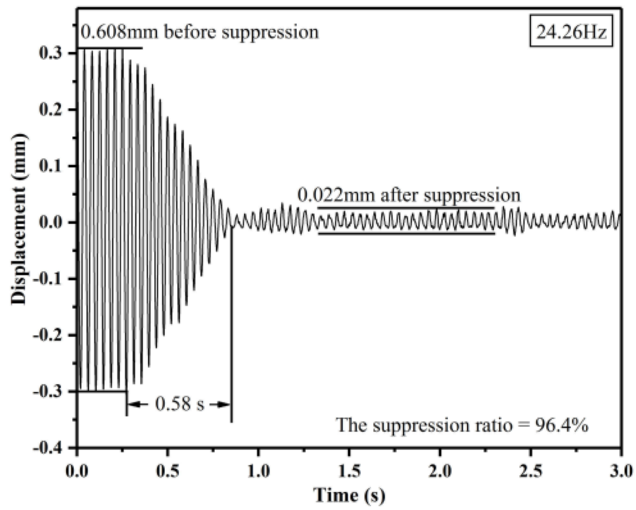

FIGURE 10. Results of the vibration suppression experiment.

circuit constructed by IC_2 is also grounded, output voltage U_2 is equal to zero. The two output voltages are transformed into output voltage U_3 through the differential amplifier, which then outputs to U_{out} after the signal conditioning circuit and STM32F407. In the open-loop working state, the waveform shape of U_{out} is the same as that of U_1 and can reflect the vibration state of the beam. Fig. 9 shows the output signals of U_1, U_2, and U_{in} at the open-loop condition.

In the open-loop working state, if the vibration must be suppressed, the system should be switched into the closed-loop condition by turning off switch S2 and turning on switch S1. Then, the output voltage (U_{out}) of the PID controller is fed back to the input of the mirror circuit to control the vibration of the beam. The excitation source still excites the cantilever beam in the first-order resonance state. The output voltage (U_1) of the piezoelectric self-sensing driving circuit is composed of U_{in} and voltage $U_{(f)}$. The output voltage (U_2) of the mirror compensation circuit is only produced

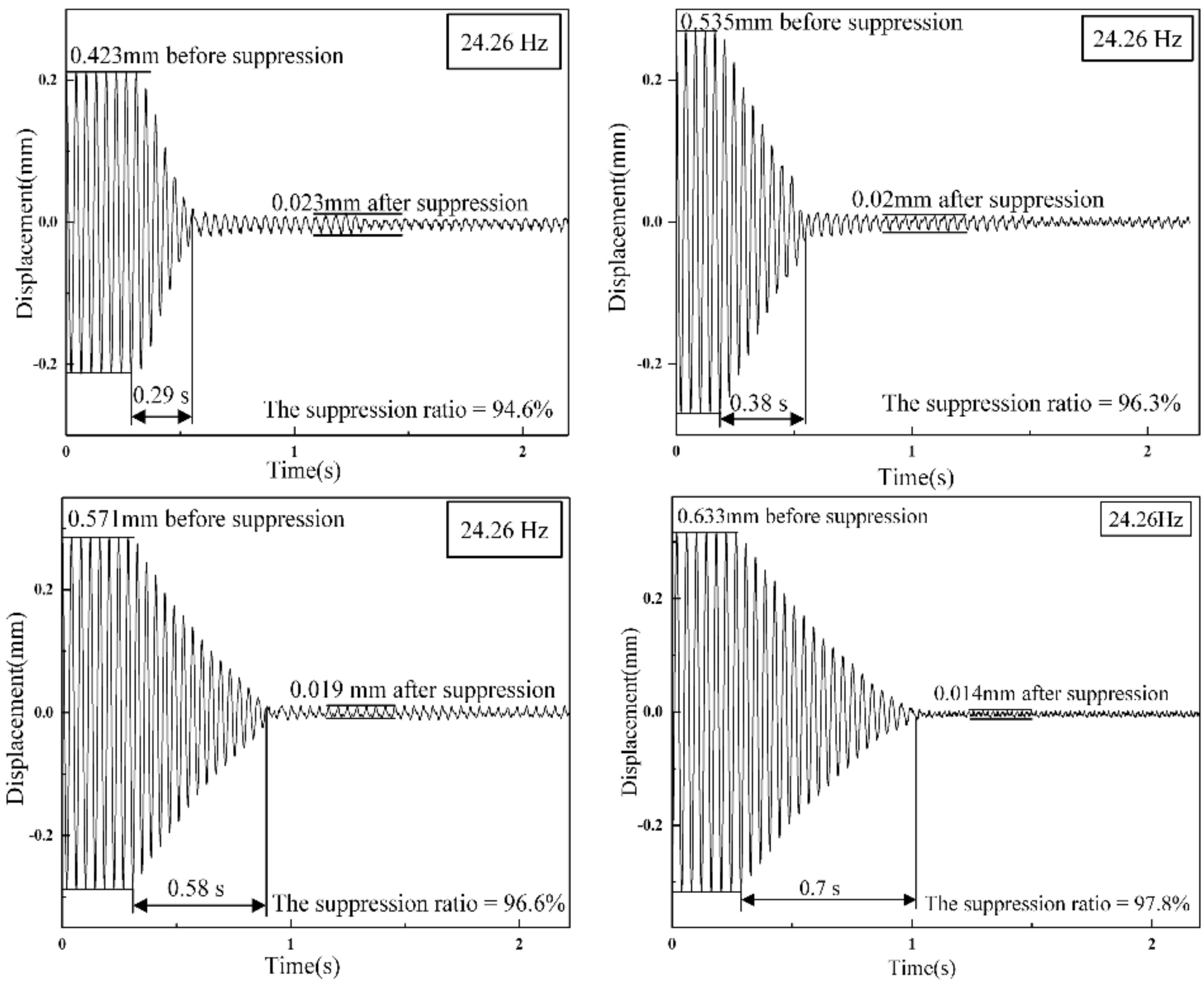

FIGURE 11. Results of the vibration suppression experiment under different displacements.

by U_{in}. Given the symmetry of the mirror circuit, the dynamic voltage ($U_{(f)}$) can be preliminarily separated as a reference signal for vibration suppression. The output voltage (U_{out}) is automatically adjusted by the signal conditioning circuit and the PID controller and is fed back to the input of the mirror circuit. During vibration suppression, the output voltages, U_1, U_2, and U_{out}, will reach a new dynamic equilibrium state as shown in Fig. 9.

When the system is switched from the open-loop to the closed-loop state, the suppression effect of the vibration can be characterized by the free-end displacement measured by the laser displacement sensor. The result of the suppression is shown in Fig. 10. The peak value of the vibration displacement before suppression is 0.608 mm. Through the self-sensing vibration suppression system, the vibration of the free end of the beam tends to reach dynamic equilibrium within 0.58 s. The peak value of the displacement is 0.022 mm. The displacement is reduced by 96%. Therefore, the self-sensing mirror circuit with a PID controller can effectively suppress the vibration of a cantilever beam. Compared with previous experiments [25], the continuous adjustment of the capacitance is unnecessary, making the entire experiment process simple and easy to operate.

To verify the adaptability of the self-sensing vibration control system, the amplitude of the excitation voltage is changed to obtain different vibration displacements at the end of the cantilever beam. Initial vibration displacements of 0.423 mm, 0.535 mm, 0.571 mm and 0.633 mm at the same frequency 24.26 Hz are chosen. The corresponding processes and results of the vibration suppression are shown in Fig. 11. According to the results, the displacements after restraint are all about 0.02 mm, and the suppression ratios are over 94%. The performance demonstrate that the improved mirror circuit has a good effect and consistency on vibration suppression of the cantilever beam at resonance.

To test the suppression characteristics of the vibration control system in the non-resonant state, the frequency sweep experiments are conducted with and without the vibration control. During the progress of the experiments, the voltage applied to the piezoelectric plate (PZT-2) for external excitation is kept constant. At each test frequency, first, turn off the switch S1 and turn on S2 in Fig. 2, making the cantilever

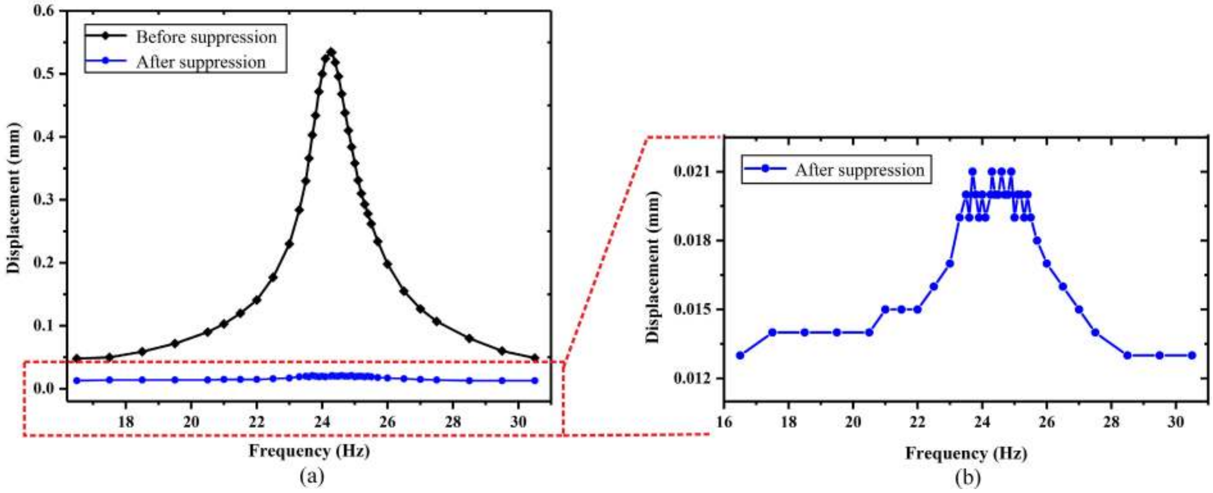

FIGURE 12. The frequency sweep test with and without vibration control.

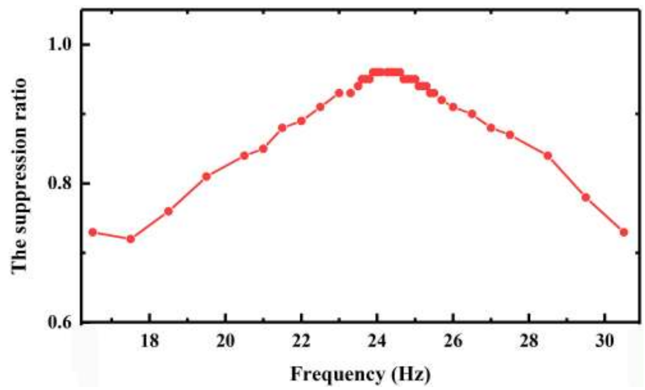

FIGURE 13. The vibration suppression ratio under different frequencies.

beam working at the open-loop state, and then measure the displacement before suppression at the free end. Next, turn on the switch S1 and keep the switch S2 turning off. Now the PID feedback control circuit is connected to the self-sensing piezoelectric plate (PZT-1) and to control the vibration. The displacements after suppression are also measured at the same position. The experimental results are measured from 16.5 Hz to 30.5 Hz, containing the resonance frequency 24.26 Hz in the range.

The detailed experimental data are shown in Figures 12 and 13. The displacement curves before and after suppression demonstrate that the vibration control system has a good vibration suppression effect in the whole test frequency range. Within the frequency range from 23 Hz to 25.5Hz, due to the relatively large displacements near resonance, the suppression performance is quite obvious and the suppression ratios are all above 93%. Within the non-resonant frequency ranges from 16.5 Hz to 22.5 Hz and from 27 Hz to 30.5 Hz, the vibration control system also performs well, but the suppression ratios are less than 90%. This is because that under the non-resonant state, the cantilever beam cannot be easily excited, and the initial vibration amplitudes are relatively small though with the same excitation. However, after the control system connected to the cantilever beam, the vibrations are well suppressed within very weak levels, and the displacements at the free end are around 0.02 mm stably after suppression, similar to the suppression effect near resonance.

TABLE 3. Q value and loss factor of the system before and after suppression.

	Q value	Loss factor
Open-loop	18.8	0.053
Closed-loop	3.5	0.288

In combination with the experimental data in Fig. 12, according to the definitions, the Q values and loss factors of the vibration control system in the open-loop and closed-loop states can be calculated [5].

The loss factor reflects the energy dissipation of a system. And the vibration suppression of a system, to some extent, is to change the energy dissipation of the system. When operation at the open-loop state, the piezoelectric cantilever beam is not connected with the feedback vibration control system, therefore the electromechanical coupling structure has a high Q value and a low loss factor as shown in Table III. When the PID feedback control circuit is connected to the piezoelectric cantilever beam, the system is working at the closed-loop state. As shown in Table III, at this time the Q value of the system is greatly reduced, and the loss factor is increased from 0.053 to 0.288. These results imply that the improved mirror circuit with PID control has a good suppression effect on the vibration generated by external excitation.

IV. CONCLUSION

In this work, an improved self-sensing technique for vibration suppression is presented for a piezoelectric cantilever beam.

This method is based on the idea of improving the mirror circuit. Experimental results show a good improvement in the active vibration suppression of the cantilever beam with the improved mirror circuit based on a PID feedback control.

Choosing a mirror circuit is the first advantage since the circuit does not require precise separation of the sensing and driving signals during the self-sensing operation. This feature avoids the problem of accurately adjusting the capacitance balance while maintaining good vibration control. Furthermore, using the mirror circuit based on the PID algorithm can avoid the drawbacks of manually and untimely adjusting parameters to meet the system requirements. Compared with the previous mirror circuits without the PID algorithm, this improved method is successfully used in an active damping system and could be built and adjusted easily and effectively. The Q values and loss factors measured in the frequency sweep test before and after vibration control show that this mirror circuit using the PID algorithm has the ability to achieve good vibration suppression performance. The method has potential use in numerous fields, including scanning probe microscopy, vibration suppression, and structure health monitoring.

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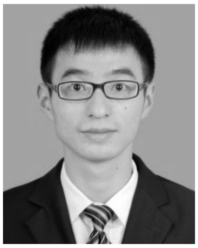

BIN JU was born in 1990. He received the B.E. and Ph.D. degrees from the University of Science and Technology of China (USTC), Hefei, China, in 2011 and 2016, respectively. He is currently a Lecturer with the College of Electrical Engineering and Automation, Anhui University, Hefei, China. His research interests include the piezoelectric device and power electronics, structural health monitoring, and simulation technology in multiphysics.

ZHIHUA GUO received the B.E. degree from Zhengzhou University, Zhengzhou, China, in 2016. He is currently pursuing the M.S. degree with Anhui University, Hefei, China. His research interest includes the structural health monitoring.

YONGBIN LIU received the M.S. and Ph.D. degrees in mechanical engineering from the University of Science and Technology of China, Hefei, China, in 2004 and 2011, respectively. He is currently a Professor with the College of Electrical Engineering and Automation, and also with the National Engineering Laboratory of Energy-Saving Motor and Control Technology, Anhui University, Hefei. His current research interests include smart material actuators, machinery condition monitoring, and fault diagnosis.

GANG QIAN received the B.E. degree from Huangshan University, Huangshan, China, in 2015. He is currently pursuing the M.S. degree with Anhui University, Hefei, China. His research interest includes the signal processing-based machine fault diagnosis.

LANBING XU received the B.E. degree from Anhui University, Hefei, China, in 1998, where she is currently a Senior Experimenter. Her research interest includes the computer control technology.

GUOLI LI received the B.E. and M.S. degrees in electrical engineering from Hefei Polytechnic University, Hefei, China, in 1983 and 1987, respectively, and the Ph.D. degree in nuclear energy science and engineering from the Hefei Institute of Material Sciences, Chinese Academy of Sciences, Hefei, China, in 2006.

She was a Lecturer, from 1983 to 1997, an Associate Professor, from 1997 to 2002, and a Professor, from 2002 to 2007, with the Hefei Polytechnic University, Hefei. From 2007 to 2010, she was a Professor with Zhejiang Polytechnic University, Hangzhou, China. Since 2010, she has been a Professor with Anhui University, Hefei. Her research interest includes optimization design of motor, robot, and special motor design.

Prof. Li's awards and honors include the Vice-Chairman of the special committee of Low Power Electrical Machinery, China Electrical Technology Society, a member of the China Electrical Technology Society, and a member of the Electronic Control System and Device Professional Committee, China Electrical Technology Society. She is currently the Director of the National Local Joint Engineering Laboratory of High Energy-saving Motor and Control Technology.