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Fast Fuzzy Controller of Electromagnetic Levitation Micro-actuator

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Abstract. An electromagnetic levitation micro-actuator was described. Aiming at the characteristics of the micro-actuator, a fuzzy control method was proposed. The input and output signals and the control parameters of control unit were analyzed and corrected. To verify the traceability of the micro-actuator, the real test experiments were performed using the step, square signals. The real test experimental results show that the control method for the micro-actuator was correct and feasible.

Keywords: Micro-actuator; Fuzzy control; Track.

1. Introduction
Electromagnetic levitation micro-actuator uses the principle of magnetic levitation run, which is a new type of micro-actuator driven by magnetic field force [1-3]. The proper control method is the key to realize the micro drive control in the micro-actuator [4, 5], whether its performance is good or bad is directly related to the success or failure of the micro drive. Because when the motion part of the micro-actuator track the change of the control signal, the motion lags behind due to its own inertia. The boundary effect of the magnetic field, distortion, the error of the approximate analysis of the magnetic field [6], the vortex noise of the circuit, external vibration interferences exist at any time, which make the drive control produce errors. Therefore, in order to meet the rapidity of micro-actuator for control signal tracking, the stability and steady precision of motion process, the control systems need adjust the parameters of the control system online for the actual motion features of the micro-actuator, and make the actuator work in the optimal state.

2. Working Principles of Micro-Actuator
The structure diagram of electromagnetic levitation micro-actuator is shown in Figure 1. The vertical and horizontal 240 circle wire are orthogonally stacked on the bottom surface constituted by the weakly magnetic materials, and the epoxy resin is fixed to form the 240 x 240 wire array magnetic field [7]. The electric current in the vertical and horizontal directions produce five regional magnetic fields above the wire plane, the five peaks distributed in the magnetic field and magnetic field intensity distribution of permanent magnet array in air gap are mutually exclusive, make them behave as repulsion, and it is suspended by adjusting the current strength. The permanent magnet array motion body is composed of 7 x 7 small magnets with different magnetic pole directions, these small magnets according to Halbach array arrangement [8], and arranged by 45° rotation angle vector superposition
The experimental reflection measuring mirror and driving connection device above the motion body. With the corresponding high precision eddy current displacement sensor, high precision measurement for displacement is carried out. The current size and direction after digital processing system regulated bottom wire array control its motion.

![Figure 1. Wire Structure Diagram of Actuator](image)

![Figure 2. Halbach Array](image)

### 3. Fast Fuzzy Controller Design

#### 3.1. Design of Fast Controller

The error which actuator responds to control signals is bigger in the early stage, in order to realize the actuator to quickly follow and respond the control signal, the controller needs to have great control output; fast controller is designed based on this principle, which is made up of logical judgment module and fast control module two parts. The expression is shown in formula (1).

\[
U_i = \begin{cases} 
1 & E > a \\ 
0 & E \leq a 
\end{cases}
\] (1)

When actuator start respond to control signals, the position error \( E \) is bigger, the logical judgment module compare error and setting error threshold \( a \), when error is greater than the threshold, the logic judgment module output signal similar to 1, and makes the actuator respond to drive signal with the fastest speed. When the error is less than the setting threshold \( a \), logic judgment module output signal similar to 0, control error through fuzzy PID control link, dynamically adjust PID parameter values in a small scale, and improve the control precision.

#### 3.2. Fuzzy PID Controller Design

According to the actual situation of the control system, the error and change rate of the controlled process can only be observed, therefore, the error \( E \) and change rate of error \( Ec \) are taken as input of the controller in the fuzzy control system. The function of fuzzy controller is to adjust the parameters of PID controller in real time, therefore, the fuzzy controller is determined as the structure of the two-input three-output, as shown in Figure 3.
3.2.1. Fuzziness of Input Quantity. The method of linear transformation is used to convert the actual value of system feedback to required domain scope, if the actual input is $x'_0$, the change range is $[x'_\text{min}, x'_\text{max}]$, if the required domain is $[x_\text{min}, x_\text{max}]$, the linear transformation is used, then:

$$x_0 = \frac{x'_\text{min} + x'_\text{max}}{2} + k(x'_0 - \frac{x'_\text{min} + x'_\text{max}}{2})$$  \hspace{1cm} (2)$$

$$k = \frac{x_\text{min} + x_\text{max}}{x'_\text{min} + x'_\text{max}}$$  \hspace{1cm} (3)$$

$k$ is the scaling factor.

Set the basic theory domain as $[-e, e]$, the domain of fuzzy sets is $X = \{-n, -n+1, ..., 0, ..., n-1, n\}$, $n$ is number which error continuously change $0 \sim e$ range after discretization. In actual control, the change of the error is usually not the element in the domain $X$, and it need scaling factor to do domain change. Once the scaling factor is determined, any error in the system can always be quantified as an element of the domain $X$.

The input quantity of the fuzzy controller is the error $E$ of the system feedback and the error change rate of the calculated error $Ec$. The input variables are divided by the fuzzy subset of finite numbers. In the normal case, fuzzy state language variables of input quantity are divided into seven levels: positive big (PB), positive medium (PM), positive small (PS), zero (ZO) and negative small (NS), negative medium (NM), negative big (NB).

3.2.2. Establishment of Fuzzy Rule. The fuzzy control rule is a summary, and it embodies that the actuator track control signal. Because the fuzzy controller uses the fuzzy quantity, the control quantity $u$ is also the fuzzy quantity. In addition, the control quantity needs to be carried out fuzzy definition similar to deviation $E$. The fuzzy control rule table covers the pre-designed control rules, namely, how to determine which most reasonable rules to set the parameters in the face of multiple inputs. The fuzzy control rule table designed in this paper is shown in table 1.
Table 1. Corresponding Table of Fuzzy Rules

| E   | (a) $K_p$ | (b) $K_i$ | (c) $K_d$ |
|-----|-----------|-----------|-----------|
| Ec  | NB NM NS  | Ec        | NB NM NS  |
|     | NB O O O O | NB M B B B | NB B B B M |
|     | NM M B S S | NM S B B B | NM M M M S |
|     | NS B M S S | NS O M M M | NS M M M S |
|     | ZO B S S S | ZO O S S S | ZO O O O S |
|     | PS B S S S | PS O M M M | PS S S S M |
|     | PM M B S S | PM B B B B | PM O S M M |
|     | PB O O O O | PB B B B M | PB O S M M |

The following parameter setting rule can be obtained:

1. If the error $E$ is large, quick control should be taken to minimize the error with the fast speed, $K_p$ is used, integral coefficient $K_i$ can be ignored.

2. If $E \cdot Ec > 0$, It shows that error tends to increase. If the absolute value of $E$ is small, medium $K_p$ is used, larger $K_i$ increase steady-state precision, smaller $K_d$ avoid oscillation. If the absolute value of $E$ is larger, it is proper to use the larger $K_p$ to change the trend, smaller $K_i$ and larger $K_d$ make the system quickly stable.

3. If $E \cdot Ec < 0$, It shows that the error tends to decrease. If the absolute value of $E$ is smaller, the steady-state precision can be taken at the same time, and smaller $K_p$ can avoid oscillation. If the absolute value of $E$ is larger, it is appropriate to change the trend with medium $K_p$, smaller $K_i$ and larger make the system rapidly stable, ensure the precision and reduce the steady-state error.

The results of the above fuzzy inference are all fuzzy values, which cannot be applied directly to the controlled object, and they need to be transformed into the exact amount that an executing agency can execute. This process is generally called as the solution fuzzy process, and it can be regarded as the mapping of fuzzy space to clear space. By adopting the gravity method [10] (weighted average method), the calculation formula of inference results is as follows:

$$K^* = \left( \frac{1}{n} \sum_{i=1}^{n} \mu(K_i) K_i \right) / \sum_{i=1}^{n} \mu(K_i)$$  \hspace{1cm} (4)

$K^*$ is corresponding to $K_p$, $K_i$, $K_d$ three fuzzy output, $K_i$ express the $i$ th language variable. $\mu(K_i)$ Represents the membership function value obtained by the $i$ th rule.

The quantization errors in the solving fuzzy process need to be solved by the modified algorithm. The parameter correction formula of $K_p$, $K_i$, $K_d$ are as follows:

$$K_p = \{E_i, Ec_i\} \times \Delta P$$  \hspace{1cm} (5)

$$K_i = \{E_i, Ec_i\} \times \Delta I$$  \hspace{1cm} (6)

$$K_d = \{E_i, Ec_i\} \times \Delta D$$  \hspace{1cm} (7)

$\{E_i, Ec_i\}$ is the value of corresponding table 1 between the error $E$ and error change rate $Ec \cdot \Delta P$, $\Delta I$ and $\Delta D$ the modifying factor, the initial values are: 2.5, 1.2 and 1.6. The establishment of fuzzy rules is completed and the design of whole fuzzy controller is completed.

Finally, the structure of the fast fuzzy controller is shown in Figure 4.
4. Establishment of Experimental System
The control system uses the lower computer to carry out the core operation; the upper computer performs the data display and the parameter adjustment structure. The high-speed digital processing chip TMS320F2812 is used as the operation core of control system, 16 bit modulus conversion chip AD7656 is used to collect the position analog signal from position sensor feedback, The control signal is output to the digital analog conversion chip DAC7744 after operation to realize the conversion from digital control quantity to analog control quantity, The analog control quantity is changed to the position transformation signal of the magnetic field through wire commutating circuit, finally, the motion of actuator is realized through power amplification. There are high-precision electrical vortex sensors around the actuators and measure the motion position of micro-actuators. The upper computer monitor system adopts LabVIEW real-time measurement software, combined with 12 bit 16 channel high speed data acquisition card 6023E, collect, observe and preserve measurement data in real time, and carry on the subsequent analysis. The structure block diagram of the test system for the micro-actuator is shown in Figure.5.

5. Experiment and Data Analysis
5.1. Dynamic Response Experiments
The dynamic response experiment adopts unit step signal and square signal to carry out simulation. The purpose is to test the dynamic performance of the micro-actuator under the action of the controller, mainly adjusting time $T_s$, overshoot $\sigma\%$ and steady-state error $E_r$ as research object. The experimental curve of unit step signals in the vertical direction is shown in Figure. 6.
As can be seen from the figure, the actuator will be slowly stabilized under only the action of driving signals. But overshoot and adjusting time have exceeded the scope of the design. After adding control, the performance of the driver can be improved greatly, and it can reflect the characteristics of step signal.

Adding square signal with 0.2 mm offset, 2 Hz frequency, 0.8 mm amplitude, the experimental results are shown in figure 7, it can be seen that the actuator will not be able to reflect the characteristics of the control signal under uncontrolled conditions. After adding control, it can be seen clearly from the figure that adding control can realize fast, high precision, stable tracking of signals. The experimental data are summarized in table 2.

**Table 2. Parameter Comparison Table**

|                     | Tr(s) | σ (%) | Err(mm) |
|---------------------|-------|-------|---------|
| **step response**   |       |       |         |
| uncontrolled        | 1.32  | 24%   | 0.103   |
| controlled          | 0.42  | 14%   | 0.003   |
| **square wave response** |     |       |         |
| uncontrolled        | 1.3   | 25%   | ∞       |
| controlled          | 0.51  | 13%   | 0.004   |
5.2. **Interference Test**

The ability to maintain a stable state in the practical application is also critical to the actuator. Therefore, in this paper, a disturbance signal with 0.5mm amplitude is added after the step signal of actuator in the stable state, and it can be used to verify the anti-interference ability of the actuator. The red line in figure 8 is the interference signal, and figure 9 is the output variation diagram of the actuator. It can be seen that fast fuzzy control has a more obvious response to the interference signal, which corresponds to its fast tracking ability.

![Fig.8 Anti-Interference Experiment](image)

![Fig.9 Output Experiment of Controlled Quantity](image)

After a large number of experiments, combined with each of data change, a certain change rule should be summed up. The selection of the domain is different for different controlled objects, and the parameters should be adjusted from the traditional to the special method. This rule has certain value for mastering the range selection of input and output variables, so the parameters need to be analyzed.

5.3. **Scaling Factor Analysis.**

Whether the selection of proportional factor $k$ is suitable and directly affects the dynamic and static performance of fuzzy controller. The feedback signal of actual sensor is a variable $w$ of unknown $S$ domain, so it is necessary to determine the scaling factor when determining the scope of the fuzzy domain $[-n, -(n-1), \ldots, 0, (n+1), n]$. The determination method can be measured by the extremum method and dichotomy. First, the adjustment factor of PID controller is set to $\Delta P = 1$, $\Delta I = 0$, $\Delta D = 0$, and only the fuzzy controller works, the adjustment point of the fast controller is 0.6, and the force is
selected at 10. The scaling factor of the error $E$ is marked as $\Delta E$, the proportional factor of the error change rate $EC$ is marked as $\Delta EC$.

Table 3 summarizes and marks this process, only typical representative values are recorded in the table, and many experimental data are not listed here. As can be seen from the table above, if the fuzzy value calculated by actual software exceed the range of domain, then it will make the quantitative results beyond the scope of fuzzy domain, and incalculable values emerge, this will cause the calculation error of software, such as data 1-2. If the selections of $\Delta E$ and $\Delta EC$ are too small, the sensitivity decreases and the control accuracy is too low. If the selections of $\Delta E$ and $\Delta EC$ are too large, it will reduce the response rate of the system, otherwise it will increase system shock.

### Table 3. Test form of Scaling Factor

| E    | $\Delta E$ | EC   | $\Delta EC$ | Tr(s) | Err(mm) | $\sigma$ % | result description  |
|------|------------|------|-------------|-------|---------|------------|--------------------|
| 1 [-6,+6] | 1000  | [-6,+6] | 1000 | $\infty$ | $\infty$ | $\infty$ | cannot run        |
| 2 [-6,+6] | 0.1  | [-6,+6] | 0.01 | $\infty$ | $\infty$ | $\infty$ | cannot run        |
| 3 [-6,+6] | 0.01 | [-6,+6] | 0.001 | 0.82 | 0.6 | $\infty$ | cannot track signal |
| 4 [-6,+6] | 0.01 | [-6,+6] | 0.0001 | 0.751 | 0.15 | 10% | good drive effect  |

The effect of $\Delta E$ and $\Delta EC$ to system performance is summarized as follows:

1. If there is a major overshoot, $\Delta I$ should be reduced, and maintain $\Delta P$, $\Delta D$ unchanged. The enhancement integral will affect the adjustment strength and delay the response time. Only the proper integral coefficient can show the control effect.

2. If there is attenuation phenomenon after reaching the stable condition, $\Delta P$ should be reduced, maintain $\Delta I$ and $\Delta D$ unchanged. The increase of the proportional coefficient will only increase the adjustment intensity, resulting in oscillation.

3. If overshoot return to steady state slowly, $\Delta D$ can be properly increased. The adjustment of differential coefficient can change the sensitivity and the predictive ability of the system to the error.

### Table 4. PID Parameter Adjustment Table

| $\Delta P$ | $\Delta I$ | $\Delta D$ | $T_i$ (s) | $E_{rr}$ (mm) | $\sigma$ % |
|------------|------------|------------|-----------|--------------|----------|
| 1          | 0.2        | 1          | 0.45      | 0.0037       | -15%     |
| 2          | 0.3        | 1          | 0.22      | 0.005        | 3.2%     |
| 3          | 0.3        | 0.2        | 0.35      | 0.043        | 0.01%    |
| 4          | 0.3        | 1          | 0.46      | 0.0028       | 0.15%    |
| 5          | 0.3        | 0.5        | 0.44      | 0.0032       | -0.002%  |

According to the data in the table, the following rules can be summarized:

1. If there is a major overshoot, $\Delta I$ should be reduced, and maintain $\Delta P$, $\Delta D$ unchanged. The enhancement integral will affect the adjustment strength and delay the response time. Only the proper integral coefficient can show the control effect.

2. If there is attenuation phenomenon after reaching the stable condition, $\Delta P$ should be reduced, maintain $\Delta I$ and $\Delta D$ unchanged. The increase of the proportional coefficient will only increase the adjustment intensity, resulting in oscillation.

3. If overshoot return to steady state slowly, $\Delta D$ can be properly increased. The adjustment of differential coefficient can change the sensitivity and the predictive ability of the system to the error.
6. Conclusion
A fast fuzzy controller which combines the optimal control principle is designed from the characteristics and principles of fuzzy logic control. The selection of working process and fuzzy parameters of the input and output variables in the fuzzy controller are introduced in detail. The corresponding fuzzy control program is written, and the control experiment system is established. Step signal, square wave signal are conducted experiments, by analyzing the experimental results, it is proved that the fast fuzzy controller has good fast tracking performance for signals with dynamic and continuous change, and the steady-state precision meets the design requirements of micro-actuator.

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