A driving power with filter compensator for micro-positioning improvement of piezoelectric bimorph actuators

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Abstract. To improve the micro-positioning accuracy of piezoelectric bimorph actuators, a driving power was designed with filter compensator. Amplifier modular was designed with high-voltage operational amplifier, and filter compensator modular is responsible for charge signal. Simulation results show that the output of filter compensator modular is proportional to the electric charge on the actuator. Experimental results indicate that the maximum error is 10μm without filter compensator modular, and reduced to 5μm with proposed driving power.

1. Introduction
In the recent years, micro-positioning has become one of the key technologies in advanced manufacturing industry. Due to high displacement resolution, fast response and small volume, piezoelectric bimorph actuators play an important role in precision engineering, micro-positioning, aerospace engineering etc. The performance of the micro-positioning system designed with piezoelectric actuators mainly depends on its driving power.

In the micro-positioning with piezoelectric actuators, a major limitation is the hysteresis nonlinearity of piezoelectric materials. It not only degrades the positioning accuracy, but also may lead system instability. Because the hysteresis between electric charge and displacement is much smaller than the hysteresis between voltage and displacement, the charge-controlled driving power is a satisfied method to improve the positioning accuracy [1]. Andrew J. Fleming designed a charge drive method for reducing hysteresis, which got a 92% improvement [2]. Jianqiang Ma Eliminated hysteresis of piezoelectric deformable mirror by charge control [3]. Chen Yang proposed a charge controller with self-sensing for piezoelectric actuators in a wide bandwidth [4]. Martin Spiller studied Hybrid charge control for stick–slip piezoelectric actuators [5].

In this paper, a driving power was proposed with high-voltage operational amplifier and filter compensator in the feedback branch. This power can drive piezoelectric bimorph actuator, and reduce the hysteresis effect to improve the micro-positioning accuracy.

2. Driving power design
2.1. Amplifier modular
Amplifier modular was designed with a high-voltage operational amplifier as shown in Fig. 1 According to the principal, the gain \( A_f \) of the amplifier modular can be calculated by

\[ A_f = \frac{R_f}{R_i} \]
\[ A_f = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \]  

(1)

where \( V_{in} \) and \( V_{out} \) are the input and output voltage respectively. Obviously, the output voltage can be changed by adjusting the resistors \( R_1 \) and \( R_2 \).

\[ \text{Operational amplifier} \]

\[ \text{Vin} \quad \text{R}_1 \quad \text{Vout} \]

Fig. 1 Amplifier modular

\[ \text{Operational amplifier} \]

\[ \text{C}_f \quad \text{R}_3 \quad \text{R}_4 \quad \text{U}_1(t) \quad \text{U}_2(t) \]

Fig. 2 Filter compensator

2.2. Filter compensator modular

Filter compensator as shown in Fig. 2 is widely incorporated in control system tuning, which can improve the system performance. The following equation can be obtained by circuit theory,

\[ \frac{U_1(t)}{R_3} = C_f \frac{d(U_2(t))}{dt} + \frac{U_2(t)}{R_4} \]  

(2)

where \( U_1(t) \) and \( U_2(t) \) are the input and output respectively. Capacitor \( C_f \) is parallel connected with resistor \( R_4 \) that is series connected with \( R_3 \). By solving equation (2), the output is

\[ U_2(t) = \left( \frac{U_1(t)e^{\frac{t}{RC_f}}}{R_C} + C_1 \right) e^{-\frac{t}{RC_f}} \]  

(3)

where \( C_1 \) is a constant.

In most of practical application, the input is some kinds of modulated sinusoidal wave. To simply the analysis, substitute \( U_1(t) = \sin(\omega t) \) into equation (3) and discard the attenuation term,

\[ U_2(t) = -\frac{R_4 \left( \cos(\omega t) R_4 C_f \omega - \sin(\omega t) \right)}{R_3 (\omega^2 R_4^2 C_f^2 + 1)} \]  

(4)

Where \( \omega \) is the angular velocity, then expand the above equation,

\[ U_2(t) = -\frac{R_4 \cos(\omega t) R_4 C_f \omega}{R_3 (\omega^2 R_4^2 C_f^2 + 1)} + \frac{R_4 \sin(\omega t)}{R_3 (\omega^2 R_4^2 C_f^2 + 1)} \]  

(5)

If chose very large resistor \( R_3, R_4 \), and very small capacitor \( C_f \), the first term is much larger than the second term which can be omitted.

Define that,

\[ K = \frac{R_4^2 C_f \omega}{R_3 (\omega^2 R_4^2 C_f^2 + 1)} \]  

(6)

Then the equation (5) can be simplified as

\[ U_2(t) = -K \cos(\omega t) \]  

(7)

It should be noted that equation (7) is the integration of input. If the input is current signal, then the output is proportional to charge signal.

2.3. Driving power

With the above two modular, a driving power is designed for micro-positioning improvement as shown in Fig. 3. Amplifier modular receive the signal from generator, and amplify the signal to drive the
piezoelectric bimorph actuator. Filter compensator modular integrates the current for charge feedback control.

![Diagram](image_url)

**Fig. 3 diagram of proposed driving power**

### 3. Simulations and experiments

#### 3.1. Simulation with Multisim

In order to validate circuit design, a simulation was performed with Multisim software. The piezoelectric bimorph actuator was modelled by a 200 MΩ resistor and a parallel capacitor of 33 nF. Amplifier modular is based on the high-voltage operational amplifier LTC6090-5, and the filter compensator modular is designed with LM358N. As shown in Fig. 4, the input and output were monitored by oscilloscope. The results in Fig. 5 indicate the proposed output of filter compensator circuit is the electric charge on piezoelectric bimorph actuator.

![Simulation](image_url)

**Fig. 4 Simulation of proposed driving power**
4. Experimental results

The size of the piezoelectric bimorph actuator is 60×10×0.8 mm as shown in Fig. 6. The amplifiers LTC6090-5 and LM358N were supplied by DC powers. The feedback branch was realized by cRIO-9030, which is a real-time controller. A laser displacement sensor (Type IL-1000) from Keyence Inc. measure the motion of actuator. The oscilloscope records the voltage and displacement signals.

The result without filter compensator modular is shown in Fig. 7. The hysteresis loop is obviously and the maximum error is 10 μm. With the proposed driving power and filter compensator modular, the hysteresis loop reduced shown in Fig. 8. Its maximum error is only 5 μm, which is much small than it without filter compensator modular. The results indicate that the proposed driving power can effectively compensate hysteresis loop of piezoelectric bimorph actuator, and significantly improve the micro-positioning accuracy.

![Simulation result](image1.png)

**Fig. 5 Simulation result**

![Experimental setup](image2.png)

**Fig. 6 Experimental setup**

![Experimental result without filter compensator modular](image3.png)

(a) Desired displacement and measured displacement

(b) Hysteresis loop without filter compensator modular

**Fig. 7 Experimental result without filter compensator modular**

![Experimental result with filter compensator modular](image4.png)

(c) Desired displacement and measured displacement

(d) Hysteresis loop with filter compensator modular

**Fig. 8 Experimental result with filter compensator modular**
5. Conclusion
A driving power with filter compensator was developed for micro-positioning improvement of piezoelectric bimorph actuator. Simulation results show that the output of filter compensator modular is proportional to the electric charge on the actuator. Experimental results indicate the proposed driving power can effectively compensate hysteresis loop of piezoelectric bimorph actuator, and significantly improve the micro-positioning accuracy.

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