Research on electro-hydraulic force servo system and its control strategy considering transmission clearance and friction[1]

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Abstract. The nonlinear factors such as transmission clearance and friction force in the electro-hydraulic force servo system are analyzed in detail; the corresponding mathematical model is established. In this paper the authors mainly aim at the clearance between the moving parts of the motion pair in the power mechanism, and the clearance is easy to cause large amplitude vibration of the whole system, and even instability and other adverse consequences. At the same time, it is easy to eliminate the influence of the friction in the mechanism, such as the tracking error of the system, and the appropriate friction force can improve the stability margin of the system. An evolutionary algorithm based on the ant colony algorithm and its control strategy for the above mentioned problems are studied. The ant colony algorithm is a heuristic search algorithm based on population optimization, and ant colony algorithm is to find the optimal path through positive feedback and distributed collaboration. The path optimization model can combine the rapidity of the problem solving, the global optimization and the rationality of the limited time answer. The effectiveness of the new simulated evolutionary optimization method, which is based on the ant colony algorithm, is determined and experimentally studied, and the corresponding experimental results are obtained. The nonlinear factors are controlled to improve the effect of comprehensive control performance index of the electro-hydraulic force servo system, such as the fast, dynamic and static accuracy and the stability of the system.

Key words. Electro-hydraulic force servo system, transmission clearance, friction, nonlinear factor, power mechanism, ant colony algorithm, control strategy.

1. Introduction

Hydraulic power mechanism is the core component of electro-hydraulic servo-system, and is also an important part of electro-hydraulic force servo system [1]. The performance indexes of the hydraulic power mechanism mainly are the quality of the load (inertia), hydraulic natural frequency, hydraulic spring stiffness, hydraulic damping ratio, output force accuracy (output value) etc. The hydraulic power mechanism is usually composed of electro-hydraulic servo valve, servo cylinder, load and other parts [2]. The working principle of hydraulic power mechanism is realized by changing the voltage value of the input signal of the hydraulic power mechanism, and by transforming the input signal from voltage into current. By control of current of the valve, the direction of its opening can be changed and controlled effectively, and, consequently, the direction and amount of the fluid that is used to drive the load movement.

The electric hydraulic force servo system is an important part of electro-hydraulic servo control technology. Its role is based on the signal generator output size and its polarity. According the strength and direction of the signal, the electro-hydraulic force servo system can assign the driving force the exact value and direction in order to control and drive the inertia load, elastic load and viscous load. Its schematic diagram is shown as Fig. 1. The electric hydraulic force servo system with excellent comprehensive performance should have the advantages of large power volume ratio, fast output response, and high anti-disturbance stiffness [3]. The electric hydraulic force servo system in the process of work is required to have good dynamic characteristics. For their determining, we need a detailed analysis of transmission clearance, friction, stiffness and other nonlinear factors, and need to find out their specific impact on performance, so as to provide a practical basis for good control of these factors in the design of the system, to ensure that the electric hydraulic force servo system can play its superior comprehensive performance [4].
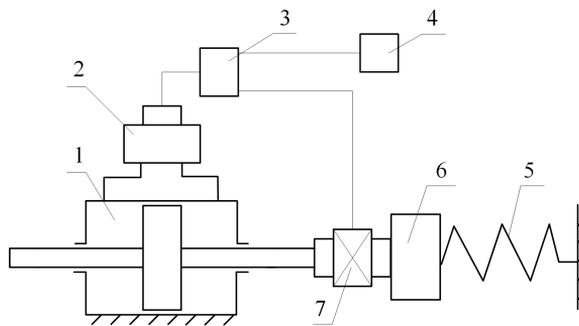

Fig. 1. Schematic diagram of electro-hydraulic servo system: 1–cylinder, 2–electro hydraulic servo valve, 3–controller, 4–signal generator, 5–spring load, 6–mass load, 7–force sensor

2. Electro-hydraulic force servo system

Electro-hydraulic force servo control system researched in this paper, which is the active force control system and its power mechanism is the structure form of the servo valve controlling hydraulic cylinder with its load. We can set the fuel supply pressure as a fixed value, and this pressure returns oil directly to the fuel tank. The slide valve flow equation, hydraulic cylinder flow continuity equation and hydraulic cylinder with the load force balance equation of electro-hydraulic servo control system [5] represent three classical equations, that must be supplemented with the expressions of the related electrical components [6]. We can conclude, that the mathematical analytic expression of the electric hydraulic force servo control system researched in this paper can provide mathematical fundamentals for analysis of the system and also strategy and development of a new controller [7].

$$U_e = U_r - U_f \,, \tag{1}$$

$$U_f = K_f F_g \,, \tag{2}$$

$$\Delta I = K_a U_e \,, \tag{3}$$

$$G_{sv}(s) = \frac{X_v}{I} = \frac{K_{sv}}{\frac{s^2}{\omega_{sv}^2} + \frac{2\xi_{sv}s}{\omega_{sv}} + 1} \,. \tag{4}$$

Here, U_r, U_f denote the command voltage signal and feedback voltage signal, respectively. Symbols K_f and F_g stand for the force sensor gain and hydraulic cylinder output force. Symbol K_a represents the servo amplifier gain, K_{sv}, ω_{sv}, and ξ_{sv} are the electro-hydraulic servo valve flow gain (m^3, natural frequency, and dimensionless damping ratio, respectively.

Secondly, we consider the conditions [8] satisfied, namely:

1. The flow of each throttle orifice in the electro-hydraulic servo valve is turbulent, and the influence of the compressibility of the liquid in the valve can be neglected.

2. The response capability of electro-hydraulic servo valve is perfect.

3. The hydraulic cylinder is an ideal double rod symmetrical hydraulic cylinder.

4. The oil supply pressure of the system is constant, and the oil return pressure is zero.

5. The pressure in each working chamber of the hydraulic cylinder is the same.

6. The internal and external leakage of the hydraulic cylinder is laminar flow.

Then the dynamic situation of the mechanism of the system can be described by the slide valve flow continuity equation, flow continuity equation of hydraulic cylinder, and force balance equation of hydraulic cylinder in the form

$$Q_L = K_q X_v - K_c P_L \,, \tag{5}$$

$$Q_L = AsY + \left(C_{tc} + \frac{V_t s}{4\beta_e} \right) P_L \,, \tag{6}$$

$$AP_L = ms^2 Y + B_c sY + KY + F \,. \tag{7}$$

Here, Q_L, K_q, X_v, K_c and P_L are, in turn, the load flow of electro-hydraulic servo valve, flow gain, opening of valve core, flow pressure coefficient, and load pressure of hydraulic cylinder. Symbols A, Y, C_{tc}, V_t, and β_e are, in turn, effective area of the piston of the hydraulic cylinder, piston displacement, total leakage coefficient of hydraulic cylinder, total volume of the two chambers of the hydraulic cylinder, and equivalent volume elastic modulus of hydraulic oil. Finally, m and B_c are, in turn, the comprehensive quality of the hydraulic cylinder piston assembly and viscous damping coefficient of the mechanical structure of the piston of the hydraulic cylinder, while K is elastic load stiffness and F is the external disturbance force.

In the simultaneous formulae (5)–(7), the displacement of the valve core can be input as X_v and hydraulic cylinder output force as F_g, so that the transfer function can be obtained in the form $K_{ce} = K_c + C_{tp}$, Due to the usual conditions, conditional $(K_c + C_{tc})/A^2 << 1$ was established. So we immediately get

$$\frac{P_L}{X_v} = \frac{K_q}{C\,K_{ce}} \left(\frac{s^2}{\omega_m^2} + \frac{2\xi_m s}{\omega_m} + 1 \right) , \tag{8}$$

where

$$C = (s/\omega_r + 1)(s^2/\omega_0^2 + 2\xi_0 s/\omega_0 + 1)\,, \quad K_{ce} = K_c + C_{tc}\,,$$

$$\omega_h = (4\beta_e A^2/V_t m)^{1/2}\,, \quad \omega_m = (K/m)^{1/2}\,, \quad \omega_0 = (\omega_h^2 + \omega_m^2)^{1/2}\,,$$

$$\xi_m = B_c/(2(mK)^{1/2})\,, \quad \omega_r = 1/(1/\omega_1 + 1/\omega_2)\,, \quad \omega_1 = 4\beta_e K_{ce}/V_t\,,$$

$$\omega_2 = K_{ce}/A^2\,, \quad \xi_0 = (1/2\omega_0)(4\beta_e K_{ce}/(V_t(1 + K/K_h)) + B_c/m)\,.$$

3. Ant colony algorithm and intelligent control strategy

Ant colony algorithm is a kind of essential parallel algorithm [9–10]; it mainly solves the problem of path optimization and similar problems. This algorithm has a strong positive feedback structure in the design, and has strong robustness, but also has the characteristics of easy combining with other algorithms; it has been widely used in the relevant field of studying algorithms and control strategy.

3.1. Basic principle of ant colony algorithm

The basic principle of ant colony algorithm is described in [11]. If there exists a graph $G = (V, E)$, where V is a set of nodes in the graph and E is a set of two nodes connected to any nodes in the graph, the line is assigned a certain weight. The path planning problem of the ant colony algorithm is to find a path between these two nodes in the graph $G = (V, E)$ with the lowest weight. At the same time, it can also be understood as the control strategy in the structure of the graph theory, and as the theoretical and applied research on the parameter optimization of controller; in these areas the application of the ant colony algorithm may be considerably wide. The ant colony algorithm process is shown in Fig. 2. The specific implementation of ant colony algorithm can be described by the following steps.
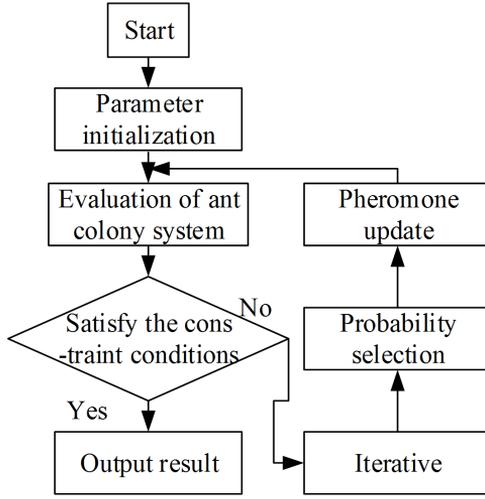
Fig. 2. Flow chart of ant colony algorithm

1. Initialization of parameters: The initial value of pheromone concentration is $\tau_{ij}(0) = \text{const.}$; its increment is also a constant.

2. According to the objective function to determine the merits of the ant colony system, to determine whether the iterative calculation.

3. In the process of searching, the ants always want to go from one node v_i to the other node v_j. Their motivation p_{ij} to use this path is given by the formula

$$\begin{cases} p_{ij}(t) = \dfrac{\tau_{ij}^{\alpha}(t)\eta_{ij}^{\beta}(t)}{\sum_{s \in M_k} \tau_{ij}^{\alpha}(t)\eta_{ij}^{\beta}(t)}\,, & v_j \in M_k\,, \\ p_{ij}(t) = 0 \text{ otherwise}\,, \end{cases} \tag{9}$$

where $\tau_{ij}^{\alpha}(t)$ is the pheromone concentration, $\eta_{ij}^{\beta}(t)$ denotes the visibility of side $(\eta_{ij}^{\beta}(t) = 1/d_{ij}$, where d_{ij} is the distance between the nodes v_i and v_j, $v_i, v_j \in V)$. The visibility factor reflects the inspiration degree for the choice of side $e(v_i, v_j)$, and it remains a constant in the whole process. Finally, β denotes a desired heuristic factor, which indicates the relative importance of visibility and α is an information elicitation factor that represents the relative importance of the pheromone trail.

4. Pheromone update: once the cycle is completed, the pheromone on each path is updated according to the formulae

$$\tau_{ij}(t+1) = \rho\tau_{ij}(t) + \Delta\tau_{ij}(t, t+1)\,, \tag{10}$$

where

$$\Delta\tau_{ij}(t, t+1) = \sum_{k=1}^{n} \Delta\tau_{ij}^{k}(t, t+1). \tag{11}$$

Here, symbol τ_{ij} is the intensity of the pheromone on the edge of $e(v_i, v_j)$, ρ is a residual volatile coefficient, which is used to show the persistence of pheromone less than 1, and $\Delta\tau_{ij}(t, t+1)$ stands for the increment of pheromone in the cycle.

In the research and practical application, the advantage of the ant colony algorithm is very obvious. At the same time, in the early stage of the search algorithm due to the lack of a certain quantity and effectiveness of strong pheromone, it will make the algorithm in the initial phase of the search speed is very slow, especially the impact of transmission clearance and friction factors existed in the system case. The two factors affect the initial threshold and the hysteresis, and the adverse effects on the system performance are difficult to be solved by ant colony algorithm. But after a gradual search, with the amount of information to a certain number and intensity, it will quickly improve the search for the best solution. The main idea of the study of the algorithm is, by using colony, global and fast random search, to generate an initial solution, and its applied directly to the initial information required for the distribution of ant algorithm, then ant algorithm is the use of feedback, tend to search the advantage of target value of the gradient to obtain optimal solution [12].

3.2. Research on control strategy and parameter optimization of control strategy based on ant colony algorithm

From the perspective of search optimization to understand, the tuning of the controller is to search for an optimal set of parameters from n-dimensional search space composed of the appropriate n parameters, so that the controller can achieve the best effect [13]. Its structure is shown in Fig. 3.
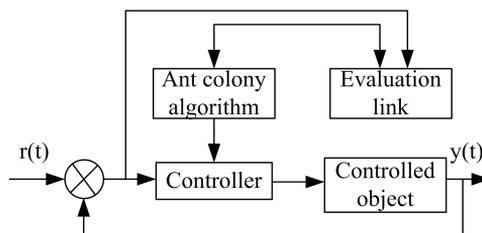

Fig. 3. Structure of controller satisfying ant colony algorithm

Taking into account the influence of transmission clearance and friction factor, the transfer function of the controller can be given by the second-order model with delay in the form

$$G(s) = \frac{K}{As^2 + Bs + C}e^{-\tau s}, \tag{12}$$

where A, B, C and K are appropriate constants and τ means the delay. The op-

timization of controller parameters is based on finding the minimum value of the objective function. In order to obtain satisfactory static and dynamic characteristics, reach a fast performance of the system, stability, overshoot and small control performance requirements, the objective function is selected as

$$F = \int_0^\infty t\,|e(t)|\ \mathrm{d}t\,, \tag{13}$$

where $e(t)$ is the time-dependent error.

In accordance with the following type of access to initialize the pheromone:

$$T_0(i) = \exp(-F(x))\,, \tag{14}$$

where $F(x)$ is the value of the evaluation function. The evaluation function value is negatively correlated with the concentration of pheromone. Then, we calculate the objective function of each ant, record the current initial optimal value, and obtain the global transition probability

$$p = \frac{\exp(T_0(\text{BestIndex}) - T_0(j_\mathrm{g})}{\exp(T_0(\text{BestIndex}))}\,, \tag{15}$$

where T_0 is pheromone update function to be optimized and j_g is the random function of independent variable value of the point g.

Further it is necessary to update pheromone. The pheromone update formula is a function that is related to the function to be optimized:

$$T_0(t_t) = (1 - \text{Rou})T_0(t\_t) + (\exp(-F(x)))\,, \tag{16}$$

where t_t is an independent factor parameter of optimization process and Rou is the ratio of the lengths of two adjacent paths with different pheromone in each calculation. In this step, the optimization process is completed, and after the complete optimization is done, the optimal set of data is found, as well as the optimal result of the output controller.

At the same time, in the process of calculating and solving the equation, the following parameters need to be initialized: ant size, number of iterations, search step length and length of each sub region. The search step size can be expressed as follows:

$$step = 0.1rand\,, \tag{17}$$

where $rand$ is the random search step. The length of the sub range is set according to the specific problem, and can be used as the following equation

$$Len_j = (end_j - start_j)/Ant\,, \tag{18}$$

where the value of j depends on the dimension of the equations, end_j is the value at the end of the jth position search, $start_j$ is the value at the start of the jth position search and Ant is the ant search path. We also need to initialize the search location.

The initialization position can be expressed as

$$X(i, j) = (start_j + (end_j - start_j)rand(j)),\qquad(19)$$

where X represents the parameters to be solved.

In order to shorten the time of solving nonlinear equation group with transmission clearance and friction force factors, we transform the solution of nonlinear equations into a function optimization problem, namely, nonlinear equation in the nonlinear equation group

$$G(x) = [g_1(x), g_2(x), \ldots, g_p(x)]^\mathrm{T},\qquad(20)$$

$$g_i(x) = 0.\qquad(21)$$

The roots of this equation belong to the interval (c_i, d_i). There is only one real root of the equation that lies in $[a_i, b_i]$, and $[a_i, b_i] \in (c_i, d_i)$. We can easily prove that the root $x*$ of the equation is equivalent to the function V_i in $[a_i, b_i]$ such that

$$V_i(x) = (g_i(x))^2.\qquad(22)$$

It is a very small point in $[a_i, b_i]$.

At the same time, the solution optimum solution of nonlinear equations can be converted to

$$M(x) = \sum_{i=1}^{p} c_i(g_i(x))^2,\qquad(23)$$

where $a_i < x < b_i$, $p \in N$, $i \in N$, a_i and b_i are the upper and lower bounds of the variable vector x_i, and $c_i,\ i = 1, 2, \cdots, p$ is the weight coefficient.

4. Experimental study of electro-hydraulic force servo control system

The experimental platform of experimental research includes industrial control computer, electrical part of signal transmission and processing, mechanical hydraulic parts of the test bench (including the experimental platform, servo valve control servo hydraulic cylinder, force sensor, parallel double cylinder support sliding track, split mass block, stiffness adjustable spring plate) and several more important parts. The hydraulic pipe and oil source and other auxiliary components are also necessary conditions for the experiment.

The realization of the control software of the experiment platform is based on the hardware in the loop simulation system which is generally used in the research with high confidence level. Fast control prototype (FCP) system based on virtual controller and real object is used in this experiment. It is a kind of hardware in the loop simulation experiment. This method can be used to study and experimental verify the new control strategy in the paper, which is efficient, fast and credible in real time hardware. We can on-line modify (through the actual test) the prototype structure or parameters, and then proceed repeatedly to the next round of testing, until we get the prototype of high precision and high reliability control of dynamic

and static index requirements [14–15].

In order to verify the accuracy of the mathematical model of electro-hydraulic force servo system considering the nonlinear factors of transmission clearance and friction, and the control strategy based on ant colony algorithm and the effectiveness of the controller design and parameter optimization on the system control, the experiment research contents of the electrical hydraulic force servo control system are studied in this paper. Fig. 4 shows the system response experiment curve of the system without using ant colony algorithm in the case of intelligent control strategy. Fig. 5 shows the response curve of the intelligent control strategy of ant colony algorithm to control the system, at the same time the accurate mathematical model of electro-hydraulic force servo control system based on the problem of transmission clearance and friction is established. Curve 1 and curve 2 in the figure, respectively, is the input and the output curve of the system.
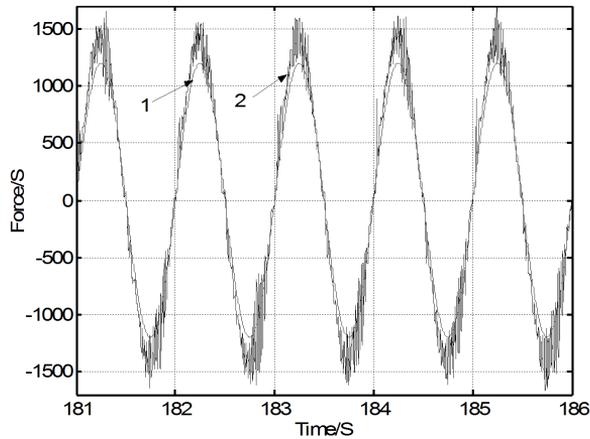

Fig. 4. Response curve of ant colony algorithm is not used

We can see from the diagram in Fig. 4 under the condition of the operating frequency is 1 Hz, output overshoot and peak area are affected by transmission clearance and friction force, and dynamic characteristics is bad. The curves in Fig. 5 are the dynamic characteristics of accuracy and rapidity in the condition of 3 Hz; especially the dynamic characteristics of the transmission clearance and friction in the peak area have obvious improvement. This above all shows the accuracy of the model and the effectiveness of the control strategy based on ant colony algorithm.

5. Conclusion

In this paper, the nonlinear factors of the transmission clearance and friction force in the electro-hydraulic force servo control system are considered, and a more accurate system mathematical model is established. At the same time, the control strategy based on ant colony algorithm to design the controller and optimize its parameters is researched. The research shows that it is effective for the control of the
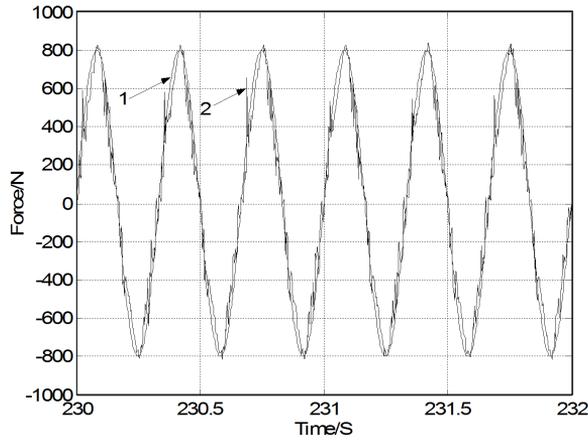
Fig. 5. System response curve of gap and friction and ant colony algorithm

system, and then the experimental study is carried out. In this paper, based on the algorithm of ant colony algorithm for the control of the controller parameter interval is a continuous optimization problem, the parameter interval of the controlled object is discretized, then the ant colony algorithm with global searching speed is used to find the optimal solution. We have completed the optimization process by means of research and implementation of initialization parameters, initialization optimization position, calculation of the optimization of the objective function, with the new pheromone, and repeated calculation and judgment. Finally, by using the ant colony algorithm to consider the nonlinear factors of the transmission gap and friction of the two steps in the process of adding hysteresis to do the experimental study. The result shows that the optimization effect of ant colony algorithm is quite good, and the control effect of the whole electro-hydraulic force servo control system is very obvious. The comprehensive dynamic characteristic of the system is improved obviously.

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