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Control of liquid column height in electromagnetic casting with fuzzy neural network model[①]

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[Abstract] The control of suitable and stable height of liquid column is the crucial point to operate the electromagnetic casting(EMC) process and to obtain ingots with desirable shape and dimensional accuracy. But due to the complicated interact parameters and special circumstances, the measure and control of liquid column are quite difficult. A fuzzy neural network was used to help control the liquid column by predicting its height on line. The results show that the stabilization of the height of liquid column and surface quality of the ingot are remarkably improved by using the neural network based control system.

[Key words] electromagnetic casting; shape of liquid column; fuzzy neural network; pattern recognition
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1 INTRODUCTION

During EMC process, the continuously poured liquid metal above the ingot is constrained by the electromagnetic force and forms a section of liquid column. The superheat and latent heat of fusion of liquid column are extracted from the jetting water around it, so the column solidifies with free surface. At the same time, the bottom block moves downward, thus an ingot with certain length can be obtained[1~9].

Undoubtedly, the right shape of liquid column is quite important for the right shape of ingot. The requests to liquid column include suitable height, vertical side faces and stable surface. Among them, the suitable and stable height of liquid column determines the balance of static pressure and electrical force and should be precisely controlled during the casting process as well[10, 11].

In this paper, a fuzzy neural network (FNN) based control system has been used to forecast and control the height of liquid column[2~4, 12].

FNN is a system that combines the advantages of both the ANN (artificial neural network) and fuzzy logic system. It can deal with those fuzzy or indefinitely information and at the same time has self-learning function. FNN has now found its wide application in modeling function, control, pattern recognition and many other domains.

In this paper, the fuzzy rules of fuzzy system and the self-learning and self-adapting abilities of ANN are used to deal with the electric signals of the process parameters during EMC process and forecast the height of liquid column. The results show that FNN has excellent ability to learn and forecast the height of liquid column in EMC process.

2 SHAPE OF LIQUID COLUMN

During EMC process, the electromagnetic force and the static pressure of liquid column should be kept on balance for the right shape of liquid column. Among those aspects to evaluate the quality of liquid metal, the suitable height is the most important factor. After the position of screen and the value of electric parameters are chosen, size qualified ingot can be produced if only keeping the suitable height of liquid column and keep the side faces of liquid column vertical.

The height of liquid column directly influences the shape parameter S_A of liquid column, which is shown in Fig. 1. Here h_z refers to the height of liquid column. D is the distance from the liquid-solid interface surface to the top liquid. S_e is the area includes h_z and D. The more closer the S_A near 1, the bigger the shape parameter, and the better the quality of liquid column. If the height of liquid column is low, the top of the liquid column will shrink inwards because of the corresponding small static pressure, then S_A will be decreased. On the other hand, if the height of liquid column is high, the static pressure of the bottom will be big too, so the bottom side faces of liquid column will lean outward, then S_A will also be decreased, sometimes it can even lean to leakage of liquid metal and break down the casting process. The results of the experiments indicate that the ideal height of liquid column should be set and maintained between 35~ 45 mm and should not change during the casting process. The fluctuation of the height of the liquid column not only destroys the size and shape accuracy of the ingot, but also tends to occur cracks and coarse surface of ingot.

As the height of liquid column is determined by the top surface and liquid-solid interface, the control of

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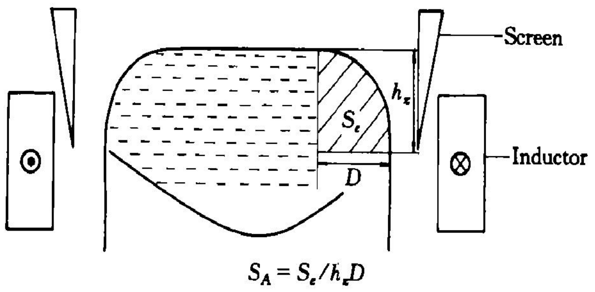

Fig. 1 Schematic diagram of EMC liquid column

liquid column should include both the control of top surface and the liquid-solid interface. The main reasons that cause the top surface unstable are: the decrease of liquid level in the furnish, the inclusions in the liquid flow, the temperature, viscosity and flow rate change of liquid metal, the solidifying and melting of the liquid metal of the sluggers. The main reasons that cause the change of liquid-solid interface are temperature, casting speed and cooling intensity fluctuation.

So it is important to check and control the position of top surface and liquid-solid interface on line. If the top surface changed, usually the pouring speed can restore it. But if the liquid-solid interface changes, it means the heat balance has been destroyed, the casting speed should be changed. If the casting speed changes, the top liquid level and the pouring speed should also be changed. Then, it belongs to complicated process control problem. In order to control the liquid column, first the top liquid level should be checked all the time. As the liquid metal lies in the circumstance that has high temperature and high magnetic field, it is very difficult to check and measure the position. In this paper, the needle method was used.

Needle method is using a step-in motor brings a needle move upward and downward to measure the liquid level. The output voltage changes if the needle contacts with the liquid metal, and the liquid level is calculated according to the moving distance of needle. As the output voltage of the needle is 2 V and 5 V while the needle contacts with the liquid, it is easy for the computer to recognize. The anti-noise of the system is heavy, the measuring accuracy is ±0.5 mm. If the liquid level is away from the normal value, the pouring velocity should be changed, the step-in motor can bring the stopper move upward or downward.

The measurement of the liquid-solid interface is more complicated. The ultrasonic wave can be used to determine the position according to the time difference of sending and accepting waves. But now the ultrasonic wave sensor has its shortcomings such as too large volumes, too high cost or low accuracy. So this paper put forward a new method to measure and control the height of liquid column on line. That is, to use FNN to recognize the temperature pattern of the four thermocouples to check and control the liquid-solid interface. The parallel working method of ANN makes the velocity of the whole system quicker, so will decrease the react time of the whole control system.

3 CONSTRUCTION OF FNN

3.1 Structure of network

In EMC process, as the electromagnetic force is largest at the middle height of the inductor, to keep the balance of the static pressure of liquid metal and magnetic force, the liquid-solid interface should be at the mid-height of the inductor. Four thermocouples have been placed at the four corners of the cross section to measure the temperatures. The electric signals will be used as the four inputs of the FNN. Use the solidus temperature as reference, the temperature change tends are unchanging, increasing and decreasing. These modes will be used as the fuzzy aggregates. Use the experimental data as the learning samples, the learned FNN will judge if the casting speed need to be changed and realize the check and control of liquid-solid interface.

The structure of FNN used in this paper is shown in Fig. 2. The network is a mixed network that made up of two parts of character network and function network. Character network is used to make the membership functions, and the function network is used to realize the fuzzy rules.

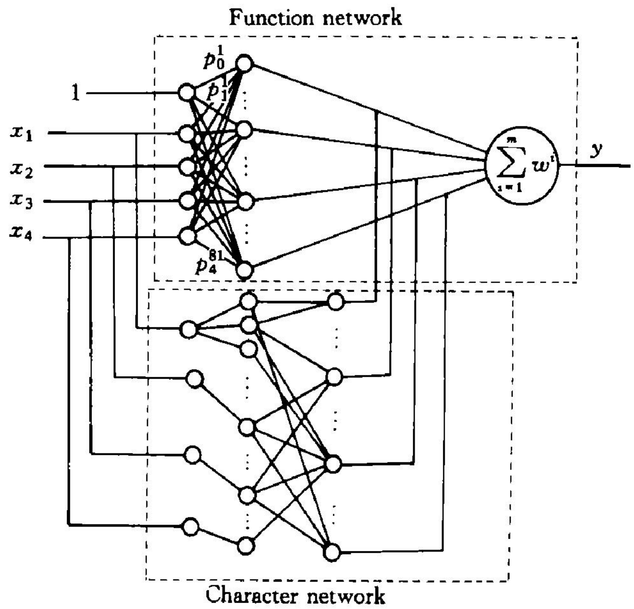

Fig. 2 Structure of fuzzy neural network

The nodes of input layer of character network layer are composing to the input messages. The second layer means to classify the input value. Every node corresponds to a fuzzy language. As only considering the measured value difference to the solidus temperature, the fuzzy classification in this paper are NS(negative small), ZE(zero), PS(positive small). The second layer finished the calculation of the membership functions, because this function can approximate any other functions. That is

$$\mu A_j^i = \exp[-(x_j - a_j^i)^2 / b_j^i] \quad (1)$$

where μA_j^i is the membership function of the fuzzy subaggregate. a_j^i and b_j^i are the average value and variance of the normal function respectively.

The third layer will finish the minimum calculation of fuzzy variables to obtain corresponding rules. That is

$$w^i = \prod_{j=1}^{k} \mu A_j^i(x_j) \quad (2)$$

where k is input variable number, $x_j (j = 1, 2, \cdots, k)$ are the input values.

The function network has three layers. The first layer is input layer, it pass the input value to the second layer. Among them, the second layer is to calculate the fuzzy control rules, equals to fuzzy inference engine. The fuzzy rules in this paper are "if-then" rules. This rule has strong generation and can include other rules. The describe of the rule is

If x_1 is A_1^i, x_2 is A_2^i, $\cdots$, x_k is A_k^i,

Then $y^i = p_0^i + p_1^i x_1 + p_2^i x_2 + \cdots + p_k^i x_k$ (3)

where A_j^i is fuzzy collection, y^i is the output value according to the fuzzy rules. p_j^i is conclusion parameter.

The third layer is to calculate the summation. The adding parameter are the output of character network, that is, the grade of fit of every fuzzy rule.

Finally, the output of the network is the average of summation of every y^i, that is

$$y(x) = \sum_{i=1}^{m} w^i y^i / \sum_{i=1}^{m} w^i \quad (4)$$

where m is rule number, w^i is the summation parameter, it can be obtained by Eqn. 2.

3.2 Correction of weight

The weights of network are the key value that reflects the information. The FNN generates the fuzzy rules by correcting the weights. In this paper, the initial weight of the network is arbitrary value, and using gradient decreasing method to correct the concluding parameters and membership functions. Use the object function as

$$E = \sum_{p=1}^{n} \frac{1}{2}(y_d^p - y^p)^2 \quad (5)$$

where y_d^p and y^p refer to the expect output and actual output of the pth sample, n is the training number. According to the gradient decreasing method,

$$p_j^i(k+1) = p_j^i(k) - \eta_1(\partial E / \partial p_j^i) \quad (6)$$

$$\frac{\partial E}{\partial p_j^i} = \frac{\partial E}{\partial y^p} \frac{\partial y^p}{\partial p_j^i} = -(y_d^p - y^p) \frac{w^i}{\sum_{i=1}^{m} w^i} \cdot \frac{\partial y^p}{\partial p_j^i} \quad (7)$$

For a_j^i and b_j^i, there are

$$a_j^i(k+1) = a_j^i(k) - \eta_2(\partial E / \partial a_j^i) \quad (8)$$

$$b_j^i(k+1) = b_j^i(k) - \eta_2(\partial E / \partial b_j^i) \quad (9)$$

where η_1 and η_1 are the learning rate, its value is among the inter-plot [0, 1]. If the value is too high, the network will not converge. In this paper, the trying value of η_1 and η_2 are 0.000 12 and 0.000 8.

4 FNN BASED CONTROL SYSTEM

In order to check the learning ability and generation, the network was checked before using. The results show that the network has stable and excellent forecasting ability.

As mentioned above, the height of liquid column is determined by the liquid level and liquid-solid interface. To keep the stable height of liquid column, the casting speed and cooling intensity should be kept unchanged to the best.

While the liquid-solid interface is closely related to the solidification rate, usually the cooling water intensity and the casting speed should be kept stable to keep the stability of liquid-solid interface. However, the fluctuations of casting temperature, cooling intensity and casting speed will also be led to the upward or downward movement of the liquid-solid interface, and spoil the heat balance and cannot be ignored. Both the cooling water and casting speed can change the solidification speed. But the effect of the cooling water is rather limited, and the effect will not be as fast as changing the casting speed.

So is necessary to change the casting speed to correct the liquid-solid interface. Of course, if the casting speed should be changed, the pouring speed will also be changed. The relationship between casting speed and pouring speed can be obtained through calculation and experiments, approximately as follows

$$\Delta v_p = S(v_{c1} - v_{c0}) \quad (10)$$

where Δv_p is the change of pouring speed(m^3/s), S is the cross section area of the ingots(m^2), v_{c1} and v_{c0} are the casting speeds (m/s) before and after the change.

The change of casting speed is realized by the change of rotating velocity of the electric machine that drives the casting machine. Using the asynchronous motor-electromagnetic clutch system, the error can be controlled under 3%.

Because the temperature change mode of the thermocouples has three kinds: unchanging, increasing and decreasing, so the arrange order of the four thermocouples are 81. So the fuzzy rule parameters amounts to 81 groups. Using the accumulated experimental data as the learning samples, the network can be obtained and recognize the temperature modes of the thermocouples. The whole height of liquid column control system is shown in Fig. 3.

During the practice of controlling the height of liquid column, considering the inertia of the electric machine, when increasing or decreasing the speed and the reaction time of other mechanical equipments, the time interval to collect the temperature modes is 5 s. The output value, which is the position of the liquid-solid interface, is checked. If its difference with the ideal value larger than 1 mm, then the casting parameters should be considered to change. If the liquid-solid interface moves upward, it means the solidification speed increases; the casting speed should be increased. On the contrary, the casting speed should be decreased if interface moves downward. The relationship between the casting speed and height of liquid column is shown in Fig. 4. When the height of liquid column h_z changes, the casting speed v_c will change, the relationship between h_z and v_c can be determined by calculation and experiments.

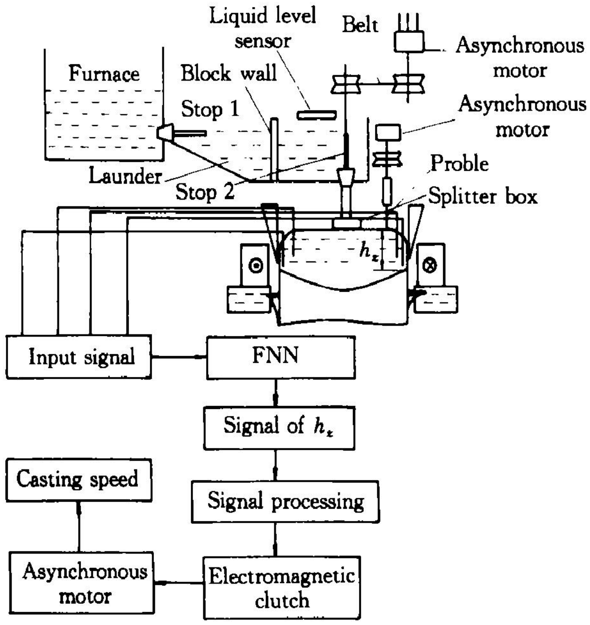

Fig. 3 Fuzzy neural network based control system for stable height of liquid column

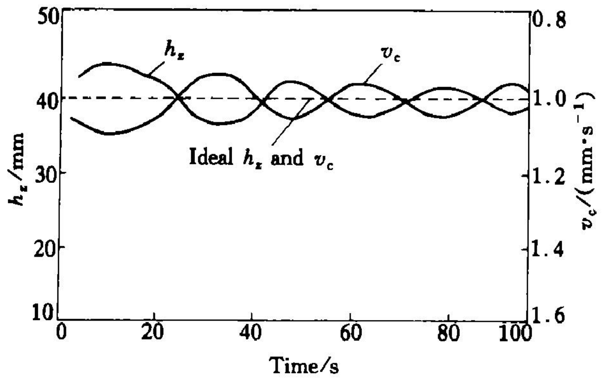

Fig. 4 Relationship between height of liquid column and casting velocity

Fig. 5 shows the fluctuation of the height of liquid column. It can be seen that with the help of forecasting and pattern recognition ability of the FNN, the control effect increases greatly, the fluctuation of the height of liquid column decreases, and the casting process needs shorter time to enter the stationary phase. It is beneficial to the stable process of the casting process. The dimensional accuracy and surface quality of ingot increases greatly.

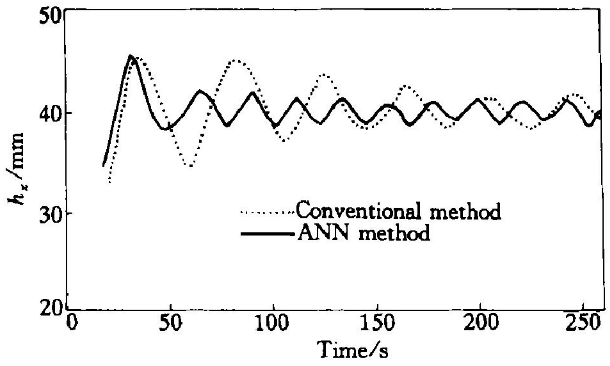

Fig. 5 Comparison of results between controlling of conventional and ANN methods

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