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Study on the Integral Separation PID Control in Piezoelectric Crystal Positioning Process

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Abstract: The Preisach control model is one of the effective methods for piezoelectric crystal control. However, unstable data sampling brought considerable influence and errors to the control process. For the purpose of improving the precision and stability of positioning control in implementation procedure, this paper applied the integral separation PID control technology to piezoelectric crystal positioning process. Desirable results of precision control have been acquired.

Key words: Piezoelectric crystal, integral separation PID control, parameter tuning, preisach mode

INTRODUCTION

High precision and high-resolution ultra-precision feed system plays an extremely important role in modern industrial production and scientific research is an important factor to ensure the accuracy of part size and processing precision and ultra precision machining necessary means of piezoelectric ceramics micro-displacement of small size, high displacement resolution, high frequency response, large carrying capacity, no noise, no heat and so on (Yu *et al*., 2002), providing a relatively easy way to input voltage of the drive into nanoscale precision precision motion is an ideal nano-micro displacement components show excellent prospects for application in optics, electronics, aerospace, machinery manufacturing, bioengineering, robotics and other technical fields (Sebastian and Salapaka, 2005). Piezoelectric ceramic inherent non-linearity, hysteresis (Abidi and Sabanovic, 2007), creep, leading to the nonlinear effects of the piezoelectric ceramic and brought difficulties to the control of the piezoelectric ceramics (Dubra *et al*., 2005):

- **Open-loop control method based on feedforward nonlinear hysteresis model:** The establishment of the piezoelectric ceramic voltage-displacement model approximation of the hysteresis curve of the piezoelectric ceramic from a mathematical point of view. These models have their own characteristics, accurate open-loop control system can achieve better results in theory, become the research focus of many scholars but the method in the application of the need for further research and improve (Song *et al*., 2011)
- **Charge control methods:** The core of the method is based on charge control of drive power and current source instead of the voltage source but because of high internal resistance of the piezoelectric ceramic, so the charging current is small, slow response, making this method is only suitable for static situations (Rakotondrabe and Ivan, 2010)
- **Closed-loop control:** High-precision, high response displacement sensor, closed-loop control, an effective solution of the nonlinear error due to non-linear characteristics of piezoelectric ceramics, have a great advantage in system reliability and practicality. The piezoelectric ceramic is a capacitive element between the layers by adhesive bonding, there is elastic deformation, the drive voltage input and displacement output between the linear and quadratic curve is not ideal conditions the relationship between the output displacement of the existence of hysteresis, nonlinearity, creep properties, which caused some errors to the bench positioning and repeatability. Machining accuracy and assembling accuracy cannot infinitely increase under the premise, it is necessary to further improve the positioning accuracy. The certain control strategy must be taken

Precisely because of the hysteresis nonlinearity of piezoelectric ceramics, the bench and during operation,

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due to wear and tear, aging, drift and environmental change, its characteristics are constantly changing and this change is unknown, uncertain the. Therefore, to obtain precise enough but micro-positioning table but divided into a complex mathematical model is a prerequisite of the design control. Preisach model is a more extensive application of the model, the superposition of a number of the simplest hysteresis generator, showing the global memory can be described piezoelectric ceramic actuator hysteresis curve of the complex process of multi-pole. Using this model and greatly improve the tracking accuracy of the piezoelectric ceramic actuators. The realization of this model is more complex and difficult to adapt to dynamic changes in the signal, therefore need to find a relatively simple structure and easy-to-line adjustment of model forms (Zhu *et al*., 2011).

Preisach control model has become a widely used control model in the field of piezoelectric crystal control for its simple structure and easy programming implementation. However, since open-loop Preisach control process has considerable errors, PID and other feedback control process should be introduced to improve controlling precision of the system. The feed-forward and feedback control process based on PID can diminish the curve tracking error within 5 nm (Rakotondrabe, 2011).

The integral separation PID control technology used in this paper for precision positioning control of piezoelectric crystal, compared to previous open-loop control and proportional control method, showed a better performance on the improvement of controlling precision and stability.

PREISACH MODEL AND PZT OPEN-LOOP, VARIABLE PROPORTION CONTROL PROCESS

Preisach model principle and application: The present formulas of Preisach model is based on the Mayergoyz conclusion and its deductive forms:

$$f(u)=\sum_{k=1}^{n-1}(f_{a_k\beta_k}-f_{\alpha_k\beta_{k-1}})+f_{u(t)}-f_{u(t)\beta_{n-1}},\ (n>=2) \qquad (1)$$

$$f(u)=\sum_{k=1}^{n-1}(f_{a_k\beta_k}-f_{\alpha_k\beta_{k-1}})+f_{a_n u(t)}-f_{a_n\beta_{n-1}},\ (n>=2) \qquad (2)$$

where, $\{\alpha_k\}$ and $\{\beta_k\}$ are respectively sequences of extreme points of rising and falling process of piezoelectric crystal voltage; n donates the number of terms of the sequences; f_α and $f_{\alpha\beta}$ donates displacement corresponding to the process of voltage rising process a and displacement corresponding to β in the first order recoil line, respectively. Equation 1 is applicable to the case that voltage ends with rising status; Eq. 2 is applicable to the case that voltage ends with falling status. It can be seen from Eq. 1 and 2 that displacement f(u) corresponding to an arbitrary voltage $u(t)\{\{\beta_k\}<\}<u(t)<\{\alpha_k\}\}$ can be determined according to the changes of voltage ($\{\alpha_k\}$, $\{\beta_k\}$) applied to ceramics together with the displacement $f_{\alpha i}$, $f_{\alpha i\beta i}$ and $f_{\alpha i\beta\text{-}i}$ that correspond to each extreme point. Similarly, in the micro positioning process, the required input voltage of ceramics u(t) can be determined by back-calculation of equation (1)and (2) according to the required displacement f(t) and changes of voltage ($\{\alpha_k\}$ and $\{\beta_k\}$) from zero initial status.

Preisach mode general control process: The value of u(t) that required in experiment is calculated by $f_{\alpha i}$, $f_{\alpha i\beta i}$ and $f_{\alpha i\beta\text{-}i}$ that was determined by previous data acquisition. However, under the circumstance without insurance of the repeatability of piezoelectric crystal controlled process, there would be errors among each data acquisition process. In the practical positioning process, open-loop positioning process can not ensure a desirable result of PZT deformation (Mohammadzaheri *et al*., 2012). Table 1 shows the experimental result of open-loop positioning control process (Rakotondrabe *et al*., 2010). As shown in Table 1, in the open-loop control process, even if Preisach control model was used, there were significant errors (maximum-1.89 um/37.8%, minimum 0.79 um/15.8%), a result that can not satisfy the precision control requirement. Meanwhile, it is also indicated from Table 1 that if piezoelectric crystal was applied exclusively a zero-voltage, positioning error increase with the increase of experiments due to the hysteresis of piezoelectric crystal, in other words, hysteresis loop of rising process is not coincident with that of falling process as shown in Fig. 1.

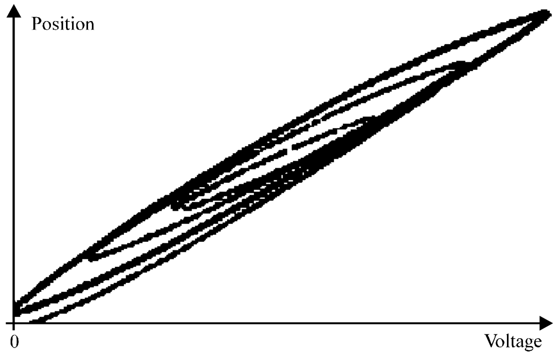

Fig. 1: Piezoelectric ceramic hysteresis loop

Table 1: Preisach model open-loop control result (um)

Times	Initial objective value	Actual initial value	Error	Positioning objective value	Actual position value	Error
1	10	9.68	-0.32	5	3.55	-1.45
2	10	9.44	-0.56	5	3.32	-1.68
3	10	9.07	-0.93	5	3.11	-1.89
4	10	10.04	0.04	5	4.21	-0.79
5	10	9.67	-0.32	5	3.74	-1.26
6	10	9.44	-0.36	5	3.45	-1.55

Table 2: Preisach model variable proportional control process result (um)

Times	Initial objective value	Actual initial value	Error	Positioning objective value	Actual position value	Error
1	10	10.12	0.12	5	5.07	0.07
2	10	10.05	0.05	5	4.98	-0.02
3	10	10.28	0.28	5	4.84	-0.16
4	10	10.28	0.28	5	4.85	-0.15
5	10	10.28	0.28	5	4.8	-0.2
6	10	10.3	0.3	5	5.05	0.5

Although, increasing the number of times of data acquisition is an effective mean to minimize random error in data acquisition, it fails to completely solve the problems in positioning. Therefore, close-loop feedback control should be used to realize more precise positioning process. Six experiment results of the system that used variable proportional feedback control was shown in Table 2.

The results in Table 2 indicate that positioning errors were greatly diminished in the process of variable proportional feedback control (maximum 0.20 um/4%), though following problems still existed:

- The time for precision positioning was increasingly longer as more experiments were conducted
- Typically, multi-times continuous positioning still resulted to the increase of error

There was instability of feedback process, namely misconvergence in few positioning processes. In this system, the convergence threshold of variable proportional feedback was 0.25. If the convergence threshold was smaller, the time for convergence would be longer and thus more misconvergence.

PID CONTROL PROCESS

PID control principle: From the above analysis shows that the piezoelectric ceramics there are nonlinear characteristics such as hysteresis, creep, hysteresis caused by the displacement uncertainty is generally (15-20%), non-linear (2-10%), creep (1-5%). Based on the above features, the precision approach to the piezoelectric ceramic actuator displacement output of the system is nonlinear. At the same time, depending on the operating conditions in actual use but also there is interference, it must control be eliminated to ensure stability and linear precision feed system displacement output.

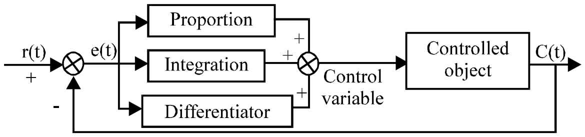

Fig. 2: PID control system schematic

In order to improve the piezoelectric ceramic micro-displacement nonlinear, closed-loop control system designed to have a high ability to quickly respond. Displacement feedback generated by the displacement sensor precision into the implementation of appropriate closed-loop control to the table, to some extent, eliminate the lag errors caused by the piezoelectric ceramic physical properties, to obtain a higher displacement resolution and dynamic stiffness the positioning error of the system through software algorithms to achieve accurate positioning accuracy. The service life of the piezoelectric ceramic is calculated in accordance with the stretching hundreds of millions of times, life is short, you need to control processes and improve the service life of the piezoelectric ceramic and efficient.

Figure 2 shows the principle diagram of general PID control system. Typical PID controller is a sort of linear controller in which three parameters proportional (P), the integral (I) and derivative (D) values are summed to calculate the output of the PID controller as controlled variable according to the "error" value e(t) = r(t)-c(t) as the difference between a given value r(t) and actual output value c(t). The form of PID algorithm is:

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}] \qquad (3)$$

where, K_p is proportional coefficient, Ti is integral time constant and Td is derivative time constant.

For implementation on computer, the discretization of Eq. 3 is obtained as:

$$u(k) = K_p[e(k) + \frac{T}{T_i}\sum_{j=0}^{k} e(j) + \frac{T_d}{T}(e(k) - e(k-1))] \qquad (4)$$

The T is the sampling period, e (k) for the deviation of the k samples, k = 0, 1, 2, 3, ...; Ki is the integral coefficient K_d is a differential coefficient. Equation 4 for the positional PID regulator output u(k) is the full output, the output and the historical state, the heavy workload of the computer operator, the error signal e(k) accumulation.

PID digital regulator output is only incremental, relatively small impact in the computer malfunction; easy to do in a manual or automatic switching, with bumpless transfer formula in cumulative value is related to sampling, only in recent times, so easy to obtain better control effect:

$$\Delta u_p(k) = K_p[e(k)-e(k-1)] \tag{5}$$

$$\Delta u_i(k) = K_i e(k) \tag{6}$$

$$\Delta u_d(k) = K_d[e(k)-2e(k-1)]+e(k-2) \tag{7}$$

Thus:

$$\Delta u(k) = \Delta u_p(k)+ \Delta u_i(k)+ \Delta u_d(k) \tag{8}$$

Integral separation PID control structure: The integral term was introduced to system for the purpose of diminishing static error, improving controlling precision (Sutor *et al*., 2011). However, in such cases as step signal input, system may have a huge deviation leading to integral accumulation in PID calculation, thus the calculated controlled variable will exceed system limit as a result. In this system, we adopted integral separation PID control, whose implementation process as follows.

Let ϵ as threshold, integral process ceases if $|e(k)|>\epsilon$, in which case only PD control process is used, avoiding overshot but spurring response; if $|e(k)|<\epsilon$, PID control is used to ensure controlling precision.

The PD control algorithm is expressed as:

$$\begin{aligned} u(k) &= K_p\{e(k)+\frac{T_d}{T}[e(k)-e(k-1)]\}, \\ &= K_p(1+\frac{T_d}{T})e(k)-(K\frac{T_d}{T})e(k-1) \end{aligned} \tag{9}$$

where, integral coefficient is zero.

In the PID control process, derivation of Eq. 9 is:

$$\Delta u(k) = K_p\Delta e(k)-K_i e(k)+ K_d[\Delta e(k-1)] \tag{10}$$

$$\Delta e(k) = e(k)-e(k-1) \tag{11}$$

In which, K_i is integral coefficient and K_d is the derivative coefficient.

The system control diagram and program flow diagram was shown in Fig. 3. PID control or PD control was chosen in accord with the actual error. The voltage output of threshold switch control varied within the voltage output range of DAQ card.

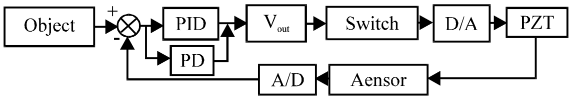

Fig. 3: Diagram of control system

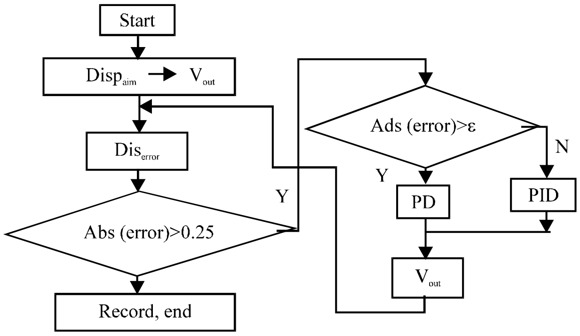

Fig. 4: Diagram of program flow of integral separation control process

It is shown that the diagram of program flow of integral separation control process in Fig. 4. Before the program runs through the man-machine interface input, enter the feed step, feeding frequency and feed interval time, the system is in standby state. Start signal through an external release, precision into the system; the displacement parameters based on the input, the system based on displacement-voltage data model, draw the system needs to output the digital voltage by the DA conversion to digital voltage is converted to analog voltage, analog the output voltage is magnified by the piezoelectric ceramic drive power to the piezoelectric ceramic driven precision approach to the table; sophisticated detection system will be real-time measurement of displacement feedback in the form of analog voltage signal back to the computer by AD conversion for digital voltage transmission to compensate for processing, until the completion of the step movement.

PID parameter tuning: Since Ziegler and Nichols proposed PID parameter tuning method, many technologies have been used for manual and automatic PID parameter tuning as different tuning methods. Normalized PID parameter tuning was put into use in this paper. In Eq. 3, four parameters T, K_p, T_i, T_d should be determined for parameter tuning of PID controller. For simplicity, we introduced constraint conditions to reduce the number of parameters to be tuned. For example, let $T = 0.1T_r$, $T = 0.5T_r$, $T = 0.125T_r$ substitute them into Eq. 9, then:

$$\Delta u(k) = K_p[2.45e(k)-3.5e(k-1)+1.25e(k-2)] \tag{12}$$

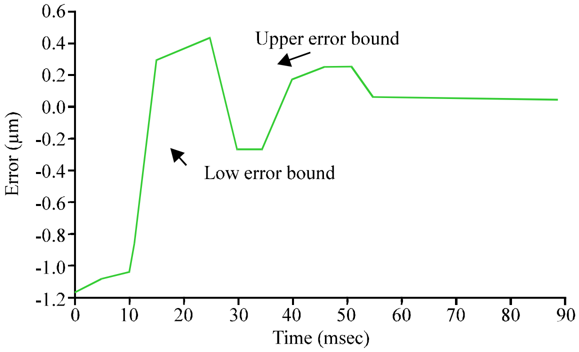

Fig. 5: PID position control process of PZT

Table 3: Result of Preisach model integral separation PID control process (um)

Times	Initial objective value	Actual initial value	Error	Positioning objective value	Actual position value	Error
1	10	10.14	-0.14	5	4.93	-0.07
2	10	10.02	0.02	5	4.87	-0.13
3	10	10.02	0.02	5	4.91	-0.09
4	10	10.02	0.02	5	4.89	-0.11
5	10	10.04	0.04	5	4.85	-0.15
6	10	10.05	0.05	5	4.91	-0.09

Kp is determined as 0.2 after adjusting and tuning.

EXPERIMENTAL RESULTS

After PID adjusting and control, we obtained desirable results of PZT precision positioning control. the results of 6 times of continuous integral separation PID control was shown in Table 3. The positioning process was illustrated in Fig. 5.

The same measuring point, the test repeated measurements, each output value is not the same, its size is random. From 2-12 µm every 1 um as a location point, each location point, respectively, for 10 measurements the repeatability deviation ÄRmax = 0.027µm (repeatability of positioning at 8 µm).

Stability refers to the system output changes in the case of long working hours, sometimes also called the long job stability. Positioning the system output in 5 and 10 µm and then were measured every three hours apart, measured data are shown in Table 1. By the data in the table, the error between the system output value specified expectations -0.14 to -0.05 (at the 10 um), -0.15 to -0.07 um (5 um when); around twice the difference between the output value is stable error.

CONCLUSION

Both theoretical analysis and experimental results show that by using integral separation PID control, higher precision control process can be realized, the time for stabilization is greatly shortened compared to variable proportional control. Moreover, oscillation and misconvergence will not occur in the process.

Additionally, in the case of multi-degree of freedom micro position platform which is composed of multi-piezoelectric crystals, if the position variation of single piezoelectric crystal can be precisely controlled, translational displacement and axial rotation of micro position platform in x, y, z directions can be precisely controlled under the circumstance that position variation of each piezoelectric crystal is immediately measured.

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