Decoupling Strategy and Dynamic Decoupling Model of Flatness Control in Cold Rolling Strip

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Taking a 1 420 mm UCM six-high cold rolling mill as the research object, by calculating and analyzing the relative gain array of flatness adjustments, the flatness control strategy of independent control primary flatness, decoupling control quadratic and quartic flatness is proposed, which simplifies the complex three-loop decoupling to the two-loop decoupling, and facilitates the design of flatness control system. In order to overcome the shortcomings of the long response time and the process fluctuation of the static matrix decoupling control, based on the multi-input and multi-output decoupling control theory, a method and model for the whole process decoupling of quadratic and quartic flatness control loops is proposed by introducing dynamic decoupling matrix instead of static decoupling matrix. The simulation results show that the dynamic matrix decoupling control method can make the system adjust quickly and smoothly, and by controlling the primary, quadratic and quartic flatness, the cubic flatness can also be controlled effectively. This paper opens up a new way and method for developing a simple, practical and high-performance flatness control system.

KEY WORDS: flatness control; influence matrix; relative gain array; static decoupling matrix; dynamic decoupling matrix; process decoupling.

1. Introduction

Flatness control is an important key technology in cold rolling strip production and how to establish a simple, fast and stable control model is a very difficult scientific problem.1–6) According to the flatness representation method, the flatness control model can be divided into two kinds. One is to represent the flatness by the flatness set of many points, and establish a mathematical model between the adjustment parameters of flatness and the flatness of each point according to the rolling deformation theory, which is called multi-point flatness control method.7–9) The other is to represent the flatness by the superposition of the main flatness components, and establish a mathematical model between the adjustment parameters of flatness and the coefficient of each flatness component according to the rolling deformation theory, which is called component flatness control method.10,11) Multi-point flatness control method does not need flatness pattern recognition, but there are many target parameters, complex control model and large amount of calculation. Component flatness control method has fewer target parameters after flatness pattern recognition, usually 3 and the control model is concise and the calculation is small. Component flatness control method grasps the main contradictions and achieves the purpose of controlling the flatness of each point by controlling the main flatness components. In this paper, the decoupling model of component flatness control is studied.

At present, six-high rolling mill is widely used to cold rolling strip. Its online flatness adjustment means are roll tilting (RT), work roll bending (WRB) and intermediate roll bending (IRB). The main components of flatness control are primary, quadratic and quartic flatness. It is a multi-input and multi-output (MIMO) coupling control system. There are decoupling and non-decoupling control modes for MIMO coupling control systems, and the control modes need to be selected according to their relative gain array (RGA).15,16) Over the years, many scholars have established a flatness decoupling model based on influence matrix, but it is limited to steady-state decoupling control, not achieving the process decoupling of flatness control. Because the process coupling still exists in the control system based on the decoupling of the influence matrix, which results in the adjustment time of flatness control becoming longer and response of the actuators producing fluctuation. Moreover, the previous flatness decoupling control strategy decouples all control loops, which is feasible when process decoupling is not involved, but when process decoupling is involved, with the increase of coupling loops, the decoupling model...
is very complex and the practicability is poor. \(^{19}\) In order to solve the above problems, the RGA theory \(^{20}\) is applied to simplify the complex three-loop decoupling to the two-loop decoupling, and the control strategy of independent control primary flatness, decoupling control quadratic flatness and quartic flatness is proposed. And applying the idea of influence matrix model and process decoupling, the static and process coupling are all decoupled, the whole process decoupling control scheme using dynamic decoupling matrix is proposed, which achieves the whole process decoupling control of the flatness control system.

2. Decoupling Strategy for Flatness Control

2.1. Principle of Flatness Control

The intermediate rolls shifting (IRS) of a 1420 mm UCM (universal crown control mill) six-high cold rolling mill is controlled by setting value, that is, the intermediate rolls are shifted to a certain position according to rolling technology before rolling and remain unchanged during rolling process. There are three kinds of on-line flatness adjustment means: RT, WRB and IRB control. According to the rolling deformation theory and the engineering practice, RT mainly controls primary flatness, WRB and IRB mainly controls quadratic and quartic flatness. The principle of flatness control is shown in Fig. 1, in which, \(\sigma = \{\sigma_1, \sigma_2, \ldots, \sigma_m\}\) is a vector of the flatness of each section along the strip width direction measured by the shapemter, and \(m\) is the number of measurement sections. \(A = \{a_1, a_2, a_4\}\) is the measured flatness component coefficient vector by flatness pattern recognition, \(a_1, a_2\) and \(a_4\) represent the measured primary, quadratic and quartic flatness component coefficient respectively. \(A^T = \{a_1^T, a_2^T, a_4^T\}\) is the target flatness component coefficient vector, \(a_1^T, a_2^T\) and \(a_4^T\) represent the primary, quadratic and quartic target flatness component coefficient respectively. \(E = A^T - A = \{e_1, e_2, e_4\}\) is the vector of flatness deviation component coefficient, \(e_1, e_2\) and \(e_4\) represent primary, quadratic and quartic flatness deviation component respectively. \(\Delta U = \{\Delta u_1, \Delta u_2, \Delta u_4\}\) is the regulator vector of given flatness adjustment parameter, \(\Delta u_1, \Delta u_2\) and \(\Delta u_4\) are the given RT displacement adjustment, WRB and IRB force adjustment respectively. \(\Delta U^* = \{\Delta u_1^*, \Delta u_2^*, \Delta u_4^*\}\) is the actual output flatness adjustment parameter adjustment vector, \(\Delta u_1^*, \Delta u_2^*\) and \(\Delta u_4^*\) are the actual adjustment of RT displacement adjustment, WRB and IRB force adjustment respectively. In each control cycle, the flatness control system makes the target flatness \(A^T\) minus the measured flatness \(A\) to get the flatness deviation \(E\), firstly, then calculates the adjustment amount \(\Delta U\) according to the flatness deviation \(E\) and gives it to the hydraulic system. Finally, the hydraulic system of each actuator outputs the actual adjustment amount \(\Delta U^*\) to the roll system according to its dynamic response, and adjusts flatness through the deformation of roll system.

2.2. Open-loop Flatness Control System

Figure 1 shows that the flatness control system of the 1420 mm UCM six-roller cold rolling mill is a three-input-three-output MIMO coupling control system. In order to discuss the problem conveniently, an open-loop flatness control system is constructed as shown in Fig. 2, in which \(G_{RT}(s) = G_{RT}(s)\), \(G_{WRB}(s) = G_{WRB}(s)\), \(G_{IRB}(s) = G_{IRB}(s)\), \(G_{RT}(s)\), \(G_{WRB}(s)\), \(G_{IRB}(s)\) are the transfer functions of RT, WRB, IRB and shapemter respectively. \(\Delta u_1, \Delta u_2, \Delta u_4\) are the change of the flatness coefficients of primary, quadratic and quartic flatness respectively, \(\Delta u_1^*, \Delta u_2^*, \Delta u_4^*\) are the initial measured (last time) primary, quadratic and quartic flatness coefficient respectively. Element \(c_\ell\) is the open-loop gain of the flatness control system, whose physical meaning is the influence coefficient of the \(\ell\)-th adjustment means on the \(i\)-th flatness component coefficient, \(^{21}\) which constitutes the open-loop gain matrix of the flatness control called the

![Diagram of Flatness Control Principle](image-url)
flatness adjustment influence matrix \( C \).

\[
C = \begin{bmatrix}
c_{11} & c_{12} & c_{13} \\
c_{21} & c_{22} & c_{23} \\
c_{31} & c_{32} & c_{33}
\end{bmatrix},
\]

\[
c_{ij} = \frac{\Delta u_i}{\Delta u_j} \quad \cdots (1)
\]

The hydraulic system of RT, WRB and IRB of cold rolling mill and the shapemeter can be approximated to a first-order model, \(^{22)}\) and their respective transfer functions are as follow. In the Formula, \( T_r, T_w, T_t \) and \( T_M \) is the time constant of the RT, WRB, IRB system and shapemeter respectively.

\[
G_r(s) = \frac{1}{T_r s + 1}, \quad G_w(s) = \frac{1}{T_w s + 1},
\]

\[
G_t(s) = \frac{1}{T_t s + 1}, \quad G_M(s) = \frac{1}{T_M s + 1} \quad \cdots (2)
\]

### 2.3. Relative Gain of Flatness Adjustment

Decoupling control is an effective method to solve MIMO coupling systems. However, with the increase of coupling loops, the complexity of decoupling controllers increases and the practicability of decoupling structures decreases. In this paper, the relative gain theory is applied to calculate the coupling degree between the loops, pick out the control loops that do need decoupling, simplify the decoupling structure, reduce the difficulty of decoupling design, so as to make the flatness control system more practical. Relative gain is a level used to measure the effect of a preselected regulating amount on a particular regulated amount. If the relative gain is between 0.3 and 0.7 or greater than 1.5, it indicates that there is a very serious coupling in the system, relative gain is between 0.3 and 0.7 or greater than 1.5, it indicates that there is a very serious coupling in the system, and the closed \( c_{ij} \) approaches 0, the smaller the influence. From Formula (3) to Formula (7), the RGA of the flatness control system can be determined after the influence matrix is obtained. The rolling model of rolling mill, i.e. the flatness control deformation mechanism model, is needed to calculate the influence matrix.

\[
-c_{11} = \frac{c_{11}c_{22}c_{43} - c_{11}c_{23}c_{42}}{|C|} \quad \cdots (4)
\]

\[
-c_{22} = \frac{c_{22}c_{11}c_{43} - c_{22}c_{13}c_{41}}{|C|} \quad \cdots (5)
\]

\[
-c_{33} = \frac{c_{33}c_{11}c_{22} - c_{33}c_{12}c_{21}}{|C|} \quad \cdots (6)
\]

\[
-c_{12} = \frac{c_{21}c_{13}c_{42} - c_{21}c_{12}c_{43}}{|C|} \quad \cdots (7)
\]

The meaning of each element \( c_{ij} \) in the RGA represents the degree of influence of the j-th adjusting parameter on the i-th flatness component. The closer the \( c_{ij} \) approaches 1, the greater the influence, and the closer the \( c_{ij} \) approaches 0, the smaller the influence. From Formula (3) to Formula (7), the RGA of the flatness control system can be determined after the influence matrix is obtained. The rolling model of rolling mill, i.e. the flatness control deformation mechanism model, is needed to calculate the influence matrix.

### 2.4. Flatness Control Deformation Mechanism Model and Simulation

Two key models of flatness control deformation mechanism model are strip plastic deformation model and roll elastic deformation model. Firstly, the strip plastic deformation model is established by using the principle of strip element variational method, and the roll elastic deformation model is established by using the influence function method. Then a set of linear equations is directly formed according to the deformation coordination and force balance conditions of strip and roll system. Without iteration, the transverse distribution of flatness, cross section shape, rolling pressure and inter-roll pressure can be solved at one time, which has advantages of high accuracy, fast speed and good stability. \(^{23)}\)

Given the transverse distribution of strip exit thickness, the transverse distribution of the rolling pressure and front tension (flatness) calculated by the strip plastic deformation model can be abbreviated as follows.\(^{24)}\)

\[
(p_t, \sigma_t) = f_t(\sigma_r, \mu, h_0, h_1, B, T_0, T_1) \quad \cdots (8)
\]

In the Formula, \( \sigma_r \) is the average deformation resistance, \( \mu \) is the friction factor, \( h_0 \) and \( h_1 \) are the transverse distribution of strip entry and exit thickness respectively, \( B \) is the width of strip, \( T_1 \) and \( T_0 \) are the front and post total tension respectively, \( \sigma_r \) and \( p_t \) are the transverse distribution of front tension (stress) and per unit width rolling pressure respectively. Generally, only the transverse distribution of exit thickness is an unknown parameter, so the Formula (8) can be abbreviated as follows.

\[
(p_t, \sigma_t) = f_t(h_1) \quad \cdots (9)
\]

Given the transverse distribution of rolling pressure, the transverse distribution of strip exit thickness calculated by the elastic deformation model of roll system can be abbreviated as follows.

\[
h_1 = f_t(p_t) \quad \cdots (10)
\]

Formula (9) and Formula (10) show that the transverse
distribution of strip exit thickness and rolling pressure is causal to each other. The usual calculation method is that the results of Formula (9) and Formula (10) are iterated with each other, which is called the coupling method of calculation results, whose calculation speed is slow and the stability is not good. In order to solve this problem, strip plastic deformation model and roll elastic deformation model are solved together in reference 23), and a model coupling method is formed, which can solve the transverse distribution of rolling pressure and exit thickness directly at one time.

\[(\sigma_1, p_1, h_1) = f_1(X_1, X_2) \] .............................. (11)

In the Formula, \(X_1\) is a series value of strip parameters, \(X_2\) is a series value of rolling mill and the flatness control parameters.

In order to verify the correctness and accuracy of the mechanism model, the measured flatness of the 1420 mm UCM six-high cold rolling mill are compared with the calculated flatness. Many examples have been validated. The rolling conditions of two examples are shown in Table 1, and the comparison results between measured and calculated flatness are shown in Fig. 3. It can be seen that the calculated results are in good agreement with the measured results, which proves that the established flatness calculation model and algorithm are of high accuracy.

### 2.5. Closed-loop Flatness Decoupling Control Strategy

Using the established rolling model of rolling mill, the flatness adjustment influence matrix and the RGA under various rolling conditions are established in units of 1 μm change in RT, 1 kN change in WRB and 1 kN change in IRB. The flatness adjustment influence matrix and RGA under four rolling conditions are shown in Table 2. A large

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Strip width/mm</th>
<th>Rolling force/T</th>
<th>Entry thickness/ mm</th>
<th>Exit thickness/ mm</th>
<th>Front force/kN</th>
<th>Post tension/kN</th>
<th>WRB/kN</th>
<th>IRB/kN</th>
<th>IRS/mm</th>
<th>RT/μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1150</td>
<td>820</td>
<td>1.14</td>
<td>0.89</td>
<td>105</td>
<td>75</td>
<td>120</td>
<td>130</td>
<td>105</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>1016</td>
<td>2.40</td>
<td>1.60</td>
<td>146</td>
<td>52</td>
<td>160</td>
<td>170</td>
<td>130</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Influence matrix and relative gain array of flatness adjustment under four rolling conditions.

<table>
<thead>
<tr>
<th>Strip width/mm</th>
<th>Rolling force/T</th>
<th>Entry thickness/ mm</th>
<th>Exit thickness/ mm</th>
<th>Front force/kN</th>
<th>Post tension/kN</th>
<th>IRS/mm</th>
<th>Influence matrix</th>
<th>RGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1297</td>
<td>1130</td>
<td>2.29</td>
<td>1.65</td>
<td>140</td>
<td>117</td>
<td>82</td>
<td>-0.1509</td>
<td>0.0003</td>
</tr>
<tr>
<td>1230</td>
<td>864</td>
<td>1.04</td>
<td>0.79</td>
<td>107</td>
<td>80</td>
<td>115</td>
<td>-0.1829</td>
<td>-0.0001</td>
</tr>
<tr>
<td>1151</td>
<td>972</td>
<td>1.54</td>
<td>1.11</td>
<td>136</td>
<td>112</td>
<td>155</td>
<td>-0.1417</td>
<td>-0.0002</td>
</tr>
<tr>
<td>1012</td>
<td>880</td>
<td>1.24</td>
<td>0.85</td>
<td>95</td>
<td>75</td>
<td>224</td>
<td>-0.1332</td>
<td>-0.0002</td>
</tr>
</tbody>
</table>

Fig. 3. Comparisons between calculated flatness and measured flatness. (Online version in color.)
number of calculations show that the calculated \( c_{11} \) is close to 1, while \( c_{12} \) and \( c_{13} \) are close to 0, which shows that \( \Delta a_1 \) is mainly affected by \( \Delta u_1 \), and \( \Delta u_2 \) and \( \Delta u_3 \) have very little influence on \( \Delta a_1 \), which can be regarded as interference to \( \Delta a_1 \). The coupling effect of the primary flatness control loop to the quadratic and quartic flatness control loops is very weak, and decoupling is not necessary. \( c_{22}, c_{23}, c_{42} \) and \( c_{43} \) are between 0.3 and 0.7, while \( c_{21} \) and \( c_{31} \) are close to 0, which shows that quadratic and quartic flatness control loop are seriously coupled and need to be decoupled, \( \Delta u_1 \) has little influence on \( \Delta a_2 \) and \( \Delta a_4 \), which can be regarded as interference. Therefore, the primary flatness can control independently, and the quadratic and quartic flatness need decoupling control.

According to the strategy of independent control primary flatness, decoupling control quadratic and quartic flatness, the closed-loop flatness decoupling control system is shown in Fig. 4, in which \( G_1(s), G_2(s) \) and \( G_4(s) \) are the controller of primary, quadratic and quartic flatness respectively. \( E^* = \{e_1^*, e_2^*, e_4^* \} \) is the flatness deviation component coefficient vector output by PID controller, \( e_1^*, e_2^* \) and \( e_4^* \) are primary, quadratic and quartic flatness deviation coefficient of the output by PID controller respectively. Because the closed-loop flatness control is negative feedback control, the flatness deviation is also the increment of flatness needed for flatness control.

3. Decoupling Model of Flatness Control

3.1. Influencing Matrix Static Decoupling Model

The essence of decoupling is to design a computational network to cancel the correlation in the process, so as to ensure that the control systems of each loop can work independently. Ignoring the interference of RT, the decoupling part of Fig. 4 is taken out and the dual input and dual output coupling system as shown in Fig. 5 is obtained.

According to decoupling control theory, for the coupling system shown in Fig. 5, the purpose of decoupling is to decouple it into two independent generalized control systems as shown in Fig. 6.

For component flatness control method, a static decoupling matrix control model based on influence matrix was proposed by predecessors. The static coupling equation for flatness adjustment is as follow.

\[ \Delta A = C \times \Delta U \]  \hspace{1cm} (12)

Since only quadratic and quartic flatness need decoupling control, the influence matrix \( C \) is second-order. That is to say:
\[
\begin{align*}
\Delta A &= \begin{bmatrix} \Delta a_2 \\ \Delta a_4 \end{bmatrix}, \quad \Delta U = \begin{bmatrix} \Delta u_2 \\ \Delta u_4 \end{bmatrix}, \quad C = \begin{bmatrix} c_{22} & c_{23} \\ c_{42} & c_{43} \end{bmatrix} \quad \cdots \quad (13)
\end{align*}
\]

Considering that the closed-loop flatness control system is a negative feedback control system, in order to eliminate the steady-state flatness deviation, the required flatness increment is \( \Delta A = E' \), and the required flatness adjustment is as follow.

\[
\Delta U = C^{-1} \times E' \quad \cdots \quad (14)
\]

In the Formula, \( C^{-1} \) is the static decoupling matrix, there are only static items and no dynamic items. Therefore, the decoupling control based on static matrix only decouples the final steady-state and does not decouple the control process.

To further illustrate this problem, a flatness control system based on the static decoupling matrix as shown in Fig. 7 is established. Then there are:

\[
\begin{align*}
\begin{bmatrix} \Delta a_2 \\ \Delta a_4 \end{bmatrix} &= \begin{bmatrix} c_{22} & c_{23} \\ c_{42} & c_{43} \end{bmatrix} \times \begin{bmatrix} \Delta u_2 \\ \Delta u_4 \end{bmatrix} \quad \cdots \quad (15)
\end{align*}
\]

Simplification and simultaneous Formula (15) and Formula (16), the Formula (17) can be obtained.

\[
\begin{align*}
\begin{bmatrix} \Delta a_2 \\ \Delta a_4 \end{bmatrix} &= \begin{bmatrix} c_{22}c_{43}G_{Wy}(s) - c_{23}c_{42}G_{Wy}(s) \\ c_{22}c_{43}(G_{Wy}(s) - G_{Wy}(s)) \end{bmatrix} + \begin{bmatrix} c_{22}c_{43}G_{Wy}(s) - c_{23}c_{42}G_{Wy}(s) \\ c_{22}c_{43}(G_{Wy}(s) - G_{Wy}(s)) \end{bmatrix} \times \begin{bmatrix} e^*_2 \\ e^*_4 \end{bmatrix} \\
&= \begin{bmatrix} \Delta u_2 \\ \Delta u_4 \end{bmatrix} \quad \cdots \quad (17)
\end{align*}
\]

The simplified quadratic and quartic flatness control system based on static decoupling matrix is obtained as shown in Fig. 8. It can be seen that after static matrix decoupling, two independent generalized control systems are not obtained as shown in Fig. 6. There are still interacting terms between the two control loops. Because \( G_{Wy}(s) = G_w(s)G_{id}(s), G_{id}(s) = G_t(s)G_{ir}(s) \), \( G_w(s) \) and \( G_t(s) \) are first-order inertia model, when time \( t \) approaches \( T_{max} \), the difference of \( G_{Wy}(s) \) and \( G_{id}(s) \) approaches 0, and the coupling between the two control loops will disappear.

### 3.2. Dynamic Matrix Whole Process Decoupling Model

High-level flatness control model must realize complete decoupling of control system. The commonly used methods for the complete decoupling design of MIMO include feed forward, feedback and diagonal matrix decoupling.\(^{27-29}\)

Among them, diagonal matrix decoupling theory is widely used,\(^{30}\) which achieves complete decoupling by adding a dynamic decoupling matrix to the control system, which makes the product of the dynamic decoupling matrix and the transfer function matrix of the controlled object to a diagonal matrix. The quadratic and quartic flatness control scheme based on dynamic decoupling matrix is shown in Fig. 9. The dotted line part is decoupling structure, in which \( G_{id2}(s) \), \( G_{id4}(s) \), \( G_{id2}(s) \) and \( G_{id4}(s) \) are four elements of dynamic decoupling matrix \( G_{id}(s) \).

According to the diagonal matrix decoupling theory, when the dynamic decoupling matrix satisfies Formula (18), the flatness control system is completely decoupled.
The dynamic decoupling matrix \( G_D(s) \) is obtained by solving the Formula (18).

\[
G_D(s) = \frac{1}{c_{22}c_{43} - c_{23}c_{42}} \begin{bmatrix}
- c_{43} & - c_{23} \\
- c_{42} & c_{22}
\end{bmatrix} G_{WM}(s) G_{IM}(s)
\]

The decoupling control system represented by Fig. 9, Formula (18) and Formula (19) is equivalent to the decoupled generalized control system shown in Fig. 6, whose sub-diagonal element of the transfer function matrix is zero, and the two control loops are no longer related, and are two generalized single-input and single-output control systems, realizing the complete decoupling of the control process.

4. Decoupling Simulation of Flatness Control

4.1. Decoupling Simulation of Open-loop Flatness Control

It is known that \( T_T, T_W, T_I, \) and \( T_M \) are 0.05 s, 0.15 s, 0.25 s and 0.003 s of a 1 420 mm UCM six-roll cold rolling mill in a factory respectively. In order to compare the decoupling effect of the two above decoupling models, the strip with 1 230 mm of Table 2 is taken as the research object, and the simulation system of open-loop MATLAB based on static decoupling matrix and dynamic decoupling matrix are established as shown in Figs. 10 and 11 respectively.

Suppose the initial flatness \( a_2^0 = 0, a_4^0 = 0 \) and let \( e_2^* = 0, \ e_4^* = 10, \ e_2^* = 10, \ e_4^* = 0 \) respectively, the response of the two loops is shown in Fig. 12. It can be seen that using static decoupling matrix, when only one flatness deviation is existed, another flatness deviation will occur in the adjustment process and when time \( t \) approaches 1 s(5\( T_I \)), the another flatness deviation will approach 0, which shows that the two control loops only achieve steady-state decoupling, but not process decoupling. Using dynamic decoupling matrix, when only one flatness deviation is existed, there is no another flatness deviation in the adjustment process, which shows that the two control loops achieve complete decoupling.

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**Fig. 9.** Closed-loop control system of quadratic and quartic flatness based on dynamic matrix decoupling.

**Fig. 10.** Open-loop flatness control simulation system based on static decoupling matrix.

**Fig. 11.** Open-loop flatness control simulation system based on dynamic decoupling matrix.
4.2. Decoupling Simulation of Closed-loop Flatness Control

In order to compare the closed-loop control effects of the above two decoupling models, using the same controller, the MATLAB simulation system of static decoupling matrix shown in Fig. 13 and dynamic decoupling matrix shown in Fig. 14 are established, in which PID2 and PID4 are the quadratic and the quartic flatness controller respectively. The commonly used Ziegler-Nichols method is selected to tune the PID parameters, and the proportional, integral and differential coefficients of PID2 are 1.8, 12 and 0.005 respectively and that of PID4 are 3, 12 and 0.003 respectively. Suppose the target flatness $a_{T20}=0$, $a_{T40}=0$, and let the initial flatness $a_{20}=0$, $a_{40}=10$ and $a_{20}=10$, $a_{40}=0$, the response comparison of the two decoupling modes shown in Fig. 15 is obtained respectively. It can be seen that in the process of static decoupling matrix control, when only one kind of flatness deviation component is controlled, another kind of flatness deviation component will be generated, while dynamic decoupling matrix control does not have this problem, and the whole process decoupling control can be realized.

In order to further prove the advantages of dynamic matrix decoupling, the simulation of closed-loop flatness control in two production practices is carried out. The initial flatness of strip 1 is $a_{120}=7.789$, $a_{140}=-25.048$, that of strip 2 is $a_{220}=-30.374$, $a_{240}=10.505$, and that of target is $a_{T20}=0$, $a_{T40}=0$. The changes of the component coefficients of flatness and the adjustments of the actuator are shown in Figs. 16 and 17 respectively. It can be seen that the flatness component coefficients of the dynamic matrix decoupling control and the adjustments of the actuator maintain a fast and non-overshoot response. However the static matrix decoupling control will extend the quadratic flatness adjustment time from 0.53 s to 1 s, and the quartic flatness adjustment time from 0.53 s to 1.25 s, moreover, the response of WRB, especially IRB produce fluctuation.

In summary, the static matrix decoupling control system has process coupling, which makes the adjustment time longer, the response of adjustment actuator fluctuate, while the dynamic matrix decoupling control system removes the process decoupling, with a shorter system adjustment time.
Fig. 15. The decoupling effect comparison of closed-loop flatness control. (Online version in color.)

Fig. 16. Comparison of closed-loop flatness control processes of strip 1. (Online version in color.)

4.3. Closed-loop Decoupling Simulation of Comprehensive Flatness Control

In order to verify the effectiveness and practicability of the control strategy shown in Fig. 4, a comprehensive simulation system based on dynamic decoupling matrix as shown in Fig. 18 is established, in which, PID1 is a primary flatness controller with proportional, integral and differential coefficients of 8.4, 17.4 and 0.46 respectively. The parameters of PID2 and PID4 are the same as above, and target flatness $A_i^T = \{0, 0, 0\}$. The initial setting value of TR is 0 μm, the initial setting value of WRB is 110 kN, the initial setting value of IRB is 120 kN, the initial setting value of IRS is 115 mm. The adjustment of parameters, the flatness component coefficients and the whole flatness change process are shown in Fig. 19. It can be seen that the adjusting quantity of each actuator has reached the ideal value quickly without overshoot, and the controlled primary, quadratic and quartic flatness component coefficients have reached the target value quickly without overshoot, and the cubic flatness coefficient without special control measures is also
adjusted from the initial $-1.055$ to the vicinity of 0, and the flatness values of the strip transverse parts are within $+1.1$. The simulation results show that the flatness control strategy of independent control primary flatness, decoupling control quadratic and quartic flatness is effective.

5. Conclusion

(1) By calculating and analyzing the RGA of flatness adjustment, the flatness control strategy of independent control primary flatness, decoupling control quadratic and quartic flatness is proposed, which simplifies the complex three-loop decoupling to the two-loop decoupling, and facilitates the design of flatness control system.

(2) The method and model of decoupling the whole process of quadratic and quartic flatness control loop by introducing dynamic decoupling matrix are proposed. The simulation results show that the dynamic decoupling model can make the system adjust quickly and process smoothly.

(3) The simulation results show that by controlling the primary, quadratic and quartic flatness, the cubic flatness can be controlled to a great extent, and the flatness deviation can be eliminated to the greatest extent under the existing control actuator technology conditions.

(4) The control strategy and model of flatness for cold rolling based on whole process decoupling control presented in this paper provide a new way and method for developing simple and practical flatness control system with higher precision, more stable process and faster speed.
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