An Altering-Frequency Adjustable Speed System Used in a Cold Spinning Machine without Spinning Chuck

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Abstract: In this article we derive the necessary conditions which ensure synchronous rotation between the main shaft and forming roll in spinning process according to the features of one-forming of spinning machine without spinning chuck. In order to overcome the shortages of hydraulic system, an adjustable speed system which consists of variable-frequency power and squirrel-cage motor is proposed. Because the dynamic features of adjustable-speed AC drive system are extremely complicated and the load torque of motor changes in a wide range during spinning process, adjustment of classical control system is much difficult. Thus a parameter self-adjustable fuzzy controller using a single chip computer is designed. The principle of parameter self-adjustment and the roles of proportional constants are analyzed. The step responses of the fuzzy controller and PID controller with different loads are given. After a number of experiments, the system has successfully been used in a one-forming spinning machine Φ0. 8m without spinning chuck. It is proved by theory and practice that the design is correct and the system is simple, reliable and inexpensive.

Key words: machine without spinning chuck; cold spinning; variable frequency power; fuzzy controller

1 Introduction

As the technique of cool spinning is better than that of hot compression, there is a tendency of using cool spinning technique to replace hot compression technique in making head of container. Since 1980 one-forming spinning machine without spinning chuck has been rapidly developed. We began to study it in 1982, as a major project of China. Since then, the prototype of spinning machine without spinning chuck with Φ0. 8m and the industrial prototype of one with Φ2. 4m have been appraised. Comparing with other ones in structure and performance, these novel ones have a lot of advantages.

In order to overcome the shortages of hydraulic system, an adjustable-speed AC drive system is used, which ensures synchronous rotation between the main shaft and forming roll. This drive system has successfully been used in the one-forming cold spinning machine without spinning chuck with Φ0. 8m.

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2 Control of Synchronous Rotation Between the Main Shaft and Forming Roll

2.1 Structure and Principle of Spinning Machine

2.1.1 Structure

The spinning machine mainly consists of following parts as shown in Fig. 1.

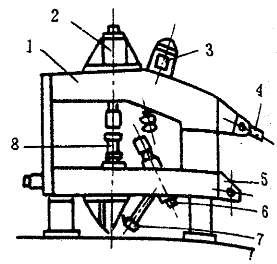


Fig. 1 Spinning machine

1) Frame: In which all other parts are fixed.

2) Compressing cylinder: By which the blank work piece is oppressed on the main shaft during spinning process.

3) Cylinder for longitudinal motion of spinner by which a suitable force is applied to the blank work piece during spinning process.

4) Cylinder for transversal motion of spinner: With which the spinner moves along the transversal direction.

5) Cylinder for transversal motion of forming roll: With which the forming roll moves along the transversal direction.

6) Rotator of forming roll: It makes the forming roll rotate and drive work piece to realize spinning process.

7) Regulator of moving radius of forming roll: With different radius we can obtain different size head.

8) Rotator of main shaft: It makes the main shaft rotate and drive work piece to realize spinning process.

2.1.2 Operation Principle

One-forming of the cool-spinning without spinning chuck is derived from with die. In fact, if we use the forming roll which is synchronous with the main shaft to replace the die, we obtain a spinning machine without spinning chuck. The rotation center of circular blank work piece is located between the tray of main shaft and compressing cylinder. The workpiece is rotated with the main shaft. The forming roll is used as an inner support, and the spinning roll applies a suitable force from outside. At the beginning, the spinning roll moves along a circle according to the requirement of shape of the machined head. The motion of the spinning roll must be synchronous with that of forming roll. The workpiece gradually becomes drum-shape. Then stop the forming roll, and let the spinning roll rotate around the outside of the forming roll. Until the edge of the drum-shaped workpiece becomes a right angle, thus we obtain the head.

2.2 Synchronous Rotation between Main Shaft and Forming Roll

There are many motive parts in a spinning machine without spinning chuck. Motion of the different parts should be well coordinated, especially the synchronous rotation between main shaft and forming roll must be kept all the time. The synchronous problem is highly important and we should pay close attention to it.

The key to steady spinning is to keep the line velocity of spinning point in a constant during spinning process. When spinning point moves from the center to the edge of the workpiece, if the line velocity of the spinning point is constant v, then the rotation speed n_1 of main shaft should be reduced, because the distance r_1 from engagement point to the main shaft becomes large (see Fig. 2)

$$n_1 = v/2\pi r_1. \quad (1)$$

The rotation speed of forming roll must be coordinated with that of main shaft. Let the distance from engagement point to the forming roll be r_2, then

$$n_2 = v/2\pi r_2. \quad (2)$$

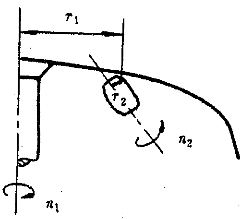


Fig. 2 Spinning processes

Only in case of n_1 and n_2 meeting equations (1) and (2) respectively, the line velocity at engagement point is equal and the synchronous condition can be achieved. When the engagement point moves, the distance from the point to forming roll r_2 changes and thus the rotation speed n_2 changes as well. As the forming roll is not parallel to the main shaft and it has a drum shape, it is difficult to measure r_2 and control the synchronous system. In fact, the change of r_2 is not very large, it is reasonalbe to use a squirrel motor to drive the forming roll directly. But the r_1 changes a lot. We use an altering frequency adjustable speed system which consists of a varialbe-frequency power and squirrel-cage induction motor to drive the main shaft. Rotation speed of main shaft depends on the distance r_1 which is available from the micro-computer. Rotation speed of main shaft is also controlled by an additional power to compensate speed mismatch. The speed mismatch is caused by the change of r_2. It is well known that, when the main shaft and forming roll act on each onther, in order to overcome the deformation resistance of workpiece, there is a force acting on the engagement point. The force causes the rotation of workpiece. Deformation power is shared by the main shaft and the forming roll. If the r_2 becomes small during spinning process, then the line velocity at the engagement point of the forming roll is smaller than that of the main shaft. In this case, the faster main shaft shares larger power. At the same time, the rotation speed of faster main shaft has to be reduced with a power adapter to coordinate with the rotation speed of forming roll; or otherwise, the rotation speed of main shaft has to be increased.

3 Control System

3.1 The Drive System

The whole system consists of a spinning machine, a asynchronous AC motor, a variable-frequence power, a detect unit and a control unit as shown in Fig. 3.

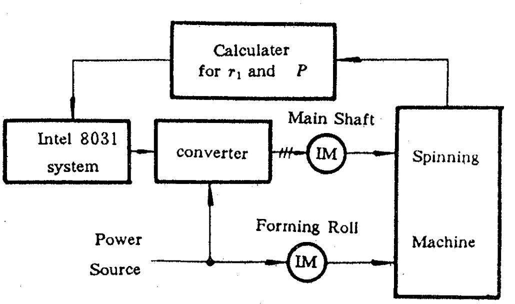


Fig. 3 System block diagram

Single-chip microcomputer computes the rotation speed of main shaft based on the detected value of r_1. The computer also samples the load power values at the moment, then modifies the rotation speed through calculation, finally sends the results to the variable-frequency power. Output frequency of variable-frequency power is regulated and so is done the rotation speed of the AC motor to ensure synchronous operation between the main shaft and the forming roll.

3.2 Parameter Self-Adjustable Fuzzy Controller

It is difficult to regulate a classical control system. The reasons are: 1) The dynamic characteristic of a adjustable-speed AC drive system is extremely complicated; 2) During spinning process the moment of motor changes in a wide range with the radius of workpiece, for an example, for a spinning machine without spinning chuck of Φ0.8m, it changes from 25% to 100%. In this case, a fuzzy controller has to be used. As a matter of fact, comparing with PID regulator, a fuzzy controller exists a series of advantages: It has a faster response and a smaller overshoot; it is insensible to changes of various parameters, i. e it exists a strong robust character which can overcome the effects caused by nolinear factors. In order to increase the accuracy of the fuzzy controller, error and its quantizing grades must be increased, but at the same time, the content of check table expands rapidly.

3.3 The Roles of Proportional Constants k_1, k_2 and k_3 and Its Self-Adjustment

Proportional constants k_1, k_2 and k_3 of a fuzzy controller have a strong effect on the performance of the system (see Fig. 4). Let the input-output relationship of object be

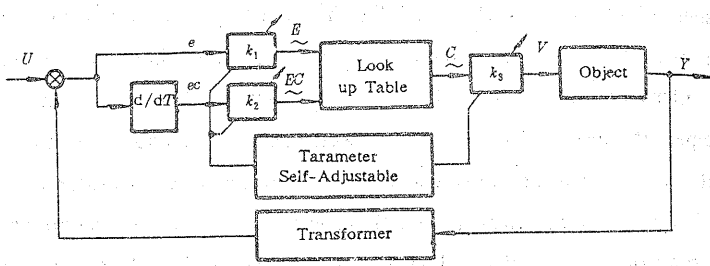


Fig. 4 Fuzzy control block diagram

$$y(n) = f[v(n)], \tag{3}$$

$$E(n) = \mathrm{int}[e(n)k_1], \tag{4}$$

and

$$EC(n) = \mathrm{int}[ec(n)k_2], \tag{5}$$

then the instantaneous control output C of the controller depends on $E(n)$ and $EC(n)$:

$$C(n) = [E(n) \times EC(n)] \circ R. \tag{6}$$

Consequently, the output of the controller is

$$V(n) = Q[k_3 \sum_{i=1}^{n} (e(i)k_1 \times ec(i)k_2) \circ R + U_0], \tag{7}$$

then

$$Y(n) = f[V(n)] = f\{Q[k_3 \sum_{i=1}^{n} (e(i)k_1 \times ec(i)k_2) \circ R + U_0]. \tag{8}$$

It is known from the equation (8) that, $Y(n)$ not only relates with E and EC before sampling moment nT, but also with k_1, k_2 and k_3 is not linear. In fact it is a nolinear relation in three dimensions (e, ec and v).

In this application:

The E variable is quantized into 14 points, the EC variable is quantized into 13 points and the C variable is quantized into 15 points (see appendix). The fuzzy relation R is a matrix of dimensions 14×13×15, it is requires 2.7k storage locations[3].

The control system is implemented using a single-chip-microcomputer. The control action which results from evaluating the rules is deterministic. So, for the same process state, E and EC in this case, the same control action will always be made, unless the control rules are altered. The control policy can be implemented directly by evaluating the rules at each sampling interval but this is not computationally efficient[2]. A considerable saving in on-line computer time can be achived by extracting the control action from a precomputed lookup table (see Table 1), which has 182 elements in this case. Such a decision table directly relates the controller output, $C(n)$, with the inputs $E(n)$ and $EC(n)$ and is precalculated from the control rules (see Table 2) before the controller is run.

Table 1 Decision Table

error e \ change in error, ec	−6	−5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6
−6	7	6	7	6	7	7	7	4	4	2	0	0	0
−5	6	6	6	6	6	6	6	4	4	2	0	0	0
−4	7	6	7	6	7	7	7	3	3	2	0	0	0
−3	6	6	6	6	6	6	6	3	2	0	−1	−1	−1
−2	4	4	4	5	4	4	4	1	0	0	−1	−1	−1
−1	4	4	4	5	4	4	1	0	0	0	−3	−2	−1
−0	4	4	4	5	1	1	0	−1	−1	−1	−4	−4	−4
+0	4	4	4	5	1	1	0	−1	−1	−1	−4	−4	−4
+1	2	2	2	2	0	0	−1	−4	−4	−3	−4	−4	−4
+2	1	1	1	−2	−3	−3	−4	−4	−4	−3	−4	−4	−4
+3	0	0	0	0	−3	−3	−6	−6	−6	−6	−6	−6	−6
+4	0	0	0	−2	−4	−7	−7	−7	−7	−6	−7	−6	−7
+5	0	0	0	−2	−4	−6	−6	−6	−6	−6	−6	−6	−6
+6	0	0	0	−2	−4	−7	−7	−7	−7	−6	−7	−6	−7

output C

Table 2 Control Rules

error \ change of error	NB	NM	NS	0	PS	PM	PB
NB	PB	PB	PB	PB	PM	0	0
NM	PB	PB	PB	PB	PM	0	0
NS	PM	PM	PM	PM	0	NS	NS
NO	PM	PM	PS	0	NS	NM	NM
PO	PM	PM	PS	0	NS	NM	NM
PS	PS	PS	0	NM	NM	NM	NM
PM	0	0	NM	NB	NB	NB	NB
PB	0	0	NM	NB	NB	NB	NB

Experimental results have shown that when k_1 increases, steady accuracy increases, rise time of the system's step response decrease and oversoot becomes large, when k_2 decreases, speed and overshoot increase, or otherwise, the error sensitivity of controller at the given value increases and overshoot becomes small, when k_3 is large, rise time is small but overshoot is large.

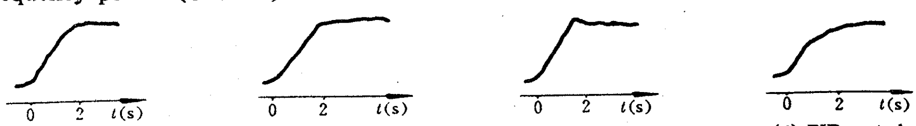
Obviously, a set of constant k_1, k_2 and k_3 does not meet the requirement of the spinning machine. Therefore a parameter self-adjustable fuzzy controller based on a single-chip-microcomputer is developed. The fuzzy controller works well at any operation point, because a self-adaption control is introduced in a general fuzzy computation, which may modify the parameters k_1, k_2 and k_3 with change of radius r_1. That is

$$k_1 = 0.75, \quad k_2 = 1.5, \quad k_3 = 1, \quad \text{if } 0 < r_1 < 250;$$
$$k_1 = 1.1, \quad k_2 = 0.9, \quad k_3 = 1, \quad \text{if } 250 < r_1 < 400.$$

4 Experiments of the Control System

4.1 Simulation Experiment

Considering the real operation condition of the spinning machine without spinning chuck, a control system has been undergone a number of test in static and dynamic characteristics in our laboratory. We did it using fuzzy control computation and PID control computation respectively. The step responses of different loads are shown in Fig. 5(a), 5(b), 5(c) and 5(d). The experimental set-up consists of an AC motor (1kW), a DC generator as a load (0.7kW) and a variable-frequency power (3.5kW).



(a) Fuzzy control (load 60%) (b) PID control (load 60%) (c) Fuzzy control (load 100%) (d) PID control (load 100%)

Fig. 5 The step responses of different loads

4.2 Industrial Experiment

After a series of simulation experiments, the control system was tested on a spinning machine without spinning chuck in 1989 and the result was better than expected.

1) Rotation speed regulation of main shaft met technological requirements. The motor rotational speed n_1 of main shaft versus distance from engagement point to main shaft r_1 is show in Fig. 6.

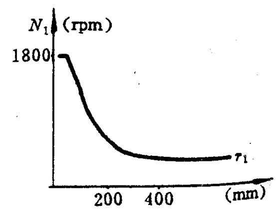


Fig. 6 N_1 versus r_1

2) It has a high drive efficiency. For manufacturing a same head of container the power of motor to drive main shaft is only 2.2kW, if a hydraulic system is used the power of motor will be 5kW. In fact, the motor average power to drive main shaft and forming roll (includes the loss of variable-frequency power) is 2.16kW, whereas the average power of hydraulic system is as high as 7.8kW.

Since May 1990, the control system has being manufactured in batches.

5 Conclusions

The conclusins are:

1) A novel altering-frequency adjustable speed system is used in a spinning machine without

spinning chuck. The performance is better than that of hydraulic one, the efficiency is high, the spinning process is stable and the quality of products is good.

2) When the mathematical model of tested object is unknown, a fuzzy control using computer can well control the tested object. It has a high adaptability and robust performance as the parameters of object change.

3) It is convenient for site test to realize fuzzy control with single chip computer and control table, and it is of benefit to system stability to combine parameter self-adjustment of proportional constants k_1, k_2 and k_3.

4) The adjustable-speed AC drive technique and the controller mentioned above are in common use, expansionary, simple, reliable and easy to maintain. They can be used in other machines if the control programming is changed.

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Appendix

The E (speed error) variables are quantized into 14 points ranging from maximum negative error through zero error to maximum positive error. The zero error is further divided into negative zero error (N0-just below the set point) and positive zero error (P0-just above the set point). The subjective fuzzy sets definning these values are:

Table A_1

	−6	−5	−4	−3	−2	−1	−0	+0	+1	+2	+3	+4	+5	+6
PB	0	0	0	0	0	0	0	0	0	0	0.1	0.4	0.8	1.0
PM	0	0	0	0	0	0	0	0	0	0.2	0.7	1.0	0.7	0.2
PS	0	0	0	0	0	0	0	0.3	0.8	1.0	0.5	0.1	0	0
P0	0	0	0	0	0	0	0	1.0	0.6	0.1	0	0	0	0
N0	0	0	0	0	0.1	0.6	1	0	0	0	0	0	0	0
NS	0	0	0.1	0.5	1.0	0.8	0.3	0	0	0	0	0	0	0
NM	0.2	0.7	1.0	0.7	0.2	0	0	0	0	0	0	0	0	0
NB	1.0	0.8	0.4	0.1	0	0	0	0	0	0	0	0	0	0

The EC (change in speed error) variables are similarly quantized without the further division of the zero state (13 points). The subjective definitions are:

Table A_2

	−6	−5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6
PB	0	0	0	0	0	0	0	0	0	0.1	0.4	0.8	1.0
PM	0	0	0	0	0	0	0	0	0.2	0.7	1.0	0.7	0.2
PS	0	0	0	0	0	0	0	0.9	1.0	0.7	0.2	0	0
0	0	0	0	0	0	0.5	1.0	0.5	0	0	0	0	0
NS	0	0	0.2	0.7	1.0	0.9	0	0	0	0	0	0	0
NM	0.2	0.7	1.0	0.7	0.2	0	0	0	0	0	0	0	0
NB	1.0	0.8	0.4	0.1	0	0	0	0	0	0	0	0	0

The C (control output) variables is quantized into 15 points ranging from a change of −7 steps through 0 to +7 steps (15 points). The subjective definitions are:

Table A_3

	−7	−6	−5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6	+7
PB	0	0	0	0	0	0	0	0	0	0	0	0.1	0.4	0.8	1.0
PM	0	0	0	0	0	0	0	0	0	0.2	0.7	1.0	0.7	0.2	0
PS	0	0	0	0	0	0	0	0.4	1.0	0.8	0.4	0.1	0	0	0
0	0	0	0	0	0	0	0.2	1.0	0.2	0	0	0	0	0	0
NS	0	0	0	0.1	0.4	0.8	1.0	0.4	0	0	0	0	0	0	0
NM	0	0.2	0.7	1.0	0.7	0.2	0	0	0	0	0	0	0	0	0
NB	1.0	0.8	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0

In this work the Table 2 is of the form

If E and EC then C

and the value of C is determined by evaluating

$$C = (E \circ Re) \wedge (EC \circ Rec). \tag{a1}$$

Where Re is the fuzzy relation then written as

$$Re = (E_1 \times C_1) \vee (E_2 \times C_2) \vee \cdots = R_1 \vee R_2 \vee \cdots \vee R_n, \quad n = 28,$$

and results will be

$$Re = \begin{matrix}
1.0 & 0.9 & 0.7 & 0.2 & 0.2 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.8 & 0.8 & 0.7 & 0.7 & 0.7 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \\
0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.5 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 \\
1.0 & 0.9 & 0.7 & 0.2 & 0.7 & 1.0 & 0.5 & 0.7 & 1.0 & 0.7 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.3 & 0.7 & 0.8 & 0.5 & 0.8 & 0.8 & 0.7 & 0.7 & 0.8 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.9 & 0.7 & 0.8 & 0.7 & 1.0 & 0.5 & 1.0 & 1.0 & 0.7 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 1.0 & 0.5 & 1.0 & 1.0 & 0.7 & 0.7 & 0.8 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.8 & 0.7 & 0.8 & 0.5 & 0.8 & 0.8 & 0.7 & 0.3 & 0.7 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 1.0 & 0.5 & 0.7 & 1.0 & 0.7 & 0.2 & 0.2 & 0.7 & 0.9 & 1.0
\end{matrix}$$

$$
\begin{matrix}
0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.5 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 \\
0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.7 & 0.7 & 0.7 & 0.8 & 0.8 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.2 & 0.2 & 0.7 & 0.9 & 1.0
\end{matrix}
$$

The fuzzy relation *Rec* is written as

$$Rec = (EC_1 \times C_1) \vee (EC_2 \times C_2) \vee \cdots = R_1 \vee R_2 \vee \cdots \vee R_m, \quad m = 31,$$

and results will be

$$
Rec = \begin{matrix}
1.0 & 0.9 & 0.7 & 0.2 & 0.2 & 0.2 & 0.2 & 0.1 & 0 & 0.2 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.7 & 0.7 & 0.7 & 0.5 & 0.1 & 0 & 0.2 & 0.7 & 0.8 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 1.0 & 0.5 & 0.1 & 0 & 0.2 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.5 & 0.1 & 0 & 0.2 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 1.0 & 0.5 & 0.3 & 0.3 & 0.3 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.8 & 0.7 & 0.8 & 0.5 & 0.8 & 0.8 & 0.7 & 0.7 & 0.8 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 1.0 & 0.5 & 1.0 & 1.0 & 0.7 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.8 & 0.7 & 0.8 & 0.5 & 0.8 & 0.8 & 0.7 & 0.7 & 0.8 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 0.3 & 0.3 & 0.7 & 1.0 & 0.7 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.2 & 0.2 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 \\
1.0 & 0.9 & 0.7 & 1.0 & 0.7 & 0.2 & 0.2 & 0.7 & 1.0 & 0.7 & 0.7 & 1.0 & 0.7 & 0.9 & 1.0 \\
0.8 & 0.8 & 0.7 & 0.8 & 0.7 & 0.2 & 0.2 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.7 & 0.8 & 0.8 \\
1.0 & 0.1 & 0.7 & 1.0 & 0.7 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.7 & 0.9 & 1.0
\end{matrix}
$$

Using Table A_1, Table A_2, Table A_3, Table 2, we calculate equation (a_1), taking as the final result the decision table (see Table 1).

无胎冷旋压机中的交流变频调速控制系统

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摘要：本文根据一次成形封头无胎冷旋压机的工作特点，导出了在旋压过程中保证主轴与成形辊同步旋转的条件．针对液压调速系统存在的问题，提出了由变频电源和鼠笼式交流电机组成的调速驱动方案；研制了以单片机为核心的参数自调整模糊控制系统．经大量的模拟试验后，该控制系统已被成功地应用于Φ0.8米一次成形封头无胎冷旋压机中．理论和实践证明，该系统设计正确、简单可靠、具有明显的社会意义和经济效益．

关键词：无胎；冷旋压；变频电源；模糊控制

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