The application of the fuzzy controller for tension system control of the scraper conveyor in the mines

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Abstract. The tension control of the automatic adjustment system of the scraper conveyor used for the initial tension of the chain of the scraper conveyor. A hydraulic control system was developed in accordance with the principle, and a theory of system control was created. The controller with a Fuzzy-PID controller used in the automatic tuning system was designed to limit the minimum tension point to a certain specified area. Modeling has shown that it is possible to avoid an increase in power loss due to higher tension and chain exit from the sprocket due to lower tension.

1. Introduction

As the load on the scraper conveyor becomes greater and the length becomes longer, the dynamic characteristics have an obvious influence on the performance of the drag conveyor [1, 2]. And then this will lead to instability and reduced reliability of the scraper conveyor [3-5]. Especially the dynamic chain tension among other dynamic behaviors plays an important role in improving the performance of the scraper conveyor. In this article, it is mainly considered the principle of the self-adjusting system for chain tensioning, as well as analysis methods and related control theory to ensure efficient operation of the scraper conveyor [4, 6]. The hydraulic systems were to control the tension of the scraper conveyor [8]. Moreover, the scraper conveyor was speed controlled by two PMSM motors with high stability, using the adaptive PSO-Fuzzy logic controllers [11] and the adaptive PSO-Bacterial foraging optimization speed stability control algorithm [12].

The load on the working surface of the scraper conveyor changes depending on the position of the shear (plow), and also changes the resistance to the conveyor and the tension in the chain, which leads to a change in the elastic lengthening of the conveyor chain [11]. Theoretical analysis proves that the elastic elongation of the chain of a heavy-duty 240(m) scraper conveyor is almost 0,8 m between idle and heavy-duty [13]. If the elastic elongation of the chain cannot be compensated for overtime, the tension at the point of minimum tension of the conveyor chain will decrease, even zero tension will appear. Both theories and experiments have proven that the initial tension of the scraper conveyor has...
a great influence on its running characteristics and resistance [6]. If the initial tension is too low, the operation will be unstable and the chain jump phenomenon will sometimes occur, causing the chain to get stuck and broken. In an accident, the initial voltage caused excessive resistance, resulting in high power consumption [2].

This paper presents a Fuzzy-PID controller that controls the tension of the chain conveyor under the impact of starting and stable working of the system in two cases of direct start and two-speed starting anti S type.

2. Conveyor pretension and minimum tension

The distribution of the chain tension during the operation of the scraper conveyor Figure 1 shows the dotted line is the initial, and the solid line is the tension distribution during operation, \( S_i \) is the tension at each point during stable operation, \( S_{0i} \) corresponds to the initial tension, and the drive system power is set to \( P_A , P_B \) to make \( P_A = P_B = \lambda \), about the circuit voltage as direct distribution, then

\[
S_1 - S_2 = \lambda (S_1 - S_0) , \quad W_{1b} \rightarrow W_{2b} , \quad S_1 = S_1 + W_K , \quad S_2 = S_2 + W_{2b} : \\
S_4 = S_2 + \frac{\lambda W_{2b} + W_K}{1 + \lambda} \tag{1}
\]

With \( W_{2b} \) : Load side-chain and resistance to movement of the load (N); \( W_K \) : No-load side chain resistance (N).

If \( \lambda W_{2b} + W_K > 0 \) : \( S_2 \) : point of minimum tension; \( \lambda W_{2b} + W_K < 0 , \quad S_4 \) : point of minimum tension; \( S_2 = S_4 \) : At the moment, the system has the lowest elastic elongation.

If the elastic coefficient \( k \) of the chain elasticity is constant, the elastic prolongation under pretension \( S_{01} \) is:

\[
\Delta L_0 = 2 \int_0^L \frac{S_{01}}{k} \, dt = 2.L \frac{S_{01}}{K} \tag{2}
\]

After the stable operation, the elongation is distributed along a solid line, then the elastic elongation at this time:

\[
\Delta L_1 = \frac{1}{2} \left( S_1 + S_2 \right) \frac{L}{K} + \frac{1}{2} \left( S_3 + S_4 \right) \frac{L}{K} = \frac{L}{2K} \left( S_1 + S_2 + S_3 + S_4 \right) \\
= 4.S_2 + \frac{\lambda W_{2b} - W_K}{1 + \lambda} + W_{2b} + W_K \frac{L}{2K} \tag{3}
\]
As can be seen from the above formula, if $\lambda W_{2h} - W_s = 0$, then $\Delta L_0$. The minimum is obtained, that the elastic elongation of the system is the smallest, which is the optimal configuration of the conveyor power.

For conveyors without automatic tension control, in order to make the tension at the point of minimum tension greater than zero during operation, the following must be done: $\Delta L_0 \geq \Delta L_1$, which the:

$$S_{01} \geq \left[ 4S_2 + \frac{2}{1+\lambda} (\lambda W_{2h} - W_s) + W_{2h} + W_s \right] \frac{1}{4}$$  \hspace{1cm} (4)

If $\lambda = 1$ then $S_2$ is the minimum tension point, $S_{02}$ must satisfy:

$$S_{01} \geq S_2 + \frac{1}{2} W_{2h}$$  \hspace{1cm} (5)

If $\lambda = -\omega_{2h} - \omega_h = 0$, we have:

$$S_{01} \geq S_2 + \frac{1}{4} (W_{2h} - W_s)$$  \hspace{1cm} (6)

Equations (5) and (6) are the initial voltage value when the engine power ratio is a specific value.

When $S_2 = [S_{2_{\min}}$ is substituted, the pretension is determined without an adjusting device. $[S_{2_{\min}}$ is the minimum allowable value for the point of minimum tension.

3. **Principle of automatic pretension of the scraper conveyor**

The principle of automatic adjustment of the conveyor tension is to compensate for the tension change caused by elastic elongation (or contraction) of the chain by varying the distance between the two sprockets to achieve the goal of limiting the tension to a minimum tension point within a certain range. A scraper conveyor running on a working surface can change the center distance of two sprockets only due to the hydraulic cylinder pushing the sprocket and the drive element on the housing due to the limited space. Figure 3 shows the principle of scraper conveyor tension control. Voltage signals $S_A$ and $S_B$ are output by the sensor detection system, $S_A$ and $S_B$ are calculated after analyzing and filtering the signals [8].

The actual value is then determined using the “Comparator I” signal to determine the difference between $S_A$, $S_B$ and the expected delta value. The “Comparator II” signal determines if there is whether the product exceeds the acceptable error value and outputs the trigger value. The values are given according to the following formula:

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$$e_A = \begin{cases} 1 & \Delta S_A < 0 \text{ and } |\Delta S_A| \geq |\Delta S| \\ 0 & |\Delta S_A| < |\Delta S| \\ -1 & \Delta S_A > 0 \text{ and } |\Delta S_A| \geq |\Delta S| \\ 1 & \Delta S_A > 0 \text{ and } |\Delta S_A| < |\Delta S| \end{cases}$$

$$e_B = \begin{cases} 1 & \Delta S_B < 0 \text{ and } |\Delta S_B| \geq |\Delta S| \\ 0 & |\Delta S_B| < |\Delta S| \\ -1 & \Delta S_B > 0 \text{ and } |\Delta S_B| \geq |\Delta S| \\ 1 & \Delta S_B > 0 \text{ and } |\Delta S_B| < |\Delta S| \end{cases}$$  \hspace{1cm} (7)
Figure 3. Schematic diagram of the auto-regulating of the scraper conveyor tension

The $e_a,e_B$ same role, for signal generators that control hydraulic cylinder "A" and hydraulic cylinder "B", the control logic is taken as an example of $e_a$: if $e_a = 1$, then hydraulic cylinder "A" moves and the piston rod extends $\Delta x_A > 0$; if $\Delta x_A = 0$, then hydraulic cylinder A does not move $\Delta x_A = 0$; if $e_a = -1$, the piston rod of hydraulic cylinder A is compressed $\Delta x_A < 0$.

The hydraulic control system that implements the principle of Figure 3 is shown in Figure 4. The number “1” in the figure indicates the oil pump; the “2” is a group of bypass and safety valves; the “3” is a two-position two-way electromagnetic; the “4” solenoid proportional valves; the “5” is an accumulator that stores oil under pressure; the “6” is a 2/2 ways valve; the “7” is a 3-position 4-way valve and the “8” is a pressure switch.

Figure 4. Scheme of hydraulic tension control of the scraper conveyor [8]: a - Electro-hydraulic proportional valve; b - Electro-hydraulic control of the servo valves.

A simplified mechanical model of a drag conveyor with an electro-hydraulic automatic tension control system is shown in Figure 4, and the corresponding dynamic differential equation:

$$\begin{bmatrix} M \end{bmatrix} \dddot{X} + \begin{bmatrix} C \end{bmatrix} \ddot{X} + \begin{bmatrix} K \end{bmatrix} \dot{X} = \{\Delta F\}$$

$$\{\Delta F\} = \begin{bmatrix} \Delta F_A - W_{m+1}, sgn(x_{m+1}) \end{bmatrix}, \Delta F_B - W_{m+2}, sgn(x_{m+2})$$

(8)

If the process of adjusting the tension at the initial conditions of the conveyor is investigated, the problem becomes more complex, since the force at each point of the concentrated mass of the
conveyor changes over time, but if the conveyor speed stabilizes after the conveyor starts running, the study. In the case of pre-launch conditions, the problem is relatively simple. Incremental equation:

\[ \begin{align*}
\{X\} &= \begin{bmatrix} X_1 & X_2 & \cdots & X_{j-1} & X_j & X_{j+1} & \cdots & X_{s-1} & X_s \end{bmatrix}^T \\
\{F\} &= F_1, W_1, W_2, W_3, \ldots, F_{j-1}, W_{j-1}, \ldots, W_{s-1}, F_s
\end{align*} \]

For formula (9), to take the Laplace transform, there is:

\[ \begin{align*}
\{x(i)\} &= \begin{bmatrix} H_{(i)} \end{bmatrix}^{-1} \cdot \Delta F_{(i)} \\
H_{(i)} &= [M], [S^2 + C], [S + K]
\end{align*} \]

The change in chain tension:

\[ \begin{align*}
\Delta S_A &= K_s (x_{m+1} + x_m) + C_s (x_{m+1} + x_m) \\
\Delta S_B &= K_s (x_{m+2} + x_j) + C_s (x_{m+2} + x_j)
\end{align*} \]

In order to study the basic characteristics of an even more simplified control system, a simplified closed-loop control system is shown in Figure 5. The \( U_I = U_r - U_f \), \( U_r \): control voltage signal corresponding to the desired voltage value; \( U_f \): feedback voltage signal; \( U_f = K_{f,p} \cdot S_A \) with \( K_{f,p} \) : sensor gain.

\[ \frac{q_v(S)}{S} = K_{v} \cdot G_{v(S)} \]

4. Design Fuzzy-PID controller for scraper chain tension

Figure 5, the detection circuit is partially composed of sensors, amplifiers, filters, and operations, a comparator or the like is constructed.

On-line monitoring \( F_1 \) the rate of change of output deviation voltage and deviation voltage after processing by the detection circuit, these two values are proportional to \( \Delta F_1 \) and \( \Delta F_1 \). This part of the delay is \( \tau_i \) and the control circuit is outputted by the \( U, U \) input value after fuzzy analysis and output control current \( I_{dc} \), the delay for this part is \( F_i \rightarrow I_{dc} \). The delay is \( \tau = \tau_1 + \tau_2 \). The balanced equation of the cylinder:

\[ \begin{align*}
P_A \cdot A_y - P_B \cdot A_y - P_f - F_i - F_{i-1} - m_{A_i} g \cdot \text{sgn}(x_A) - \eta_i \cdot x_A &= m_{A_i} x_A \\
F_i &= K_i (x_A + x_i + x_{i+1}) + C_i (x_A + x_i + x_{i+1}) \\
F_{i-1} &= K_{i-1} (x_A + x_{i-1} + x_{i+2}) + C_{i-1} (x_A + x_{i-1} + x_{i+2})
\end{align*} \]
The pressure-flow equation of the electro-hydraulic servo valve is:
\[ q_i = C_{v,i} x_i (P_s - P_i)^{0.5} \]
\[ x_v = K_{v} G_{sv} \]  
(14)

The pressure-flow equation for the cylinder is:
\[ q_i = A_c x_c + C_{ip} (P_s - P_0) + \frac{V_v}{\beta e} \frac{dP_v}{dt} \]
\[ V_v = V_0 - A_c x_c \]  
(15)

In the above formulas: \( P_s, A_c \) are the oil pressure and piston area of the oil inlet chamber of the cylinder (Pa.m²); \( P_0, A_0 \) are the oil pressure and annular cavity area of the oil return chamber of the cylinder, usually \( P_s \gg P_0 \), Can make \( P_0 \approx 0, P_s \) for the cylinder oil plug movement resistance (N), \( \eta \) - Adhesion resistance for cylinder and mass \( m_A \) (Ns/m), analysis \( \eta = 0 \); \( m_A, g, \mu, \text{sgn}(x.t) \) - Frictional resistance for mass operation (N); \( \mu \) -is the mass resistance coefficient of operation; \( m_A \) - is the mass of the sprocket, tailstock, motor, coupling (or scrambler), reducer and cylinder piston (kg); \( P_s \) -System oil supply pressure (Pa); \( q_i \) - Servo valve outlet flow (m³/s); \( C_d \) - Constants related to servo valve structural parameters, fluid density; \( x_c \) the opening degree of the servo valve (m); \( K_d \) - Servo valve spool control current, provided by servo circuit; \( G_{sv} \) - Transfer function of servo valve spool displacement; \( C_{ip} \) - The internal leakage coefficient of the cylinder is related to the size and pressure of the cylinder; \( V_0 \) - The initial volume of the cylinder and piping (m³); \( \beta e \) - Effective bulk modulus.

In the simulation analysis \( F_i \) and \( \dot{F}_i \) are used as detection signals, target value \( F_i(t) \Rightarrow 21.000(N) \)
\[ F_i = K_f (x_{i+1} + x_i - x_{i+1}) + C_{ip} (x_{i+1} + x_i - x_{i+1}) \]  
(16)

In the previous section, we studied the control method of the pretension of the scraper chain and constructed the mechanical and mathematical models of the control in its simplified form. However, due to the large frictional resistance of the nose and the tail, the nonlinearity of the chain stiffness and the material. The non-uniform nature of the distribution, in fact, this control system has nonlinearity and time-varying. In order to better solve such control problems, The Fuzzy-PID control applies to this system, and now its principle is briefly described. Figure 7 is the fuzzy adjustment PID controller structure.

Figure 7. Fuzzy-PID control system of chain tension of scraper conveyor
Table 1. Fuzzy variable \( E, E_C \) evaluation

| \( E/E_C \) | -3 | -2 | -1 | 0  | 1  | 2 | 3 |
|------------|----|----|----|----|----|---|---|
| PB         | 0  | 0  | 0  | 0  | 0  | 0.5| 1 |
| PM         | 0  | 0  | 0  | 0  | 0.5| 1  | 0.5|
| PS         | 0  | 0  | 0  | 0.5| 1  | 0  | 0 |
| ZO         | 0  | 0  | 0.5| 1  | 0.5| 0  | 0 |
| NS         | 0  | 0.5| 1  | 0.5| 0  | 0  | 0 |
| NM         | 0.5| 1  | 0.5| 0  | 0  | 0  | 0 |
| NB         | 1  | 0.5| 0  | 0  | 0  | 0  | 0 |

Table 2. Fuzzy variable \( K_P, K_I, K_D \) evaluation

| \( K_P, K_I, K_D \) | -3 | -2 | -1 | 0  | 1  | 2 | 3 |
|---------------------|----|----|----|----|----|---|---|
| PB                  | 0  | 0  | 0  | 0  | 0  | 0.02| 0.6| 1 |
| PM                  | 0  | 0  | 0  | 0  | 0.02| 0.5| 1  | 0.5|
| PS                  | 0  | 0  | 0.02| 0.5| 1  | 0.5| 0  | 0 |
| ZO                  | 0  | 0  | 0.5| 1  | 0.5| 0  | 0  | 0 |
| NS                  | 0.01| 0.5| 1  | 0.5| 0.02| 0  | 0  | 0 |
| NM                  | 0.5| 1  | 0.5| 0.02| 0  | 0  | 0  | 0 |
| NB                  | 1  | 0.5| 0.2| 0  | 0  | 0  | 0  | 0 |

For equations (13), (15) take the incremental equation, and turn into equations (14) into a step-by-step number to take the first-order linear term. Then we can get the linear increment equation of this equation. The Lagrangian transformation used to obtain the simplified transfer function of the system.

At this time, we ignore the frictional resistance of the mass \( M_a \), so that the transfer process of the system force is obtained, as shown in Figure 7.

\[ C = C_i + C_{i+1}; \quad K = K_i + K_{i+1}; \quad K_{fp} \]

detecting circuit gain \( e^{(\tau_1 + \tau_2)}s / s \) is the transfer function of the delay characteristics of the circuit system. According to the basic principles of engineering design, take

\[ P_s = 25 \left( MPa \right), x_{max} = 0.15(m / s), A_x = 0.5\pi(0.12)^2 = 0.022608(m^2), \]

then \( q_{max} = A_x \cdot x_{max} = 240(l / min) \), the maximum flow rate of the selected electro-hydraulic servo valve is 300(l / min), and the transfer function of the electro-hydraulic servo valve \( G_{sv(s)} \) for:

\[
G_{sv(s)} = \frac{1}{S^2 + 2\xi\omega_n + \omega_n^2}
\]

In the formula: \( G_{sv(s)} = 600(rad / s); \xi_n = 0.5 \)

\[
K_{sv} = \frac{200(l / min)}{400(mA)} = \frac{300.10^{-3}}{60 \cdot 40 \cdot 0.04} = 0.003125 \quad (m^3 / sA)
\]

\( \tau_1 + \tau_2 = 80(m\)s), Other parameters are found in the manual, according to the Fuzzy-PID control scheme constructed.

Create the dynamic differential equation of the whole system and combine the equations (8) and equations (13) - (17) to obtain the dynamic response of the system.

The scraper conveyor system was a model on Matlab-Simulink R2018b software. The scraper conveyor system parameters [13-16] are described and programmed to calculate the output parameters, as shown in Figure 8 to Figure 16.

Figure 8 to Figure 10 shows the forces of chains at point 2 in Figure 1. Figure 8 shows that during the start according used to the PID controller forces of chains, the scraper conveyor tension fluctuates.
strongly to a peak of value $2.45 \times 10^5$ (N). The oscillating force fades out after 3 cycles and stables a time of 1.25 seconds with an around the value of $2.1 \times 10^4$ (N). When starting the scraper conveyor using the Fuzzy-PID controller for forces of chains. The forces of controlling the load tension are stable with decreasing fluctuation after 3 cycles, and then stable after 0.38 seconds at value $2.1 \times 10^4$ (N) in Figure 9. Comparing the tension control of the scraper conveyor with the PID controller and the Fuzzy-PID controller, the results clearly show that the Fuzzy-PID controller gives much better quality in Figure 10.

**Figures 8.** The comparison of tension control of the scraper conveyor with PID controller

**Figures 9.** The comparison of tension control of the scraper conveyor with Fuzzy-PID controller

**Figure 10.** The comparison of tension control of the scraper conveyor with PID controller and Fuzzy-PID controller

**Figure 11.** Flex speed of the hydraulic cylinder with PID controller

**Figure 12.** Flex speed of the hydraulic cylinder with Fuzzy-PID controller.

**Figure 13.** The comparison of flex speed of hydraulic cylinder with PID and Fuzzy-PID
Figure 11 shows that the start according used to the PID controller for the hydraulic cylinder, the speed of the hydraulic cylinder large fluctuations to a peak of value $1.41 \text{(m/s)}$. The velocity of the piston gradually stops after 7 cycles and stabilizes a time of 10.25 seconds with an around the value zero. But when starting the scraper conveyor with the Fuzzy-PID controller for forces of chains, the velocity of the piston is decreasing fluctuation after 3 cycles and a peak of value $0.11 \text{(m/s)}$, and then stable after 5.8 seconds at an around the value zero in Figure 12. Figure 13 compares the piston velocity between the PID controller and the Fuzzy-PID controller, the results show in detail that the Fuzzy-PID controller gives better control quality and is more reliable.

![Figure 14. The process of changing the thrust of a hydraulic cylinder with PID controller](image1)

![Figure 15. The process of changing the thrust of a hydraulic cylinder with Fuzzy-PID controller](image2)

![Figure 16. The comparison of changing the thrust of a hydraulic cylinder with PID controller and Fuzzy-PID controller](image3)

Figures 14 and 16 describe in detail the thrust of the hydraulic system piston acting on position B in Figure 1 to stretch the chains of scraper conveyor, respectively. Figure 16 compares the thrust of the piston between the PID controller and the Fuzzy-PID controller, the results show that thrust of the piston the Fuzzy-PID controller gives better control quality and is more reliable. It can also be seen from the figure that the system tends to be stable after $t = 12.1(\text{s})$ at a around the value $3.24 \times 10^5 \text{(N)}$.

Operating conditions for starting conditions $v_{A_{\text{max}}} = 200(\text{m/s})$ and less than the designed maximum speed. The maximum extension distance of the piston rod is $x_{A_{\text{max}}} = 0.324(\text{m})$.

5. Conclusion

The principle of automatic adjustment of the pretension force of the scraper conveyor chain has been studied and the hydraulic control system has been developed. The system control theory is an analysis and the Fuzzy-PID controller is applied to the control system and simulation is performed. The simulation results clearly show that the Fuzzy-PID controller is capable of automatically stabilizing the tension of the chains of the scraper conveyor. The process of controlling the chain tension of the chains via the Fuzzy-PID controller, which adjusts the hydraulic valve opening, controls the scraper conveyor to operate stably, less vibration, friction between the chains, and the upper surface. In addition, the conveyor tension control system helps to reduce chain jam, gear breakage, reduce the
upper surface wear of the tray with the drive chain, increase the time to change new chains and gears, and increase efficiency.

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