Fuzzy Control Strategy of Relief System for Extra-High Pressure Test Equipment

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ABSTRACT: To realize accurate super-high hydraulic pressure curve control of relief system for isostatic pressure test equipment, a method of designing fuzzy control strategy, including theoretical analysis, modeling, designing fuzzy controller, optimizing fuzzy rules and simulation, was introduced. Precise mathematic model based on theoretical inferring and experimental computing was developed and used for studying control strategy and optimizing control rules. High-accurate controller based on fuzzy control theory was studied and fuzzy controller rules were optimized. A simulation platform composed of input variable, controller, mathematic model and output variable was obtained and successfully used for studying the control of relief process. Computer simulation and physical test experiments indicted that the control precision of relief system reaches ±0.5Mpa during the pressure domain above 30MPa, the fuzzy controller strategy meets the high-accurate pressure control requirements of super-high pressure test equipment.

1. INTRODUCTION

Extra-high pressure test equipment was widely used for tolerance test of ultra-high pressure for electrical devices and material forming [1-3]. In the low temperature environment, extra-high pressure was realized by the warm isostatical pressing machine (short for WIP). WIP could create equal liquid pressure in all directions of a closed liquid medium environment. WIP is composed of the main body, ultra-high pressure cavity, heating system, filling and discharging medium oil system, pressure-rising system, relief system, hydraulic drive system, electrical control system and so on [4]. The pressure control is as follows: the computer for operation sends control instructions to the programmer logical controller (short for PLC), the PLC analyzes the instructions and controls the motion of other electrical devices and the hydraulic devices, and then the control of ultra-high pressure cavity is released.

In the industrial application, basic requirements for ultra-high pressure test equipment include wide temperature domain from nature temperature to 300℃, wide pressure domain from 0 to 200MPa, precise pressure curve control and temperature curve control during the wide domain. The composition and characteristics of relief system is attributed as non-linearity system and is very different from pressure-rising system.

In this paper, the study was related with analyzing the composition and characteristics of relief system, modeling through theoretical inferring and experimental computing, designing and optimizing the fuzzy
control strategy, building the simulation platform based on SIMULINK, simulating and testing the control performance.

2. Composition and characteristics

In the view of machine classification, ultra-high pressure test equipment based on WIP belongs to hydraulic drive system. The relief system needs to realize highly precise pressure curve follow-up control with the given setting pressure curve. The common pressure relief methods for hydraulic systems includes proportionate valve based relief system, combined valves group based relief system and other complex relief system. During pressure relief process, the pressure is seriously affected and related with the flow coefficient of valve, flow viscosity, the temperature coefficient of medium oil, and the compression coefficient of medium oil and so on. Therefore, the control of relief system belongs to complex control system [5-6].

2.1. Principle of relief pressure

Increasing-pressure process is realized by filling the medium oil to the ultra-high pressure closed cavity through the increasing-pressure device. According to the theory of liquid compression, the increasing-pressure process meets the liquid compression equation that the pressure of medium oil is related with elasticity modulus and volume filled in the full and super-high pressure cavity, as shown in (1).

\[
P = K \frac{\Delta V_0}{V_0 + \Delta V_0}
\]

Where \(\Delta V_0\) is filled volume of medium oil after filling the cavity exactly, \(V_0\) is the volumes of cavities, \(K\) is the elasticity modulus, \(P\) is the pressure of the cavity.

Oppositely, the pressure relief process is deemed as the reverse process of increasing-pressure, and can be realized by controlling the relief process of liquid medium oil.

2.2. Composition of relief system

Proportional hydraulic pressure relief valve is widely used for pressure relief curve control of common high pressure hydraulic system that the pressure domain is under 40MPa. However, this method cannot meet the requirements of precise pressure control in the ultra-high relief system as the proportional valve suited for ultra-high pressure control cannot be manufactured successfully. A kind of valves group constituted by three different radius hole-valves was studied and successfully used for pressure relief in the pressure domain above 30MPa. It is a pity that the valves group cannot meet the precise pressure curve control in the pressure domain under 30MPa. So a kind of complex relief system constituted with three different radius hole valves and a proportional control valve was studied. In this paper, the control of ultra-high pressure domain above 30MPa was studied only. Diagram of relief system of WIP is as shown in figure 1.

![Figure 1 Diagram of relief system of WIP](image)

2.3. Characteristics of pressure relief system

Relief system belongs to complex, discrete and nonlinearity system in the classification of control system. the dimension style is the system of single input and single output. The performer devices include all kind of nonlinearity such as temperature effect of medium oil, viscosity of liquid oil, dynamic
process of valves group and the sealing characteristics of hydraulic system, which affects the control precision together.

3. Modeling of Relief system

Classical control theory could not be successfully used for relief system as result of the nonlinearity of system characteristics. Linearity modeling could be obtained by linearizing control characteristics. But the linearity model is too coarse to meet precise pressure curve control, the control strategy should confront the nonlinearity system. It was urgently necessary to study the intelligent control theory which suits to the nonlinearity control system.

3.1. Method of modeling for relief system

Based on the study of operation principle, system characteristics, quality and quantity analysis, the nonlinearity modeling could be obtained by theoretical inferring and experimental computing. As the factors that affect pressure control precise are too many and are seriously nonlinearity, the model is too difficult to be applied for pressure control possibly, even useless. A simple and useful model could be built by ignoring the less important factors such as the viscosity of liquid oil and the sealing characteristic, and attaching importance to the mathematic relation among pressure of cavity, the volume of medium oil released, flux and temperature of oil. After obtaining the model, simulations and experiments can be used for studying the control strategy.

3.2. Theoretical calculation of physical parameters

3.2.1. Relation between pressure and volume released

According to liquid compressing equation, as in (1), relation between pressure of cavity and volume of released medium oil is as shown in (2),

\[ P' = K \frac{\Delta V_0 - \Delta V}{V_0 + \Delta V_0 - \Delta V} \]

Where \( V_0 \) is the volumes of cavities, \( \Delta V_0 \) is the initial injected volume of oil after filling the cavity, \( \Delta V \) is released volume of oil, \( P' \) is the pressure of cavity after releasing oil.

For one isostatic ultra-high pressure test equipment, the elasticity module coefficient of medium oil \( K \) is \( 1.5 \times 10^3 \) MPa, the maximum pressure is 200 MPa and the capacity of cavity is 1.25 m\(^3\). According to (1), as the pressure reaches 200 MPa in nature temperature, the volume of oil injected in the cavity is 0.154 times of the volume of cavity. During pressure relief process, as the pressure releases from 200 MPa to 0 MPa, the volume of released oil should be 0.154 times of capacity of cavity.

3.2.2. Relation between volume and control signals

In the macroscopic view, the volume of released medium oil in the pressure relief process is the sum of the integral of the flux times control signal for three valves. The control signal can be calculated by controller system of test equipment, and the flux can be calculated by flow equation of relief valve. The volume of released oil was calculated as shown in (3).

\[ \Delta V(t) = \int_0^t q_1(\tau) \cdot k_1(\tau) d\tau + \int_0^t q_2(\tau) \cdot k_2(\tau) d\tau + \int_0^t q_3(\tau) \cdot k_3(\tau) d\tau \]

Where \( \Delta V(t) \) is the volume function of oil released, \( t \) is time variable, \( q_1(\tau), q_2(\tau) \) and \( q_3(\tau) \) are volume flow velocity of three valves, \( k_1(t), k_2(t) \) and \( k_3(t) \) are control signal of three valves.
3.2.3. Computation of flux of valves
According to flux theory of hydraulic valve, flow velocity of valve is related with pressure of cavity, cross section and density of liquid, as shown in (4).

\[ Q = C_d A_0 \sqrt{\frac{2\Delta P}{\rho}} \]  

(4)

Where \( Q \) is volume flow velocity of oil, \( A_0 \) is diameter of the valve hole, \( \rho \) is density of oil, \( \Delta P \) is the difference of pressure between the front and the end of valve, \( C_d \) is the coefficient of flux.

In the view of structure composition, as the front of valve connects with the cavity through hydraulic pipes and several direct passage valves, and the end of valve connects with the nature air, the difference \( \Delta P \) is approximately equal with the pressure of cavity \( P \), as shown in (5).

\[ Q = C_d A_0 \sqrt{\frac{2\Delta P}{\rho}} \]  

(5)

For one ultra-high pressure test equipment with the wide pressure domain between 0MPa to 200MPa and the wide temperature domain between nature temperature and 300℃, diameter of hole for three valves are 4.5×10^{-4}m, 4.3×10^{-4}m and 4.1×10^{-4}m respectively, coefficient of flux is 8.2, density of medium oil is 800Kg/m3. Then the numerical relation between the pressure of cavity and flow velocity can be calculated according to the (5). numerical relation for three valves between the pressure of cavity and flow velocity can be shown in Figure 2.

![Figure 2](image)

Figure 2 Relation between flow velocity and pressure

For one valve, flow velocity increases nonlinearity as pressure of cavity increases. In addition, flow velocity increases for equal pressure as the diameter of valve increases.

3.2.4. Effects and compensation of temperature
The characteristic that volume of medium oil will expand as temperature increases and it will shrink as temperature decreases is very serious for medium oil of test equipment. Pressure of cavity increases with the expansion of medium oil as temperature increases, and pressure of cavity decreases with the shrinking of medium oil as the temperature decreases. A modify function of compensating temperature effects, based on the relation among temperature, expanding coefficient and pressure, has been built for optimizing the model. Temperature compensation coefficient \( E(T) \) is as shown in (6), where \( e \) is expansion coefficient, \( T \) is absolute temperature.

\[ E(T) = 1 + e T \]  

(6)

According the reference, the domain of expansion coefficient \( e \) is above 0.00072 and below 0.00080, and increases as the temperature increases. The mean of \( e \) is 0.00075, which can be used for model compensation of test equipment. The initial condition of cavity is exactly filled of medium oil with 0℃ temperature and 0MPa pressure. According to (1) and (6), as the temperature of cavity
increases to 300°C, the volume of oil will expand by 0.225 times and create an ultra-high temperature of 281.25MPa, as shown in Figure 3. So it is very necessary to compensate the temperature effect for improving the precision of system control model.

![Figure 3 Pressure characteristic affected by temperature](image)

### 3.2.5. Other nonlinearity characteristics
Flow velocity decreases as the viscosity increases, which will affect velocity of relief pressure. The effect caused by sealing is very complex, unexpected, random and discrete, which will affect the control precision. Until now, the compensation equation for viscosity and sealing effect has not been built and could be ignored in modeling the system. In the view of control theory, the error created by modeling precision can be compensated by optimization of controller. As a result, the ignoring of viscosity and sealing effect is appropriate.

### 3.3. Theoretical modeling of relief system
The theoretical modeling can be obtained by the relation among several physical parameters related. As (1), initial pressure of cavity before releasing is \( P_1 \), the corresponding volume of oil over filled is \( \Delta V_0 \).

After releasing the oil with volume of \( \Delta V_i(t) \), the released pressure \( \Delta P(t) \) is as in (7).

\[
\Delta P(t) = k \left( \frac{\Delta V_0}{V_0 + \Delta V_0} - \frac{\Delta V_0 - \Delta V_i(t)}{V_0 + \Delta V_0 - \Delta V_i(t)} \right) \tag{7}
\]

Then the pressure of cavity is \( P(t) \), as in (8).

\[
P(t) = P_1 - \Delta P(t) \tag{8}
\]

Another expression is as in (9).

\[
P(t) = P_1 - k \left( \frac{\Delta V_0}{V_0 + \Delta V_0} - \frac{\Delta V_0 - \Delta V_i(t)}{V_0 + \Delta V_0 - \Delta V_i(t)} \right) \tag{9}
\]

In fact, flow velocity of three valves are constant, relation between released volume of medium oil and control signal of three valves is as in (3). As the temperature of oil affects the expanding and shrinking of medium oil and causes the changing of the pressure seriously, the temperature compensation coefficient \( E(T) \) is as in (6). According to the equations above, the mathematic modeling based on theoretical inferring could be obtained as in (10).

\[
P(t) = P_1 \left[ \frac{\Delta V_i(t)}{V_0 + \Delta V_0} + \frac{\Delta V_i(t)}{V_0 + \Delta V_0} - \frac{\Delta V_i(t)}{V_0 + \Delta V_0 - \Delta V_i(t)} \right] \tag{10}
\]
3.4. Experimental modeling of relief system

In order to improve model precision, optimize model parameters and test the performance of relief system, modeling based on experiment was also studied. The pressure relief curve of three valves was obtained individually through designing pressure relief experiments for three single valves, as in Figure 4. The pressure range is above 30MPa and below 200MPa.

According to flow velocity test experiment of three individual valves, analytical relation between pressure and time was obtained through high order fitting function. The fitting function of 1st valve through five order fitting was obtained as in (11). The same method could also be used for another both valves.

\[
P_1(t) = -4.446e-015 \times t^5 + 1.478e-011 \times t^4 - 6.175e-008 \times t^3 + 1.408e-004 \times t^2 - 2.044e-001 \times t + 2.028e+002
\]

(11)

Base on (11), analytical relation between flow velocity and time could be obtained by differential of (11), as in (12) and Figure 5.

\[
Q_1(t) = 0.124e-09 \times t^4 - 0.670e-06 \times t^3 + 0.821e-03 \times t - 0.384
\]

(12)

In order to obtain the analytical relation between flow velocity and pressure, numerical relation between flow velocity and pressure of cavity could be obtained by sampling both functions \( P_1(t) \) and \( Q_1(t) \) in the interval of 1 second during the pressure domain from 30MPa to 200MPa. Then pressure vector \( P_1(n) \) and flow velocity vector \( Q_1(n) \) could be obtained at the same sample interval. Through fitting both vectors with high orders such as five orders, analytical relation between flow velocity and pressure was obtained by taking \( P_1(n) \) as independent variable and \( Q_1(n) \) as dependent variable. As in (13), where \( n \) is discrete time variable.

\[
Q_1(n) = a_1 \times P_1(n)^5 + a_2 \times P_1(n)^4 + a_3 \times P_1(n)^3 + a_4 \times P_1(n)^2 + a_5 \times P_1(n) + a_6
\]

(13)
Flow velocity equations of another two valves were also obtained through same method. As shown in Figure 6.

\[
Q_1(P) = -9.436e-13 \times P^8 + 5.89e-10 \times P^7 + 1.191e-7 \times P^6 + 5.399e-6 \times P + 2.036e-3
\]  

(13)

4. Designing of control strategy

4.1. Discussion of control strategy

In the theory of classical control, complex physical system could be simplified as a model constituted with input variable, error between input variable and feedback variable, controller, controlled target and feedback. Input variable is given by people or higher-level system, feedback variable is measured by sensor, controller (also called adjuster) is created by people according to the control theory. With the help of controller, the controlled parameters of system can follow up the given input variable preciously. A great controller should meet the requires of stability, accuracy and fast speed [7-8].

In the view of system dimension, relief system of ultra-high pressure test equipment belongs to single input and single output system. Meanwhile, the system is nonlinearity, and the reactor is discrete. In general industrial control, the proportion-integration-differential control strategy (short for PID) was wildly used. According to the statistic, PID was applied for more than 95% of general industrial control application. Comparing with other control strategy, PID is so wildly used and ripe that most of modern industrial control systems or products include PID module such as SIMENS, LABVIEW and so on. Unluckily, PID cannot be used for controlling relief system as the system is nonlinearity and discrete. In the general application of low precision control requirement, PID are always used for solving the control problem of nonlinearity system, but not suitable for the application of high precision control requirement. In the past 30 years, control theory of nonlinearity system was deeply developed. The general used control strategy for nonlinearity system include fuzzy control, auto-adapt control, neural networks control and other intelligent control strategy. Depending on control algorithm and control strategy, the state of three relief valves was controller by control system, then the pressure curve of cavity of test equipment could follow up the given setup curve exactly. Fuzzy control strategy is very suitable for nonlinearity and discrete system, and meets the control features of relief system. Fuzzy control was used for studying the relief process of ultra-high pressure test equipment [9-10].
4.2. Designing of fuzzy controller

Fuzzy control combines fuzzy mathematic theory and control theory, is a kind of nonlinearity control strategy. As the industrial physical world is exact, the feedback value measured by sensor and the control value used for driving the reactor devices are exact, but fuzzy controller can only deal with fuzzy variables. There is a fuzzification process for the input of the fuzzy controller and a defuzzification process for the output of the fuzzy controller. Exact variable could be fuzzified by the function of membership. According to the theory of fuzzy control, during the domain of the variation, the variation could be expressed as positive big (short for PB), positive very big (short for PVB), positive small (short for PS), positive very small (short for PVS), zero, negative big (short for NB), negative very big (short for NVB), negative small (short for NS), negative very small (short for NVS) and so on. The relation of fuzzy variations (called fuzzy rule) could be expressed as the Syntax format such as ‘if…else…’. Meanwhile, theory of fuzzy numerical computation was also created in the subject of fuzzy mathematic. The alteration from the fuzzy variation to exact variation is called defuzzification which could transfer fuzzy variations such as PB, PVB and so on to exact values.

According to the dimension features of relief system, a “2-1 style” fuzzy controller was designed. The error value between given variation and feedback variation \( e \), and the differential value of the error \( \dot{e} \) are taken as input variations of fuzzy controller. The output \( u \) was used for calculating the control signal of valves group. Fuzzy input variations of controller are \( E \) and \( EC \), and fuzzy output variations is \( U \). According to the precise control requirement, main domain of \( e \) is \([-12, 2]\), main domain of \( \dot{e} \) is \([-4, 5]\). As combination species of valves group is 8, main domain of \( u \) could be fixed as \([-2.5, 3.5]\).

Considering the control precision and system complex, number of grade of \( E \) could be fixed as 9. The domain of \( E \) could be fixed as a set including NVB, NB, NS, NVS, Z, PVS, PS, PB, PVB. The membership grade function of NVB is Z style membership function (short for zmf), that of PVB is S style membership function (short for smf), and that of others subset are triangle membership function (short for trimf). Numbers of grade of \( EC \) could be fixed as 5. The domain of \( EC \) could be fixed as a set including NB, NS, Z, PS and PB. The membership function of NVB is zmf, that of PVB is smf, that of others subset is trimf.

| Domain of \( e \) | \( E \)  | Domain of \( \dot{e} \) | \( EC \)  |
|------------------|--------|-----------------|--------|
| above 2          | NVB    | above 5         | NB     |
| 0~2              | NB     | 2~5             | NS     |
| -2~0             | NS     | -1~2            | Z      |
| -4~2             | NVS    | -4~1            | PS     |
| -6~4             | Z      | Below -4        | PB     |
| -8~6             | PVS    | ——              | ——     |
| -10~8            | PS     | ——              | ——     |
| -12~8            | PB     | ——              | ——     |
| Below -12        | PVB    | ——              | ——     |

According to system composition, number of grade of \( U \) could be fixed as 8. The domain of \( U \) could be fixed as a set including NB, NS, NVS, Z, PVS, PS, PB and PVB. The membership function of NB is zmf, that of PVB is smf, that of others subset of the collection is trimf.

4.3. Fuzzy computation of control signals

According to the calculation and analysis, flow velocity of 1st valve is slowest, the 2nd one is middle and the 3rd one is the fastest. 7 kinds of flow velocity for relief system, created by combination of three different valves, which are suitable for flow velocity control of relief system for test equipment. The
fastest combination is that three valves are all opened, and the slowest one is that the 1st valve is opened and another both valves are closed. According to the experiment of characters test for relief system, the flow velocity curve could be obtained by calculation as in Figure 7. Where combination of valve group can be shortly written as XYZ, X indicates control signal of 3rd valve, Y indicates that of 2nd valve, Z indicates that of 1st valve. The range of the control signal includes closed state and opened state. Closed state is shorten as ’0’, and opened state is shorten as ‘1’.

According to flow velocity of valves group from fast to slow, combination of valve group is 111, 110, 101, 100, 011, 010 and 001 in the order. The defuzzification of $U$ was realized by maximum membership method. Relation between $U$ and control signal of valves group can be obtained as in Table 2.

| $U$   | $u$     | Combination | Valve 1 | Valve 2 | Valve 3 |
|-------|---------|-------------|---------|---------|---------|
| NB    | Below -2.5 | 000         | Close   | Close   | Close   |
| NS    | -2.5~1.5  | 001         | Close   | Close   | Open    |
| NVS   | -1.5~0.5  | 010         | Close   | Open    | Close   |
| Z     | -0.5~0.5  | 011         | Close   | Open    | Open    |
| PVS   | 0.5~1.5   | 100         | Open    | Close   | Close   |
| PS    | 1.5~2.5   | 101         | Open    | Close   | Open    |
| PB    | 2.5~3.5   | 110         | Open    | Open    | Close   |
| PVB   | Above 3.5 | 111         | Open    | Open    | Open    |

4.4. Designing of fuzzy rules
For ultra-high pressure test equipment, accurate pressure curve control of relief system is very difficult as result of the nonlinearity and discrete behavior. Based on system theory model, experiment model and some complex calculation, the initial fuzzy rules have been built. Fuzzy rules builds the relation between output variation $U$ and input variations including $E$ and $EC$. In the view of adjusting method, fuzzy control is similar with PID. Basic rules includes:

1. The bigger $E$, the bigger $U$ should be; the smaller $E$, the smaller $U$ should be;
2. If $E$ is constant and $EC$ increases, $U$ should also be increased; if $E$ is constant and $EC$ decreases, $U$ should also be decreased;
3. If $E$ is in NVB and $EC$ is in NB, $U$ should also be NB, which means that three valves are all closed;
4. If $E$ is in PVB and $EC$ is in PB, $U$ should also be PB, which means that three valves are all opened.
Another rules could be built according to the gradient of $E$, $EC$ and $U$. The initial fuzzy rules are as Table 3.

| $E$ | $EC$ | $NVB$ | $NB$ | $NS$ | $NVS$ | $Z$ | $PVS$ | $PS$ | $PB$ | $PVB$ |
|----|-----|------|-----|-----|-------|---|------|----|-----|------|
| $NB$ | PS | PS | PVS | PVS | NVS | NS | NS | NS | NS | NS |
| $NS$ | PB | PS | PS | PVS | Z | NVS | NS | PS | NS |
| $Z$ | PB | PB | PS | PS | PVS | Z | NVS | PS | NS |
| $PS$ | PVB | PB | PB | PS | PVS | Z | NVS | PVS | NS |
| $PB$ | PVB | PVB | PB | PB | PS | PVS | Z | PVS | NS |

5. Simulation and optimization

5.1. Designing of simulation platform

In order to test the performance of fuzzy controller and optimize the fuzzy rules, it is necessary to simulate the performance through building simulation platform and designing simulation experiment [11-12]. The simulation platform was built by SIMULINK as in Figure 8, where the fuzzy logic control module and system model were embedded. Fuzzy rules were embedded in the FIS. Both theory model and experiment model could be embedded in the simulator and used for simulating the relief process, as in Figure 9 and Figure 10. The theory model can be used for guiding the experiment, and the experiment model can be used for optimizing the theory model.

![Figure 8 Simulation platform of relief system](image_url)

![Figure 9 SIMULINK function of theoretical model](image_url)
5.2. Simulation of simple relief pressure curve

In order to optimize fuzzy rules, several pressure relief control simulation experiments about four kinds of simple pressure curve, including straight line curve, parabolic curve, elliptical curve and circle curve, were tested.

Simulation of straight line curve $y = -0.1x + 100$ was tested. During the pressure domain from 100MPa to 20MPa, the error of follow-up control precision was above -0.4MPa and below 0MPa, as in Figure 11.

Simulation of parabolic curve $y = -1.5625 \times 10^4 x^2 + 100$ was tested. The error of follow-up control precision was above -0.5MPa and below 0.1MPa in the pressure domain above 30MPa. Because of the poor extrapolation of the model, the error was a little bigger in the pressure domain below 30MPa, as in Figure 12.
Simulation of parabolic pressure curve

Simulation of elliptical curve \( y = 100 - \frac{x}{1000000} \) was tested. The error of follow-up control precision was above -0.4MPa and below 0.1MPa, as in Figure 13.

Simulation of round curve \( y = \sqrt{1000000 - x^2} \) was tested. As the tangent line of round curve stands for flow velocity of relief pressure, control strategy can realize the error of follow-up control precision above -0.5MPa and below 0.5MPa in the angle domain above 60 degree of pressure relief curve, which meet the pressure control requirements. As the ability limit of pressure relief, it cannot meet the requirement in the angle domain below 60 degree of pressure relief curve, as in Figure 14.
5.3. Simulation of complex relief pressure curve

Simulation of complex curve was simulated as the setup curve in (15). The error of follow-up control precision was above -0.4MPa and below 0.1MPa in the pressure domain above 30MPa. The rising of error in the domain of 87MPa was caused by numerical calculation and did not affect the control strategy, as in Figure 15.

\[
 y = \begin{cases} 
 100 \cdot \sqrt{1 - \frac{x^2}{1000000}} & (0 \leq x < 500) \\
 87 & (500 \leq x < 600) \\
 67 & (600 \leq x < 800) \\
 -0.1x + 100 & (800 \leq x < 900) \\
 -0.1x + 100 & (900 \leq x < 1570) 
\end{cases}
\]

(15)

5.4. Optimization of fuzzy rules

Method for optimizing fuzzy rules was realized by adjusting the output \( U \) according to the input \( E \) and \( EC \). According to the simulation test, the fuzzy rules could meet the high precision control requirement of relief system.
6. Experimental Results

In order to test the performance of control strategy, a kind of electrical control system based on PLC was built for one isostatical ultra-high pressure test equipment and the fuzzy control strategy was embedded in the PLC processor of control system. According to the complex curves follow-up control requirements, two experiments with complex pressure curves were carried out. The pressure curve of experiment is as in (16) and (17), and the experiment result is as in Figure 16 and 17.

\[
\begin{align*}
  y &= \sqrt{10000-x^2} + 86.60 & (0 \leq x < 50) \\
  y &= \frac{10000 - (x - 200)^2}{1000000} - 14.4 & (50 \leq x < 200) \\
  y &= \frac{10000 - (x - 200)^2}{1000000} - 14.4 & (200 \leq x < 400) \\
  y &= 1.5625 \times 10^{-4} (x - 600)^2 + 83.58 & (400 \leq x < 600) \\
  y &= 1.5625 \times 10^{-4} (x - 600)^2 + 83.58 & (600 \leq x < 1000) \\
  y &= 58.58 & (1000 \leq x < 1200) \\
  y &= 0.2(x - 1200) + 58.58 & (1200 \leq x < 1450)
\end{align*}
\]

Figure 16   Experiment test of complex pressure curve control

The experiments based on test equipment indicate that the control precision of relief system reaches ±0.5Mpa during the pressure domain above 30MPa, the fuzzy controller strategy meets the high-accurate pressure control requirements of isostatic ultra-high pressure test equipment.

7. Conclusions

Fuzzy control strategy used for precise control of pressure relief curve for isostatic ultra-high pressure test equipment is presented in this paper. The relations among pressure of cavity, volume of oil released, temperature, flow velocity, viscosity and sealing effect were studied and built. Theoretical and experimental modeling was used for building exact model for pressure system, which was also used for simulation and experiments. Theory of fuzzy control was deeply studied and the designing of fuzzy controller for controlling pressure relief was introduced particularly. Simulation platform, comprising with main platform, Fuzzy controller (FIS), calculator of control signal for valves group and system model, were realized by SIMULINK. Based on simulation platform, several simulation experiments were tested for testing the performance of control strategy and optimizing the fuzzy rules. Through the physical experiment based on the isostatical ultra-high pressure test equipment, it indicated that the control precision of relief system reaches ±0.5Mpa during the pressure domain above 30MPa, the fuzzy
controller strategy meets the high-accurate pressure control requirements of ultra-high pressure test equipment.

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