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AUTOMATIC COMPENSATION OF THE MILL ROLL ECCENTRICITY IN TERMS OF LIMITED SPEED OF HYDRAULIC COMPRESSION DEVICES

Purpose. To reduce deviation of vertical dimension (thickness) of rolled products from the specified value by enhancing the accuracy and shortening the setup time of an eccentricity compensation subsystem of mill rolls based on substantiation of an eccentricity compensation method. This method is based on an active search algorithm to determine the actual eccentricity parameters in real time, taking into account the actual response time of hydraulic compression devices (HCD) and investigating its effectiveness through simulation computer modelling.

Methodology. The research was based on the analytical determination of the frequency characteristics of the AGC system in sheet metal rolling, considering the actual response time of HCD of a rolling mill as well as a comprehensive model of a rolling process in a quarto mill with rolling movement and an automatic thickness control system (ATCS) that compensates for eccentricity. The study was conducted by comparing the results of computer simulation modelling of the improved ATCS, whose algorithm took into account the HCD response time, with the performance indicators of the previous system, which did not consider this factor.

Findings. It has been established that under the AGC thickness control conditions, the measured amplitude of a variable component of thickness does not match the amplitude of eccentricity due to the finite response time of HCD. The frequency characteristics of the AGC system have been determined analytically, taking into account the actual response time of HPD in a rolling mill. An improved procedure for determining the actual eccentricity amplitude in real time has been substantiated, which involves a temporary reduction in the HCD speed within the initial rolling section. A structure for an automated control system has been proposed for practical implementation of this procedure. It has been demonstrated that the proposed solutions allow for a threefold reduction in thickness variations caused by eccentricity compared to the corresponding performance indicators of the known eccentricity compensation systems with the AGC thickness control.

Originality. The influence of the HCD response time on the accuracy of AGC thickness control systems for rolled products has been established. An approximate linear relationship has been identified between the ratio of the amplitude of thickness fluctuations caused by eccentricity and the amplitude of roll gap fluctuations relative to the roll speed and HCD response time under the AGC algorithm thickness control conditions. The improved procedure for determining the actual eccentricity amplitude in real time has been substantiated.

Practical value. The effectiveness is substantiated of implementing an improved active search algorithm for determining the eccentricity parameters of mill rolls under the limited HCD response conditions in real time. This approach allows for a threefold reduction in the sheet thickness variability caused by roll eccentricity compared to the performance indicators of the known AGC thickness control systems, thereby ensuring the production of high-precision rolled products in Ukrainian sheet rolling mills.

Keywords: *thickness control of rolled products, AGC algorithm, roll eccentricity, response speed of hydraulic compression devices, computer simulation modelling*

State-of-the-art and statement of the research task. During the operation of sheet rolling mills, a challenge arises to ensure the quality of commercial products in accordance with market demands and updated standards with stricter requirements for product parameters in terms of gradual equipment wear. One of the key parameters of sheet metal is the rolled sheet thickness, which must comply with the standard requirements and fall within the tolerance field established by the respective standard. Equipment wear affects negatively the accuracy of a rolling process.

An issue of improving the thickness accuracy of rolled products is especially relevant for Ukraine, where sheet rolling mills have been in operation for quite a long time. According to the current Ukrainian standards (DSTU 8540-2015), the maximum thickness deviation for sheet products of standard accuracy, depending on its thickness, ranges from ±0.07 mm (for the thicknesses of 0.4–0.5 mm) to ±0.15 mm (for the thicknesses of 1.4–1.6 mm), while for higher accuracy rolling, it is ±0.05 and ±0.12 mm, respectively. The maximum thickness deviations for high-precision cold-rolled sheets (GOST 19904-90) are even stricter, ranging from ±0.03 mm (for the thicknesses of 0.4–0.5 mm) to ±0.07 mm (for the thicknesses of 1.4–1.5 mm). High-precision rolling is sold at a higher price and is in greater demand.

The most economically viable and quickly achievable direction for improving the competitiveness of Ukrainian rolled products is the modernization of control systems, which enables production of high-precision sheet metal. However, such modernization requires well-founded scientific and technical solutions to address this issue.

Currently, one of the main factors causing deviations in the vertical dimension (thickness) of sheet metal from the set value is eccentricity of mill rolls. The inaccuracy in manufacturing the mill rolls, which results from misalignment of the centres of their body and neck circumferences, leads to uncontrolled fluctuations in a gap between the rolls during their rotation while rolling. Since sheet rolling stands contain two pairs of rolls with different diameters – support and working rolls – fluctuations of varying amplitude and frequency overlap, creating a complex pattern of variations in the roll gap, which in turn causes corresponding changes in sheet thickness at the roll exit. Despite the efforts of scientists over the past nearly 60 years to develop methods for eliminating the effects of eccentricity, the problem remains unsolved.

The majority of over 200 domestic and foreign original technical solutions aimed at addressing the issue of roll eccentricity affecting sheet metal thickness focus on eliminating it by introducing forcibly the out-of-phase adjustments to a roll gap with the same frequency and amplitude as the gap fluctuations caused by the eccentricity of rolls [2, 3]. The differences between various technical solutions implementing this approach are in the methods used to determine frequencies, amplitudes, and phases of the uncontrolled roll gap fluctuations.

Studies [4, 5] propose to determine the eccentricity parameters by extracting and using a variable component of the rolling force caused by changes in the metal compression in a mill due to roll eccentricity and the resulting variation in a roll gap. However, extracting this variable component is a significant technical challenge due to the available harmonics in the rolling force signal, whose frequency is close to the frequency of gap changes caused by roll eccentricity in the same rolling stand. This issue of identifying roll eccentricity parameters becomes particularly acute in continuous rolling mills. Indeed, changes in the rolling force are caused not only by uncontrolled fluctuations in the roll gap due to eccentricity but also by compression fluctuations caused by variations in the thickness of the stock entering the rolls. If, in a continuous mill, these changes are caused by the eccentricity of rolls in the previous stand, whose rotation frequency is very close to the one of the roll gap fluctuations in the stand where identification is taking place, their extracting from the rolling force signal becomes excessively difficult and practically impossible.

This problem cannot be solved even with the use of improved signal filtering methods from the force sensors, as proposed by the authors in paper [6].

A significant obstacle to determine effectively the eccentricity parameters is the variability of eccentricity parameters for each pass, caused by slippage between the working and support rolls during metal gripping and filling in the respective rolling stand. The difference in slippage between the upper and lower backup rolls leads to changes in both the phase and amplitude of roll gap fluctuations, making it impossible to transition the identification results obtained from the previous pass to the next one. Because of this, methods that involve preliminary direct measurement of the roll gap face significant technical challenges [7, 8] as well as attempts to use neural network technologies [9, 10] or model predictive control (MPC) methods[11, 12] to solve this problem.

Recently, a number of technical solutions have been proposed to address the issue of compensating for the impact of eccentricity on the accuracy of sheet rolling. These solutions are based on algorithms for actively identifying the actual eccentricity parameters, particularly its amplitude and phase, with further eccentricity compensation by adjusting a roll gap using hydraulic compression devices (HCD) of a rolling stand [13, 14].

However, these solutions do not take into account the response speed limitations of HCD, and therefore, unfortunately, cannot be applied directly to the rolling mills.

Paper [13] proposes to determine an eccentricity phase using an active search algorithm. This algorithm involves preliminary introduction of forced oscillations in a roll gap with the frequency and amplitude of eccentricity ΔS_e and an arbitrary phase, measuring $\Delta h_{\max}$ amplitude of the thickness oscillations caused by these actions, and subsequent correction of phase $\Delta\phi$ of the forced oscillations.

The effectiveness of this phase correction depends entirely on the accurate determination of the eccentricity amplitude ΔS_e, which is problematic in the continuous rolling conditions. In [13], similar to [2, 5], this requires extracting a variable component of the rolling force.

This drawback is eliminated with the help of a technical solution proposed in [14], where the phase of eccentricity is determined similarly to [13], and determining the eccentricity amplitude does not involve extracting a variable component from the rolling force signal. This approach is based on the fact that the automation of modern continuous sheet rolling mills includes an automatic thickness control system (ATCS) in each finishing stand, controlled by the AGC algorithm. In the domestic literature, AGC control is known as Golovin-Sims equation control, which adjusts the roll gap by the amount

$$\Delta S = -\frac{\Delta P}{M_K}, \qquad (1)$$

which is determined by dividing deviation ΔP of the current rolling force from its baseline (initial) value by modulus M_K of the rolling stand stiffness [15, 16].

It has been proven that the use of AGC algorithm results in complete transition of eccentricity to the rolled product thickness. In other words, it allows for the measurement of eccentricity amplitude ΔS_e by measuring directly variable component Δh of the sheet thickness at the exit of the rolling stand.

However, complete transition of eccentricity to the rolled product thickness under the AGC control is possible only if the compression devices are used with very high response speeds (very small time constants) or at low rolling speeds (low eccentricity frequencies). In practice, the duration of transient processes in modern hydraulic compression devices (HCD) is about 30–35 ms (time constants are ~0.01 s). As a result, the thickness fluctuations of the rolled product will occur with the amplitude somewhat lower than that of the eccentricity. This necessitated research into the impact of the dynamic properties of HCD on the accuracy of thickness control under the AGC algorithm, particularly based on the amplitude-frequency characteristics of the AGC systems [17]. A transition function of the AGC system, where a controlled variable is thickness variation Δh of the rolled product and a controlling variable is uncontrolled change ΔS_e in a roll gap

$$W^{\Delta S}(p) = \frac{\Delta h(p)}{\Delta S_e(p)},$$

can be determined from the calculation scheme (Fig. 1), which illustrates the AGC system response to changes in a roll gap.

By substituting HCD as a first-order aperiodic link, the authors of paper [17] defined the amplitude-frequency characteristic (AFC) of the AGC system as follows

$$A(\omega) = \sqrt{\frac{T^2\omega^2 + 1}{T^2\omega^2\left(\frac{M_p + M_K}{M_K}\right)^2 + 1}}, \qquad (2)$$

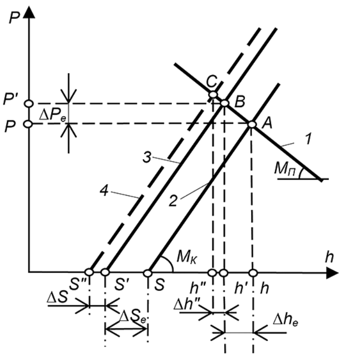

Fig. 1. Calculation scheme for thickness control of rolled products using the AGC algorithm under disturbances due to roll eccentricity

where ω is roll rotation frequency; T is time constant of HCD; M_K is modulus of rigidity of the stand (corresponding to the tangent of a slope of the elastic deformation line of the stand, line *2* in Fig. 1); M_p is modulus of rigidity of the rolled product (corresponding to the tangent of a slope of the plasticity curve, line *1* in Fig. 1).

Considering that AFC illustrates the relationship $\alpha = \Delta h/\Delta S_e$ of amplitude Δh of the thickness fluctuations to amplitude ΔS_e of the eccentricity, expression (2) helps determine how much larger the sought amplitude of the eccentricity is compared to the amplitude of thickness fluctuations, which can be measured directly.

Based on the above, the objectives of further research can be considered as follows:

1) development of a method to determine the actual amplitude of uncontrolled fluctuations in a roll gap caused by roll eccentricity, which will take into account the finite response speed of HCD and the corresponding improvement of ATCS with eccentricity compensation;

2) proving the effectiveness of the improved ATCS through simulation modelling.

Improved method for thickness control of rolled products with the eccentricity compensation. The analysis of dependency (2) of parameter α on the eccentricity frequency and time constant of HCD, conducted within the range of $\omega = 5–20\ s^{-1}$ and $T = 0.005–0.02$ s, indicates that this relationship is nearly linear and can be represented in the simplified form shown in Fig. 2.

Considering that at $T = 0$ under the operation of a non-inertial HCD, the ratio $\alpha = 1$, meaning that the eccentricity is completely transitioned to the rolled product, we can express this relationship according to Fig. 2 as follows

$$\frac{1-\alpha_1}{T_1} = \frac{1-\alpha_2}{T_2}, \qquad (3)$$

where index *1* corresponds to the parameters $\alpha_1 = \Delta h_1/\Delta S_e$; T_1 at reduced response speed, while index *2* corresponds to parameters $\alpha_2 = \Delta h_2/\Delta S_e$ and T_2 at the maximum response speed of HCD.

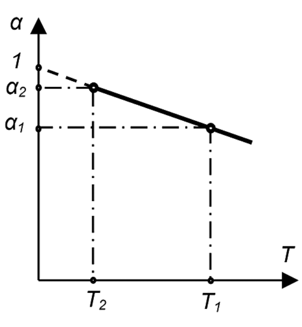

Fig. 2. Determining an eccentricity amplitude

Since time constant T of HCD has an inversely proportional relationship with their speed V, we can make the appropriate substitution in (3) and, assuming that $V_1 = V_2/k$, determine the eccentricity amplitude as

$$\Delta S_e = \frac{k}{k-1}\left(\Delta h_2 - \frac{\Delta h_1}{k}\right). \qquad (4)$$

Thus, the algorithm for determining a real eccentricity amplitude should contain the following sequence of actions:

1) before the rolling starts, set the reduced speed mode for HCD;

2) while rolling the initial section of the strip, activate the AGC-system for adjusting the strip thickness, which works according to formula (1);

3) extract a variable component of the rolled thickness at frequency ω of the rotation of support rolls and determine primary amplitude Δh_1, which corresponds to the reduced speed of HCD;

4) transition HCD to the maximum speed mode, then determine secondary amplitude Δh_2 of a variable component of the rolled thickness, which corresponds to the maximum speed of HCD, and calculate amplitude ΔS_e of the eccentricity according to formula (4).

Further ATCS operation should be according to the algorithm, which provides: implementation of forced harmonic change of a roll gap with frequency ω, amplitude ΔS_e, and arbitrary phase ϕ.

The total change in a roll gap after adding these forced changes to the eccentricity-induced gap fluctuations will be a harmonic function of argument ωt, being

$$\Delta S(\omega t) = \Delta S_e \sin(\omega t) + \Delta S_e \sin(\omega t + \phi). \qquad (5)$$

Setting the derivative of function (5) to be equal to zero

$$\frac{d\Delta S}{d(\omega t)} = \Delta S_e\left[\cos(\omega t) + \cos(\omega t + \phi)\right] = 0,$$

one can determine a value of argument $(\omega t)_{max}$ that yields the maximum value of the amplitude of the total fluctuations of a roll gap

$$(\omega t)_{max} = \mathrm{arctg}\left(\frac{1+\cos\phi}{\sin\phi}\right). \qquad (6)$$

Substituting expression (6) into (5) after a series of simple transformations makes it possible to determine amplitude ΔS_{max} of the total gap fluctuations

$$\Delta S_{max} = 2\Delta S_e \cos\left(\frac{\phi}{2}\right). \qquad (7)$$

From expression (7), it follows that a phase shift between the forced gap oscillations and the eccentricity can be defined as

$$\Delta\phi = \pi \mp 2\arccos\left(\frac{\Delta S_{max}}{2\Delta S_e}\right). \qquad (8)$$

Taking into account that the rolled product thickness at the exit from the rolls is equal to the gap value

$$\Delta h_{max} = \Delta S_{max},$$

to implement forced gap oscillations out of phase with the eccentricity, their initial phase must be shifted by the amount

$$\Delta\phi = \pi \mp 2\arccos\left(\frac{\Delta h_{max}}{2\Delta S_e}\right). \qquad (9)$$

Thus, the ATCS algorithm involves measuring amplitude Δh_{max} of a variable component of thickness within the strip section that was subjected to forced changes in a gap with the arbitrary phase, and then shifting phase ϕ of the forced changes in a roll gap by calculated value Δϕ according to formula (9).

Compensating for the eccentricity of the working rolls, whose effect on the variability of rolled product thickness is several times less than that of the eccentricity of support rolls, requires similar actions to extract a variable component of thickness at the rotational frequency of working rolls. In this case, forced oscillations of a roll gap to compensate for the eccentricity of both the support and working rolls should be performed simultaneously (in parallel) using the same algorithm as the one outlined above.

A system of automatic thickness control with compensation for roll eccentricity. Fig. 3 shows a functional diagram of ATCS that implements the proposed algorithm for compensating the eccentricity of support rolls.

An executive mechanism of ATCS is a system for positioning the working rolls, which operates on the principle of feedback. According to the task received at the input of a summator *9*, it uses a hydraulic compression device to move the rolls to the specified position.

A hydraulic compression device contains a double-acting hydraulic cylinder *10*, controlled by an electric signal from the system *8* and a gyrodistributor *11*, which is used to change directions of the hydraulic cylinder rod's movement to either increase or decrease a gap between the rolls. This is controlled by a signal from the output of the eccentricity parameter identification unit *15*. The system also includes a gyrodistributor *12* with spring return, whose position determines the speed of the rod's movement, and a throttle *13*, whose availability in the drainage line of the hydraulic system reduces the speed of the hydraulic cylinder rod's movement by *k* times.

At the input of the summator *9*, the following is received: initial gap task S^* formed before the rolling process; addition ΔS_1^* to the gap setting, generated by the AGC system to compensate for the influence of low-frequency technological disturbances; and addition ΔS_2^*, which defines the forced oscillations of the gap to compensate for the influence of roll eccentricity. The sum of these three components determines the current setting of a gap that must be executed by the system *8*.

Before the rolling process starts, a positioning system between the working rolls of a rolling stand sets the gap according to the task formed by the summator *9*, which, at that moment in time, equals the operator-defined initial value S^* due to the absence of signals ΔS_1^* and ΔS_2^* at its inputs.

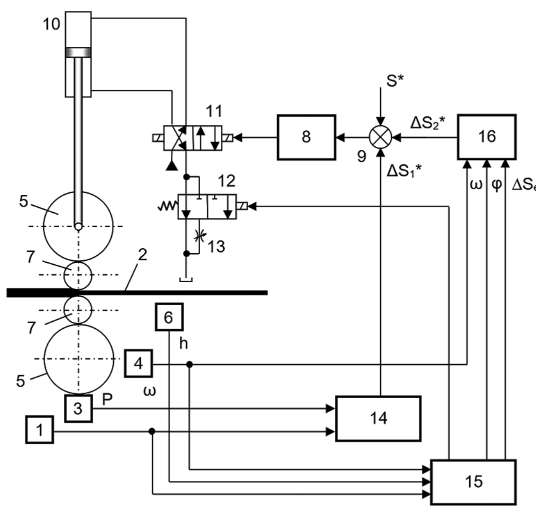

Fig. 3. Functional diagram of the proposed ATCS:

1 – product presence sensor; 2, 3 – rolling force sensors; 4 – rotation frequency sensor of rolls 5; 6 – thickness sensor at the output of the working rolls 7; 8 – roll positioning system; 9 – summator; 10 – hydraulic cylinder; 11 and 12 – hydraulic distributors; 13 – throttle; 14 – AGC system; 15 – unit of eccentricity parameter identification; 16 – generation unit

A signal from a sensor *1* indicating availability of the rolled product *2* in the rolls triggers the AGC system *14*, which, using information from the force meter *3* of rolling force *P*, calculates addition ΔS_1^* throughout the rolling process according to formula (1), ensuring compensation for all technological disturbances (deviations in thickness and stiffness of the semifinished rolled products) caused by the semifinished rolled products.

In this context, within the initial section of the strip, hydraulic distributor *12* is set to a position where throttle *13* is present in the drainage line, meaning that the movement of hydrocylinder rod *8* occurs at a reduced speed (time constant of HCD is equal to T_1, and the speed equals to V_1).

Identification of the eccentricity amplitude and phase is carried out in unit *15*.

Throughout the rolling process, a signal from a thickness meter *6* of the strip is sent to the input of the identification unit *15*, which extracts the variable component of the strip's thickness caused by the eccentricity of support rolls and determines its amplitude.

After recording amplitude Δh_1 of the variable component of thickness, occurring at a reduced speed of HCD, unit *15* sends a signal to switch a hydrodistributor *12* into a state where a throttle *13* is removed from the drain line, which corresponds to an increase in HCD response rate by *k* times ($V_2 = kV_1$).

Once a section of the strip, whose thickness was adjusted with high speed of the hydraulic control system, enters a measurement zone of a meter *6*, unit *15* records amplitude Δh_2 of a variable component of thickness and calculates amplitude ΔS_e of the eccentricity using formula (5).

From this moment on, a unit *16* begins to generate a sinusoidal signal

$$\Delta S_2^*(t) = \Delta S_{\hat{a}} \sin(\omega t + \phi),$$

with frequency ω, amplitude ΔS_e, and zero phase $\phi = 0$. When added in the summator *9* to the sum $S^* + \Delta S_1^*$, it causes additional oscillations in a roll gap, which in turn lead to corresponding fluctuations in the rolled product thickness.

After determining the amplitude of these oscillations in unit *15*, calculation of phase shift $\Delta\phi$ between the uncontrolled and forced oscillations of a roll gap is initiated. The calculated phase shift is sent to unit *16* for generation, which adjusts appropriately the parameters of the forced oscillations of the roll gap.

Thus, the proposed ATCS allows theoretically for the complete compensation of the influence of roll eccentricity on the strip thickness exiting the rolling mill, while simultaneously compensating for other technological disturbances introduced by the semifinished rolled products (variations in the thickness of semifinished rolled products and modulus of rigidity).

However, considering that formula (5), which forms the basis of the improved ATCS algorithm, is based on a simplified linear relationship of α parameter with the HCD speed, effectiveness of the proposed method requires further verification. Such verification is best conducted through simulation computer modelling, which necessitates the development of an appropriate adequate dynamic model.

Research on the ATCS effectiveness using a computer model. A dynamic model of the rolling process in a separate stand of a continuous sheet rolling mill and the proposed ATCS was created in the MATLAB-Simulink software environment. The model [13] used by the authors for studying an eccentricity compensation system [14] was the basis for this work.

Schematic of the model is shown in Fig. 4.

The actual rolling process is modelled in the *Rolling Mill* unit, to which signals simulating thickness *H* and stiffness M_n of the semifinished rolled products are inputted, while the outputs provide calculated thickness *h* of the rolled product and rolling force *P*. The thickness signal is processed using Bessel band-pass filters (*Analog Filter*) to extract the variable components corresponding to the rotational frequency of the

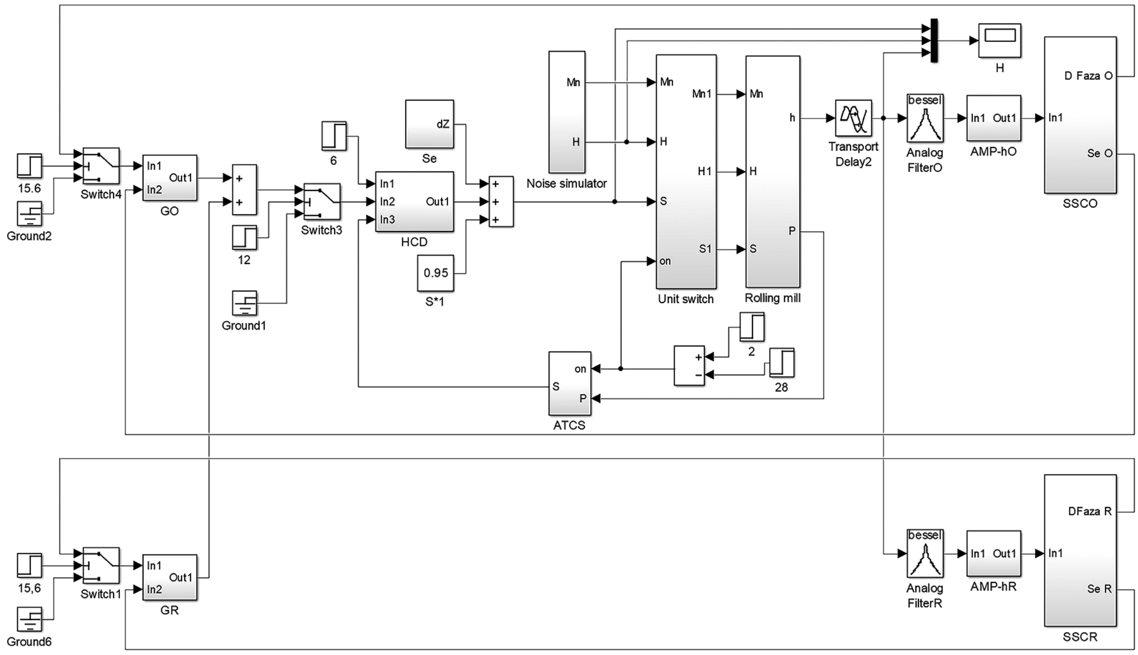

Fig. 4. Schematic of the rolling process model and the proposed ATCS in the MATLAB-Simulink environment

support and working rolls. Subsequently, their amplitude is determined in the *AMP-hO* and *AMP-hP* units.

The ATCS model includes similar compensation loops for the eccentricity of both support and working rolls.

The changes made to the base model [13] during its refinement specifically pertained to the modelling of the algorithm for determining an amplitude of uncontrolled changes in a roll gap caused by eccentricity (units SSCO and SSCR), the AGC system itself (unit *ATCS*), and the hydraulic pressing device (unit *HCD*).

Information about the thickness fluctuation amplitudes of the rolled product is sent to the inputs of units *SSCO* and *SSCR*, simulating the operation of eccentricity compensation subsystems for support and working rolls according to the previously outlined algorithm. The internal structure of these units is identical (Fig. 5). At their outputs, the values of amplitude ΔS_e and phase $\Delta\phi$ of the forced oscillations of a roll gap are generated, which are subsequently processed by HCD.

In the memory blocks *a*1 and *a*2, implemented basing on the *Triggered Subsystem*, the thickness fluctuation amplitudes of the rolled product caused by eccentricity are stored under conditions of reduced and high HCD speed. Using these amplitudes, actual amplitude of the eccentricity is calculated in units *Fcn*1 and *Fcn*2 according to formula (5), with the result stored subsequently in memory unit *a*3.

Phase $\Delta\phi$ is determined according to formula (9) in unit *Fcn*3 after recording Δh_{max} in memory unit *a*4.

The AGC-system model (unit *ACTS*) is illustrated in Fig. 6. It implements algorithm (1), using information about current rolling force *P* and previously calculated expected rolling force P^*.

The HCD was modelled in unit *HCD* (Fig. 7) in the modes that simulate maximum and reduced response rate. For this purpose, two units *Transfer Fcn*1 and *Transfer Fcn*2 were used, representing first-order aperiodic elements with different time constants: 0.02 seconds for a slow mode and 0.01 seconds for a faster operating mode of HCD. The transition from a slow mode to a fast mode is accomplished using switch *Switch*3.

A signal from the output of unit *HCD*, which defines the forced change in a roll gap caused by the system, is added in the summator unit to output gap S^* and to the eccentricity of rolls from the output of unit S_e. This signal then passes through the *Unit switch* to the *Rolling Mill* simulation unit as the actual roll gap.

The modelling was conducted for hot rolling conditions of a strip with a thickness of h = 1.47 mm, using a thickness of semifinished rolled products H = 1.89 mm, on the reversible

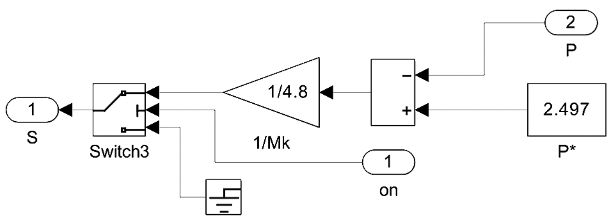

Fig. 6. Model of the AGC system of thickness control (ATCS unit)

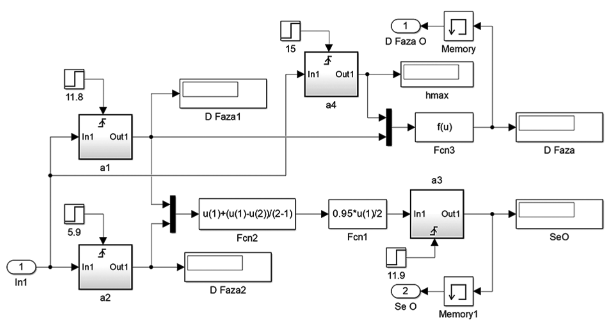

Fig. 5. Schematic of the functional unit SSCO

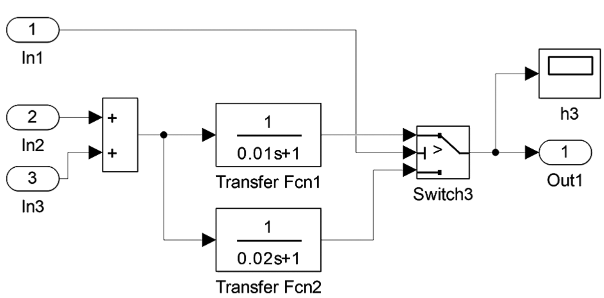

Fig. 7. Schematic of the HCD simulation unit

stand 800 of "Zaporizhstal" PJSC. The technological parameters and equipment parameters of the stand were assigned values close to the real ones: diameter of support rolls – 800 mm; diameter of working rolls – 400 mm; eccentricities of support rolls – 0.04 and 0.05 mm; eccentricities of working rolls – 0.02 and 0.03 mm; rigidity modulus of the stand – 4.8 MN/mm; rolling speed – 5 m/s; rotation frequency of support rolls – 12.5 s^{-1}; rotation frequency of working rollers – 25 s^{-1}; rolling force – 2.5 MN; rigidity modulus of the strip – 5.95 MN/mm.

The modeling was carried out in three stages.

During the first stage, a rolling process with the automatic thickness control using the AGC algorithm was investigated without automatic compensation for the eccentricity of working and support rolls.

Fig. 8 shows the oscillograms obtained from the computer experiment: rolled product thickness h at the stand exit, thickness of the semifinished rolled products H with a high-frequency component caused by the eccentricity of support and working rolls of the previous rolling stand, and roll gap S, which is changed deliberately by the AGC system throughout the entire rolling process.

As shown in Fig. 9, fluctuations in the rolled product thickness occur within the range of 1.36–1.55 mm, with an amplitude of Δh = 0.19 mm, which is slightly smaller than the amplitude of roll gap fluctuations caused by eccentricity, ΔS = = 0.21 mm. This result is entirely consistent with the studied frequency properties of the AGC system [17].

Thus, rolling with the automatic thickness control using the AGC algorithm, without automatic compensation for the eccentricity of working and support rolls, can at best produce material of only standard accuracy.

During the second stage, the ATCS operation, which implements the AGC algorithm and compensates for the eccentricity of working and support rolls as described in [14], was modelled without accounting for the limited speed of HCD (Fig. 9).

Analysis of the experimental thickness oscillogram shows that compensation for eccentricity begins at the 9^{th} second of modelling, after the system has completed the procedure for determining the parameters of eccentricity, which lasts for the first 7 seconds of rolling: determining the amplitude from 2 to 6 seconds and determining the phase from 6 to 9 seconds.

The results of the computer experiment indicate that this system is capable of compensating for eccentricity and achieving thickness variability of Δh = 0.03 mm, but only at using a hydraulic control system with time constant T = 0.001 s, which is nearly 10 times higher than currently achievable indicators.

However, if modern HCDs with a real time constant T = 0.01 s are used, the ATCS effectiveness deteriorates significantly (Fig. 10): a range of thickness fluctuations is 1.44–1.55 mm, with Δh = 0.12 mm.

Thus, the use of ATCS, which implements the AGC algorithm and compensates for the eccentricity of rolling and support rolls of the stands as described in [14], without accounting for the limited HCD response rate, allows for a reduction in variability of the rolled product by approximately 40 %. This guarantees only standard rolling accuracy, while the production of rolled products with increased precision remains problematic.

During the third stage of the study, operation of the proposed improved ATCS was modelled using the developed model (Fig. 4). A rolling process begins at the 2^{nd} second of the simulation (Fig. 11). During the first four seconds (from 2 to 6 s), the thickness is adjusted according to the AGC algorithm at a slowed-down HCD (T = 0.02 s). Here, at the 3^{rd} second, rolling appears within the thickness measurement zone, and during the following 3 seconds, the variable component of thickness caused by eccentricity is extracted using a narrowband Bessel filter, and its amplitude is determined. Duration of the transient process in the filter corresponds to approximately five roll rotations.

At the 6^{th} second of simulation, ATCS switches HCD into a high-speed mode (T = 0.01 s), as indicated by the shape of $h(t)$ oscillogram, which becomes more regular. The next 5 seconds are spent by the system waiting for the corresponding section of the rolled product to reach a thickness measurement zone and for a relevant variable component to be extracted from the rolled product thickness.

Thus, at the 12^{th} second, determination of the eccentricity amplitude is completed, and ATCS begins to adjust forcibly a

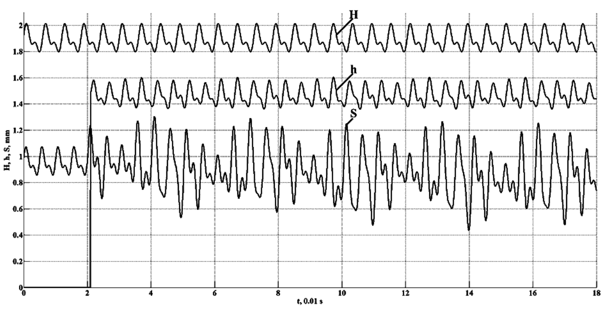

Fig. 8. Results of the rolling process simulation under AGC system operation without eccentricity compensation

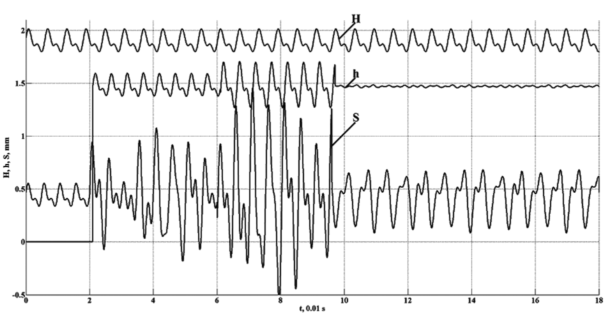

Fig. 9. Result of the ATCS operation modelling according to method [14] under applying "ideal" HCD with T = 0.001 s

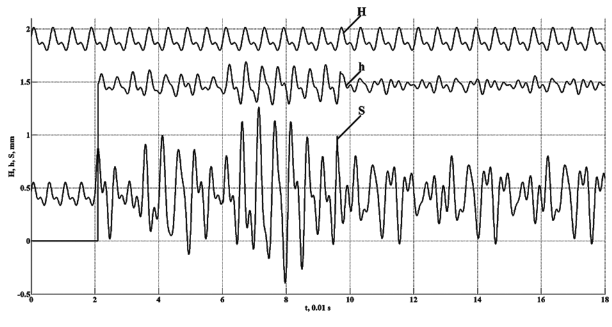

Fig. 10. Results of the ATCS operation modelling according to [14], if real HCDs with T = 0.01 s are applied

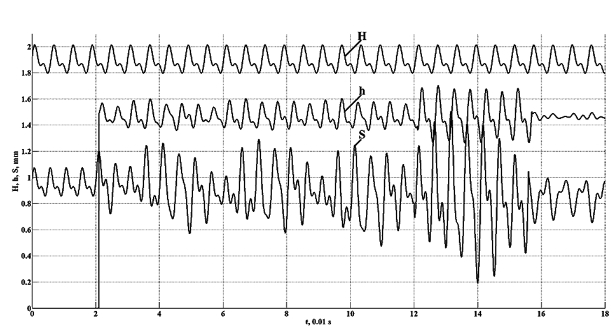

Fig. 11. Results of the improved ATCS modelling

roll gap with the specified amplitude and derivative phase. During this process, a temporary increase in the amplitude of thickness fluctuations of the rolled product is observed. This increase in amplitude should be regarded as random, caused by the incidental proximity of the phase of primary forced gap fluctuations to the eccentricity phase.

At the *15th* second of simulation, the system adjusts a phase of forced gap fluctuations, after which it transitions into the eccentricity compensation mode. As shown in Fig. 11, the rolled product thickness varies from $h = 1.436$ to $h = 1.496$ mm, with a thickness variation of $\Delta h = \pm 0.03$ mm.

Therefore, the use of the proposed improved ATCS allows for the reduction in thickness variation of the rolled product caused by the eccentricity of support and working rolls by nearly three times, achieving a level corresponding to that of high-precision rolling.

Further ATCS improvement should focus on the developing methods to reduce the time spent for filtering the thickness signal to extract the relevant variable components. This will help shorten the initial section of the rolled product that is affected adversely by eccentricity.

There is also a significant interest to the analysis of the ATCS functioning under varying rolling speeds.

Naturally, changes in the rotational speed of the rolls should not affect the actual eccentricity parameters. Therefore, if determination of these parameters is completed at a stable speed during the initial strip section rolling before a transition phase to the working speed begins, it is sufficient to switch from the generating forced gap fluctuations based on current time t to generating them basing on the rotation angle of rolls ωt. This will help avoid the impact of time delays in frequency measurement on control quality. Practical implementation of this measure poses no technical difficulties, as rolling mills are equipped with angle sensors.

However, due to changes in the rotational speed of rolls according to formula (2), parameter α may experience significant changes. Therefore, the system's performance of forced gap fluctuations in transitional modes caused by changes in rolling speed requires further investigation.

Conclusions.

1. A problem of increasing the accuracy of sheet metal thickness is particularly relevant for Ukraine, which has quite old rolling mills. The most economically justified and readily achievable direction for enhancing the competitiveness of their products is modernization of control systems that ensure the production of high-precision sheet metal.

2. Eccentricity of the mill rolls remains one of the main factors causing deviations in the vertical dimension (thickness) of sheet metal from the specified value.

3. The available automatic systems for compensating roll eccentricity, which perform out-of-phase adjustments to a roll gap relative to the eccentricity and use an active search algorithm to determine the actual eccentricity parameters, cannot ensure adequate accuracy due to the limited response speed of HCDs in rolling mills as executive mechanisms of ATCS.

4. Analytical study of the impact of HCD response speed has shown that in terms of thickness control according to the AGC algorithm, the ratio of thickness fluctuations amplitude caused by eccentricity to the amplitude of fluctuations in a roll gap decreases along with the increasing roll rotation frequency and time constant of HCD in a nearly linear manner.

5. Comparing the amplitudes of thickness variation in the rolled product at different HCD speeds helps identify the amplitude of roll gap fluctuations caused by the roll eccentricity. An improved procedure for real-time determination of the eccentricity amplitude is proposed, taking into account the actual HCD response speed, which involves a short-term reduction in HCD speed at the initial strip section segment.

6. A computer model has been developed to simulate formation of thickness variation in sheet rolling associated with roll eccentricity in the mill. This model includes the HCD model with the variable response speed and allows for adequate simulation of the operation of improved ATCS with sufficient accuracy to draw conclusions regarding its effectiveness.

7. The results of computer simulation of rolling with automatic thickness control using the AGC algorithm, without automatic compensation for the eccentricity of rolling and support rolls, indicate that in terms of Ukrainian rolling mills, it can produce rolled products with, at best, only standard accuracy.

8. The results of computer simulation of rolling using ATCS that implements the AGC algorithm and compensates for the eccentricity of working and support rolls without accounting for the limited response speed of HCD show that the thickness variation of rolled product decreases by only 40%. In the context of Ukrainian rolling mills, this guarantees only standard rolling accuracy, while the production of high-precision rolled products remains problematic.

9. The results of computer simulation demonstrate that the use of the proposed improved ATCS makes it possible to reduce thickness variation caused by the eccentricity of support and working rolls by nearly three times, achieving a level of ±0.03 mm, which corresponds to high-precision rolling.

References.

1. Prinz, K., Steinboeck, A., Müller, M., Ettl, A., Schausberger, F., & Kugi, A. (2019). Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill. *Journal of Manufacturing Science and Engineering*. https://doi.org/10.1115/1.4043575.

2. Kexin, Y., Gang, Z., & Zhe, Y. (2023). Roll Eccentricity Detection and Application Based on SFT and Regional DFT. *Nonlinear Model-Based Fault Detection for Industrial Applications*. https://doi.org/10.3390/s23167157.

3. Wehr, M., Stenger, D., Schatzler, S., Beyer, R., & Abel, D. (2020). Online Model Adaptation in Cold Rolling for Improvement of Thickness Precision. *21st IFAC World Congress. Berlin, Germany*, (pp. 12-17). https://doi.org/10.1016/j.ifacol.2020.12.2776.

4. Yang, X., Luo, H., Krueger, M., Ding, S.X., & Peng, K. (2016). Online Monitoring System Design for Roll Eccentricity in Rolling Mills. *IEEE Transactions on Industrial Electronics, 4*(63). https://doi.org/10.1109/TIE.2015.2442223.

5. Imanari, H., & Koshinuma, K. (2011). Roll Eccentricity Control Using Identified Eccentricity of Top/Bottom Rolls by Roll Force. *Transactions of the Society of Instrument and Control Engineers*, *46*, 525-531. https://doi.org/10.9746/sicetr.46.525.

6. Vuksanovic, B., & Bousbaine, A. (2013). Intelligent Control of Aluminium Rolling Mills Using Two Dimensional Adaptive Filters. *International Journal of Modeling and Optimization, 3*(5), 412-417. https://doi.org/10.7763/IJMO.2013.V3.310.

7. Gao, S., Xu, L., Li, Y., & Ji, J. (2022) Roll eccentricity extraction and compensation based on MPSO-WTD and ITD. *PLoS ONE, 17*(2). https://doi.org/10.1371/journal.pone.0259810.

8. Wehr, M., Stockert, S., Abel, D., & Hirt, G. (2018). Model predictive roll gap control in cold rolling with piezoelectric actuators. *IEEE Conference on Control Technology and Applications (CCTA)*. https://doi.org/10.1109/CCTA.2018.8511333.

9. Waleed, I. Hameed, & Khearia, A. Mohamad (2014). Strip Thickness Control of Cold Rolling Mill with Roll Eccentricity Compensation by Using Fuzzy Neural Network. *Engineering, 6*(1). https://doi.org/10.4236/eng.2014.61005.

10. Zheng, G., Ge, L.H., Shi, Y.Q., Li, Y., & Yang, Z. (2018). Dynamic rolling force prediction of reversible cold rolling mill based on bp neural network with improved pso. *In 2018 Chinese Automation Congress (CAC)*, IEEE. https://doi.org/10.1109/CAC.2018.8623139.

11. Wehr, M., Schätzler, S., Abel, D., & Hirt, G. (2020). Model Predictive Control of an Overactuated Roll Gap with a Moving Manipulated Variable. *2020 American Control Conference (ACC)*. https://doi.org/10.23919/ACC45564.2020.9147360.

12. Wehr, M., Stenger, D., Schätzler, S., Beyer, R., Abel, D., & Gerhard, H. (2020). Online Model Adaptation in Cold Rolling for Improvement of Thickness Precision. *IFAC-PapersOnLine, 53*(2), 10372-10379. https://doi.org/10.1016/j.ifacol.2020.12.2776.

13. Potap, O., Zinchenko, M., Rybalchenko, M., & Potap, M. (2018). Computer simulation of the automated system for compensating the eccentricity of rolling rolls. *System technologies, 2*(115), 75-83.

14. Potap, O., Zinchenko, M., Piven, V., & Potap, O. (2020). *The method of automatic adjustment of the strip thickness with compensation of the eccentricity of rolling rolls*. Patent UA No. 122616 C2.

15. Yang, Z., Liu, D., & Zheng, G. (2022). Roll Eccentricity Signal Detection and Its Engineering Application Based on SFFT-IAA. *Applied Sciences*, *12,* 8913. https://doi.org/10.3390/app12178913.
16. Prinz, K., Steinboeck, A., Müller, M., Ettl, A., Schausberger, F., & Kugi, A. (2019). Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill. *Journal of Manufacturing Science and Engineering,* *7*(141). https://doi.org/10.1115/1.4043575.
17. Potap, O., & Ivanichik, A. (2022). The accuracy of rolling thickness adjustment in conditions of high-frequency disturbances taking into account the speed of roll setting devices. *Fundamental and applied problems of ferrous metallurgy*, *36,* 299-307. https://doi.org/10.52150/2522-9117-2022-36-299-307.

Автоматична компенсація ексцентриситету прокатних валків за обмеженої швидкодії гідравлічних натискних пристроїв

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Мета. Зменшення відхилення вертикального розміру (товщини) листового прокату від заданого значення за рахунок підвищення точності та скорочення часу налаштування підсистеми компенсації ексцентриситету прокатних валків. Обґрунтування методу компенсації ексцентриситету, що базується на алгоритмі активного пошуку для винайдення дійсних параметрів ексцентриситету в режимі реального часу з урахуванням фактичної швидкодії гідравлічних натискних пристроїв (ГНП), та дослідження його ефективності шляхом імітаційного комп'ютерного моделювання.

Методика. Дослідження базувалися на аналітичному визначенні частотних характеристик AGC-системи листової прокатки, що враховує фактичну швидкодію ГНП прокатної кліті, та на створеній комплексній моделі процесу листової прокатки у кліті кварто з ГНП пересування валків і системою автоматичного регулювання товщини (САРТ) з компенсацією ексцентриситету. Дослідження здійснювали шляхом зіставлення результатів комп'ютерного імітаційного моделювання роботи удосконаленої САРТ, алгоритм якої враховував швидкодію ГНП, з показниками роботи попередньої системи, що її не враховувала.

Результати. Встановлено, що в умовах AGC-регулювання товщини прокату виміряна амплітуда змінної складової товщини не співпадає з амплітудою ексцентриситету через кінцеву швидкодію ГНП. Аналітично визначені частотні характеристики AGC-системи, що враховують фактичну швидкодію ГНП прокатної кліті. Обґрунтована удосконалена процедура визначення фактичної амплітуди ексцентриситету в реальному часі, що передбачає застосування короткочасного зменшення швидкості ГНП на початковій ділянці прокату. Запропонована структура автоматизованої системи управління для практичної реалізації зазначеної процедури. Доведено, що запропоновані рішення дозволяють утричі зменшити спричинену ексцентриситетом різнотовщинність прокату порівняно з відповідним показником роботи відомих систем компенсації ексцентриситету з AGC-регулюванням товщини прокату.

Наукова новизна. Установлено вплив швидкодії ГНП на точність AGC-систем регулювання товщини прокату. Виявлена наближена до лінійної залежність відношення амплітуди спричинених ексцентриситетом коливань товщини прокату до амплітуди коливань міжвалкового зазору від частоти обертання валків і швидкості ГНП в умовах регулювання товщини прокату за AGC-алгоритмом. Обґрунтована удосконалена процедура визначення фактичної амплітуди ексцентриситету в реальному часі.

Практична значимість. Полягає в обґрунтуванні ефективності впровадження удосконаленого активного пошукового алгоритму визначення параметрів ексцентриситету прокатних валків в умовах обмеженої швидкодії ГНП у режимі реального часу, який дозволяє втричі зменшити спричинену ексцентриситетом валків прокатної кліті кварто різнотовщинність прокату порівняно з відповідним показником роботи відомих систем AGC-регулювання товщини листового прокату й забезпечити виробництво прокату високої точності на листопрокатних станах України.

Ключові слова: *регулювання товщини прокату, AGC-алгоритм, ексцентриситет валків, гідравлічний натискний пристрій, імітаційне моделювання*

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