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Fuzzy-control simulation of cross-sectional shape in six-high cold-rolling mills

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Industrial summary

Shape control in producing thin cold-rolled strip is very complex because of the non-linearity of the process. Depending on the process conditions, the operator is involved with manual control during production in the steel industry. In order to implement the operator's knowledge in the shape control, a fuzzy controller and neural network emulator have been developed. The fuzzy-control system that has been developed has been utilized for simulations of cross-sectional shape control in the six-high cold-rolling of thin steel strips of less than 0.5 mm in thickness in the present investigation, the simulations being carried out on an IBM PC 486. The fuzzy logic was created based on production data to control the delivery shape at the last stand of a tandem cold mill. Steady- and non-steady state control simulations of irregular cross-sectional strip shapes and the stability of the currently applied fuzzy control scheme have been investigated. The currently applied fuzzy control scheme is found to be successful in reducing the irregularity of the cross-sectional shape of the cold-rolled thin steel strip in a stable manner for the steady and the non-steady state under the present condition. Thus, the fuzzy-control system might be useful in controlling the process as does a human operator, without introducing manual intervention in practice.

Keywords: Cold-rolling mills; Shape control; Fuzzy-control simulations

1. Introduction

Control of cross-sectional shape in the rolling of thin steel strip at room temperature has become an important issue in the steel industry because of quality control and productivity increase. The control scheme is very complicated because the process is highly non-linear, depending on the coupling effects of many process parameters such as variations of the strip materials and their geometries, roll temperatures, and deformation mechanics. When the rolled strip becomes thin it is extremely difficult to control the process parameters properly to secure flat cross-sectional shape of the cold-rolled strip.

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In order to improve the cross-sectional shape of the cold-rolled strip, many studies have been made using either numerical simulations or empirical methods. Yukio et al. [1] studied a new plane-view control technique in plate rolling. In this work, slab was provided in a dog-bone configuration and the plane view of the rolled plate was particularly elongated, showing a round tongue shape at the top- and end-portions in order to reduce yield losses. Ishikawa et al. [2] calculated the non-symmetric deformations of both the rolls and the strip using three-dimensional analysis for strip rolling, in which elastic deformation of the rolls was considered. Yamamoto et al. [3] developed a new compact multi-reduction mill, which could substitute one stand for two or three stands in a cold tandem mill obtaining good shape controllability, such that the edge-drop of the rolled strip was 30 to 50% less than that for normal rolling with three one-pass rolls. Leven et al. [4] carried out simulation of the strip and plate profile and edge drop for flat rolling in four-high mills. They showed that work-roll bending could be used in controlling the profile or flatness without making a great influence on edge drop. Yamamoto et al. [5] constructed a dynamic simulation model of a strip shape by estimating the strip shape and thermal crown of a work roll in a simplified manner. They analysed the controllability of the strip shape of six-high mills with work- and intermediate-roll bender forces and an intermediate roll-shift based on their model.

Due to the recent development of knowledge-treatment techniques, a knowledge-base control system becomes practical using qualitative and ambiguous human knowledge. The function and organization of human neurons have been studied for many years, since these studies allow researchers to produce mathematical models to test their theories of the underlying principles of the brain. The neural network has learning ability and can be substituted for any arbitrary input/output relationship. Since the treatment of information is carried out independently at each node, the computational efficiency increases. In addition, the distributive information storage leads to a stable computational model for the system. Due to these characteristics, the neural network can be used in controlling complex and ill-defined systems effectively. As a result, neural network and fuzzy theory have emerged into one of the most fruitful areas for research in industrial applications [6–10].

In cold-rolling processes, shape control of the cold-rolled strips is carried out by mathematical control models. However, the operator must control the process manually when these models do not work properly in practice. Therefore, the operator's skill and knowledge are of importance in the control process to carry out the shape control stably and to improve the product quality. Thus, fuzzy theory was introduced in the control of strip shape in six-high cold-rolling mills in order to implement the operator's knowledge. In previous work, a feasibility study of the application of a fuzzy-control algorithm was carried out [11].

In the present study, simulations of the shape control of cold-rolled strip for various irregular cross-sectional types have been carried out on an IBM PC 486 for two cases, steady-state and non-steady-state shape control, using the fuzzy control algorithm that has been developed. As introduced in Ref. [11], the non-flat strip shape was modelled geometrically by shape parameters, Λ_2 and Λ_4. These parameters and changes of work-roll and intermediate-roll bending forces (ΔF_w and ΔF_i) were chosen as primary contol input and output variables throughout a correlation study of production data from a steel company.

For the steady-state control simulation, irregular cross-sectional shapes of cold-rolled steel strips were classified into six types such as 'edge-wave type', 'centre-buckle type', 'W-2 type', 'W-3 type', 'M-1 type', and 'M-4 type', based on the shape parameters Λ_2 and Λ_4. For each irregular type, the developed fuzzy control set was applied continuously until the strip shape converged to the desired flat shape. The capability of the developed fuzzy controller was tested for the various irregular shape patterns by changing the initial shape-parameter values.

Finally, the non-steady-state control simulation of irregular cross-sectional strip shape was investigated. In this case, the cross-sectional strip shape was assumed to change to randomly-introduced irregular shapes in sequence. Then, the control patterns for the randomly-assumed disturbances in sequence were simulated by the developed fuzzy controller. The stability of the current fuzzy-control system was also investigated.

The simulated results were depicted using the emulator studied by the neural network theory using multi layer perceptron.

2. Shape-control simulation of cold-rolled strip

The cold-rolling system considered in the present study was a six-high tandem mill system with four stands. Amongst the four stands, the developed fuzzy-control algorithm was assumed to be applied at the fourth delivery stand since the actual control system in practice is applied there. This stand consists of six rolls: a pair each of back-up, intermediate, and work rolls.

The incoming workpiece is rolled by various roll forces, depending on the thickness, the width, and the type of material. The fabrication of thick strip of greater than 0.7 mm thickness is relatively easy to control, but it is very difficult to control the cross-sectional shape in thin-strip rolling. When the workpiece is not properly controlled in such process, the extension of the incoming strip in the width direction is not uniform and contributes to producing an irregular cross-sectional shape in the thickness direction.

Since detailed information about the development of the fuzzy-control algorithm is available in Ref. [11], only the highlights of the fuzzy-control system will be described here.

In the fuzzy-control system, the control algorithm was divided into two parts, coarse control and fine control, in order to improve the computational efficiency. When either the Λ_2 or the Λ_4 values were located outside of ± 5 *I*-unit, the coarse-control algorithm was applied, otherwise the fine-control algorithm was applied. The measured values of the control input/output variables, Λ_2, Λ_4, ΔF_w and ΔF_i are given as crisp values, so it is required to map the crisp values to the fuzzy sets.

Table 1
Linguistic variables used in the fuzzification

'Coarse' control linguistic variables
LPB: large positive big
PB: positive big
PM: positive medium
PS: positive small
ZE: zero
NS: negative small
NM: negative medium
NB: negative big
LNB: large negative big
'Fine' control linguistic variables
LN: large negative
SN: small negative
ZE: zero
SP: small positive
LP: large positive

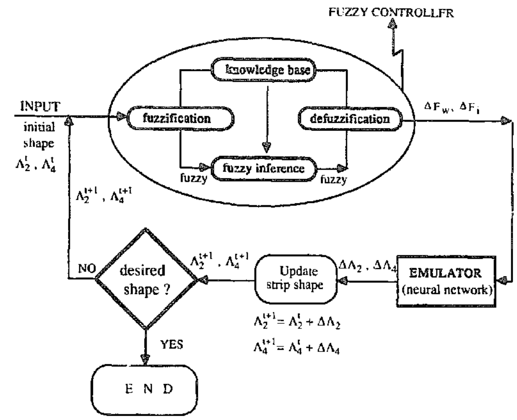

Fig. 1. Structure of the fuzzy shape control simulation.

The linguistic variables used for fuzzification are presented in Table 1, variables constituting the triangular form of fuzzy sets as introduced in Ref. [11] for the coarse control and fine control. For the case when both the Λ_2 and Λ_4 values are within ± 5 I-unit, i.e., the fine control case, the control range becomes smaller to secure a stable result without oscillation. For the coarse-control case, the calculated values of ΔF_w and ΔF_i become greater to make them converge to the desirable values quickly.

For the coarse-control case, the membership matrix table, as shown in Table 1, consists of nine linguistic sets, including LPB, PB, PM, PS, ZE, NS, NM, NB, and LNB, and each set consists of 13 level numbers. In the fine-control case, the membership matrix table, as shown in Table 1, consists of five linguistic sets, including LN, SN, ZE, SP, and LP, and each set consists of five level numbers.

Table 2
Fuzzy variables and values of ΔF_w and ΔF_i (the output variables of the fuzzy controller)

Fuzzy variable	Fuzzy singleton (ton)
Coarse control	
LPB	1.00
PB	0.75
PM	0.50
PS	0.25
ZE	0.00
NS	−0.25
NM	−0.50
NB	−0.75
LNB	−1.00
Fine control	
Fuzzy variable	**Fuzzy singleton (ton)**
LP	0.50
SP	0.25
ZE	0.00
SN	−0.25
LN	−0.50

Table 2 shows the fuzzy variables and values of the control output variables, ΔF_w and ΔF_i. As shown in this table, ΔF_w and ΔF_i have nine fuzzy variables and each variable has a fuzzy singleton from − 1 to 1 ton for the case of coarse-control and they have five fuzzy variables and each variable has a fuzzy singleton from −0.5 to 0.5 ton for the case of fine-control.

The cold-rolled strip shape was classified into six types: 'edge-wave type', 'centre-buckle type', 'W-2 type', 'W-3 type', 'M-1 type', and 'M-4 type'; based on their irregularities according to the range of Λ_2 and Λ_4 as follows:

edge-wave type: $\Lambda_2 > \Lambda_4 > 0$
centre-buckle type: $\Lambda_2 < \Lambda_4 < 0$
W-2 type: $\Lambda_4 < \Lambda_2 < 0$
W-3 type: $\Lambda_2 > 0$, $\Lambda_4 < 0$
M-1 type: $\Lambda_4 > \Lambda_2 > 0$
M-4 type: $\Lambda_2 < 0$, $\Lambda_4 > 0$

For each type, the fuzzy-control rules were developed between the control input variables, Λ_2 and Λ_4, and the control output variables, ΔF_w and ΔF_i, based on the production data and the operator's knowledge. For example, the fuzzy rules for 'centre-buckle type', 'W-2 type', and 'M-1 type' are given as follows:

⟨centre-buckle type⟩

1. If Λ_2 is LNB then ΔF_w is LNB, ΔF_i is LNB
2. If Λ_2 is NB then ΔF_w is LNB, ΔF_i is NB
3. If Λ_2 is NM and Λ_4 is NM, then ΔF_w is NB, ΔF_i is NM

4. If Λ_2 is NM and Λ_4 is NS, then ΔF_w is NB, ΔF_i is NM
5. If Λ_2 is NM and Λ_4 is ZE, then ΔF_w is NB, ΔF_i is NS
6. If Λ_2 is NS and Λ_4 is NS, then ΔF_w is NM, ΔF_i is NS
7. If Λ_2 is NS and Λ_4 is ZE, then ΔF_w is NS, ΔF_i is ZE
8. If Λ_2 is ZE then ΔF_w is NS, ΔF_i is ZE

⟨W-2 type⟩

1. If Λ_2 is LPB, then ΔF_w is PB, ΔF_i is NM
2. If Λ_2 is PB, then ΔF_w is PB, ΔF_i is NS
3. If Λ_2 is PM and Λ_4 is NB, then ΔF_w is PB, ΔF_i is NM
4. If Λ_2 is PM and Λ_4 is NS, then ΔF_w is PB, ΔF_i is NS

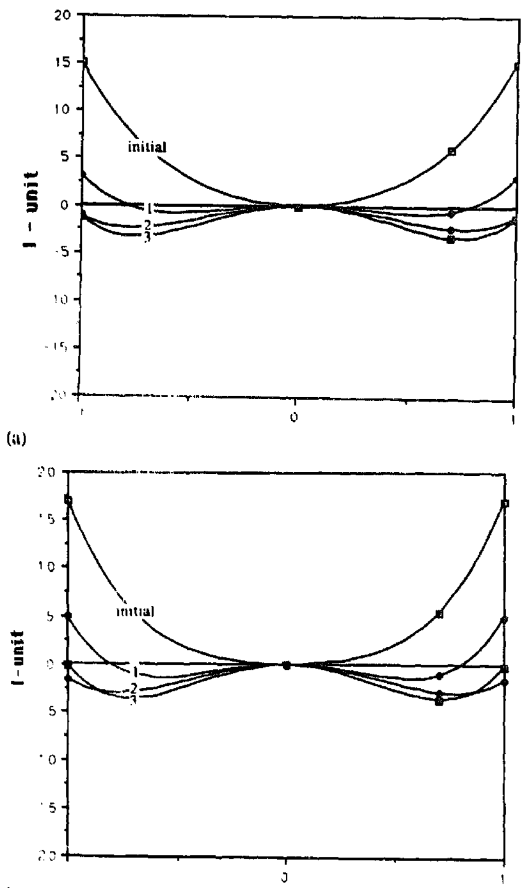

Fig. 2. Simulation results for the continuous shape control of the 'edge-wave type' (a) initial shape: $\Lambda_2 = 15.0$ l-unit, $\Lambda_4 = 6.0$ l-unit; (b) initial shape: $\Lambda_2 = 18.5$ l-unit, $\Lambda_4 = 12.6$ l-unit.

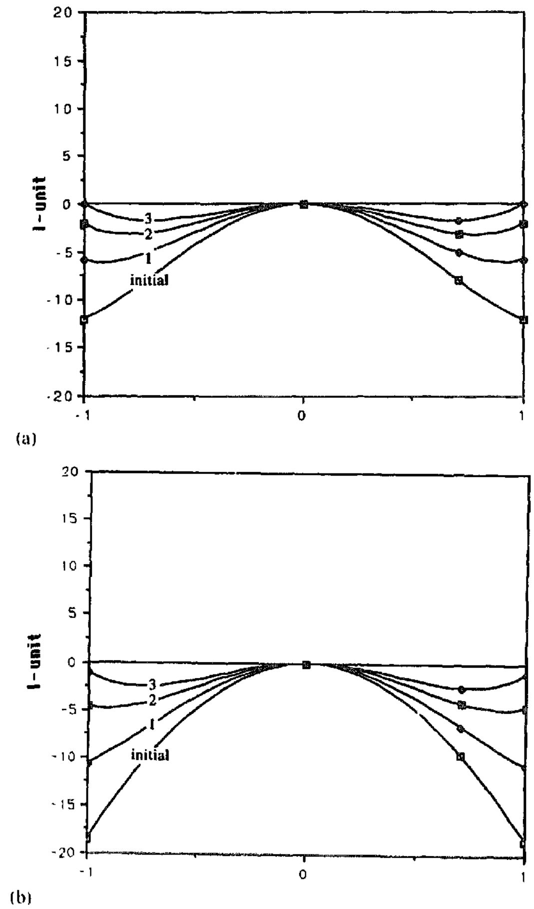

Fig. 3. Simulation results for the continuous shape control of the 'centre-buckle type': (a) initial shape: $\Lambda_2 = -18.5$ l-unit $\Lambda_4 = -9.6$ l-unit; (b) initial shape: $\Lambda_2 = -12.0$ l-unit, $\Lambda_4 = -8.0$ l-unit.

5. If Λ_2 is PM and Λ_4 is ZE, then ΔF_w is PM, ΔF_i is NS
6. If Λ_2 is PS and Λ_4 is NB, then ΔF_w is PM, ΔF_i is NB
7. If Λ_2 is PS and Λ_4 is NS, then ΔF_w is PM, ΔF_i is NS
8. If Λ_2 is PS and Λ_4 is ZE, then ΔF_w is PS, ΔF_i is ZE
9. If Λ_2 is ZE and Λ_4 is NB, then ΔF_w is PM, ΔF_i is NB
10. If Λ_2 is ZE and Λ_4 is NS, then ΔF_w is PS, ΔF_i is NM
11. If Λ_2 is ZE and Λ_4 is ZE, then ΔF_w is PS, ΔF_i is ZE

⟨M-1 type⟩

1. If Λ_2 is LPB and Λ_4 is LPB, then ΔF_w is LPB, ΔF_i is LPB
2. If Λ_2 is PB and Λ_4 is LPB, then ΔF_w is PB, ΔF_i is LPB

3. If Λ_2 is PM and Λ_4 is LPB, then ΔF_w is PM, ΔF_i is LPB
4. If Λ_2 is PS and Λ_4 is LPB, then ΔF_w is PS, ΔF_i is LPB
5. If Λ_2 is ZE and Λ_4 is LPB, then ΔF_w is ZE, ΔF_i is LPB
6. If Λ_2 is PB and Λ_4 is PB, then ΔF_w is PB, ΔF_i is LPB
7. If Λ_2 is PM and Λ_4 is PB, then ΔF_w is PM, ΔF_i is PB
8. If Λ_2 is PS and Λ_4 is PB, then ΔF_w is ZE, ΔF_i is PB
9. If Λ_2 is ZE and Λ_4 is PB, then ΔF_w is ZE, ΔF_i is PB
10. If Λ_2 is PM and Λ_4 is PM, then ΔF_w is PM, ΔF_i is PM

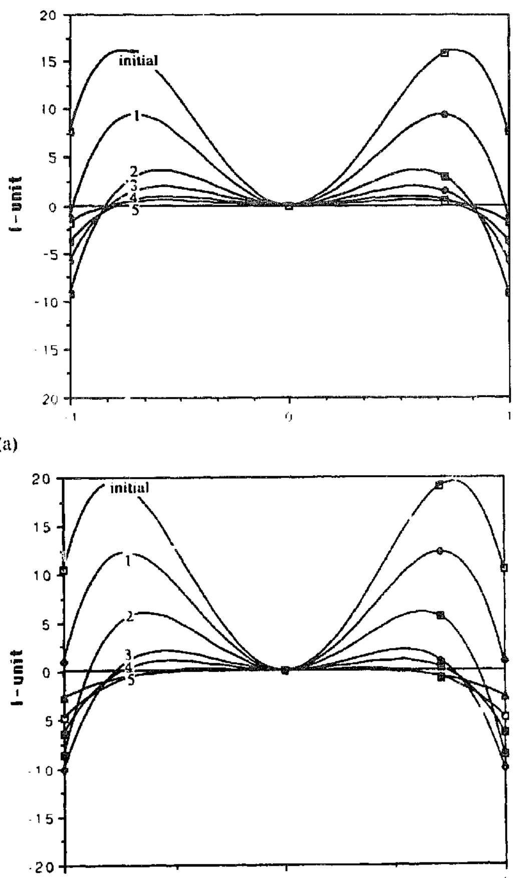

Fig. 4. Simulation results for the continuous shape control of the 'M-1 type': (a) initial shape: $\Lambda_2 = 7.6$ I-unit, $\Lambda_4 = 15.9$ I-unit; (b) initial shape: $\Lambda_2 = 10.5$ I-unit, $\Lambda_4 = 19.0$ I-unit.

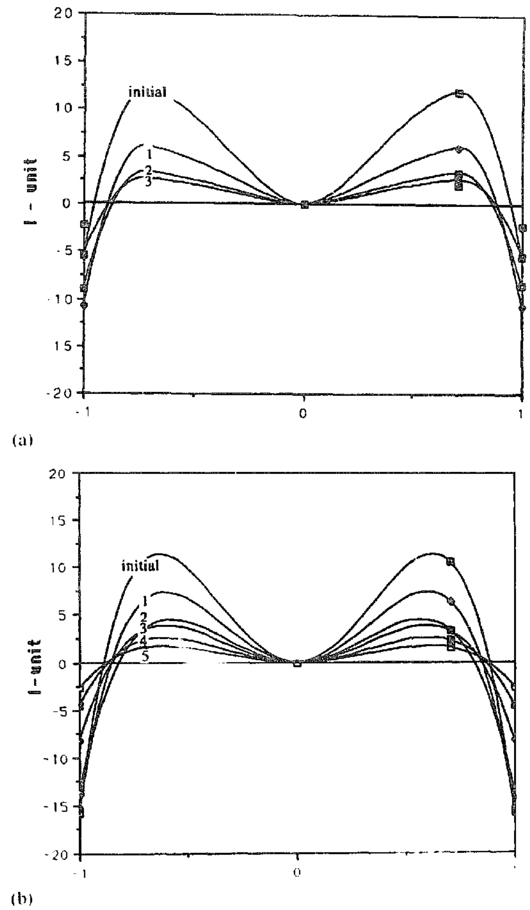

Fig. 5. Simulation results for the continuous shape control of the 'M-4 type': (a) initial shape: $\Lambda_2 = -15.0$ I-unit, $\Lambda_4 = 10.5$ I-unit; (b) initial shape: $\Lambda_2 = -5.5$ I-unit, $\Lambda_4 = 12.0$ I-unit.

11. If Λ_2 is PS and Λ_4 is PM, then ΔF_w is PM, ΔF_i is PM
12. If Λ_2 is ZE and Λ_4 is PM, then ΔF_w is PS, ΔF_i is PM
13. If Λ_2 is PS and Λ_4 is PS, then ΔF_w is PM, ΔF_i is PM
14. If Λ_2 is ZE and Λ_4 is PS, then ΔF_w is PS, ΔF_i is PM
15. If Λ_2 is ZE then ΔF_w is ZE, ΔF_i is PS

Fig. 1 presents a schematic description of how the fuzzy-control simulation was carried out. For any given initial strip shape in terms of Λ_2 and Λ_4 the fuzzy controller calculated the control output values ΔF_w and ΔF_i. During this process, the initial strip-shape values were transformed into the fuzzy values, and control output values were calculated as fuzzy values based on the fuzzy-control rules using Mamdani's minimum operation method [12], for inference. Then, the calculated output fuzzy values were transformed into the crisp values using the centre of area method for defuzzification [12].

The calculated values of ΔF_w and ΔF_i were passed to the emulator, which was constructed by neural network theory. Then, the emulator predicted the changes of strip shape $\Delta\Lambda_2$ and $\Delta\Lambda_4$ at every time step. Using the calculated changes of strip shape $\Delta\Lambda_2$ and $\Delta\Lambda_4$, the shape-deformation parameters Λ_2 and Λ_4 were updated. If the updated shape-deformation parameters Λ_2 and Λ_4 were within the desired range of flatness (± 3 *I*-unit), the cross-sectional shape was understood to be satisfactory and the simulation was stopped: if not, the simulation continued until the values were within the desired range.

The emulator was constructed based on the production data from a steel company [13], and was developed

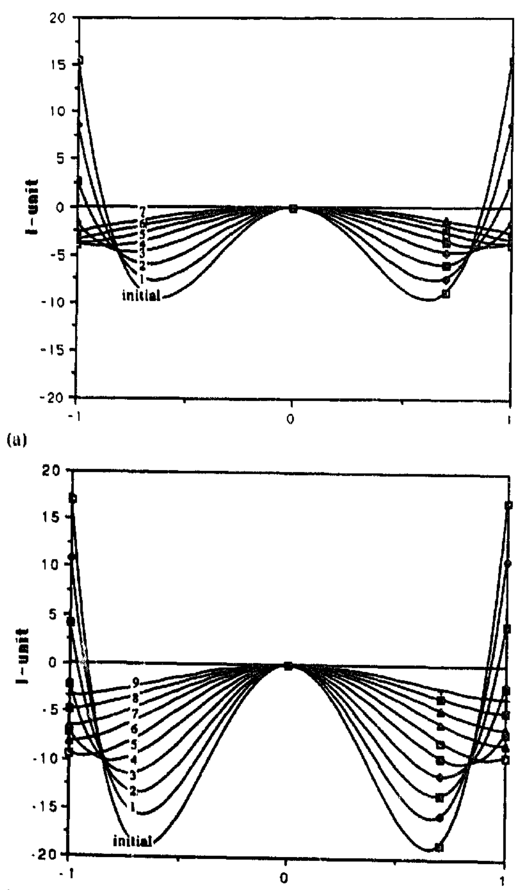

Fig. 6. Simulation results for the continuous shape control of the 'W-2 type': (a) initial shape: $\Lambda_2 = 15.5$ *I*-unit, $\Lambda_4 = -8.9$ *I*-unit; (b) initial shape: $\Lambda_2 = 17.0$ *I*-unit, $\Lambda_4 = -18.5$ *I*-unit.

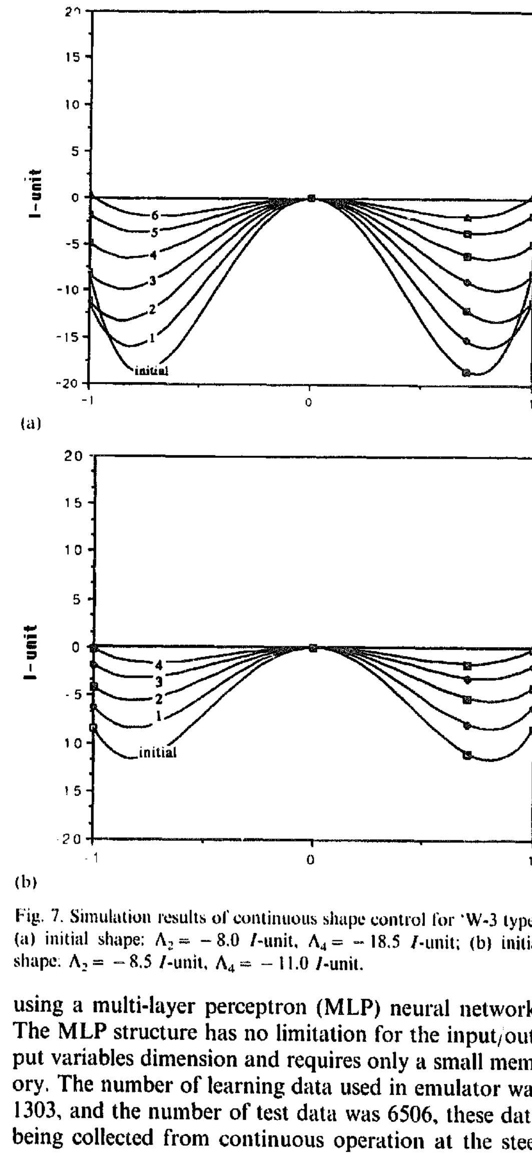

Fig. 7. Simulation results of continuous shape control for 'W-3 type': (a) initial shape: $\Lambda_2 = -8.0$ *I*-unit, $\Lambda_4 = -18.5$ *I*-unit; (b) initial shape: $\Lambda_2 = -8.5$ *I*-unit, $\Lambda_4 = -11.0$ *I*-unit.

using a multi-layer perceptron (MLP) neural network. The MLP structure has no limitation for the input/output variables dimension and requires only a small memory. The number of learning data used in emulator was 1303, and the number of test data was 6506, these data being collected from continuous operation at the steel company.

The neural network structure of the emulator consists of eight input nodes, i.e., F_w, ΔF_w, F_i, ΔF_i, Λ_2, $\Delta\Lambda_2$, Λ_4, and $\Delta\Lambda_4$, two hidden layers that have 16 and 8 nodes, respectively, and two output nodes, i.e., Λ_2 and Λ_4. The emulator used the back-propagation algorithm [14]. To reduce the effect of noisy data on the performance of the emulator, the production data was normalized by $(x - x_{avg})/\sigma$, where x represents the sampled data x_{avg} the average value of the sampled data, and σ the standard deviation of the sampled data. The accuracy of the currently-used emulator was tested to be valid in Ref. [13].

The simulations were carried out for two cases. For the steady-state shape control case, the control was performed for various irregular strip shapes until the values of the shape deformation parameters Λ_2 and Λ_4 were located within ± 3 *I*-unit, whilst for the non-steady-state case, the cross-sectional strip was assumed to change to unexpected shapes suddenly, in sequence, this case simulating the real dynamic cold-rolling process. Through these simulations the accuracy and applicability of the currently developed fuzzy controller were tested.

3. Results and discussion

For each of the previously-classified shape patterns, simulation results of steady-state fuzzy shape control are shown in Figs. 2–7; in these figures the numbers represent the number of iterations during simulations.

In Fig. 2, simulation shape control results for two different 'edge-wave types' are depicted. For the given initial shape of $\Lambda_2 = 15.0$ *I*-unit and $\Lambda_4 = 6.0$ *I*-unit (the case of Fig. 2(a)), the simulation was carried out by calculating the changes of bender forces, ΔF_w and ΔF_i, to be 0.67 ton and 0.48 ton, respectively, as a result of the proposed fuzzy-control scheme at the first iteration. These values of ΔF_w and ΔF_i were passed into the emulator as input for numerical iterations. After the first iteration, the emulator predicted the changed strip shape as $\Lambda_2 = 3.071$ *I*-unit and $\Lambda_4 = 0.566$ *I*-unit and then these values were used as input values for the second iteration. Checking whether these *I*-unit values were located to within ± 3 *I*-unit, the limiting value of the cross-sectional flatness of the strip, the simulation was continued. According to the simulation results from the current fuzzy-control system for 'edge-wave type', the desired strip shape was obtained successfully within four iterations.

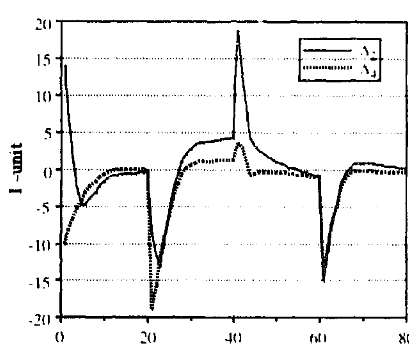

Fig. 8. Non-steady-state shape control results for arbitrary disturbances (arbitrary disturbances were introduced at every 20 iterations).

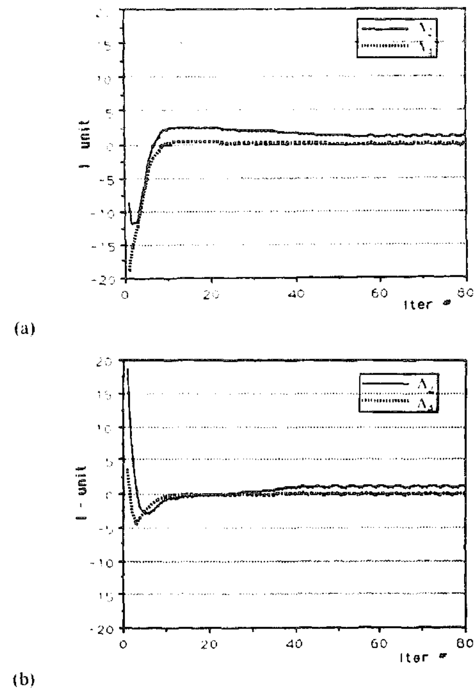

Fig. 9. Test results for the stability of the currently developed fuzzy controller: (a) initial shape: $\Lambda_2 = -8.5$ *I*-unit, $\Lambda_4 = -18.9$ *I*-unit; (b) initial shape: $\Lambda_2 = 18.7$ *I*-unit, $\Lambda_4 = 3.7$ *I*-unit.

For the case of the 'centre-buckle-type', the simulation results are shown in Fig. 3. For the given initial strip shape of $\Lambda_2 = -18.5$ *I*-unit and $\Lambda_4 = -9.6$ *I*-unit, the desired strip shape was obtained after three iterations, as shown in Fig. 3(a). Because of the relatively simple irregular cross-sectional shapes, the fuzzy-control simulations reached the desired level within a few iterations.

Figs. 4 and 5 show the simulation results for the 'M-1 type' and the 'M-4 type', respectively. Similarly to the previous cases, the number of numerical iterations required to obtain the desired shape was five or six, depending on the initial shape patterns. It is seen in Fig. 4(a) for the given initial strip shape of $\Lambda_2 = 7.6$ *I*-unit and $\Lambda_4 = 15.9$ *I*-unit, that Λ_2 was changed suddenly from -1.155 to -9.242 at the second iteration. This was attributed to the previous values of ΔF_i and Λ_4 which were positively large at the first iteration and affected the Λ_2 more than the small negative value of ΔF_w.

The simulation results for 'W-2 type', as presented in Fig. 6, show that the values of the work- and intermediate-roll bender forces were oscillating in the earlier stage of fuzzy control. Since the cross-sectional shape was not simple for this case, the control of the bender forces was not uniform compared to the 'edge-wave type' or 'centre-buckle type', where the change of bender forces was relatively uniform and simple. As shown in this figure, the reduction of the work-roll bender forces should be sufficiently high to induce their change of sign at the fourth iteration whilst reduction of the intermediate roll-bender forces should be minimized in order to keep their sign the same. Because of this, the controlled cross-sectional shape of the 'W-2 type' was changed to the 'centre-buckle type' at the fifth iteration in the same figure, in order to obtain the desired cross-sectional flat shape.

Similar results were obtained for the case of the 'W-3 type', as shown in Fig. 7, the desired strip shape being obtained within six iterations for this case.

From these continuous shape-control simulation results, it was found that the changes of the bender forces, ΔF_w and ΔF_i, depended on the sign of the shape parameters, Λ_2 and Λ_4, respectively. If Λ_2 was negative, the work-roll bender force decreased whilst if Λ_2 was positive, the work-roll bender force increased in order to compensate for the irregular deformation of the strip. The same relationship was found to be valid between Λ_4 and ΔF_i. By interviewing the operation engineers, it was found that the simulation results obtained from the currently-developed fuzzy-control system were similar to the actual control scheme used in practice.

In order to simulate the real cold-rolling process, where unexpected arbitrary disturbances intervened during the process, depending on the process conditions, the non-steady-state case was investigated, as shown in Fig. 8, this figure demonstrating fuzzy-control simulation results for arbitrarily assumed disturbances at every 20 steps.

For the initially given strip shape $\Lambda_2 = 14.0$ *I*-unit and $\Lambda_4 = -10.0$ *I*-unit (the W-2 type), fuzzy-shape control was performed until the strip shape became $\Lambda_2 = -0.548$ *I*-unit and $\Lambda_4 = -0.161$ *I*-unit at the 19th iteration and the arbitrarily assumed disturbance was changed to the strip shape of $\Lambda_2 = -8.531$ *I*-unit and $\Lambda_4 = -18.87$ *I*-unit (W-3 type) at the 20th iteration.

For this changed strip shape, the fuzzy controller was applied for simulations. The cross-sectional strip shape converged to the desired strip shape quickly for this case, but the results were shown to overshoot after seven iterations.

Since this kind of overshooting should be avoided in real practice, the stability of the fuzzy controller was checked by simulating the case of $\Lambda_2 = -8.531$ *I*-unit and $\Lambda_4 = -18.7$ *I*-unit continuously for 80 iterations, as shown in Fig. 9(a). This case also shows overshooting at the earlier stage of control, but the results converged to a stable range without introducing any other overshooting or oscillation as the simulations continued. Fig. 9(b) shows another example for the given initial shape of $\Lambda_2 = 18.7$ *I*-unit and $\Lambda_4 = 3.7$ *I*-unit, similar results being obtained in this case, as seen in the figure. At the later stage of iterations the cross-sectional strip shape converged to a flat strip in a stable manner. From these simulation results, it was found that the currently developed fuzzy-control system is stable.

4. Conclusions

In this investigation, fuzzy-control simulations of strip shape at the last, fourth, delivery stand in six-high cold rolling mills were carried out. From the simulations under the present conditions, the following conclusions were obtained:

1. The major controlling parameters, ΔF_w and ΔF_i, were identified from the production data for the control of the cross-sectional shape in the cold-rolling of thin steel strip.
2. For simple shape patterns such as the 'edge-wave type' or the 'centre-buckle type', the desired shape was obtained within three to five iterations, and for the complex shape patterns such as the 'M (M-1, M-4) type' or the 'W (W-2, W-3) type', the desired shape was obtained within six to nine iterations.
3. To reproduce the dynamic characteristic of the cold-rolling process, randomly assumed disturbances were introduced and simulated, in the control of such disturbances, stable solutions being obtained.
4. The steel company obtained comparable production results to the conventional control scheme when applying the developed control system.
5. Although the proposed fuzzy-control system worked very well for the control of symmetrically-shaped parts, further research on the development of the control scheme for non-symmetric shapes is necessary in order to improve the quality control for thin-strip cold-rolling. In addition, more detailed study considering deformation mechanics will be necessary.

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