Power Supply of Macro-Micro Driven Linear Piezoelectric Motor

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Abstract: To investigate a novel macro and micro driven linear piezoelectric motor composed of an ultrasonic motor with macro movement and a piezoelectric actuator with micro movement, a digital signal processing (DSP) based macro and micro power supply is designed, which fits the new linear piezoelectric motor. The power supply comprises a control circuit, a voltage conversion circuit, an amplifier circuit, a half-bridge module, an optical isolators-drive circuit, etc, where the DSP of TMS320F28335 is used as the controller. When the linear piezoelectric motor working in a macro driven state, the power supply outputs alternating currents with high frequency and high voltage, which drives the linear piezoelectric motor dynamically at an ultrasonic frequency; while working in the micro driven state, the power supply outputs direct currents with high voltage, which drives the linear piezoelectric motor in micro driven statically. Here a prototype of the macro-micro power supply is designed. After a series of experiments on the power supply with and without loads, the results show that the power supply can drive and control the macro micro driven linear piezoelectric motor, and realizes quick and seamless switch between macro and micro drive. In addition, the power supply can drive and control the ultrasonic motor or piezoelectric ceramic micro actuator individually. The power supply achieves the multiple parameters of output signals adjustable simultaneously and exhibits good control characteristics.

Key words: linear piezoelectric motor; macro-micro drive; DSP; half-bridge module

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0 Introduction

With the rapid development of the manufacture of IC chip lithography and packaging, the manufacture of micro electro mechanical system (MEMS) device packaging and assembly[1-2], and high speed scanning detection, it puts forward a high demand for positioning system of large travel, high speed, acceleration and high precision. Researches on high speed and high precision positioning system are conducted[3-6] to meet the demand of high precision large travel drive motors in the electronic information industry and other fields. Zhang et al. presented a novel linear motor composed of a macro moving ultrasonic motor and a piezoelectric micro moving actuator and its driven control system[7-9]. During the operation process, the movement of the motor can be divided into two parts, i. e., macro motion and micro motion. The mechanism of the macro motion is same with that of the linear ultrasonic motor, while the micro motion is driven by the piezoelectric micro actuator. The macro motion characterizes high speed, large travel movement, while the micro motion features small stroke, high precision positioning movement to compensate the residual position error of the macro motion, thus achieving the goal of large stroke, high speed, high precision, high frequency response for the linear motor as a whole[3].

To improve the performance of the linear piezoelectric motor, it is necessary to build a macro-micro control system, which can be widely used in large stroke, high resolution and high precision positioning system. The key technology of the macro-micro driven system of the novel linear piezoelectric motor is studied in this paper.

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1 Driven System of New Linear Piezoelectric Motor

The macro-micro driven linear piezoelectric motor is shown in Fig. 1. It consists of a composite vibrator, a mover, and a preloading mechanism. The preloading mechanism locks the composite vibrator and mover, then adjusts the preload. When the power supply outputs high frequency and high voltage alternating currents, two groups of piezoelectric ceramic transducer (PZT) discs which locate in the composite vibrator motivate two groups of standing wave with the longitudinal vibration of the transducer, then drives the macro motion. While the power supply outputting direct currents with high voltage, two groups of PZT discs motivate static deformation along axial direction of the double wedge, and then generate the micro motion.

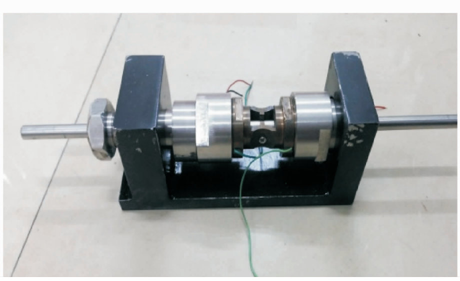

Fig. 1 Macro-micro driven linear piezoelectric motor

The driven system of the new linear piezoelectric motor integrates the existing independent macro-micro driven system[10], thus simplifying the existing macro-micro driven systems. The system's structure block, as shown in Fig. 2, encompasses a control circuit, a voltage conversion circuit, an amplifier circuit, a half-bridge module, and an optical coupler isolation driven circuit. The control circuit receives and processes the system input signals, then generates the control signals to the amplifier and optical coupler isolation circuit. The optical coupler isolation driven circuit isolates and amplifies the driven signals, then drives the half-bridge module. The voltage conversion circuit supplies power for each chip. The amplification circuit includes a digital-to-analog conversion circuit and a two-stage operational amplifier circuit, which is used to amplify the output of DC signal of the analog-to-digital conversion circuit, and output to the half-bridge module. The half-bridge module is composed of three half-bridge topology circuits with six insulated gate bipolar transistors (IGBTs), which works in the macro or micro driven state according to different driven signals of the opto-coupler isolation drive circuit. When working in the macro driven state, the driven system outputs the alternating currents with high frequency and high voltage. While working in the micro driven state, the driven system outputs a high-voltage DC.

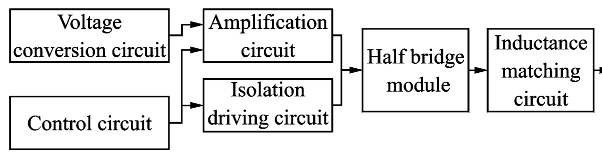

Fig. 2 Structure of driven system

2 Design of Hardware Circuit

2.1 Half-bridge circuit

The macro-micro driven system is to achieve the function of macro and micro drive. However, the macro and micro drive need different driven signals. The macro drive needs AC signals with an ultrasound frequency, and the micro drive requires a high-voltage DC signal.

To meet the disparate requirements for power supply of macro and micro drive in the same circuit, we design the half-bridge module circuit, as shown in Fig. 3. The half-bridge module consists of three half-bridges with six IGBTs.

When working in the macro driven state, the IGBTs of Q_3, Q_4 are broken. The two half-bridges inverter circuit composed of Q_1, Q_2, Q_5 and Q_6, inverts the DC voltage (V_h) into two AC sig-

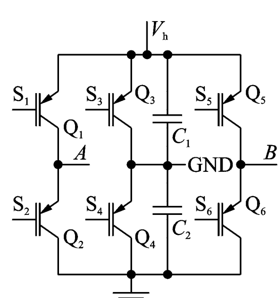

Fig. 3 Schematic of half-bridge module circuit

nals, then drives the linear piezoelectric motor[11-15]. The IGBT driven signals generated by the pulse width modulation (PWM) module of digital signal processing (DSP) controller. When changing the frequency and phase of PWM signals, the output AC signals will change. Changing the output voltage of DA, the size of V_h will change, so as to change the amplitude of the output signal in macro-driven sate.

When working in the micro drive state, the IGBT of Q_2, Q_3, Q_5 are broken, Q_1, Q_4, Q_6 are conducting. The B port outputs the voltage of HDC, and the A port outputs 0. This is a single channel for output. Moreover, when the IGBT of Q_2, Q_3, Q_6 are broken, Q_1, Q_4, Q_5 are conducting. The A and B ports output the voltage of V_h simultaneously. This becomes the double channel for output. When changing the Q_1—Q_6 switch on-off time, it can output the negative voltage. The controller DSP can update the size of V_h with changing the DA output voltage. With the change of V_h, the amplitude of the output DC signal of micro drive will change too.

From the above analysis, as long as the correct choice of switch tube of the circuit working state is given, the half-bridge circuit can make the circuit output different signals, meeting the requirements of the macro-micro driven.

2.2 Amplifying circuit

From the small voltage signals that the DAC circuit outputs to the high voltage (V_h) that the half-bridge module needs, they require linear amplification through the amplifying circuit. The amplifying circuit adopts a two-stage operational amplifier structure[17], as shown in Fig. 4, being composed of OP07 and PA85. Put a low-voltage error amplifier of OP07 front to obtain a smaller input offset voltage and high band width, and put high-voltage power amplifier with PA85 of APEX company back to obtain high output power and high-voltage withstand characteristics. The OP07 uses the symmetric power supply as $U_{CC1} = +15$ V, $U_{SS1} = -15$ V. The PA85 uses asymmetric power supply as $U_{CC2} = +420$ V, $U_{SS2} = -25$ V, the asymmetric power supply is designed to ensure that the amplifier output can vary from 0 V.

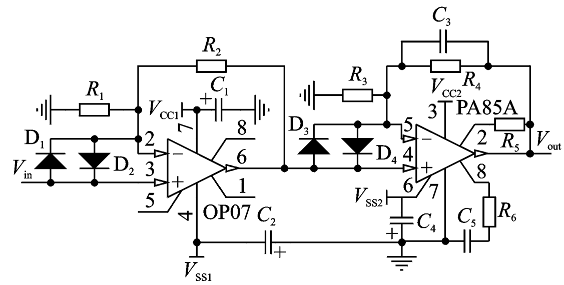

Fig. 4 Amplification circuit

Magnification of the amplifying circuit is determined by R_1, R_2 and R_3, R_4. The closed loop magnification can be derived by

$$A_1 = \frac{R_2 + R_1}{R_1} \tag{1}$$

$$A_2 = R_4 + R_3 \tag{2}$$

$$A = A_1 \times A_2 \tag{3}$$

where the closed-loop magnification of OP07 is A_1, which can be obtained by Eq. (1). The closed-loop magnification of PA85 is A_2, which can be obtained by Eq. (2). The magnification of the two-stage amplification circuit is A, being the product of A_1 and A_2, as expressed by Eq. (3).

The output voltage of DA is 0—5 V, and the output of the amplification circuit is 0—400 V. So the magnification of the amplification circuit is 80. This paper defines the magnification of OP07 as 2, and the magnification of PA85 as 40. When $R_1 = 100$ kΩ, $R_3 = 6.5$ kΩ, the result of the calculation: $R_2 = 100$ kΩ, $R_4 = 253.5$ kΩ.

2.3 DA conversion circuit

The digital to analog conversion circuit uses the chip of DAC7724, which has a good performance of low power consumption. The output range of DA conversion circuit is 0—10 V. The relationship between input and output of DA is shown as

$$V_{out} = (V_d \times 10)/65\,535 \tag{4}$$

where V_d is the digital signal output value, ranging from 0—65 535 and V_{out} the output voltage of DA, whose unit is V. When specific voltage signal is needed, the data value can be calculate by Eq. (4).

3 Design of Software

The software design is mainly aimed at driving and controlling the macro-micro driven linear piezoelectric motor[14]. It includes the programming on system initialization, AD conversion, DA output, PWM signal generation, parameter adjustment, etc. The system software flow chart is shown in Fig. 5.

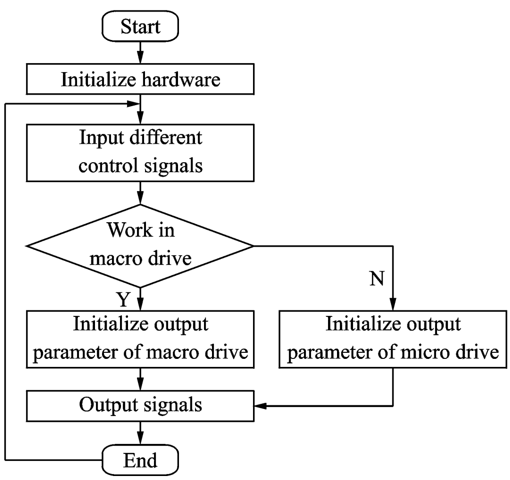

Fig. 5 Flow chart of system software

When the system is connected with power, after the completion of the system initialization of DSP, according to the different control signals, the drive system will output different voltages. When working in a macro-driven state, the drive system will output two-phase sine signals that has the phrase difference. Meanwhile, according to the different input control signal, the system can change the parameters of the output in real time, like the frequency, amplitude and phase difference of two signals. When working in the micro-driven state, the drive system will output DC signal through programming. According to the different input control signal, the system can change the output signal amplitude, direction and channels of signal. Simultaneously, the LCD displays the corresponding parameters of various states of the system and the output signal in real time.

4 Test and Result Analyses

The experiments of the power supply system consist of the test of each module and the whole system. Among them, the system tests include the no-load and load tests of macro-micro drive.

4.1 Test of each module

4.1.1 Data analysis of AD conversion

The analog signal realizes the digital analog conversion through the AD module of DSP, the conversion results are stored in the DSP registers. As shown in Fig. 6, the curves display the relationship of the input analog voltage to the theoretical value and the measured value of the AD conversion. From Fig. 6, the theoretical values of AD conversion are basically the same as the measured values, and the analog input voltage is ideally linear with the switching value.

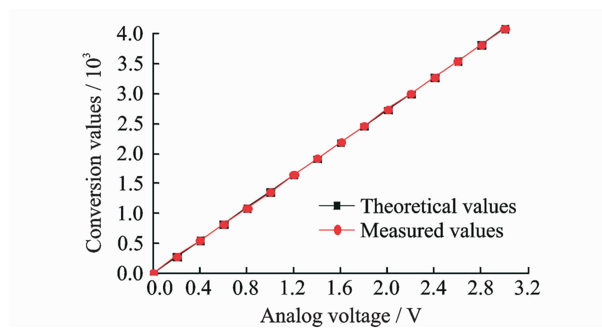

Fig. 6 Theoretical and measured curves of AD conversion value

4.1.2 Data analysis of DA conversion

The relationship between input and output of DA conversion is shown in Fig. 7. The relationship between input voltage and theoretical voltage is plotted in black, and the relationship between the input and the testing voltage values is marked in red. From Fig. 7, the theoretical values of the DA conversion are generally in accordance with the measured ones. The input and output are in an ideally linear relationship.

4.1.3 Relationship between input and output of amplification circuit

Fig. 8 shows the relationship between input and output when the input is a triangle wave signal. The blue line is a triangular wave input signal with the peak of 5 V. The output signal of the

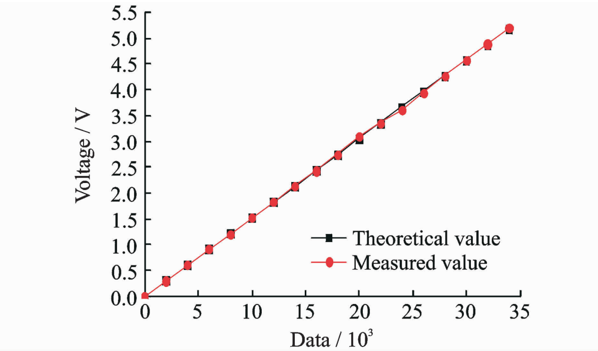

Fig. 7 DA input and output

amplifying circuit is the red triangle wave whose peak is 400 V. Fig. 7 shows that the input and output signals are in a linear relationship and the magnification is 80, which are consistent with the theoretical design.

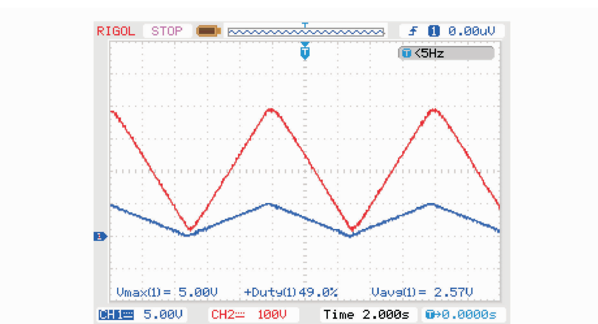

Fig. 8 Relationship between input and output signals

4.2 Tests

4.2.1 No-load test of macro driven

When the power supply working in a macro driven state, adjust the amplitude knob of the input circuit to output 130 V DC through the direct amplifier, that is loaded in the input DC voltage of inverter circuit for the half-bridge module. The matching inductance is 1.21 mH in the power supply. The output AC signals of the inverter circuit are shown in Fig. 9.

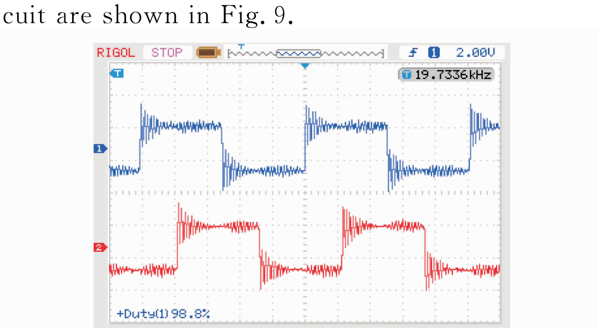

Fig. 9 Output signals of half-bridge inverter module

The no-load test of the macro driven status includes the control characteristics of amplitude, frequency and phase difference of the output AC signals. The amplitude regulation characteristics, in the absence of matching inductance, is the same as that of the micro driven.

The frequency adjustable characteristic includes the coarse and fine tunings of frequency. The coarse frequency characteristic is shown in Fig. 10 and the fine one is shown in Fig. 11. The abscissa value is the output theoretical frequency, and the ordinate value is the value of the measured output frequency. As shown in Figs. 10, 11, the adjustable range of frequency is 15—55 kHz. The values of theoretical and actual output are almost the same, so the frequency output characteristic of the power supply is satisfying.

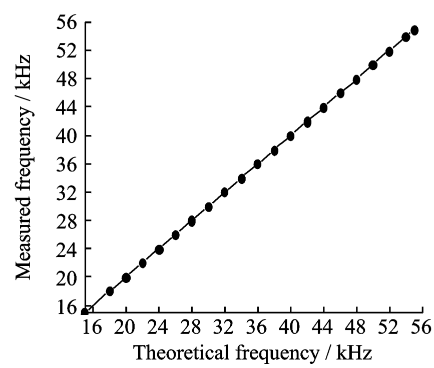

Fig. 10 Coarse frequency curve

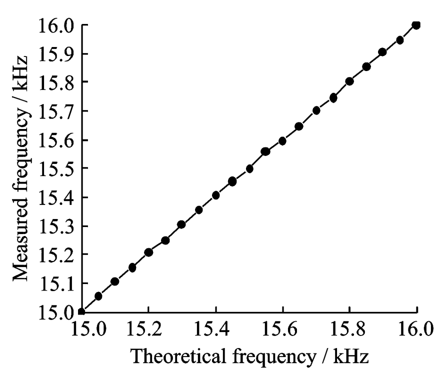

Fig. 11 Fine-tuning frequency curve

The phase difference adjustment is the effect of the phase difference change on the phase difference of two output signals. The phase adjustment curve is shown in Fig. 12, where the abscissa is the theoretical values, and the ordinate is the measured values. The adjustment range of the phase difference is −90°—90°. The theoritical results agree well with the measured ones. The phase difference regulating characteristics of the output signal is satisfying.

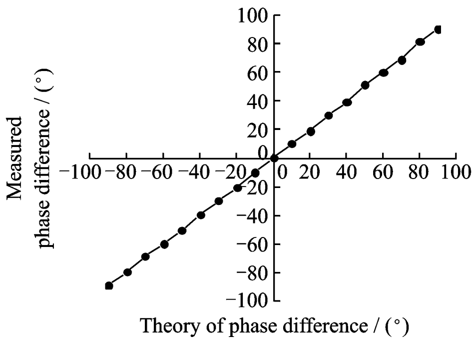

Fig. 12 Phase difference regulating curve

4.2.2 No-load test of micro driven

The unload test of micro driven refers to the characteristic test of the output voltage amplitude modulation, including the coarse and fine control characteristics. As shown in Figs. 13, 14, the abscissa refers to the input circuit potentiometer AD conversion value. Fig. 13 is the characteristic curve of voltage coarse control, and the coarse resolution 20 V. Fig. 13 shows the characteristic curve of voltage fine control, and the fine resolution 1 V. As shown in Figs. 13, 14, the amplitude range of the output voltage of driven system is 0—400 V, the coarse resolution 20 V, and the fine resolution 1 V, which indicates that the output of the drive system has good voltage regulation characteristics.

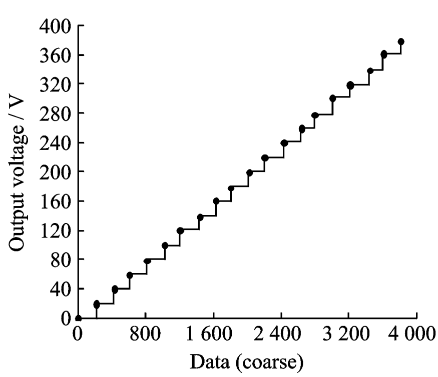

Fig. 13 Coarse tuning output voltage

4.2.3 Load test of new linear piezoelectric motor

The load test of the proposed linear piezoelectric motor includes tests of macro-driven and micro driven. When working in the macro-driven

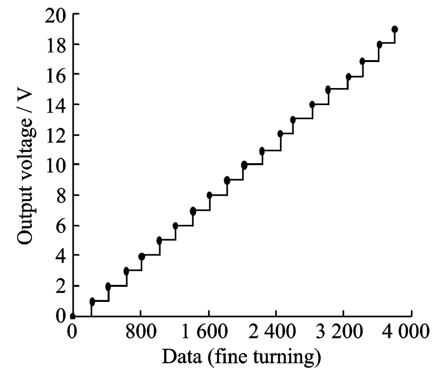

Fig. 14 Fine-tuning output voltage

state, the speed of the motor is measured by the grating ruler. The output signals' wave of the system is shown in Fig. 15.

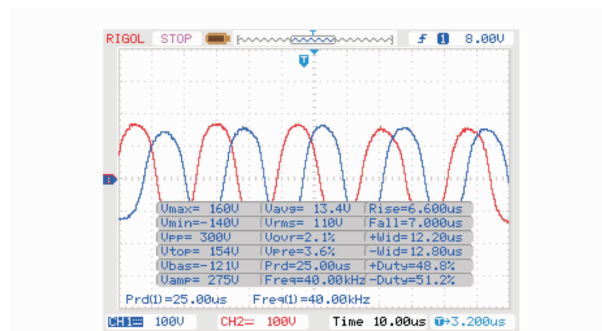

Fig. 15 Output signals of macro driven

When working in a macro driven state, change the amplitude of output signal of the driven system, and the new linear piezoelectric motor's speed will change. As shown in Fig. 16, the curve between speed and voltage is measured under the circumstances with the output signals' frequency of 35 kHz and the phase difference of 90°. From Fig. 16, when the output signal amplitude (peak to peak) is more than 80 V, the new linear piezoelectric motor starts to run. In the affordable range of piezoelectric ceramic, the speed of the motor increases along with the increase of the amplitude. The correlation between the amplitude of output signal and the motor's speed is positive.

When changing the frequency of output signal of the driven system, the new linear piezoelectric motor' s speed will change. As shown in Fig. 17, the curve between speed and frequency is measured under the circumstances of the output signals' amplitude (peak to peak) being 304 V

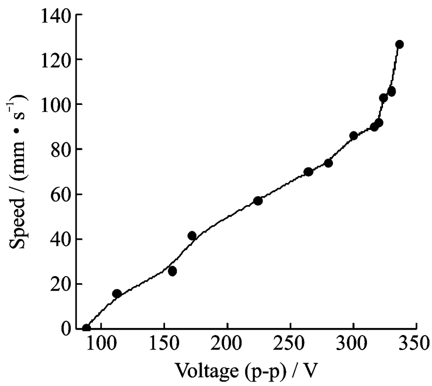

Fig. 16 Relationship between voltage amplitude and speed of macro driven

and the phase difference being 90°. From Fig. 17, the new linear piezoelectric motor's driven frequency is 32.5—40.5 kHz. That is to say, the speed increases with the raising of the frequency between 32.5 kHz and 40.5 kHz, and velocity decreases with the raising frequency between 37 kHz and 40.5 kHz.

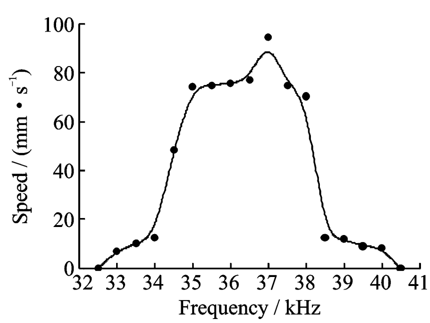

Fig. 17 Relationship between frequency and speed of macro driven

When changing the phase difference of output signals of the driven system, the new linear piezoelectric motor's speed will change. As shown in Fig. 18, the curve between speed and phase difference is measured under the conditions that the output signals' amplitude (peak to peak) is of 304 V and frequency of 35, 36 and 37 kHz. From Fig. 18, the speed increases with the phase difference between the two output signals. The speed and the phase difference phase between the two output signals are positively related.

When working in the micro driven state, changing the amplitude of output signal of the driven system, the new linear piezoelectric motor's micro displacement will change. The displacement of micro motion is measured by the la-

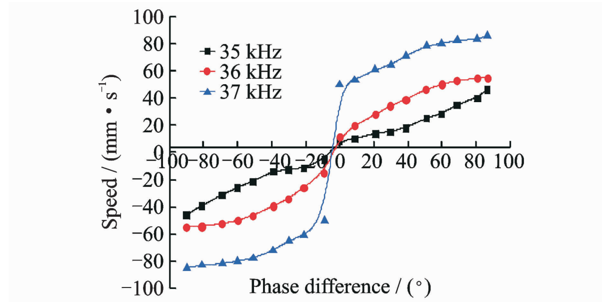

Fig. 18 Relationship between phase difference and velocity of macro driven

ser vibrometer OFV-505/5000 of Polytec. As shown in Fig. 19, the displacement of the motor shaft increases with the raising of DC voltage and they are akin to the linear relationship. Figs. 16—19 show that the power supply can actuate the macro-micro motion of the new linear piezoelectric motor.

The drive system can drive a new type of linear piezoelectric motor, not only for macro motion but also for micro motion.

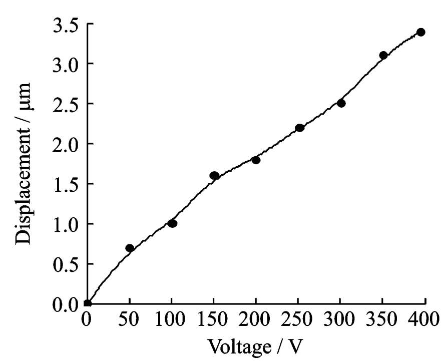

Fig. 19 Relationship between displacement and voltage of micro driven

5 Conclusions

The macro-micro driven system of a novel linear piezoelectric motor is designed, which realizes the integration of the macro and micro drive power, and meets the driven requirements of the linear piezoelectric motor with a good control characteristic. Test results demonstrate that the amplitude range of the output signal of the driven system is 0—400 V, and the resolution is 1 V. The adjustment range of frequency is 15—55 kHz, with the resolution of 20 Hz. The adjustment range of the phase difference is −90°—90°, with the resolution of 1°.

Acknowledgements

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