Optimization of Bridge Crane Control System Using Fuzzy PID Control and Speed Control of Frequency Converter

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Abstract. Objective: As a carrier, bridge cranes are widely used in port cargo handling. Due to the structure of the crane itself, the load inevitably produces displacement deviation and lifting weight swing. Therefore, the optimization investigation of the bridge crane control system is carried out to guarantee the fast and secure operation of the crane. Method: According to the characteristics of bridge cranes, combined with the experience of on-site operating staff, the fuzzy rules that meet the working conditions of the site are designed by using the advantages of fuzzy PID (Proportion-Integration-Differentiation) control algorithm without relying on an accurate mathematical model, to set the parameters of the fuzzy PID controller. The speed control technique of frequency converter is adopted to design the system to improve the safety of the overall system. Results: The results show that the adjustment time of the swing angle of crane weight of the traditional PID control requires 6.79s, and the maximum swing angle of crane weight is 0.039rad, and the adjustment time under the fuzzy control is 4.89s, and the swing angle of crane weight is 0.013rad. The fuzzy PID controller surpasses the traditional PID controller in the positioning accuracy. It is not sensitive to changes in the internal parameters of the system. Also, it has strong adaptability to changes in operating conditions. The swing angle of crane weight is smaller, which further improves the robustness. The vector frequency conversion speed control has a more precise control effect on the speed and running track of the operating mechanism of the bridge crane. This method can be applied to the automatic operation mechanism of bridge cranes and achieve good control performance. Conclusion: The conducted optimization investigation of the bridge crane control system makes the control system flexible, simple and robust, providing important theoretical support for related explorations.

Keywords: bridge crane; fuzzy PID control; speed control of frequency converter; optimization of control system.
1. Introduction

Bridge crane is a lifting device. It conducts the lifting and transportation for materials by crossing the workshop, warehouse and material yard. Its two ends are placed on tall concrete pillars or metal supports, shaped like a bridge [1, 2]. The frame runs along the rails laid on the elevated sides on both sides in the longitudinal direction. In this way, it can take full advantage of the space under the bridge frame, thereby lifting materials with no hindrance by ground device. Based on above advantages, the bridge crane has become the most extensively used lifting machinery. Also, its number is largest [3-5]. After the implementation of the reform and opening-up policy in China, a large number of foreign crane builders began to come to China to seek a way out, which has produced a benign stimulus to the bridge crane industry. Some relatively underdeveloped countries have begun to purchase bridge cranes from China, prompting the rapid development of China's bridge crane industry and meeting the standards of mastering advanced technologies worldwide [6]. For bridge cranes, the optimization of the speed control system will greatly reduce the impact of starting and braking on the overall metal structure of the bridge crane. The optimization of the control algorithm will greatly improve the efficiency of the cargo transportation of the bridge crane, and can make a certain contribution in the production cycle of the product. Therefore, the bridge crane optimization from the two aspects of control algorithm and speed control system will be explored [7].

Scholars worldwide have more investigations on bridge crane control algorithms and other safety aspects. Ouyang et al. (2019) explored the system controller of bridge crane, which has double pendulum effect. The linearized and decoupled dynamic model of the double-swing overhead bridge was established by disturbance observer and modal analysis technology [8]. Zhu et al. (2019) established a dynamic model for the bridge crane system under the Lagrange equation. They proposed a crane anti-sway scheme according to the phase plane analysis algorithm. With the given acceleration and the condition of the maximum speed limit, different motion trajectories can be calculated online by industrial-grade bridge cranes without performing offline optimization calculations [9]. Chen et al. (2018) proposed a bridge crane safety evaluation method under cluster analysis and fuzzy neural network. Also, they established a bridge crane safety evaluation index system. The effectiveness of this method was verified by engineering examples. The evaluation results coincide with the actual situation [10].

Scholars from various countries have scattered investigations on bridge cranes, and have not conducted systematic explorations on their control systems and frequency conversion speed control. Therefore, based on previous works, the bridge crane control system and frequency conversion speed control method are explored.

2. Method

2.1. Mathematical Model of Bridge Crane Control System

Bridge crane is an important device for the achievement of mechanizing and automating the production process. In this way, the labor strength of the operator can be reduced, improving productivity. Bridge cranes are commonly used in many aspects, such as industrial and mining enterprises, railway transportation, steel and chemical industry, as well as logistics turnover. It is an indispensable equipment in people's production activities [11].

There are many types of bridge cranes, among which general bridge cranes and gantry cranes are the most common. The structure and operation method of these two types of cranes are almost the same. The difference lies in the location of the running track of the cart. The general bridge crane is at high altitude, and the gantry crane is on the ground, which brings different support structures. The bridge crane is constitutive of a lifting mechanism, a trolley running mechanism and a trolley frame. Among them, the motor, brake, reducer, drum and pulley block are contained in the lifting mechanism. The drum is driven by the motor to rotate through a speed reducer. Then, the wire rope is wound on the drum or laid down from the drum to raise and lower the weight. In addition, the trolley frame is a frame that...
supports and installs components such as the lifting mechanism and trolley running mechanism. It is usually a welded structure [12, 13].

The rotation mode of the trolley is divided into two classes based on the installation position of the reducer. The first is installed in the middle of the driving wheel of the trolley. Then, the torque of the output shaft of the trolley reducer and the rotating shafts on both sides is relatively uniform. The second is that the reducer is installed on the side of the driving wheel of the trolley. This type of rotation is more convenient for installation, repair, and maintenance, but the torsion of the trolley body will not be stable [14].

Although there are different types and models of bridge cranes, and their shapes and structures are different, they all share a common characteristic. That is the working method of the intermittent circulation. A working cycle generally includes the following. The material is displaced through the lifting and lowering of the fetching device. Then, it moves in the opposite direction and returns to the original position or another position for the next working cycle. Between two working cycles, there is generally a short intermittence [15]. It can be seen that while the bridge crane is working, the various mechanisms are in alternate motion states of starting, running, braking, forwarding and reversing.

The bridge crane control system is to accurately position the cargo and reduce the swing angle of the cargo as much as possible. The bridge crane system model is established, as shown in Figure 1.

In Figure 1, M indicates the mass of the vehicle, and m indicates the mass of the cargo. For the convenience of calculation, the mass of the rope and the hook is ignored here. F represents the driving force of the vehicle, and f represents the sliding friction force of the vehicle, and F1 represents the elastic force of the rope. θ represents the swing angle of the cargo when it is lifted. The Lagrange equation is used to get the equation of the bridge crane system. It is exhibited in equation (1).

\[
\begin{align*}
(M + m)\ddot{x} + mL \sin \theta + 2mL\dot{\theta} \cos \theta + mL\dot{\theta}^2 \cos \theta - mL\dot{\theta}^2 \cos \theta + \mu x &= F \\
2\dot{L}\dot{\theta} + L\ddot{\theta} + X \cos \theta + g \sin \theta &= 0 \\
mL + m\ddot{x} \sin \theta - mL\dot{\theta}^2 - mg \cos \theta &= F_1
\end{align*}
\]

Where: x represents the current position of the vehicle. g represents the acceleration of gravity. L represents the length of the rope. To facilitate the follow-up investigation, under the premise of considering the actual situation, it is assumed that the length of the rope is always consistent during the horizontal movement of the crane. Also, the positioning of the motor is accurate, and the speed of the swing angle of the cargo to decay to 0 is fast, and the elongation of the rope itself is ignored. Then, the simplified equation shown in equation (2) can be obtained.

\[
\begin{align*}
M\ddot{x} - mg\theta + \mu x &= F \\
-l\ddot{\theta} - g\theta &= \ddot{x}
\end{align*}
\]
Laplace transform on the above equation can obtain the following equation.

\[
\begin{align*}
x(s) = & \left[ f(s) + mg\theta(s) \right] / (Ms^2 + \mu s) \\
\theta(s) = & -x(s)s^2 / (ls^2 + g)
\end{align*}
\]  

(3)

2.2. Design of bridge crane control system

PID controller (Proportion-Integration-Differentiation) is constitutive of proportional unit P, integral unit I and differential unit D [16, 17]. Moreover, the parameters, namely, Kp, Ki and Kd, are set. Then, the controller is usually used in the system without changing in basic linearity and dynamic features with time.

From the mathematical model, the crane is a multi-variable nonlinear system, and its uncertainty is strong. With the traditional PID controller, achieving the ideal control effect is difficult. For the fuzzy control method, it hardly depends on the system mathematical model. In this investigation, the design of fuzzy adaptive controller combines the two above. Also, it is applied to the control system of bridge crane.

In industrial control applications, PID controller is a feedback loop component [18]. The data is acquired and compared with a given reference value. A new input value can be calculated by the difference between the two. The value makes the system data reach or maintain the given reference value. Different from other control computations, the input value can be adjusted by the PID controller in line with historical data and the occurrence rate of the difference. Then, the system will have high accuracy and stability. The PID feedback loop is proved to be able to make the system has high stability if other methods lead to stability errors or process iterations in the system through the mathematical methods [19].

Fuzzy adaptive PID algorithm is mainly is constitutive of fuzzy controller and PID controller. The former takes the error E and the error change rate EC as inputs. The Kp, Ki, and Kd of the PID controller are adaptively adjusted by fuzzy rules to keep the controlled object in a better dynamic and static stable state. The fuzzy adaptive PID is more flexible and stable. In particular, for the controlled objects with large time-varying and non-linear, its advantages are more prominent. Figure 2 exhibits the structure of fuzzy PID.

Designing fuzzy adaptive PID control requires the following steps.

1. Determining fuzzy control rules. (the rules can be obtained mainly through expert experience and sampling data)

2. The fuzzy rule table is used to fuzzify E (error) and EC (error change rate) to get the corresponding membership degree.

3. \( \Delta K_p, \Delta K_i, \Delta K_d \) are calculated by using the obtained membership degree and the abscissa of the corresponding membership degree into the equation.

The equation is shown below.
\[ y = \frac{\sum_{i=1}^{n} \mu_{A_i}(x) \mu_{B_i}(y) z_i}{\sum_{i=1}^{n} \mu_{A_i}(x) \mu_{B_i}(y)} \quad (4) \]

Where: \( \mu_{A_i}(x) \) and \( \mu_{B_i}(y) \) represent the degree of membership found, \( z_i \) represents the abscissa corresponding to the degree of membership.

The adjusted parameters \( K_p, K_i \) and \( K_d \) obtained by
\[ K_p = K_p + \Delta K_p \]
are substituted into the PID controller for calculation. The PID equation is shown below.

\[ Output = K_p e(t) + K_i \int e(t) dt + K_d \frac{d}{dt} e(t) \quad (5) \]

2.3. Frequency conversion speed control method of bridge crane

The frequency conversion speed control technology is grounded on the proportional relationship between the motor speed and the input frequency of the working power supply. Through the change in the working power frequency, the motor speed can be changed.

The three-phase asynchronous motor speed equation is shown below.

\[ n = 60 f (1 - s) / p \quad (6) \]

From the above equation, the changes in the power supply frequency \( f \), the number of pole-pairs \( p \) of the motor, and the slip ratio \( s \) can all realize the change in the rotation speed. From the essence of speed control, different speed control methods are changing the synchronous speed of the alternating-current (AC) motor or not changing the synchronous speed. In production machinery, widely used speed control methods whose synchronous speed is not changed are the rotor string resistance speed control of the wound motor, the chopping speed control, the cascade speed control, as well as the application of electromagnetic slip clutch, hydraulic coupling, oil film clutch [20]. There are multi-speed motors changing the number of stator pole pairs to change the synchronous speed. The frequency conversion speed control changing the stator voltage and frequency can control the speed of the motor without commutation. From the energy consumption during speed control, there are two classes of high-efficiency and low-efficiency speed control methods. High-efficiency speed control means the method of constant slip ratio. Thus, there is no slip loss, such as multi-speed motors, frequency conversion speed control and speed control methods that can recover slip loss (such as the cascade speed control). The speed control method with slip loss belongs to low-efficiency speed control, such as the rotor string resistance speed control method, the energy is lost in the rotor circuit. In the electromagnetic clutch speed control method, the energy is lost in the clutch coil. In the fluid coupling speed control, the energy is lost in the oil of the fluid coupling. In general, slip loss increases with the speed control range. If the speed control range is not large, the energy is lost small.

The comparative investigation on the methods based on sinusoidal pulse width modulation (SPWM) and vector frequency conversion speed control will be conducted to obtain more targeted results.

All motors operate in accordance with the following equation.

\[ T_e - T_L = \frac{GD^2}{375} \frac{dn}{dt} \quad (7) \]

Where: \( T_e \) indicates the electromagnetic torque of the motor. \( T_L \) indicates the load torque of the motor. \( \frac{GD^2}{375} \) indicates the moment of inertia of the motor. From the above equation, if the frequency conversion speed control system needs more excellent dynamic characteristics, the electromagnetic torque of the motor must be quickly and accurately controlled. The electromagnetic torque equation of the AC asynchronous motor is shown below.
\[ T = K_f \Phi I_2 \cos \varphi_2 \]  

Where: \( K_f \) represents the constant in relation to the motor structure. \( \Phi \) represents the magnetic flux of each pole of the motor. \( \cos \varphi_2 \) represents the power factor of the rotor circuit. Due to the mutual coupling between parameters such as magnetic flux and power factor, the relationship is more complicated, which brings certain difficulties to the frequency conversion speed control. Therefore, the three-phase current of the stator winding is converted into a two-phase direct current (DC) in an equivalent rotating coordinate system through coordinate transformation, so that the rotating magnetic field generated by the three-phase current has the same size, direction and speed. In this way, after being equivalent, the speed of the AC motor can be controlled like a DC motor.

### 2.4. Simulation experiment

The simulation parameters are set as follows: the mass of trolley is 250kg and the weight of spreader is 100kg. In the simulation process, the initial speed of the trolley is 65m / min, the target moving distance is 20m, the initial swing angle of the spreader is -0.141 rad, the initial rope length of the spreader is 1 m, and the descent distance is 0.5m, as shown in Table 1

| Parameter                              | Category | Unit  |
|----------------------------------------|----------|-------|
| The car quality                        | 250      | kg    |
| Sling quality                          | 100      | kg    |
| Initial velocity of trolley            | 65       | m/min |
| Target moving distance                 | -0.141   | rad   |
| Initial swing Angle of spreader        | 20       | m     |
| Initial length of spreader rope        | 1        | m     |
| Final length of spreader rope          | 1.5      | m     |

The simulation block diagram of fuzzy PID control for positioning and anti swing system of port quay crane is built as shown in Figure 3.

![Figure 3. Simulation block diagram of fuzzy PID control](image-url)
3. Results

3.1. Comparative analysis of traditional PID and fuzzy PID
The traditional PID and fuzzy PID in the case of precise positioning of the dolly and cart as well as the change of the swing angle of crane weight are compared. The comparison results are shown in Figures 4-6.

Figure 4. Comparison of traditional PID and fuzzy PID (precise positioning)

Figure 5. Comparison of traditional PID and fuzzy PID (swing angle of crane weight)

Figure 6. Simulation diagram of cable length
As can be seen from Figure 4 no matter whether the traditional PID method is precise positioning PID or precise positioning PID and swing angle of crane weight, the precise position curve of the two vehicles simultaneously controlled by PID shows a poor state compared with the fuzzy PID algorithm. The precise position curve of the dolly is superior to the cart. The fuzzy PID control method achieves an earlier time for the precise positioning curve to reach a steady state, and the error of the final precise position curve is relatively small. The PID controllers in this investigation are designed under the assumption of ideal conditions. Therefore, in actual situations, bridge cranes will be limited by factors such as their friction and nonlinearity during operation, leading to results that are not as good as those obtained in this work.

From Figure 5, the fuzzy PID control method is more obvious for the suppression of the swing angle of crane weight. By comparing the response result curves of the two control algorithms, the adjustment time of the swing angle of crane weight of the traditional PID control requires 6.79s, and the maximum swing weight angle is 0.039rad, and the adjustment time under fuzzy control is 4.89s, and the swing angle of crane weight is 0.013rad. It is concluded that under the interference of the square wave signal, the precise positioning and swing angle of crane weight using the fuzzy PID control algorithm are more inclined to a stable state, and the anti-interference performance is stronger. Although the effect of the traditional PID control method is not good, it has the simple structure and small amount of calculation. Since fuzzy control does not rest upon the mathematical model, its calculation results only change according to the measured changes. Therefore, the fuzzy PID control method has become an excellent control method of the bridge crane nonlinear system.

3.2. Comparative analysis of frequency conversion speed control

After the parameters in the SPWM and the vector frequency conversion speed control models are determined, the simulation starts to run. The running results are compared and analyzed in terms of speed response and running track deviation. The simulation shows the comparison between the output and input speed curves of the motors for the dolly and cart of the two frequency conversion speed control systems. It is exhibited in Figure 7.

As can be seen from Figure 7, SPWM frequency conversion speed control can complete the speed follow-up as a whole. During the startup process, there will be a certain speed jitter due to the direct start with load. When reaching the peak for uniform motion, the speed is not stable. In the third-stage running path, the motor speed of the cart cannot reach the ideal maximum speed, and the peak value reached by the dolly is higher than the ideal peak value. The method of vector frequency conversion speed control shows that the output speed curve and the input speed curve are almost coincident in the case of the cart and dolly. It can be concluded that the vector frequency conversion speed control method can achieve better control effects in the corresponding speed and steady-state accuracy. Thus, it can show that the control performance of the vector frequency conversion speed control method is excellent.
The running distance of the dolly and the running distance of the cart in the simulation results are the horizontal and vertical coordinates respectively. The real running trajectory of the operating mechanism controlled by the two speed control systems can be obtained. The comparison between the real running path and ideal running path of the two speed control systems is shown in Figure 8.

![Figure 8. Comparison of real path and ideal path](image)

From the results shown in Figure 8, there are certain differences between the two frequency conversion speed control methods for the following situation of the ideal path. Although the SPWM control method can almost follow the ideal path, there will be a certain deviation, and it cannot coincide with the ideal path. The vector control method can almost coincide with the ideal path. Thus, in comparison, the vector control method embodies more excellent vehicle path control performance.

Through the example simulation and result analysis of the two speed control systems, it can be proved that the vector frequency conversion speed control has a more accurate control effect on the speed and running trajectory of the bridge crane operating mechanism. This method can be applied to the automatic operation mechanism of bridge cranes and achieve good control performance.

4. Discussion

At present, bridge cranes still use many traditional mechanical control methods, and their positioning methods are also based on human experience. It results in low control accuracy of the bridge crane, and the effect cannot reach a satisfactory standard. Moreover, the traditional bridge crane control method cannot carry out joint control on the positioning, traveling route and swing angle of the crane, which greatly reduces the accuracy of the bridge crane [21,22]. In view of the above problems, fuzzy PID control and the frequency conversion speed control method are used for investigation. Then, the fuzzy PID control method is more obvious for the suppression of the swing angle of crane weight. By comparing the response result curves of the two control algorithms, the adjustment time of the swing angle of crane weight of the traditional PID control requires 6.79s, and the maximum swing weight angle is 0.039rad, and the adjustment time under fuzzy control is 4.89s, and the swing angle of crane weight is 0.013rad. It is concluded that under the interference of the square wave signal, the precise positioning and swing angle of crane weight using the fuzzy PID control algorithm are more inclined to a stable state, and the anti-interference performance is stronger. The vector frequency conversion speed control technology is applied to the speed control of the dolly and cart of the bridge crane. The method of vector frequency conversion speed control shows that the output speed curve and the input speed curve are almost coincident in the case of the cart and dolly. It can be concluded that the vector frequency conversion speed control method can achieve better control effects in the corresponding speed and steady-state accuracy. Thus, the control performance of the vector frequency conversion speed control method is excellent.

The design results can vastly enhance the working efficiency and operating accuracy of the bridge crane. In theory, the investigation method promotes the automation and intelligence of bridge cranes, providing a certain amount of possibility for the future intelligent development of bridge cranes and even driverless driving.
5. Conclusion
For bridge cranes, the optimization of the speed control system will greatly reduce the impact of starting and braking on the overall metal structure of the bridge crane. The optimization of the control algorithm will greatly improve the efficiency of the cargo transportation of the bridge crane, and can make a certain contribution in the production cycle of the product. Therefore, the bridge crane optimization from the two aspects of control algorithm and speed control system is explored. It is concluded that the precise positioning and swing angle of crane weight using the fuzzy PID control algorithm are more inclined to a stable state, and the anti-interference performance is stronger. Also, the vector frequency conversion speed control method can achieve better control effects in the corresponding speed and steady-state accuracy. Although some results have been achieved, there are still some shortcomings. The current investigation is only in the two-dimensional space, and the influence of air and friction is not considered in the process. Therefore, the results obtained may deviate from the results obtained in actual use. The next step is to conduct an actual experimental exploration based on this investigation to consolidate the results.

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