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Multi-Resolution Hardness Feed-Forward Automatic Gauge Control for Hot-Rolling Mill Based On Wavelets

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Abstract— **In hot-rolling process, the hardness (temperature) variations of entry strip is the major factor effecting final thickness, however it is not easy to counteract using conventional Automatic Gauge Control (AGC) method. This paper presents a novel Hardness Feed-Forward Automatic Gauge Control method based on multi-resolution decomposition using wavelets (MR-HFF-AGC), the roll force of F1 stand are decomposed into signals at different scales using wavelets, then signals containing hardness information is converted into control decisions used for feed-forward control in latter stands. The performance improvement of MR-HFF-AGC method is shown via the simulation using the real coil data.**

Key words: Hot-Rolling; Hardness Feed-Forward (HFF); Multi-Resolution Decomposition; Wavelets, Multi-Resolution Hardness Feed-Forward Automatic Gauge Control (MR-HFF-AGC)

I. INTRODUCTION

The purpose of an Automatic Gauge Control (AGC) system in the finisher of a hot strip mill is to maintain uniform product thickness in spite of factors that act to vary that thickness. The major such factors are:

-Varying material hardness (mostly from varying temperature)

-Varying thickness in the incoming product (from the rougher)

-Varying unloaded roll bite size due to roll stack eccentricity.

Additional sources of disturbance such as incoming product width variations, or variations in inter-stand tension are usually already within acceptable limits in a well-managed mill.[1]

Conventional AGC systems perform in excellent fashion to counteract the second factor. Many roll eccentricity controllers have attained good performance when confronted by roll stack eccentricity. However they face a unique challenge with regard to material hardness variations, for this kind of variations will be transferred to latter stand, conventional AGC is inadequate because of time delays between the sensor and the stands. We had a different point of view, we focused on hardness variations instead of other factors. This paper concerns Hardness Feed-Forward method to compensate for this drawback of conventional AGC relating to hardness variations. However obtaining the instantaneous product hardness information while masking other disturbance contained in the roll force of F1 stand in the finisher is critical and not easy to realize. We apply wavelet decomposition to extract major varying hardness information from the roll force and feed forward control decisions to subsequent mill stands. Note that wavelet decomposition, provides much higher resolution in obtaining hardness variations from the roll force, therefore, we name this method Multi-Resolution Hardness Feed-Forward Automatic Gauge Control (MR-HFF-AGC). This method was applied to the 1700mm hot rolling strip mill in the Angang.

This paper is organized as follows; in section II, we analyze that hardness variations is the major variations compared to thickness variations. In section III, a brief description of wavelet transforms and multi-resolution decomposition is given. In section IV, a method of decomposition of roll force using wavelets is introduced. In section V, the algorithm of MR-HFF-AGC is presented. In section VI, the result in the plant is shown by the real coil data. Finally, a summary of the work is presented.

II. HARDNESS VARIATIONS

Hardness variations and thickness variations are major disturbance of incoming product, which one effects the final thickness most? Consider entry thickness variations δH_0 and entry temperature variations δT_{FT0}, then compute the steady-state variations of final thickness caused by each of them. First we introduce an affecting factor K_a^b , a represents a disturbance variable, b represents an object variable, K_a^b represents the effect that disturbance a affects b . Entry thickness variations δH_0 affects exit thickness variations following the equation (2.1)

$$K_{H_0}^{h_7} = \frac{\partial h_1}{\partial h_{01}} \bullet \frac{\partial h_2}{\partial h_{02}} \bullet \frac{\partial h_3}{\partial h_{03}} \bullet \frac{\partial h_4}{\partial h_{04}} \bullet \frac{\partial h_5}{\partial h_{05}} \bullet \frac{\partial h_6}{\partial h_{06}} \bullet \frac{\partial h_7}{\partial h_{07}} \quad (2.1)$$

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and the expression of $K_{K_0}^{h_7}$ is more complex than $K_{H_0}^{h_7}$ as the following reasons:

(1) When hardness variations δK_0 enter a stand it will generate new hardness variations δK_i, ($\delta K_i = \beta_i \bullet \delta K_0$, β_i is a gain, depending on rolling types)

(2) δK_i will cause a thickness variation δh_i at i th stand, and δh_i will affect succeeding stands.

Entry hardness variations δK_0 affects exit thickness following the equation (2.2)

$$K_{K_0}^{h_7} = \left[\frac{\beta_1 \frac{\partial P}{\partial K}}{C_p - \frac{\partial P}{\partial h_1}}\right] \bullet K_{h1}^{h_7} + \left[\frac{\beta_2 \frac{\partial P}{\partial K}}{C_p - \frac{\partial P}{\partial h_2}}\right] \bullet K_{h2}^{h_7} + ... + \left[\frac{\beta_6 \frac{\partial P}{\partial K}}{C_p - \frac{\partial P}{\partial h_6}}\right] \bullet K_{h6}^{h_7} + \left[\frac{\beta_7 \frac{\partial P}{\partial K}}{C_p - \frac{\partial P}{\partial h_7}}\right] \qquad (2.2)$$

Through the above two expressions, we get the following results [1]:

(1) If $\delta H_0 = 1mm$ (about 3% of the thickness of slab), it only causes the final thickness variations 0.0013 mm (2.0 mm rolling type) and 0.0002 mm (7.0 mm rolling type) without AGC operating, so variations of entry thickness are not critical.

(2) If $\delta T_{FT0} = 20^o C$ (about 2% of the temperature of slab), it causes the final thickness variations 0.0512～0.0545 mm (2.0 mm rolling type), if $\delta T_{FT0} = 30^o C$ (about 3% of the temperature of slab), it causes the final thickness variations 0.080 mm (2.0 mm rolling type), so variations of entry temperature (hardness) are critical.

(where, H_0 :entry thickness of F1, δ :the deviation from the starting point, $h_i, i = 1,2...7$:exit thickness of i th stand, $h_{0i}, i = 1,2...7$:entry thickness of i th stand, K_0 : entry hardness of F1, $K_i, i = 1,2...7$: entry hardness of i th stand, P :roll force, C_p :mill constant)

III. WAVELETS AND MULTI-RESOLUTION DECOMPOSITION

Wavelets and the concept of multi-resolution analysis (MRA) provided a natural framework for hierarchical representation of functions or signals on different scales. The basic idea of multi-resolution analysis is to represent a function as a limit of successive approximations. Each of these successive approximations is a smoother version of the original function with resolution improved. Wavelets are terminating basis vectors used to decompose signals into a set of coefficients. Consider a continuous signal, $f(t)$, and generate the following sequence of approximations [2],

$$f^m(t) = \sum_{n=-\infty}^{\infty} f_{m,n}\phi(2^m t - n)_{m=0,1,2,...} \qquad (3.1)$$

Each approximation is expressed as the weighted sum of the shifted versions of the same function, $\phi(t)$, which is called the scaling function. If the (m+1) th approximations is required to be a refinement of the m th approximation, then the function $\phi(2^m t)$, should be a linear combination of the basis functions spanning the space of the (m+1) th approximation, i.e.

$$\phi(2^m t) = \sum_k h(k)\phi(2^{m+1}t - k) \qquad (3.2)$$

If V^{m+1} represents the space of all functions spanned by the orthogonal set, $\{\phi(2^{(m+1)}t - k); k \in Z\}$, the set of integers}, and V^m the space of the coarser functions spanned by the orthogonal set, $\{\phi(2^{(m)}t - p); p \in Z\}$ then $V^{(m)} \subset V^{(m+1)}$. Let

$$V^{(m+1)} = V^{(m)} \oplus W^{(m)} \qquad (3.3)$$

then, $W^{(m)}$, is the space that contains the information added upon moving from the coarser, $f^{(m)}(t)$, to the finer, $f^{(m+1)}(t)$, representation of the original function, $f(t)$ .Mallat[2] shows that there are spaces, $W^{(m)}$ that are spanned by the orthogonal translates of a signal function, $\psi(2^m t)$, thus leading to the following equation

$$f^{(m+1)}(t) = f^{(m)}(t) + \sum_{n=-\infty}^{\infty} f_{m,n}\phi(2^m t - n) \qquad (3.4)$$

The function, $\psi(2^m t)$ is called a wavelet and is related to the scaling function $\phi(2^{m+1}t)$, through the following relationship

$$\psi(2^m t) = \sum_k g(k)\phi(2^{m+1}t - k) \qquad (3.5)$$

$h(k)$ and $g(k)$ from a conjugate mirror filter pair. Summarizing the discussion a wavelet series representation of the signal $f(t)$ is given by

$$f(t) = \sum_{k=-\infty}^{\infty} c_k\phi(t-k) + \sum_{j=0}^{m-1}\sum_{k=-\infty}^{\infty} d_{j,k}\psi_{j,k}(t)$$
$$c_k = \int f(t)\bar{\phi}(t-k)dt$$
$$d_{j,k} = \int f(t)\bar{\psi}_{j,k}(t) \qquad (3.6)$$

Where, $\bar{\phi}(t)$ and $\bar{\psi}(t)$ are the conjugate functions corresponding to $\phi(t)$ and $\psi(t)$ respectively.

Thus a wavelet transform decomposes a signal $f(t)$ into trend (c) and detail coefficients (d) as given in (3.6). The trend signal captures the high scale (low frequency) information and detail signal captures the low scale (high frequency) information contained in the signal $f(t)$ Depending upon the number of decomposing levels the end product of a multi-resolution decomposition is a set of these signals at different scales (frequencies) as shown in (3.7). Where f_{d_1} is the high scale signal, f_{a_N} is the low scale signal and $f_{d_i}, i = 2,...N$ are the medium scale signals with N number of decomposition levels, a wavelet transform simultaneously extracts both low-frequency and high-frequency signals, but with different frequency resolutions.

$$f(t) = f_{d_1}(t) + f_{d_2}(t) + ... + f_{d_{N-1}}(t) + f_{d_N}(t) + f_{a_N}(t) \quad (3.7)$$

IV. HARDNESS IDENTIFICATION

Identifying and predicating hardness characteristics of material from measured roll force of F1 stand is vital for MR-HFF-AGC, for based on hardness information MR-HFF-AGC performs all predictive calculations for F2 through F7.There are many factors which generate force variations; roll eccentricity with high frequency, entry thickness variations of material with low frequency, or entry hardness variations. Among them, we know that entry hardness variations are dominating. The disturbance severely influencing hardness are the trend mark of the body of strip due to different duration of heat radiation from head to ends of strip and it is a ramp trend, the skid mark due to non-uniform slab heating in the reheating furnace and the black head mark due to longer duration of cooling water purging in the beginning part of strip. These three factors have different frequency and time domain characteristics, so using wavelet multi-resolution decomposing of roll force, we can simultaneously extract them, which is critical for hardness feed-forward control. Since there are a number of different wavelets, choice of a wavelet affects the performance of the HFF-AGC, when selecting a right wavelet for our application, we change the wavelet and time scales and observe the output of each coefficient, using this technique, we found that "Daubechies" of order 4 is the optimum wavelet. Fig. 1 shows the separating roll force of F1 with screw-downs motionless of an entire slab measured from a real plant, we name it P_1, which contains the cumulative effect of uncertainties such as measurement noise, eccentricity signal, incoming material hardness and thickness variations. Fig. 2,3,4 shows the results of performing a level 10 decomposition of P_1. Fig. 2 shows the level 10 approximation signal of P_1 which is the slowest part of the signal, the result is the overall trend of P_1, it approximates the part of force caused by trend mark. Fig. 3 shows the detail signal at level 7, it approximates the force caused by black head. Fig. 4 shows the detail signal at level 8, it approximates the force caused by skid mark signal. In this level-10 analysis, we note that the major factors of hardness variations become clear, by decomposing roll force at different scale, we can extract the major signal components that cause hardness variations, then feed-forward the hardness information of F1 to latter stand, it will produce a very smooth control signal and drastically reduce the effect of eccentricity and other disturbances.

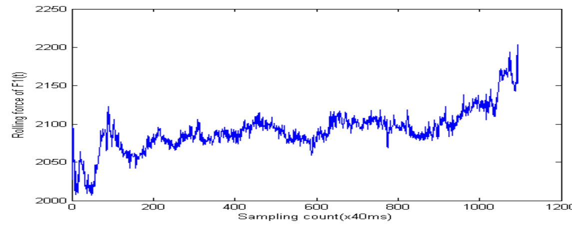

Fig. 1. Roll force of F1 stand

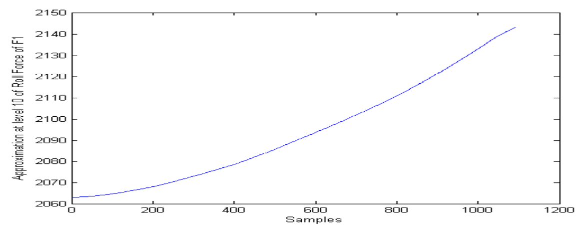

Fig. 2. Approximation signal at level 10

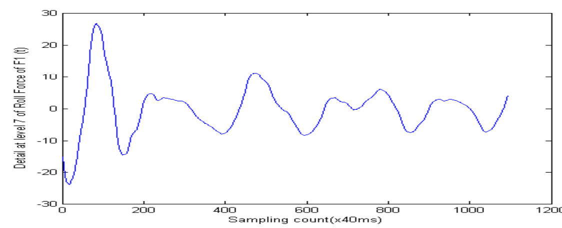

Fig. 3. Detail signal at level 7

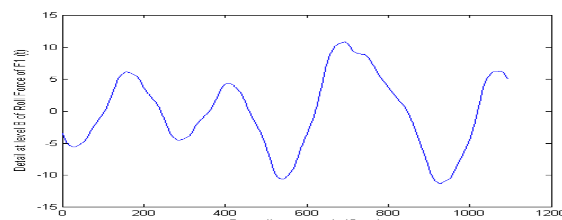

Fig. 4. Detail signal at level 8

V. MR-HFF-AGC ARGORITHM

The MR-HFF-AGC system derives its name from the fact that hardness information gathered using multi-resolution analysis from roll force in the first finishing stand is converted into control decisions. The controller takes the estimated hardness variations out of the first stand and stores them in a delay line ready to be used for control in latter stands. The system measures the force in the first stand while the screw-downs are motionless, thereby removing the error of mill friction and of most of the hysteresis from the force measurement. The measurement is made N (N is an positive integer) times per second, allowing the system to deal with "segments" of 1/N *th* of a second's worth of steel. The hardness information contained in this pure roll separating force forms the basis of complex but accurate multi-resolution decomposition calculations of the behavior of each segment of steel further along in the finisher. The system accurately tracks the individual segment through the entire finisher. Screw-downs in latter stands are operated in response to MR-HFF-AGC outputs, determined prior to the arrival of the relevant segment of steel in each of those stands. In other words, the system has the ability to anticipate the position the screws must take, in each instant in time, in each succeeding mill stand after the first stand. Consequently, multi-resolution decomposition with its relatively complex algorithm and long computing time (as compared to conventional AGC algorithm) are at no disadvantage for control of product thickness. The measured roll force of F1 is multi-resolution decomposed by using wavelet.

$$P_1 = P_{1d_1} + P_{1d_2} + ... + P_{1d_N} + P_{1a_N} \quad (5.1)$$

we define the noise signal of P_1 as P_{1noise}, the noise contains the high frequency of P_1 ,such as measurement noise and other high frequency disturbances,

$$P_{1noise} = \sum_{i=1}^{N_1} P_{1d_i} \quad (5.2)$$

N_1 is an integer and $1 \le N_1 < N$

we note that the force mainly caused by skid mark and black head mark as P_{1d_s} and P_{1d_b} (s , b are integers , $1 < s,b \le N$) (Where, P_i :roll force of i th stand, N :number of decomposition level, P_{1d_i} :detail component roll force of F1 at level i , P_{1a_i} :approximation component roll force of F1 at level i)

we use the following model describing the deformation process and the mill stand characteristics:

$$h_1^* = S_1^* + \frac{P_1^* - P_{1noise}}{C_B} - \frac{P_{1pre}}{C_o} + O + G \quad (5.3)$$

(Where, O : thickness of oil film， G : roll gap constant， C_B , C_o :mill constant ， P_1^* : measured roll force of F1, P_{1pre} :preset roll force, S_1^* : set value of roll gap, h_1^* : exit thickness of F1, $l_C^{'}$:touching length of roller and steel strip, Q_p :material plastic coefficient)

Using related equations to calculation $l_C^{'}$, Q_p with the value of H_1 and h_1^* , then we calculate the hardness coefficient as follows

$$K_1^* = \frac{P_{1aN} + P_{1ds} + P_{1db}}{B l_C^{'} Q_p} \text{ , } \quad \delta K_1 = K_1^* - K_{1S} \quad (5.4)$$

(Where, K_1^* :computed hardness coefficient of F1, K_{1S} :set point of hardness coefficient of F1.)

$\delta K_i = \beta_i \delta K_1$, β_i :ratio of harness variations reduction, depending on i th stand, we obtain a transfer function with the desired additional roll gap set point:

$$\delta S_i = -\alpha_i \left(\frac{\frac{\partial P}{\partial K_i}}{C} \right) \delta K_i \quad (a_i \text{ :control gain, less than 1})$$

Further, we should calculate the exact control time according to the looper angle, hydraulic actuator delay, control period delay and strip speed, etc. Fig.5. shows MR-HFF-AGC block diagram.

VI. APPLICATION RESULTS

The MR-HFF-AGC method has been applied to the 1700mm hot-rolling mill at the Angang works. The experimental results in the production mill are shown in Fig.6, Fig.7. Fig.6 shows the final exit thickness of the strip, where the MR-HFF-AGC was not applied to the all stand,

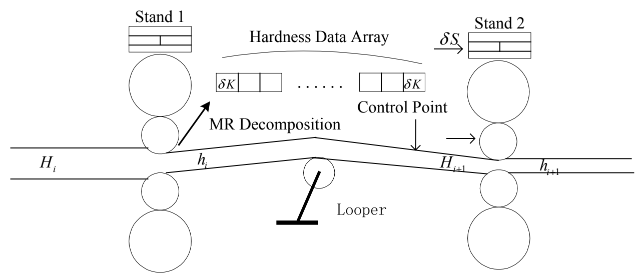

Fig. 5. MR-HFF-AGC process

the skid mark and black head mark appears distinctly. Fig.3. shows the final thickness of the strip, where the suggested MR-HFF-AGC is applied to the all stands. As a result, thickness deviation are considerably reduced in the suggested MR-HFF-AGC result compared with that in the conventional AGC result. The suggested MR-HFF-AGC significantly improves the quality of the rolled product.

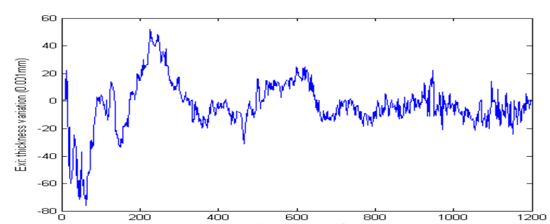

Fig. 6. The final thickness variations (before MR-HFF-AGC)

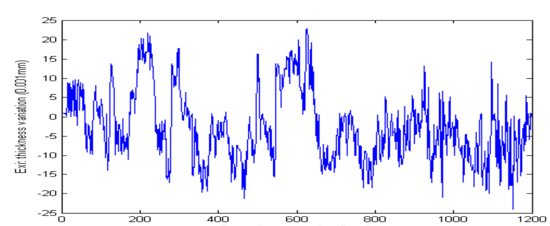

Fig. 7. The final thickness variations (after MR-HFF-AGC)

VII. CONCLUSION

In this paper, a novel MR-HFF-AGC method for hot-rolling mill is proposed. The hardness characteristics is unmasked by using multi-resolution decomposing of roll force of F1 stand, enable the hardness information is feed-forward to control latter stands. Implementation of the wavelet in industry is in progress.

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