Study on Mechanical and Electrical Coupling characteristics of Milling system based on CMAC-PID Compound Control

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Abstract. Taking boring and milling machining center as the research object, analyze and optimize the dynamic characteristics of milling control system. Use Simulink software to create mathematical model and simulate the dynamic characteristics of milling control system. Based on the theory of CMAC, consider the theory of the CMAC-PID compound control in the way of M function in Simulink Control language. Apply the theory, calculate the relevant parameters of milling system and model its transfer function, and all the parameters are solved by CMAC-PID compound control in Simulink. Verify the optimization of milling control system, and obtains the method of optimizing the mechanical and electrical coupling characteristics based on the CMAC-PID compound control theory.

Keywords: Boring-milling machining center, the CMAC-PID compound control, M function, the mechanical and electrical coupling, Simulink.

1. Introduction
Nowadays, with the continuous improvement of machining precision, the technology development of boring and milling machining center has the characteristics of intelligentization, high speed, precision, modularization, compounding and so on. The static and dynamic characteristics of the machine tool are the important factors affecting the machining accuracy and stability of the machine tool. Therefore, it is an urgent problem to analyze the static and dynamic characteristics and explore the measures to improve the characteristics. [1-2]

In this paper, the Simulink module set is used to set up the control platform of the milling system CAMC and PID. The control mode of the milling system is realized by two M functions under the control language of Simulink, which are controlled by CMAC and PID. On the one hand, it can make up for the deficiency of PID control ability to complex objects, such as non-linearity, large delay, no accurate mathematical model of the object and so on. On the other hand, the perfect combination of CMAC control and PID control makes up for the disadvantages of CMAC control, such as poor control
quality and low steady-state precision, and improves the control performance and machining precision of the system.

2. Milling system based on PID Control

When PID controller is used to control milling system separately, the value of gain parameter kp determines the control effect to a great extent. However, when the external load of the machine tool changes, the PID parameters need to be adjusted relatively in order to obtain the best control effect. PID parameters determine the control quality of the system. At the same time, the single PID control law is only a kind of linear control, it also contains the weakness of the traditional control theory, and the control effect in the simple linear uni-variate system can also be achieved. However, the control effect is not satisfactory in the nonlinear control of complex numerical control system. [3-6]

3. Optimization Modeling of CMAC and PID parallel Systems

3.1. CMAC-Cerebellar Model Articulation Controller

At present, CMAC-Cerebellar Model Articulation Controller has many kinds of control forms, such as CMAC feed forward control, CMAC feedback control and CMAC direct inverse motion control [7-9]. The parallel control milling structure based on CMAC and PID is shown in figure 1.

![Figure 1. CMAC and PID parallel Control Architecture Diagram](image)

The feed forward and feedback control of milling system is realized by parallel control of CMAC and PID:

(1) The cerebellar model CMAC realizes the feed forward control, accurately realizes the inverse dynamic model of the controlled object, improves the control response speed, and reduces the overshoot, which can enhance the control precision.

(2) PID is used for feedback control to ensure the stability of the control system and suppress the disturbance.

The control algorithms for milling system are:

\[ u_n(k) = \sum_{i=1}^{c} a_i a_i \]  \hspace{1cm} (1)

\[ u(k) = u_n(k) + u_p(k) \]  \hspace{1cm} (2)

In the expression, \( a_i \) is the binary selection vector, \( c \) is the generalization parameter, \( u_n(k) \) is the output value of CMAC, and \( u_p(k) \) is the output value of PID.
When each cycle of control cycle is closed, the CMAC outputs \( u_c(k) \), and compares with the general control output \( u(k) \) to modify the weights by adjusting the index function as the basis of optimization calculation. The adjustment index function of CMAC is as follows:

\[
\omega(k) = \omega(k-1) + \Delta \omega(k) + \alpha \left( \omega(k) - \omega(k-1) \right)
\]

In the expression, \( \eta \) represents the learning rate of the grid, and \( \eta \in [0,1] \), \( \alpha \) indicates the coefficient of inertia, \( \alpha \in (0,1) \).

The Simulink module set can accurately control the motion mode of milling system, so the Simulink module set is used to build the control platform of milling system CAMC and PID, CMAC and PID are controlled by two M functions under Simulink control language to realize its control mode. As shown in figure 2, CMAC and PID jointly control the overall process.

![CMAC and PID Joint Control overall process](image)

Figure 2. CMAC and PID Joint Control overall proc

3.2. Mathematical Modeling

1) Related parameters of milling system and its transfer function.

(1) Moment of inertia converted to motor shaft by load

\[
J_w = M \left( \frac{P_x}{2 \pi} \right)^2
\]

(4)

(2) Screw moment of inertia

\[
J_s = \frac{M_s D_s^2}{8}
\]

(5)

The total load inertia is:

\[
J_L = J_w + J_s
\]

(6)

Selection of equivalent stiffness of milling system

The milling system total drive stiffness calculation formula is as follows:

\[
\frac{1}{K} = \frac{1}{K_c} + \frac{1}{K_s \left( \frac{2 \pi}{P} \right)^2 \times 10^{-\gamma}}
\]

The transfer functions of the system are:

\[
J_f \ddot{\theta} + c \dot{\theta} + K_s \theta = M
\]

(7)
When Laplacian transformation is carried out, it is possible to obtain:

\[
G(s) = \frac{1}{J_s S^2 + cS + K}
\]  

(8)

The system transfer block diagram is shown in figure 3:

![Figure 3. System transfer block diagram](image)

The transfer function of the whole system can be obtained from the above figure:

\[
G(s) = \frac{K_u \cdot K_m}{J_s S^2 + cS + K}
\]  

(9)

4. Analysis of coupled characteristics of mechatronics

The Simulink module set is used to build the control platform of milling system CAMC and PID. The control mode of CMAC and PID is realized by two M functions under the control language of Simulink. Use the persistent instruction to keep the milling system dynamic parameters in the M function of PID control, adopt the global command to realize the parameter sharing, and adopt the clock signal Clock to realize the initialization of the parameters. The actual transfer function of the system is inputted into the milling system of the boring and milling machining center milling system. The control flow diagram is shown in figure 4. S is the type of input instruction signal. The input instruction is a step signal control when S=1, the input instruction is a sine signal control when S=2, and the input signal is a square wave signal when S=3 is used.

![Figure 4. Flow chart of actual control for milling system](image)

(1) Sine Control based on CMAC and PID

Use the clock Clock instruction to initialize the weights of the neural network in the M function of milling system controlled by CMAC and PID. Among them, the parameters of PID are kp = 2.0, Ki = 0, KD = 0.28, C = 50, \( \tau = 0.10 \), \( \alpha = 0.04 \). When the Simulink simulation time is 1 s, when the learning time t = 5 s, the sine signal is input to control, as shown in figure 5, 6 and 7, the tracking curve,
controller output curve and system error curve of the boring and milling center milling system output t=1s are shown.

Figure 5. Tracking curve at t=1s

Figure 6. The output curve of the controller at t=1s

Figure 7. Error curve when t=1s
From the simulation results of the system error curve in fig. 7, it can be seen that the tracking effect of the system is better. Take the sine response input in the Simulink control program, and the CMAC controller is added at t = 0.1s. As can be seen from the diagram, the output signal quickly tracks the given curve in a very short time. The maximum error of the output is reduced from 0.17 to 0.01 when PID is controlled alone, which fully shows that the cerebellar model has the characteristics of fast learning speed and quick response. As can be seen from figure 7, when the CMAC cerebellar network is added, the output of the PID controller decreases rapidly, and the CMAC controller plays a major role, which is determined by the learning algorithm of Formula 6.6. The essence of learning is to make CMAC become the total control input and enhance the stability of milling system.

(2) The influence of parameters on the stability of milling system control.

After adding the CMAC cerebellar model to the nonlinear control system, the performance of the nonlinear control system is greatly improved. Based on the above results, the CMAC-PID control structure shown in figure 6.8 should be studied. Analyze the different parameters (gain coefficient kp, learning rate η, generalization parameter C, etc.) on the stability of milling system enables the system to obtain the best control parameters. In order to explore the influence of each parameter on the stability of milling system, the other parameters are kept constant when simulating the influence of one parameter on the system.

(1) Effect of PID Control scale coefficient kp on milling system

When only the scale factor of the control system is changed, the kp, simulation results are shown in Table 1. The kp represents the PID control scale coefficient, the ep represents the maximum output error in each period of the PID control, and ec represents the minimum of the maximum output error in the CMAC-PID composite parallel control period, ts represents the time when the system reaches the steady state.

| kp  | 1   | 1.5 | 2   | 2.5 | 3   | 3.5 |
|-----|-----|-----|-----|-----|-----|-----|
| ep  | 0.395 | 0.297 | 0.175 | 0.161 | 0.143 | 0.135 |
| ec  | 0.011 | 0.013 | 0.010 | 0.0095 | 0.0094 | 0.015 |
| ts (s) | 0.085 | 0.095 | 0.0098 | 0.124 | 0.052 | 0.135 |

As can be seen clearly from Table 1 above:
(1) The larger the scale coefficient kp is, the smaller the value of ep is.
(2) The value of ec is basically stable at about 0.01, and it does not change with the change of kp. It is also obvious from here that the output of PID controller weakens rapidly in this kind of control structure. The real main controller is the CMAC cerebellar network.
(3) In general, the smaller the scale coefficient kp is, the longer the steady-state time ts is.
(2) The influence of learning rate η

Table 2. The influence of Learning rate η on the system

| η   | 0.05 | 0.1 | 0.2 | 0.4 | 0.6 | 0.8 |
|-----|------|-----|-----|-----|-----|-----|
| ec  | 0.016 | 0.010 | 0.011 | 0.009 | 0.162 | 0.195 |
| ts (s) | 0.089 | 0.098 | 0.095 | 0.086 | 0.079 | 0.072 |

It can be seen from Table 2 that the minimum value of the maximum output error of the CMAC-PID compound parallel control period with the change of the learning rate η value is irregular. However, it can be found that in general, the larger the learning rate, the shorter the time for the system to reach the steady state, that is, the system reaches the stable state after less time milling system.
(3) Influence of generalization coefficient C
### Table 3. Influence of generalization coefficient C on system

| C  | 80  | 70  | 60  | 50  | 40  | 30  |
|----|-----|-----|-----|-----|-----|-----|
| $e_c$ | 0.0162 | 0.010 | 0.0124 | 0.0095 | 0.0201 | 0.0185 |
| $t_s$ (s) | 0.395 | 0.286 | 0.195 | 0.126 | 0.090 | 0.085 |

As you can see from table 3, in general, the larger the generalization parameter, the shorter the time to reach the steady state of the system. It is shown from a point of view that the larger the generalization parameter C is, the lower the learning rate will be. Therefore, the size of learning rate is an important factor affecting the stability of milling system.

(4) The influence of differential coefficient $k_d$

### Table 4. The influence of differential coefficient $k_d$ on the system

| kp | 0.08 | 0.18 | 0.28 | 0.38 | 0.48 | 0.58 | 0.68 |
|----|------|------|------|------|------|------|------|
| $e_c$ | 0.0188 | 0.0112 | 0.0156 | 0.0111 | 0.0121 | 0.0165 | 0.0121 |
| $t_s$ (s) | 0.085 | 0.095 | 0.097 | 0.112 | 0.139 | 0.182 | 0.195 |

### Table 5. Influence of Inertial coefficient $\alpha$ on system

| $\alpha$ | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 |
|----------|------|------|------|------|------|------|------|
| $e_c$ | 0.0197 | 0.0132 | 0.0165 | 0.0099 | 0.0134 | 0.0178 | 0.0132 |
| $t_s$ (s) | 0.081 | 0.092 | 0.099 | 0.102 | 0.145 | 0.178 | 0.192 |

From the above data analysis, it can be concluded that in general, the response speed of increasing the value of $\eta$, milling system will be accelerated, but this relationship is not absolute. When the kp is fixed, $\eta$ will also decrease within a certain range, which will be more favorable to the rapid response of the system. When the value of $\alpha$ , $k_d$ decreases gradually, the response speed of the system is accelerated, but when the $\alpha$, $k_d$ is to a certain extent, the response speed of the system becomes slower and slower when the value of $\alpha$ is increased. The influence of generalization parameter C on the response performance of the system is negatively correlated with the learning rate $\eta$ under normal conditions. The changes of kp and $k_d$ significantly accelerate the response speed of the system, and it is obvious that the system has a relatively good response speed. At the same time, after the parameters change, the milling system still has good dynamic response performance and steady-state response performance, which fully illustrates that the CMAC-PID composite parallel controller has better fast response and good robustness.

### 5. Conclusion

In this chapter, the milling system mechanics simulation model of boring and milling machining center is taken as the research object. Study the electromechanical coupling characteristics based on the parallel compound control strategy theory of CMAC and PID. The main conclusions are as follows:

(1) CMAC-PID compound control, on the one hand, introduces CMAC control, which makes up for the deficiency of PID control to complex object control ability, such as nonlinear, large delay, no accurate mathematical model of the object and so on. On the other hand, the perfect combination of CMAC control and PID control makes up for the disadvantages of CMAC control, such as poor control quality and low steady-state precision, and improves the control performance and machining precision of the system.

(2) The control structure of CMAC-PID is studied, and the effects of various parameters (gain coefficient kp, learning rate $\eta$, generalization parameter C, etc.) on the stability of milling system are
analyzed. The simulation results show that, in general, the response speed of increasing the value of $\eta$, milling system will be seeded up. However, this relationship is not absolute. When the kp is fixed, $\eta$ will also decrease within a certain range, which will be more conducive to the rapid response of the system. When the value of $\alpha$,kd decreases gradually, the response speed of the system is accelerated, but when the $\alpha$,kd increases to a certain extent, the response speed of the system becomes slower and slower when the value of $\alpha$ is increased. The influence of generalization parameter C on the response performance of the system is negatively correlated with the learning rate $\eta$ under normal conditions. The changes of kp and kd significantly accelerate the response speed of the system, and it is obvious that the system has a relatively good response speed.

(3) The CMAC-PID compound control improves the dynamic and static characteristics of the system compared with the PID control, and carries out the selection of optimization parameters and optimization methods and optimization objectives, establishes the optimization scheme, and finally obtains the optimal parameters of machining center operation.

The research lays a foundation for the dynamic characteristic analysis and stiffness analysis of milling system, and it is also of great significance for the mechanical and electrical joint simulation modeling of the whole machine.

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