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Design of a Fuzzy Feed-forward Controller for Monitor HAGC System of Cold Rolling Mill

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***Abstract*—**In this study we propose a novel monitor hydraulic automatic gauge control (HAGC) system based on fuzzy feed-forward controller. This is used in the development of cold rolling mill automation system to improve the quality of cold strip. According to features/ properties of entry steel strip like its average yield stress, width of strip, and desired exit thickness, this controller realizes the compensation for the exit thickness error. The traditional methods of adjusting the roller position, can't tolerate the variance in the entry steel strip. The proposed method uses a mathematical model of the system together with the expert knowledge to perform this adjustment while minimizing the effect of the stated problem. In order to improve the speed of the controller in rejecting disturbances introduced by entry strip thickness variations, expert knowledge is added as a feed-forward term to the HAGC system. Simulation results for the application of the proposed controller to a real cold mill show that the exit strip quality is highly improved.

***Keywords*—**Fuzzy feed-forward controller, monitor HAGC system, dynamic mathematical model, entry strip thickness deviation compensation

I. INTRODUCTION

STEEL strips with different thicknesses are important products in iron and steel industry and have wide uses in automobile manufacturing, food packaging, household electric, machinery, and other fields. With development of end products, higher quality of plate and strip supplied by iron and steel enterprises are requested in terms of thickness and shape tolerance, thereby how to improve the precision of products is always a hot research topic in metal processing field. Rolling process involves several control systems, such as thickness, speed, tension, shape, and etc. Accuracy of the automatic control system plays a significant impact on products quality [1]. In this paper we discuss on one of the terminal sections in cold rolling mill which is called skin-pass section. Its major tasks are simultaneous improvement of the quality of strip and creation of desired thickness reduction.

The hydraulic automatic gauge control (HAGC) system consists of dynamic components like hydraulic cylinder, electro-hydraulic servo valve, mill stand, sensors, and controllers [2]. A dynamic mathematical model of thickness and roll gap control system is derived in this article.

In general, the most effective parameter in thickness control system is roller position. As proposed in some papers, cascade control system is used that roller position control is its inner loop and then a dynamic roll gap adjustment is output to eliminate exit thickness error [3].

As the gauge meter is installed at 1-3m behind mill stand, usually a delay time exists in thickness measuring. So the monitor HAGC system is a pure time delay system. This delay time depends on the distance from the gauge meter to the middle of the mill and strip velocity. It will reduce system stability. Since exact velocity measurements are available, smith predictor control can solve system oscillation problem caused by pure delay in system [3], [4].

Strip products thickness precision is an important quality parameter. Compensating the disturbances of entry strip thickness is necessary and otherwise the exit thickness will have undesired deviations in the practical production. Strip thickness deviations are created generally by reasons like roll eccentricity (roll defects, distortions, or irregularities in bearings), mill mechanical vibrations (mill chatter problem), and thermal noises in hot rolling mill, and usually have periodic nature [5], [6]. Internal mode control (IMC) [7], traditional feed-forward control [8], and adaptive feed-forward control [9] are the methods that have good results in rejecting entry strip thickness deviations, but it is not purposed that adjusting the roll gap for compensating these disturbances depends on the properties of the strip and must be regulated for each coil exactly.

The main goal of this paper is the exit thickness control in proportion to the features/ properties of the entry strip. This is performed by the application of the developed algorithm to the hydraulic automatic gauge and roll gap control system. We propose a fuzzy feed-forward controller and show its ability in compensating thickness deviations through simulations for a real cold mill.

The rest of the paper is organized as follows. Section II presents the model of the system. In section III fuzzy feed-forward controller is designed. Simulation results are illustrated in section IV and finally the conclusion is given in section V.

II. DYNAMIC MODEL OF COLD ROLLING MILL

In this section, mathematical models of hydraulic servo system, rolling process, and roll stand structure separately are derived and therefore a complete model of plant is achieved by composing them into an aggregated model. Due to the access the number of parameters used, the readers are referred to table II for their definitions.

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A. Dynamic model of hydraulic servo system

Hydraulic system consists of a number of equipments, among which electro-hydraulic servo valve and hydraulic cylinder are most important. As shown in fig. 1 this system is the core of the position control loop. The output current of position controller is applied to servo valves and subsequently oil volume flow forces the hydraulic cylinder in a form to enable the proper adjustment of the roller gap.

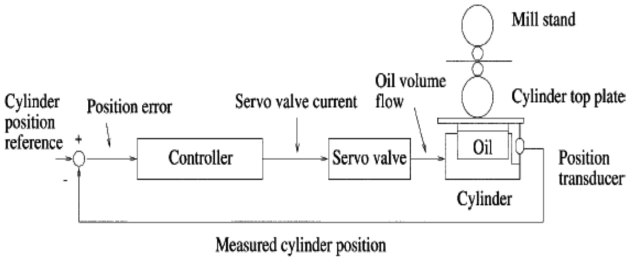

Fig. 1 Hydraulic system in position control loop

Electro-hydraulic servo valve is a nonlinear device with an inherent frequency below 50 Hz, so it can be regarded as a secondary-order oscillation link [1], its transfer function is:

$$\frac{\Delta Q_L}{\Delta I} = \frac{K_V}{\frac{1}{\omega_V^2}s^2 + \frac{2\delta_V}{\omega_V}s + 1} \tag{1}$$

Where I is the input current to the servo valve and Q_L is the oil volume flow. The continuous flux equation of the cylinder is [10]:

$$Q_L = A_P s X_P + K_{ce} P_P + \frac{V_t}{4\beta_e} s P_P \tag{2}$$

Where X_P is the piston position and P_P is the outlet pressure of the valve, and so the hydraulic force for adjusting the roll gap is achieved.

B. Dynamic model of rolling process

A mathematical model of rolling process is a necessary tool for improving the performance of thickness control and strip quality. Equation (3) is the rolling model proposed by Orowan [11], [12]. Ignoring the small variations in the strip width, one can assume that plain-stress condition is achieved. Next rolling force is obtained from product of the average yield stress and the strip surface that is engaged by the roller.

$$P = 1.2KW\sqrt{R'(H-h)} \tag{3}$$

Where P is the rolling force, H is the entry strip thickness, h is the exit strip thickness, and W is the strip width. K is the average yield stress (this is the inner resistance of materials in response to the exerted pressure and depends on strip materials). The Constant factor, 1.2, represents a correction factor for the friction and heterogeneous deformation. Fig. 2 shows the geometry of the dynamic rolling process.

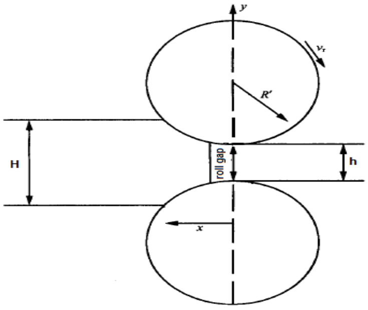

Fig. 2 Geometry of rolling process

Besides, the extremely high rolling force in the roll gap leads to the work roll flattening effect [11], [12]. R' is the loaded roll radius and proposed by Hichcock to compute the rolling force more exactly and is given by:

$$R' = R\left(1 + \frac{CP}{W(H-h)}\right) \tag{4}$$

C. Dynamic model of roll stand structure

The cold rolling mill system is a multi-mass spring system that is made up of two back-up rolls and two work rolls. According to the study purpose and the requirements of accuracy, it can be simplified to one degree or multi-degrees of freedom system [13]. As shown in fig. 3 a 2-degree-freedome multi-mass spring system is used in this paper.

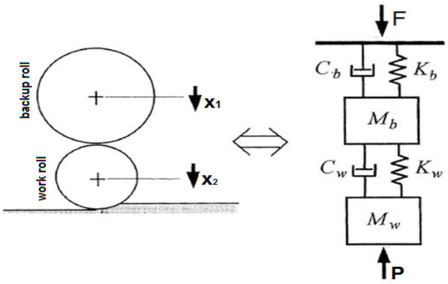

Fig. 3 Roll stand's structure

The relationships between the displacements of rollers and forces are given by:

$$\begin{aligned} F &= M_b\ddot{x}_1 + (C_b + C_w)\dot{x}_1 - C_w\dot{x}_2 + (K_b + K_w)x_1 - K_w x_2 \\ P &= M_w\ddot{x}_2 - C_w\dot{x}_1 + C_w\dot{x}_2 - K_w x_1 + K_w x_2 \end{aligned} \tag{5}$$

Where F is the hydraulic force applied to back-up roll, P is the rolling force applied to work roll, x_1 and x_2 are back-up and work roll displacements respectively.

Ignoring elastic resilience displacement of milled strip, exit thickness is equal to roll gap. But detailed equation between

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exit and entry strip thickness and roll gap is mentioned in [5].

$$h = \frac{M_m}{M_m + M_s} S + \frac{M_s}{M_m + M_s} H \qquad (6)$$

Where S is the roll gap, M_m is the mill module and M_s is the strip module

III. FUZZY FEED-FORWARD CONTROLLER AND ITS APPLICATION IN ENTRY STRIP THICKNESS DEVIATION COMPENSATION

Improvement of the strip quality and compensating the disturbances in entry thickness are very important in cold rolling mill. As shown in fig. 4, these disturbances usually have periodic nature and created generally by roll eccentricity and mill mechanical vibrations.

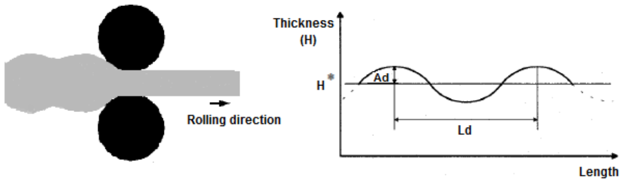

Fig. 4 Entry strip thickness deviation

To reduce exit thickness error, rolling force and roll gap should both be regulated simultaneously according to entry strip thickness deviation. This is clearly indicated in fig. 5. H^*, S^*, P^* are set values of entry thickness, roll gap, and rolling force respectively and h^* is desired exit thickness.

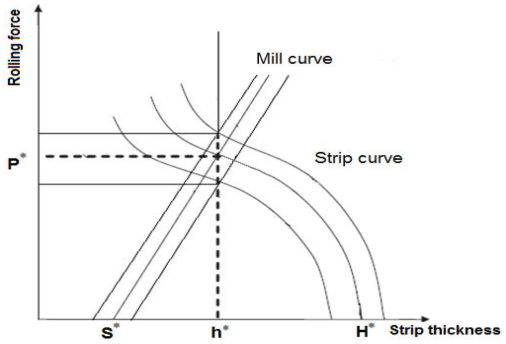

Fig. 5 Force and roll gap regulation diagram

Mill curve is a linear function whose slope depends on elastic module of all components of rolling mill. Strip elastic deformation curve's slope depends on properties of strip like average yield stress, strip width, and etc. [12].

When entry strip thickness is more (or less) than H^*, the mill curve should be shifted to left (or right) to access smaller (or bigger) roll gap and higher (or lower) force and thus achieving a fixed exit thickness.

The equation relating the rolling force to available manipulated parameters is given in (3). Rolling force increases (or decreases) as well as entry thickness increases (or decreases). As a result, hydraulic force, cylinder pressure and servo valve current increase (or decrease). This will fix the exit thickness. But there is no obvious mathematical model for adjusting the roll gap. It is generally an accepted fact that strip properties and desired thickness reduction $(H^* - h^*)$ are parameters which are affective in roll gap adjustment. So a proper model-free controller is necessary to regulate the roll gap and guaranty exit strip quality.

We propose a fuzzy feed-forward controller to regulate the roll gap according to strip properties and minimum exit thickness error. This controller has three inputs and one output as shown in fig. 6.

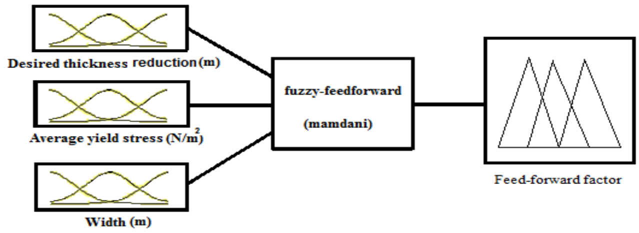

Fig. 6 Fuzzy controller diagram

Controller inputs are desired thickness reduction, strip width, and strip average yield stress. The typical ranges for these parameters are $[0.5 \times 10^{-4}(m), 4.5 \times 10^{-4}(m)]$, $[0.5(m), 1.55(m)]$, and $[10^{8}(N.m^{-2}), 3 \times 10^{8}(N.m^{-2})]$ respectively. The output of the controller is feed-forward factor (FF.fac) that regulates roll gap and its range is $[1,13]$. Membership functions are designed by expert knowledge and process operator experiences. As shown in fig. 7 Membership functions are triangular and their overlap can reduce the response oscillation. Fuzzy linguistic terms are expressed as very very small (VVS), very small (VS), small (S), medium (M), big (B), very big (VB), and very very big (VVB).

Fuzzy controller adopts Mamdani fuzzy inference in which "max" operator uses for "or" and "min" operator uses for "and".

Fuzzy rule-base consists of a set of fuzzy IF-THEN rules in forms as follows:

"If desired thickness reduction is … and strip average yield stress is … and strip width is …, then FF.fac is …."

A rule-base is established based on engineering knowledge and through reasoning. The fuzzy rule-base for our controller is shown in table I.

Center of gravity method is used to defuzzificate the output fuzzy set.

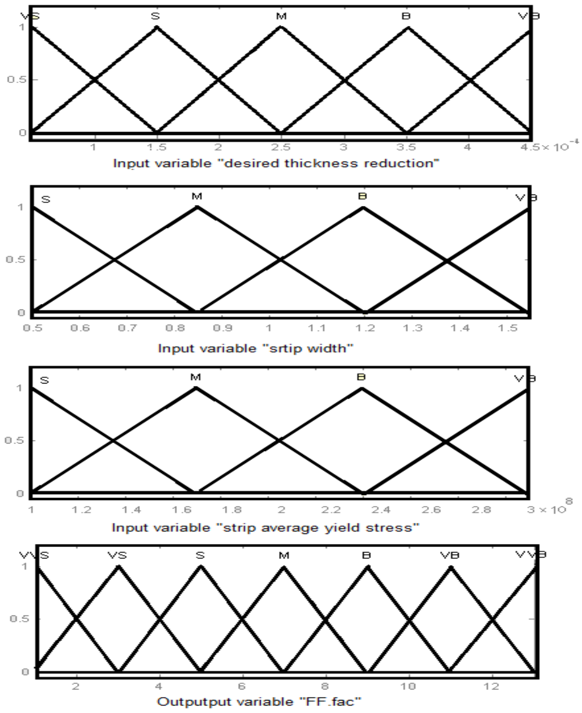

Fig. 7 Membership functions of state variables

TABLE I
RULES OF FUZZY FEED-FORWARD CONTROLLER

No.	Thickness reduction	Width	Yield stress	FF.fac
1	VS	S	S	VVB
2	VS	S	M	VB
3	VS	S	B	B
4	VS	S	VB	M
5	VS	M	S	VB
6	VS	M	M	B
7	VS	M	B	M
8	VS	M	VB	M
9	VS	B	S	B
10	VS	B	M	B
11	VS	B	B	M
12	VS	B	VB	S
13	VS	VB	S	M
14	VS	VB	M	M
15	VS	VB	B	S
16	VS	VB	VB	S
17	S	S	S	M
18	S	S	M	M
19	S	S	B	S
20	S	S	VB	S
21	S	M	S	M
22	S	M	M	M
23	S	M	B	S
24	S	M	VB	S
25	S	B	S	S
26	S	B	M	S
27	S	B	B	S
28	S	B	VB	VS
29	S	VB	S	S
30	S	VB	M	S
No.	Thickness reduction	Width	Yield stress	FF.fac
31	S	VB	B	VS
32	S	VB	VB	VS
33	M	S	S	M
34	M	S	M	M
35	M	S	B	S
36	M	S	VB	S
37	M	M	S	S
38	M	M	M	S
39	M	M	B	VS
40	M	M	VB	VS
41	M	B	S	S
42	M	B	M	S
43	M	B	B	VS
44	M	B	VB	VS
45	M	VB	S	S
46	M	VB	M	VS
47	M	VB	B	VS
48	M	VB	VB	VVS
49	B	S	S	M
50	B	S	M	S
51	B	S	B	S
52	B	S	VB	VS
53	B	M	S	S
54	B	M	M	S
55	B	M	B	VS
56	B	M	VB	VS
57	B	B	S	S
58	B	B	M	S
59	B	B	B	VS
60	B	B	VB	VSS
61	B	VB	S	VS
62	B	VB	M	VVS
63	B	VB	B	VVS
64	B	VB	VB	S
65	VB	S	S	S
66	VB	S	M	VS
67	VB	S	B	VS
68	VB	S	VB	VS
69	VB	M	S	S
70	VB	M	M	VS
71	VB	M	B	VS
72	VB	M	VB	VS
73	VB	B	S	S
74	VB	B	M	VS
75	VB	B	B	VS
76	VB	B	VB	VVS
77	VB	VB	S	VS
78	VB	VB	M	VVS
79	VB	VB	B	VVS
80	VB	VB	VB	VVS

In this control strategy, entry strip thickness deviation should be known. It is modeled by [7]:

$$\Delta H = A_d \sin(\frac{2\pi V_i}{L_d} t) \qquad (7)$$

Where ΔH is the entry thickness deviation. A_d and L_d determine amplitude and frequency of entry deviation respectively. V_i is the entry strip velocity which is measured by precise sensors. Experiences show that A_d and L_d are approximately constant for an especial coil.

Fig. 8 shows the complete block diagram of the system with its fuzzy feed-forward controller.

IV. SIMULATION RESULTS AND DISCUSSIONS

In order to evaluate the performance of the proposed controller, a real case, namely as cold rolling mill of Esfahan's

Mobarakeh steel company was selected as a test case. The related data and their descriptions are given in table II. Simulations are done by MATLAB software and fuzzy feed-forward controller is designed by its fuzzy logic toolbox.

TABLE II
MAIN PARAMETERS OF THICKNESS CONTROL SYSTEM

Symbol	Parameter	Value
K_V	Servo amplifier gain	$7.5\times10^{-3}\ m^3/A.s$
ω_V	Servo valve natural frequency	$680\ 1/s$
δ_V	Servo valve damping coefficient	0.7
A_P	Efficient area of cylinder	$0.425\ m^2$
K_{ce}	Leakage coefficient	$7.8\times10^{-8}\ m^3/Pa.s$
V_t	Cavity volume	$0.095\ m^3$
β_e	Bulk modulus of oil	$8.3\times10^{8}\ N/m^2$
R	Work roll radius	$0.305\ m$
C	Constant depending on roll's materials	$2.25\times10^{-10}\ m^2/N$
M_b	Backup roll mass	$61149\ Kg$
K_b	Spring constant of backup roll	$1.2\times10^{9}\ N/m$
C_b	Damping coefficient of backup roll	$2.5\times10^{6}\ Ns/m$
M_w	Work roll mass	$7573\ Kg$
K_w	Spring constant of Work roll	$3.5\times10^{10}\ N/m$
C_w	Damping coefficient of Work roll	$0\ Ns/m$
M_m	Mill module	$1.6\times10^{9}\ N/m$
S_0	Unloaded roll gap	$3.5\times10^{-3}\ m$

Thickness deviation compensation factor (TDCF) is defined as the ratio of the exit thickness deviation amplitude to its entry counterpart. It is used for evaluating the controllers' performance. It is clear that the better quality of strip is achieved.

Figs. 9 and 10 show the first and second simulation results over two different coils whose parameter values are given in table III. We simulate our control method and feed-forward controller proposed in [8] to compare their ability in entry strip thickness deviation compensation.

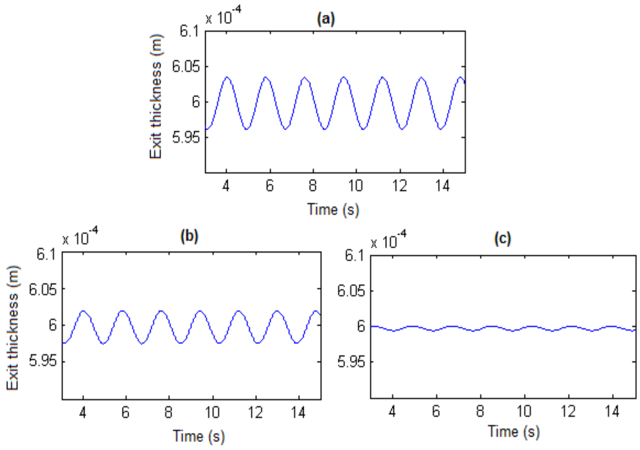

Fig. 9 Exit thickness deviation in first simulation (a) Without feed-forward controller (b) With proposed feed-forward controller in [8] (c) With fuzzy feed-forward controller

In the first simulation, TDCF is 0.663 when feed-forward controller is not used. By employing the proposed method in [8], TCDF is 0.403 and finally TCDF is 0.066 when fuzzy feed-forward controller is used. Simulation result shows that the TDCF is much smaller in our proposed method.

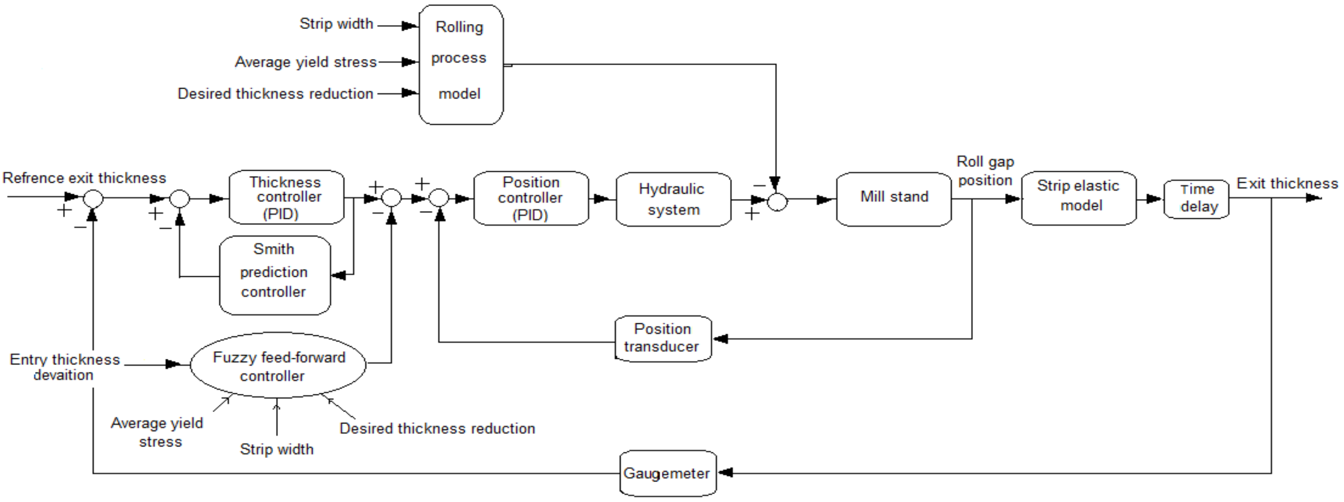

Fig. 8 System block diagram

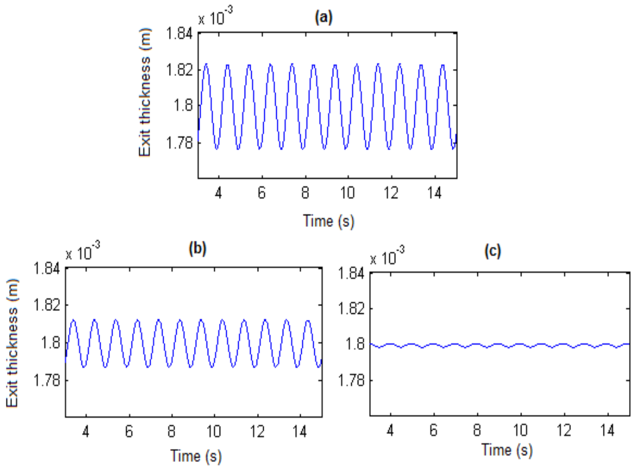

Fig. 10 Exit thickness deviation in second simulation (a) Without feed-forward controller (b) With proposed feed-forward controller in [8] (c) With fuzzy feed-forward controller

In second simulation, TDCF is 0.773 when feed-forward controller is not used. By employing the proposed method in [8] TCDF is 0.422 and finally TCDF is 0.03 when fuzzy feed-forward controller is used. Simulation results demonstrate the higher performance of the proposed controller compare to the previous works.

TABLE III
PARAMETERS OF TWO DIFFERENT COILS IN THICKNESS CONTROL SYSTEM

Symbol	Parameter's value for first simulation	Parameter's value for second simulation
W	$0.9m$	$1.4m$
K	$1.5\times10^{8}\,N/m^{2}$	$2.15\times10^{8}\,N/m^{2}$
$(H^{*}-h^{*})$	$10^{-4}\,m$	$4\times10^{-4}\,m$
A_d	$5.5\times10^{-6}\,m$	$3\times10^{-5}\,m$
L_d	$8m$	$5m$
V_i	$4.5m/s^{2}$	$5.2m/s^{2}$
h^{*}	$6\times10^{-4}\,m$	$1.8\times10^{-3}\,m$

V. CONCLUSION

A dynamic mathematical model of HAGC system in cold rolling mill is presented. Through position regulation in inner loop, exit strip thickness is controlled in outer loop. After analyzing the relationship between strip properties\features and roll gap adjustment, a fuzzy feed-forward controller is designed to compensate entry thickness deviations. Simulation results show this controller can minimize the effect of the stated problem and improve exit thickness quality.

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