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**M. Kuzmenko[1],**
**orcid.org/0000-0002-1989-242X,**
**M. Rybalchenko[1], Cand. Sc. (Tech.),**
**orcid.org/0000-0001-5162-5201,**
**O. Boyko[2],**
**orcid.org/0000-0002-9714-2843,**
**D. Beshta[2],**
**orcid.org/0000-0003-2848-2737**

1 – National Metallurgical Academy of Ukraine, Dnipro, Ukraine, e-mail: km-app@ukr.net
2 – National Mining University, Dnipro, Ukraine

# ACTIVE CONTROL SYSTEM OF MILL PRODUCTS TENSION AT THE OUTLET OF ROUGHING TRAIN IN CONTINUOUS LIGHT-SECTION MILL

**Purpose.** To find the regularities that provide control of interstand force in the roughing train.

**Methodology.** The methodology for solving the problem of control of interstand forces in a roughing train is based on the estimation of the change in the controller output of deflection/loop tension of the rolled product, which will ensure the stability of the cross-sectional dimensions of the rolled product at the outlet of the roughing group.

**Findings.** The work deals with an issue of decreasing gage interference of bar section by controlling speed rate of rolling in a roughing train. A method for controlling the interstand force in the roughing train based on the analysis of a low-frequency component of disturbance which occurs during automatic stabilization of free deflection/loop in the finishing train is substantiated and tested. The proposed system of active control of rolling tension enables to stabilize the transverse dimensions of mill bar before the finishing train. The research results have shown that the ultimate objective function of interstand forces control in the roughing trains is to minimize the scattering of dimensions of the rolled product at the outlet of the roughing trains. Active regulation of the rolling tension for stabilizing the cross-sectional dimensions of the rolled product at the roughing train outlet is rationally carried out using program control for the rolling speed rate in the first interstand space of the finishing train.

**Originality.** General regularities that provide the interstand force identification through the change of the regulator outlet of the rolling deflection/loop were determined.

**Practical value.** The organization of interstand force control in the roughing train after the obtained dependencies allows stabilizing the cross-sectional dimensions of the rolled product in the finishing train.

**Keywords**: *interstand forces, regulator, rolling, tension*

**Introduction.** The issues of the interstand force impact on the continuous rolling process were reflected in the works by A. Chekmarev, V. N. Vydrin and many other authors [1]. Briefly summarizing the results of these studies, we can say that interstand forces ensure the equalization of the outlet and inlet speed rates of rolled products in adjacent mill stands and simultaneously cause a change in the cross-section dimensions of the rolled products at the outlet from the stands to which they are attached [2]. Therefore, one of the problems solved in the automation of continuous light-section mills is the stabilization of the rolling tension at the minimum acceptable level.

**Analysis of the recent research and publications.** For the finishing trains, the problem of stabilizing the minimum tension is effectively solved by adjusting the loop/free deflection of the rolled product between the mill stands (please refer to, e.g., [3]). At the same time, this problem has been partially solved for roughing trains. When rolling a billet in the roughing section mill group, there is a disorder of the constancy of volumes per second, which leads to significant changes in interstand forces [4]. This is caused by the cross-section fluctuations of the billet due to imperfect rolling technology, as well as its surface conditioning. Further, the change in lateral forces in the first mill stands of the roughing train using the forward creep leads to a disruption in the speed rate setting in the whole mill. Therefore, the importance of direct regulation of interstand forces in the roughing train is clear.

The most effective control action on the tension value is a purposive coordinated change in the rotational speed of the rolling engines along the strike (less often against the strike) of the rolling.

The information support of algorithms for automatic speed rate adjustment of rolling in the roughing train is determined, first of all, by the methods used to identify the interstand forces.

Among the known methods for interstand force identification, only the method based on load controlling of electric motors of rolling stands [5] was applied.

The preference of this method is confirmed by the studies given in [2, 6]. At the same time, it is noted in [6] that despite the simplicity of the practical implementation of the tension control system by changing the armature current of the rolling engine, the presence of technological disturbances, primarily the spread of the cross-sectional dimensions of the billets and the uneven heating of the billets along its length, significantly reduce the accuracy and effectiveness regulation of interstand forces in the roughing train. The given research studies are confirmed experimentally by the analysis of received oscillograms of armature currents in the rolling engines of 6th and 7$^{th}$ stands of the roughing train of light-section mill 250-6 of "ArcelorMittal Kryvyi Rih" PJSC. Herewith, it is noted that temperature fluctuations along the billet length of the billet could reach 60–70 °C, which in turn were coming out in low-frequency oscillations of the rolling torques and armature currents. The filtration application was not successful, since the filters are very inertial and this factor significantly degrades the quality of regulation. The tension control systems with time restriction for regulation of the armature current in the rolling engine during the filling of the continuous mill with rolled product are also given in the work [6]. However, the working capacity of the described technical solution is entirely based on the assumption that the ratio of the armature current of the second mill stand (free rolling current) to the armature current of the first stand, when a billet enters it, is constant, and this fact requires further study and research. A modified method for identifying interstand forces in the static load of the electric engines of the stands was proposed in [7].

An unconditional novelty of this work is the transition of the objective function of stabilization of the interstand forces to the objective function of minimizing the scattering of rolled products dimensions at the outlet of the roughing train; however, there is no method for estimating such scattering in the study. At the same time, studies of perturbations of the rolling speed rate with automatic stabilization of the free deflection showed the presence of a low-frequency component of the perturbation. It is caused by the congenital variability of rolled products, which is a consequence of its rolling with tension in the roughing train [2].

**The objective** of the article is to show the capabilities of using the interstand force controlling method in roughing train based on the analysis of low-frequency component of the disturbance occurring at the automatic stabilization of free deflection/loop in the finishing train.

**Description of the research methodology.** The object of the study is the roughing train of six mill stands (rolling in this train is carried out with a speed rate that is set by the specified operator) and the first stand of a finishing or intermediate train (preliminary to it, rolling is carried out with automatic stabilization of free deflection/loop of rolling in the face of the stand). The structural diagram of the research object is shown in Fig. 1. The electric drive motor (*ED*) of the rolling stand is equipped with an automatic control system of the speed (*ASCS*), which is given a speed of rotation from the driver, which takes into account the matching factor ($K_n$) of the rotation speed of each stand. The loop/deflection sensor (*DS*) of the rolling mill provides control over the size of the loop/deflection under the conditions of changing the speed of the drives under the influence of the signal from the tension regulator (*RT*).

The development of new algorithms and control systems for a multiply connected process for the production of section mill products on continuous mills inevitably faces the need for experimental verification of their

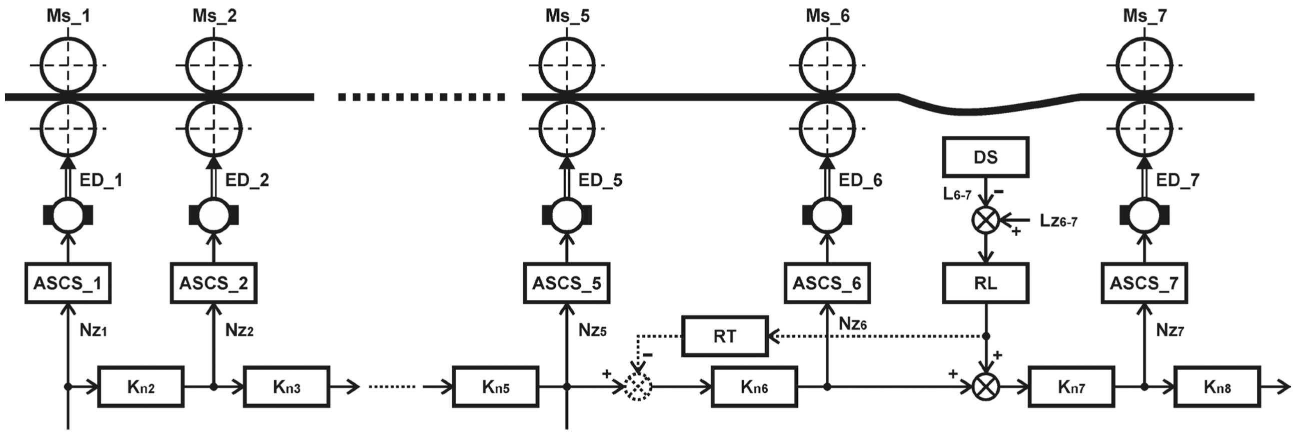


*Fig. 1. Structural diagram of the control system of the roughing trains and the first stand of the finishing train:*

*Ms_# – mill stand number #; ED_# – electric motor of rolling stand number #; ASCS_# – automatic speed control system of rolling stand number #; DS – loop/deflection sensor for rolled products; RL – regulator of the loop/deflection of rolled products; RT – the regulator of a rolling tension;* $N_{z\#}$ *– setting the rotation speed of the stand number #;* $L_{6\text{-}7}$ *– the actual length of rolled product between the roughing and finishing trains (stands six and seven);* $Lz_{6\text{-}7}$ *– the set length of rolling product between roughing and finishing trains (stands six and seven);* $K_{n\#}$ *– coefficient of matching the speed of rotation of the stand number #*

operability and comparative analysis with known systems in terms of accuracy, speed of operation, frequency characteristics, and others [6]. The most precise method for estimating the effect of changing the tension mode in the rolling process on the geometric parameters of the finished rolled product would involve carrying out experimental studies, but it is difficult to measure the length and cross-sectional area of the rolled product after the last mill stand accurately, and much less the rolling tension in the roughing train. The most effective method for obtaining an answer to these questions under the described conditions is a computer modelling of the designed systems operation. For this purpose, a mathematical model has been developed. It takes into account the majority of processing factors affecting the technological process of rolling and using known dependencies, including changes in the billet parameters.

The technological model of the control object – the process of single-continuous rolling was taken in accordance with studies [6]. It includes a number of typed blocks that simulate geometric, kinematic and power-force parameters of rolling in stands, the state of metal in the interstand spaces, the work of the main electric drives in rolling stands, and also the billet parameters [2].

The structure of the numerical scheme of the one-stand continuous rolling process in the roughing train is shown in Fig. 2.

Geometric dimensions (width $b_{0i}$ and height $h_{0i}$), temperature $T_{0i}$ of a semi-finished rolled stocks, the front $\sigma_{i,\,i+1}$ and back $\sigma_{i-1,\,i}$ tension, as well as the speed of the rolling engine $n_i$ and the roll space $z_i$ are the input variables of each Msi unit which simulates the process of metal deformation in the stand. The output variables of the Msi unit include the geometric dimensions (width $b_{1i}$ and height $h_{1i}$) and the mill product temperature $T_{1i}$ on the exit from the stand, the metal speed rates at the entrance $V_{0i}$ and on the exit $V_{1i}$ of the stand, the force $P_i$ and the rolling torque $M_i$.

A gear reduction rate $j_i$, a roll radius and a modulus $R_i$ of a stand rigidity $M_{Ki}$ were set as the constant parameters of the Msi block.

The analysis of interstand forces in the described model (Fig. 2) is carried out in the $R_{mi,\,i+1}$ blocks, which simulate the metal condition in the spaces between stands. The input variables of these blocks are the speed $V_{1i}$, geometric dimensions $b_{1i}$ and $h_{1i}$, the mill product temperature $T_{1i}$ on the exit of the previous stand, and also the speed $V_{0i+1}$ of rolling at the entrance to the next stand.

The output parameters of the $R_{mi,\,i+1}$ blocks include the specific tension $\sigma_{i,\,i+1}$, the temperature $T_{0i+1}$ and the geometrical dimensions $b_{0i+1}$ and $h_{0i+1}$ of the mill product at the entrance to the next stand. In this case, the parameters of the geometric dimensions of the mill product at the entrance to the next stand repeat the parameters at the exit from the previous one with a transport delay, which corresponds to the time of the metal moving through the interstand space.

The work of the main electric drives of the rolling stands is simulated in the $E_{di}$ blocks. The current rolling speed rate of the rolling engine is formed at the output of these blocks. Here the input variables are the set rates $n_i^*$ of the engine speed and the resistance torque of on the motor shaft, which is the torque of rolling in this stand.

The scheme of the main electric drive of the rolling stand [8], which is a direct current electric motor, whose shaft is connected to the rolling rolls via a reducer and a gear stand, as well as a power thyristor converter TC (Fig. 3) are shown in Fig. 4.

Thus, the engine is a single-loop system, in the direct circuit of which two series-connected links (aperiodic and integrating) are covered by back coupling through a proportional link with a transition factor (coefficient) c. The converter voltage US is a control action, and the torque of resistance MC (or IC) is a perturbation action.

By applying this model we:

- carry out a simulation of the rolling process simultaneously in all stands of the roughing and the first finishing stand of the mill;
- consider the effect of technological perturbations coming from the changes in the cross-sectional dimensions and the temperature of the billet along its length;
- consider the effect of dynamic modes of the main electric drive operation of rolling stands on interstand forces.

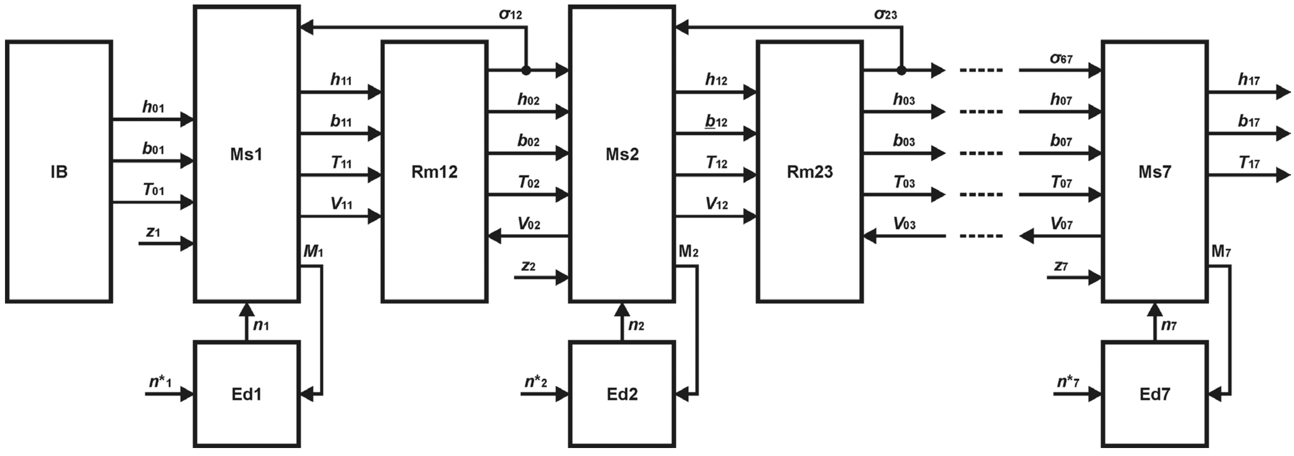


*Fig. 2. The structure of the numerical scheme of the one-stand continuous rolling process in the roughing train*

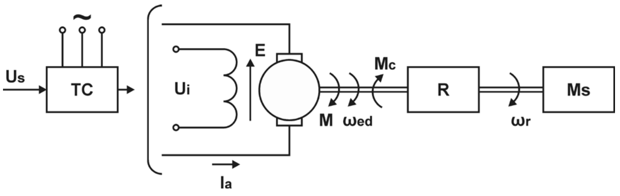


*Fig. 3. The scheme of the main electric drive:*

*TC – thyristor converter; R – reducer; Ms – rolling mill stand*

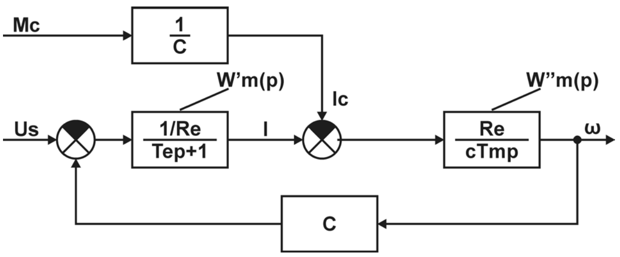


*Fig. 4. Structural diagram of the DC motor during acting on the armature voltage:*

*Te – electromagnetic time constant; Tm – electromechanical time constant; c – constructive constant; Re – active equivalent resistance of the armature circuit; ω – speed of rotation*

The effect of the variable temperature of the metal on the elasticity modulus of the section bar material was taken into account while calculating interstand forces.

The designed model allows analyzing the joint action of electric drives of vertical and horizontal rolls of a rolling stand, assessing their mutual influence on the rolling speed regime and is used in the study of advanced control algorithms.

The problem of mathematical models adequacy, which are multiply connected and have significant probabilistic nature of objects, which include continuous mills, cannot be solved by classical methods because of the extreme situation of difficult setting up of active (and even passive) experiments on similar objects, and also because the considerable part of these parameters cannot be measured [2]. The model adequacy was conducted by comparing the qualitative and quantitative effects of the mutual influence of different models with the parameters, whose presence is established in practice and confirmed by the experiment of production operation of the automation object.

The analysis of the results obtained during the simulation of the light-section mill shows that the geometric (width, compression, rolling-out), kinematic (speed gain, rolling speed) and energy (rolling torque) parameters corresponded to the rates observed in practice.

To these effects must be referred the following:

- the propagation of the interstand forces along the mill from the interstand space which is more pronounced in the rolling direction than in the direction opposite to the rolling strike;

- the “ski like” nature of the change in the horizontal dimension of the rolled product at the exit from the finishing stand, due to the lack of front tension during the filling of the mill and the back tension during its release by a billet with a large increase in thickness at the rear end of the roll as a result of a stronger effect of the back tension;

- smoothing of temperature disturbances along the length of a billet as it moves away from the entrance of the mill and to the exit from it, and so forth;

- logically explained changes in the interstand forces and the cross-section dimensions of the mill product when the adjacent billet appears and disappears in the next rolling line.

According to the authors, these effects clearly show the model adequacy to the real object and allow us to state that the created dynamic model of the roughing and finishing trains describes the rolling process in a light-section mill with sufficient accuracy.

The results of the studies performed using this model are given below.

We point out that a non-linear connection between the length of the rolled product and its tension in the interstand space was considered in this model

$$L_{i,i+1}(\tau) = L_{i,i+1}(0) + \int_0^{\tau} \left(V_{1i} - V_{0i+1}\right) dt; \qquad (1)$$

$$T_{i,i+1}(\tau) = \begin{cases} \dfrac{2 \cdot E_Y}{Q_{1i} + Q_{0i+1}} \cdot \left(1 - \dfrac{L_{i,i+1}(\tau)}{L_{0i,i+1}}\right) & \text{if } L_{i,i+1}(\tau) < L_{0i,i+1} \\ 0 \quad \text{if } L_{i,i+1}(\tau) \geq L_{0i,i+1} \end{cases}, \qquad (2)$$

where $L_{i,\,i+1}(\tau)$ is a mill product length between the $i$ and $i+1$ stands at time $\tau$; $L_{i,\,i+1}(0)$ is a mill product length between the $i$ and $i+1$ stands at the initial moment of time; $V_{1i}$ is a linear rolling speed at the output of the $i$ stand; $V_{0i+1}$ is a linear rolling speed at the input $i+1$ stand; $T_{i,\,i+1}(\tau)$ is a rolling tension between the $i$ and $i+1$ stands at time $\tau$; $L_{0i,\,i+1}$ is the distance between the axes of the $i$ and $i+1$ stands; $Q_{1i}$, $Q_{0i+1}$ are the cross-sectional areas of the mill product at the output of the $i$ stand and at the entrance to the $i+1$ stand, $E_Y$ is the Young's modulus.

**Presentation of the main research.** Continuous light-section mills are the main production lines for producing section mill products at metallurgical plants. They are characterized by high power of working stand drives, high rolling speeds, high level of automation of basic technological operations. The technology and equipment of these mills are improved on a continuous basis, their automation level increases, and maintenance also improves [1].

The main criterion determining the competitiveness of products is the quality provided by minimizing the scattering of the cross section and increasing the output measure. Rolling tension affects not only the rolling speed mode but also its geometric parameters. When rolling on high-grade mills, the geometric parameters of the section (height and width) can change due to the elastic deformation of the stand constructions and the rolling tension. The change in the elastic deformation of the stand is connected with a change in the rolling force due to a change in the deformation conditions (change in the thickness of a semi-finished rolled stocks, the temperature of the mill product, and tension). The main disturbance in the tension regulation is the mismatch of the speeds of rolls rotation in the adjacent stands.

The rolling condition in the interstand spaces of continuous light-section mill is determined by the relative or absolute speed differential of the rolled product at the exit from the previous stand and entering the next space in the stand [9]. Any change in the rolling speed in any of the stands from the gap, which results from various technological disturbances, leads to a deviation from the initial rolling mode in this interval. As we have seen, resolving this kind of deviation is achieved, by purposive rotation speed correction of the rolls in one of the stands. Naturally, in this case, the speed mode is violated in the adjacent interstand gap, which activates the tension control loop or loops in it, and then in the subsequent ones. In other words, we can talk about the transfer of a disturbance from one space to another and its spread throughout the stand.

The most effective control action on the tension value is a purposive coordinated change in the rotational speed of the rolling engines along the strike(less often against the strike) of the rolling.

The way out is to change the speed of all subsequent (or all previous) stands, simultaneously changing the speed of rotation of one of the stands of a continuous group. In this case, we should consider the consistent change in the roll rotational speed as a change which will provide the invariance of both absolute and relative mismatches of rolling speeds in each of the spaces.

Initially, the standard rolling mode was simulated without automatic tension control in the last interstand space of the roughing train. In practice, the coefficients of matching the rotation speed of the stands were chosen to make the minimum mismatch of the velocities for the interstand space be equal 1 ÷ 1.5 % in relation to the rolling speed mode corresponding to no pull. It provides the stability of the continuous rolling mode in the roughing train during uncontrolled perturbations. Harmonic oscillations of the vertical and horizontal dimensions of the billet (with amplitude of 0.5 mm and frequency of 5 $s^{-1}$) and a linear change in the temperature of the billet (from 1100 to 1060 °C) were used as technological disturbances.

Rolling with a loop or a deflection (small controlled tension) is the best technological mode, since it provides the stability of the geometric parameters of the rolled product along the entire length. Perturbing effects in the loop control circuit have a high-frequency component caused by dynamic processes in the circuit itself and a low-frequency component associated with a change in the compression mode from the front rolling section to the back section in the first finishing stand. The high-frequency components of the disturbance are suppressed by the proportional part of the regulator, and the low-frequency components by the integral part. Therefore, the output signal of the loop regulator can be used for the tension control system in the last interstand space of the roughing train with the aim of equalizing the broadening along the length of the mill product.

Fig. 5 shows the diagram of the output of the deflection/loop regulator (*a*) and the diagram of the change in the width of the rolled product at the output of the seventh stand (*b*). As you can see from the diagram, these curves in the mirror-image presentation are almost identical. Statistical processing of the results showed that the correlation coefficient between the rolled product at the outlet of the seventh stand and the outlet of the deflection/loop regulator is 0.88, which makes it possible to estimate the rolled product diversity at the outlet of the roughing train from the change in the outlet of the rolling deflection/loop regulator.

Then, as an objective function of adjusting the rolling tension in the roughing train, the amplitude of the variable component of the output of the first deflection/loop regulator can be minimized.

Regulation of the size of the rolled product at the outlet of the roughing train can be achieved by adjusting the tension of the rolled product in the interstand spaces of the train. It make sense for the roughing train to carry out such adjustment by changing the rolling speed mode in the last interstand space, in our case by mismatching the rotation speed of the fifth and sixth stands, depending on the change in the output signal of the deflection/loop regulator before the sixth stand.

In this case, the delay time in the control channel is minimized, and the control itself does not bring any noticeable perturbations into the rolling speed mode in the remaining interstand spaces of the train.

The linear structural scheme of an active control of rolling tension is presented in Fig. 6.

From this it follows that the correlation between the mismatch of the rolling speed mode in advance of stand

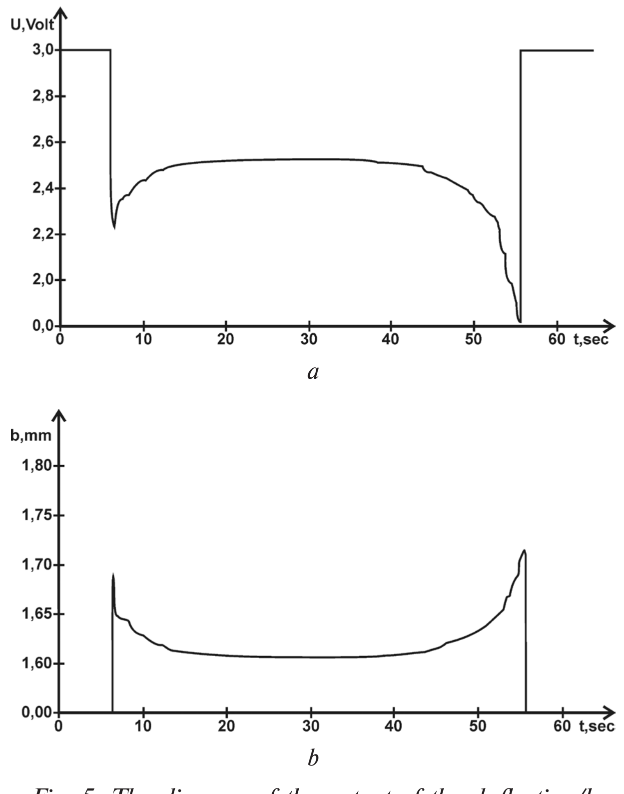


*Fig. 5. The diagram of the output of the deflection/loop regulator (a) and the diagram of the change in the width of the rolled product at the output of the seventh stand (b)*



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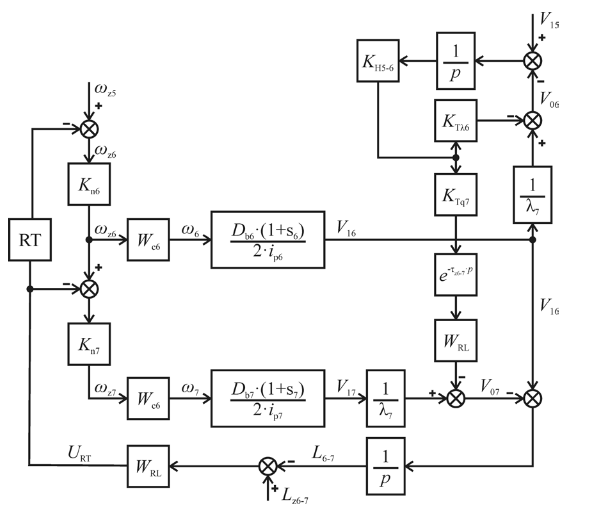


*Fig. 6. The linear structural scheme of an active control of rolling tension:*

*$W_{c6}$, $W_{c7}$ – transfer-function coefficient of closed speed control loops of stands No. 6 and No. 7 ; $i_{p6}$, $i_{p7}$ – transfer ratios of gear systems of stands No. 6 and No. 7; $D_{b6}$, $D_{b7}$ – diameters of rolls in stands No. 6 and No. 7; $s_6$, $s_7$, $\lambda_6$, $\lambda_7$ – lead factors (s) and drawing-out ($\lambda$) of a rolled product in the rolls of stands No. 6 and No. 7; $K_{H5-6}$ – the coefficient of influence of the mismatch of the speed mode on the tension (see (1.2)) for the interstand space in advance of stand No. 6; $K_{T\lambda 6}$, $K_{Tq6}$ – the coefficient of influence of tension in advance of stand No. 6 on the drawing-out coefficient of the rolled product in stand No. 6 and the dimensions of the output product in stand No. 6; $K_{q7}$ – the coefficient of influence of the change in the cross-section dimensions at the entrance to the stand No. 7 on the coefficient of drawing-out of rolled products in the rolls of the stand No. 7; $\tau_{z6-7}$ – coefficient of transport lag of rolling product movement between rolls of stands No. 6 and No. 7; $K_{n6}$, $K_{n7}$ – coefficients of matching the speeds of stands No. 6 and No. 7; $W_{RL}$ – transfer-function coefficient of the rolling deflection/loop regulator in advance of stand No. 7; RT – the tension regulator of a rolling product between stands No. 5 and No. 6*

No. 6 and the drawing-out rolled products in stand No. 7 depends on a number of technological parameters, such as the coefficient of influence of the mismatch of the speed regime on the tension, the influence coefficient of the tension in advance of a stand on the rolling ratio in the stand, the coefficient of influence of the tension in advance of the stand on the dimensions of the rolled product at the outlet from the stand, the influence coefficient of the change in the cross-section dimensions of the rolled product at the entrance to the stand to the drawing-out coefficient of a rolled product in the rolls of the stand, which, in turn, depend on the current rolling conditions.

In addition, the control object contains a transport lag link with a lag time $\tau_{z6-7}$ of which is defined as

$$\tau_{z6-7} \approx \frac{L_{z6-7}}{V_{16}}.$$

The delay time is equal to a few seconds, which is commeasurable with the time of passage of the rolling sections between stands No. 6 and No. 7, and, in general, is technologically dependent and not constant. There is a concern of the problem of the dynamics of the rolling tension regulation in these stands.

The implementation of the proposed method of active control of a rolled product tension in the last interstand space of the roughing train is achieved by introducing a tension regulator connected to the circuit elements into the existing control system, as shown using dashed lines in Fig. 1.

Considering the foregoing, it makes sense to implement the tension regulator in the proposed system as an adaptive block of hotfixe (program correction) of the rolling tension in advance of the ninth stand. The output signal is stored at the front and back sections of the rolled product during rolling the test billet. During subsequent rolling, the rotation speed of the sixth stand of the roughing train varies programmatically in order to eliminate the diversity of rolled products [10]. The intensity of rolls acceleration and braking in rolling stands during the filling of the mill and completion of rolling process is adjusted after each rolling. The criterion for the correct adjustment is the absence of trending in the signal of the loop regulator between the eighth and ninth stands at the beginning and at the end of the mill product.

The results of simulation of the operation of the system are shown in Figs. 7, 8.

As we can see from the diagram (curve *2*), there is practically no change in the width of the rolled product with the software control system.

Since the cross-sectional area of the rolled product at the output of the seventh stand of the finishing group remains almost unchanged (curve *2* in Fig. 8), the roll-

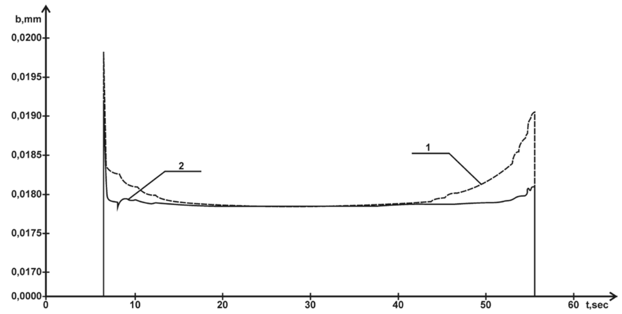


*Fig. 7. Results of the simulation of the active tension control system:*

*1 – without the control system; 2 – with the system of programmed rolling tension regulation*

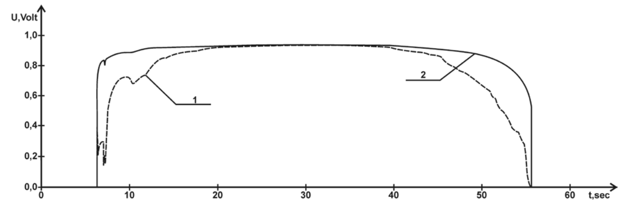


*Fig. 8. The diagram of the output signal of the loop regulator:*

*1 – without the control system; 2 – with the system of programmed rolling tension regulation* ing speed mode after the eighth stand (the output of the deflection/loop regulator – curve *2* in Fig. 7).

Thus, the proposed system of active rolling tension regulation provides the stabilization of the cross-sectional dimensions of the rolled product at the output of the eighth stand of the finishing train.

**Conclusions.**

1. The ultimate objective function of interstand forces control in the roughing trains is to minimize the scattering in the size of the rolled product at the outlet of the roughing trains.

2. The stability of the cross-sectional dimensions of the rolled product at the outlet of the roughing train can be estimated by the change of the regulator outlet of the rolling deflection/loop.

3. Active regulation of the rolling tension for stabilizing the cross-sectional dimensions of the rolled product at the roughing train outlet is rationally carried out using program control for the rolling speed rate in the first interstand space of the finishing train.

4. The proposed system of active control of rolling tension enables to stabilize the cross-section dimensions of rolling product in the finishing train.

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**Reference.**

**1.** Kuvaiev, V.M. and Beshta, D.O., 2017. Dynamic model of interaction of mechanisms on the section between the roll mill stand and the coiler in the process of wire winding by Garrett reel. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 4, pp. 61–66.

**2.** Egorov, A.P., Zvorykin, V.B., Mikhalev, A.I. and Kuzmenko, M.Yu., 2016. Modeling of multiply connected control systems for high-speed rolling mode on a continuous light-section mill. *Systemni tekhnolohiyi. Rehional'nyy mizhvuzivs'kyy zbirnyk naukovykh prats'*, 5(106), pp. 36–44.

**3.** Andryushin, I.Yu., Shubin, A.G. and Gostev, A.N., 2014. Development of mathematical model for interrelated electrical and mechanical systems of rolling mill roughing train. *Teoriya i praktika avtomatizirovannogo elektroprivoda*, 3(24), pp. 24–31.

**4.** Karandaev, A.S., Khramshin, V.R., Radionov, A.A., Andryushin, I.Yu., Galkin, V.V. and Gostev, A.N., 2013. Coordination of rolling stand electric drive speed of continuous train of rolling mill, *Vestnik IGEU*, 1, pp. 98–103.

**5.** Shubin, A.G., Gostev, A.N., Khramshin, R.R. and Odintsov, K.E., 2015. System of interstand tension compensation in roughing train of rolling mill research using mathematical modeling method. *Teoriya i praktika avtomatizirovannogo elektroprivoda*, 4(29), pp. 10–21.

**6.** Beshta, A.C., Kuvaev, V.N., Potap, O.E. and Egorov, A.P., 2014. Automation of technological processes on light-section rolling mills: monograph. Dnepropetrovsk: Zhurfond.

**7.** Kuvaev, V.N., 2010. Identification of interstand efforts at continuous rolling on static loading moment of stand's electric drives. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu* [online], 7–8, pp. 77–81. Available at: http://nvngu.in.ua/index.php/ru/arkhiv-zhurnala/po-vypuskam/637-/soderzhanie-7-8/elektrotekhnicheskie-kompleksy-i-sistemy/1763-identifikatsiya-mezhkletevykh-usilij-pri-nepreryvnoj-prokatke-po-staticheskomu-momentu-nagruzki-elektroprivodov-kletej [Accessed 5 May 2017].

**8.** Shokhin, V.V., Khramshin, V.R. and Nowicki, R.Yu., 2017. Mathematical Simulation of Roughing Electric Drives of 450 Bar and Shape Mill Mounted at Arch-Furnace Plant of Magnitogorsk Iron and Steel Works, OJSC. *Bulletin of the South Ural State University. Ser. Power Engineering*, 17(2), pp. 58–66. DOI: 10.14529/power170208.

**9.** Aleinikova, A.A. and Deryuzhkova, N.E., 2015. Mathematical model of two adjacent stands of a wire mill during rolling with loop formation. In: *Materials of the 45th scientific and technical conference of students and graduate students, April 1–14, 2015, Komsomolsk-on-Amur*, pp. 17–20. Available at: <https://knastu.ru/media/files/page_files/page_1425/SBORNIK_GOTOVYY.pdf> [Accessed 14 May 2017].

**10.** Beshta, O., Nolle, E. and Kuvaiev, M., 2016. Entwurf einer einfachen und modifizierten Rastmomentkompensation für die permanenterregte Synchronmaschine. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 6(156), pp. 95–100.

## Система активного регулювання натягу прокату на виході чорнової групи клітей безперервного дрібносортного стану

*М. Ю. Кузьменко*[1], *М. О. Рибальченко*[1], *О. О. Бойко*[2], *Д. О. Бешта*[2]

1 – Національна металургійна академія України, м. Дніпро, Україна, e-mail: km-app@ukr.net

2 – Державний вищий навчальний заклад „Національний гірничий університет“, м. Дніпро, Україна

**Мета.** Знаходження закономірностей, що забезпечують управління міжклітьовими зусиллями у чорновій групі клітей.

**Методика.** Методика вирішення завдання управління міжклітьовими зусиллями у чорновій групі ґрунтується на оцінці по зміні вихідного сигналу регулятора прогину/петлі прокату величини натягу прокату, що забезпечить стабільність поперечних розмірів прокату на виході чорнової групи.

**Результати.** У роботі розглянуте питання зниження різноширинності сортового прокату шляхом керування швидкісним режимом прокатки у чорновій групі клітей. Проведене обґрунтування й перевірка методу регулювання міжклітьових зусиль у чорновій групі клітей на основі аналізу низькочастотної складової збурювання, що має місце при автоматичній стабілізації вільного прогину/петлі у чистовій групі клітей. Запропонована система активного регулювання натягу прокату дозволяє стабілізувати поперечні розміри прокату перед чистовою групою клітей. Результати досліджень показали, що кінцевою цільовою функцією управління міжклітьовими зусиллями у чорновій групі клітей є мінімізація розкиду розмірів прокату на виході чорнової групи клітей. Активне регулювання натягу прокату для стабілізації поперечних розмірів прокату на виході чорнової групи раціонально здійснювати шляхом програмного регулювання швидкісного режиму прокатки в першому міжклітьовому проміжку чистової групи клітей.

**Наукова новизна.** Полягає у встановленні загальних закономірностей, що забезпечують ідентифікацію міжклітьових зусиль по зміні вихідного сигналу регулятора прогину/петлі прокату.

**Практична значимість.** Полягає в тому, що організація управління міжклітьовими зусиллями у чорновій групі за отриманими залежностями дозволяє стабілізувати поперечні розміри прокату у чистовій групі клітей.

**Ключові слова:** *міжклітьові зусилля, регулятор, прокатка, натяг*

## Система активного регулирования натяжения проката на выходе черновой группы клетей непрерывного мелкосортного стана

*М. Ю. Кузьменко*[1]*, М. А. Рыбальченко*[1]*, О. А. Бойко*[2]*, Д. А. Бешта*[2]

1 – Национальная металлургическая академия Украины, г. Днепр, Украина, e-mail: km-app@ukr.net

2 – Государственное высшее учебное заведение „Национальный горный университет“, г. Днепр, Украина

**Цель.** Нахождение закономерностей, обеспечивающих управление межклетьевыми усилиями в черновой группе клетей.

**Методика.** Методика решения задачи управления межклетьевыми усилиями в черновой группе основывается на оценке по изменению выходного сигнала регулятора прогиба/петли проката величины натяжения проката, которая обеспечит стабильность поперечных размеров проката на выходе черновой группы.

**Результаты.** В работе рассмотрен вопрос снижения разноширинности сортового проката путем управления скоростным режимом прокатки в черновой группе клетей. Проведено обоснование и проверка метода регулирования межклетьевых усилий в черновой группе клетей на основе анализа низкочастотной составляющей возмущения, имеющего место при автоматической стабилизации свободного прогиба/петли в чистовой группе клетей. Предложенная система активного регулирования натяжения проката позволяет стабилизировать поперечные размеры проката перед чистовой группой клетей. Результаты исследований показали, что конечной целевой функцией управления межклетьевыми усилиями в черновой группе клетей является минимизация разброса размеров проката на выходе черновой группы клетей. Активное регулирование натяжения проката для стабилизации поперечных размеров проката на выходе черновой группы рационально осуществлять путем программного регулирования скоростного режима прокатки в первом межклетьевом промежутке чистовой группы клетей.

**Научная новизна.** Заключается в установлении общих закономерностей, обеспечивающих идентификацию межклетьевых усилий по изменению выходного сигнала регулятора прогиба/петли проката.

**Практическая значимость.** Заключается в том, что организация управления межклетьевыми усилиями в черновой группе по полученным зависимостям позволяет стабилизировать поперечные размеры проката в чистовой группе клетей.

**Ключевые слова:** *межклетьевые усилия, регулятор, прокатка, натяжение*

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