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Mathematical model of rolling dynamics when filling finishing train of wide-strip mill with strip

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Abstract
The mathematical model of dynamics interaction between the stands of a continuous group of a wide-strip mill at the moment when it is filled (bitten) with the strip has been developed. The model consists of equations with absolute values of torsional oscillations in the main drive, electric motor, elastic oscillations of the stand, interstand tensions, transport-velocity lag, strip thickness deviation. Interstand tension character and values at the moment the 6-stand train is filled with the strip, which are not directly measured on the mills, are determined through computer modelling.
For the first time the importance of torsional oscillations is demonstrated. If the torsional oscillations are not taken into account the estimated values of the tension and strip thickness deviation at the exit are reduced to 30 %. The model is designed to study how the technical and structural disturbances and factors influence on the tension and the rolled stock thickness, to determine the maximum dynamic loads in the strip and equipment, as well as to calculate and set up the strain-velocity modes of continuous trains.
Key words: STRIP ROLLING MILL, MATHEMATICAL MODEL, DYNAMICS, ROLLING, FILLING, INTERSTAND TENSIONS, THICKNESS DEVIATION

Issue status.

Interaction of a continuous train of hot rolling wide-strip mill through a rolled strip was investigated in [1 ... 3], under the certain restrictions consisted of the following. Only the steady state rolling with the task of a number of disturbances was considered.

A mathematical model presented as a system of equations written in deviations was used. The torsional oscillations in the principle lines of the mill stands were not taken into account. Despite the recording of transportation lag equations, the role and influence of the latter on the process have not been assessed.

Filling the continuous group with strip is accompanied by biting the strip by rolls of each stand, intense torsional oscillations and the formation of the interstand tensions. Known linearized models cannot be applied here due to substantial disturbances.

In connection with this the set up problem the mathematical model of sequential filling of continuous n-stand group with strip was developed to study the dynamics of the initial phase of the stresses formation, which during this period is not measured, their dependences on a number of disturbances and the influence of the latter on the longitudinal gage interference of rolled products. The model is based on the previously developed and tested model of interaction between two roughing stands. [4]

The method of solving the problem is to make a system of differential equations in the absolute values and to obtain the numerical implementations of transient processes, especially in moments of elastic forces in the stands, the interstand tension and thickness of the finished strip depending on the technological disturbances.

The system of equations describing the transient processes generally consists of known kinematic equations and ratios.

1. The equations of torsional oscillations of three-mass in-line system connected to the rolls of the main drive:

$$\ddot{M}_{12} + 2n_{12}\dot{M}_{12} + \beta_{12}^2 \cdot M_{12} - \frac{C_{12}}{Q_2} M_{23} = \frac{C_{12}}{Q_1} M\partial \quad (1)$$

$$\ddot{M}_{23} + 2n_{23}\dot{M}_{23} + \beta_{23}^2 \cdot M_{23} - \frac{C_{23}}{Q_2} M_{12} - \frac{C_{23}}{Q_3} M = 0 \quad .(2)$$

Here $\ddot{M}_{12}$, $\ddot{M}_{23}$ – moments of elastic forces of the elastic constraint; C and Q – system parameters; n – damping coefficient; M_m – moment on the shaft of the electric motor; M – moment of technological resistance forces (of rolling).

2. The equation of the stand elastic oscillations adopted as single-mass m computational scheme:

$$\ddot{x} + 2k \cdot \dot{x} + \frac{C_c}{m} x = \frac{1}{m} P \quad , \quad (3)$$

where x – stand deformation; k – damping coefficient; C_s – stiffness (modulus) of the stand; P - rolling force.

3. Front T_f and back T_b tension:

$$\dot{T}_f = \frac{C_f}{L}\left(V_{in_{i+1}} - V_{out_i}\right), \quad (4)$$

$$\dot{T}_b = \frac{C_b}{L}\left(V_{in_i} - V_{out_{i-1}}\right) , \quad (5)$$

where C_f и C_b – stiffness of the strip in the longitudinal direction in front or behind of the stand calculated by a known formula.

4. Equations of the DC (AC) electric motor are well known, however we are restricted by the fact that as a result of their solutions in association with other equations the moment M_m is obtained. It is developed by the motor when biting and rolling of the strip, and the angular velocity ω_m of the rotor rotation.

The following equations are the actual final kinematic relations solved together with equations according to paragraphs 1 - 4.

5. On the input of the next i-th stand is set the thickness

$$H_{o,i}(t) = H_{1,i-1}(t - \tau_{i-1}) , \quad (6)$$

where, the transportation lag time (transfer the strip thickness deviation in the following stand at a distance $L_{i,\ i-1}$), as in [1 ... 3] is taken equal to $\tau_{i-1} = L_{i,i-1} / V_{out(i-1)}$.

6. Specific pressure p of the rolling is calculated from the known formulas of A. I. Tselikov [5], or by using the solutions for harmonic functions [6].

Tselikov formulas for flacking zone

$$p_x = \frac{2k}{\delta_0}\left[(\zeta_0\delta_0 - 1)\left(\frac{h_0}{h_x}\right)^{\delta_0} + 1\right], \quad (7)$$

and forward flow

$$p_x = \frac{2k}{\delta_1}\left[(\zeta_1\delta_1 + 1)\left(\frac{h_x}{h_1}\right)^{\delta_1} - 1\right], \quad (8)$$

where

$$\delta_0 = \frac{\mu}{tg\dfrac{\alpha+\gamma}{2}}; \qquad \delta_1 = \frac{\mu}{tg\dfrac{\gamma}{2}}.$$

Solution of plane problem by using harmonic functions:

$$\sigma_x = -\frac{k_0}{Cos A\Phi_0} \cdot \exp(\theta - \theta_0) \cdot Cos A\Phi + k_0,$$
$$\sigma_y = -3 \cdot \frac{k_0}{Cos A\Phi_0} \cdot exp(\theta - \theta_0) \cdot Cos A\Phi + k_0, \quad (9)$$
$$\tau_{xy} = \frac{k_0}{Cos A\Phi_0} \cdot exp(\theta - \theta_0) \cdot Sin A\Phi .$$

where θ и AF – plane functions of the coordinates of the deformation zone.

$$AF = AA_6 \cdot x \cdot y + AA_1 \cdot y - 2 \cdot \varphi \cdot \quad (10)$$

$$\theta = -\frac{1}{2} \cdot AA_6 \cdot x^2 + \frac{1}{2} \cdot AA_6 \cdot y^2 - AA_1 \cdot x + 2 \cdot \frac{y}{R} + C , \quad (11)$$

where $\varphi = \dfrac{\frac{l_\partial}{2} - x}{R}$, l_l - the length of the deformation zone, R - roll radius.

7. Average yield strength in the deformation zone is determined by the Zyuzin-Brovman model [7]

$$\sigma_T = \sigma_1 \cdot (\varepsilon)^{T1} \cdot (u)^{T2} \cdot exp(T_3 T) \quad (12)$$

Or by modern Hensel-Spittel model [8] taking into account the complex rheological properties of the plastic medium

$$\sigma_T = \alpha_1 \varepsilon^{\alpha_2} \cdot exp\left(\frac{\alpha_3}{\varepsilon}\right) \cdot exp(\alpha_4 \varepsilon)(1+\varepsilon)^{\alpha_5 \cdot T} \cdot u^{\alpha_6} \cdot u^{\alpha_7 \cdot T} \cdot T^{\alpha_8} \cdot exp(\alpha_9 \cdot T) \quad (13)$$

where α_i - coefficients depending on the steel grade.

8. The force P and moment M in the steady rolling process calculated by known formulas for free-rolling and considering the front and back tension, so that in general they are functions of the following parameters:

$$P = P(H_o, h_1, \sigma_T, V, \mu, T_f, T_b) \quad (14)$$

Similarly, we can write for the moment M. Here μ – the coefficient of friction in the deformation zone, which depends on the rolling speed V.

9. Angle of nonslip point γ and forward flow taking into account the tension:

$$\gamma = \gamma_o + a_\gamma (T_f - T_b) \quad (15)$$

$$S = S_o + в_s (T_f - T_b) \quad (16)$$

10. The rate of the strip output from the preceding stand $V_{out\ i-1}$ and input the following stand $V_{in\ i}$:

$$V_{out\,i-1} = (1 + S_{oi-1} + в_{i-1} \cdot (T_{b_i} - T_{f_{i-1}}))r_{i-1} \cdot (\omega_{r_{i-1}} + \Delta\omega_{ri-1}) \quad (17)$$

$$V_{in_i} = (1 + S_{oi} + в_i \cdot (T_{b_{i-1}} - T_{f_i}))r_i \cdot (\omega_{ri} + \Delta\omega_{ri}) \quad (18)$$

$$\omega_r = \omega_m - \dot{\varphi}_{12} - \dot{\varphi}_{23} \quad (19)$$

11. Equation of the metal volume per second passing through the deformation zone of the stands.

12. In the process of filling the deformation zone with the metal when biting the strip by rolls known ratios for P and M are used reflecting the specific loading of stand and drive line for sheet strip [4,9]:

$$P(\varphi(t)) = p_{av} Br[\alpha + (\varphi - \alpha_o)] \quad (20)$$

$$M(\varphi(t)) = 2\psi p_{av} Br^2 \cdot [2\alpha_o \varphi - \varphi^2 - x / r] \quad (21)$$

where φ the angle of the working roll rotation from the moment of contact with the strip to full filling of the zone with metal ; and α the angle of the working roll rotation from the moment of contact with the strip to full filling of the zone with metal ; α and αo – biting angle and contact angle:

$$\alpha_o = \sqrt{(H_o - h_1 + x_o)/r}$$

$$\alpha = \sqrt{\alpha_o^2 - x / r}$$

13.The output strip thickness $h_1 = \Delta_o + P / C_c$, where Δ o – initial gap between the rolls.

A similar system of differential equations and finite dependencies is recorded for the remaining stands. Correlation of the equations in one stand and between the stands can be traced as follows. As a result of biting the strip of the first finishing mill stand in the drive line the torsional oscillations appear.

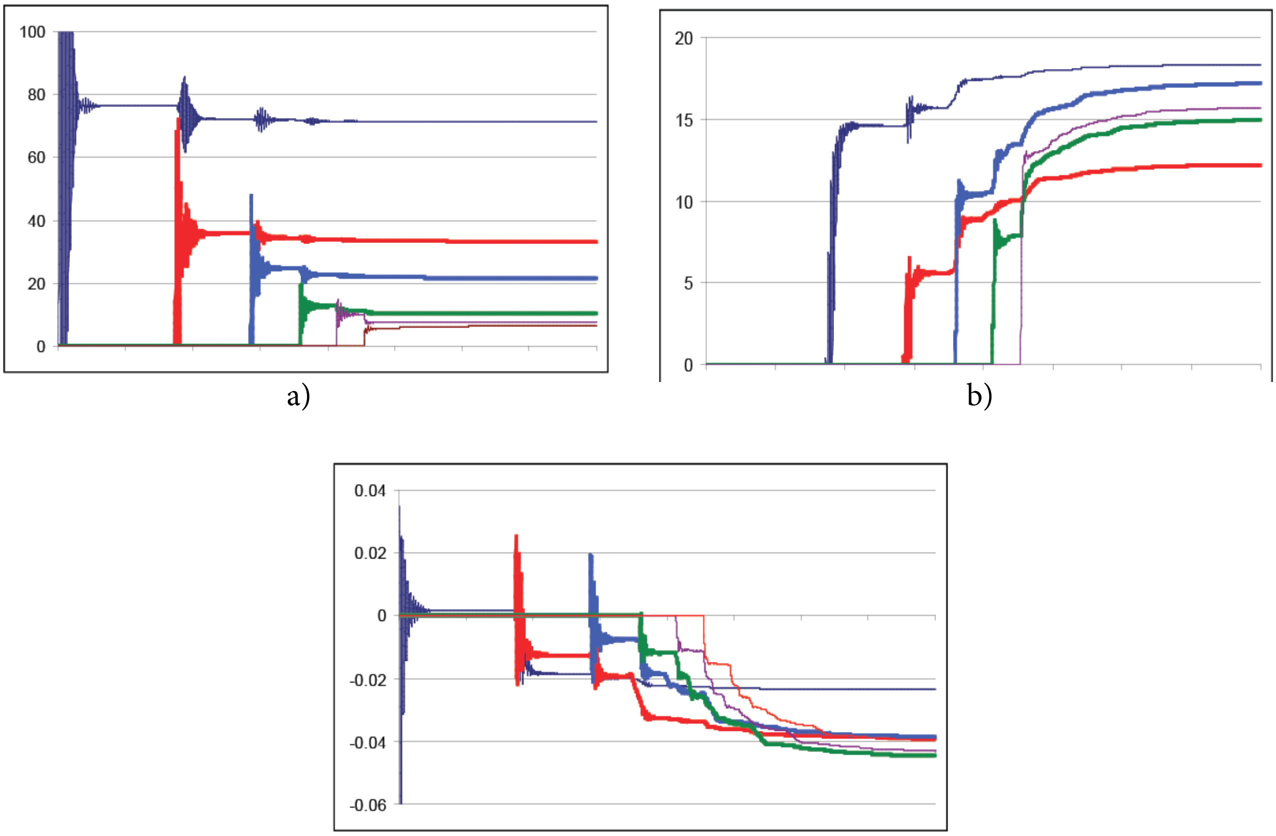
On the uniform rotation of the working rolls alternating component of the angular velocity $\Delta\omega_r(t)$ is superimposed leading to the appearance of the corresponding component of the rolling speed $\Delta V(t)$. This in turn leads to the coefficient component of friction in the deformation zone $\Delta\mu(t)$, the rate of relative deformation of metal $\Delta U(t)$, deformation resistance $\Delta\sigma_д(t)$, the force Δ*P(t)* and moment Δ*M(t)*.

These components are also the result of the motor reaction torque moment of resistance (of rolling) applied to the rolls. Due to the rolls oscillations $\Delta\omega_r(t)$ the oscillation of speed of the input $\Delta V_{in}(t)$ and output $\Delta V_{out}(t)$ of the strip, of the neutral angle $\Delta\gamma(t)$ and of the forward flow $\Delta S(t)$ are appeared. According to the force the strip thickness varies at the output of the first stand. After the transportation time 1 changing thickness of the strip enters the next stand. The above process of torsional oscillations is repeated, wherein the strip is located in two stands. Therefore, oscillations in the set parameters now also reflected in the interstand force forming in the strip. As the front and back tension it further affects Δ*P(t)* and the other parameters in two stands.

Again there is a change of the strip thickness at the output of the first and second stand. Changed thickness after the first stand enters with delay the second roll stand, and the second enters the third stand. The process is repeated after biting of the strip by the last stand when the system period of self-regulation ends. The system comes to a certain steady state.

Since the interstand forces in the strip in hot rolling mills are not directly measured, the mathematical model identified by measurements of moment of elastic forces of mill stands 1600, 1700, 2000, 2500 [4].

The figure shows the transient processes when modeling the filling process of the finishing train without introduced disturbances (nominal mode), taking into account the transportation lag. Formation of moments, tension, and thickness deviations, as well as Vout, Vin, γ S are occurred with a frequency of torsional oscillations. Self-regulation of the process ends after 5 ... 10 s after the strip inputs from the last stand. Note that the thickness of the strip in the middle part is smaller than at the beginning. This is due to the fact that even when the nominal setting of strain-speed mode, there are two related factors of disturbances such as rolling section of the strip without front tension and transportation lag.



a) b) c)

Figure 1. Transient processes when filling 6-stand continuous group with the strip with agreed strain-speed mode: a - elastic moment forces; b - interstand tension; c - thickness deviation after the stands.

A mathematical model of the filling dynamics of continuous group by strip considering torsional oscillations which is not recorded in deviations, as it is customary, and in absolute terms, in connection with the computer program allows to define more accurately the impact on the process, especially the stress load in the strip such disturbances as thickness deviation ΔH_o and temperature Δ°C of the strip at the input speed and temperature mismatch between the stands, etc. both in filling mode and when steady rolling. Especially important to know about the processes in the system (stand, strip, drive line, thickness, etc.) where there are two or more disturbance. In this case, using the known equations in deviations the problem can be solved only qualitatively.

On the basis of the modeling in absolute values a number of new results were established. Thus, when reducing thickness of the input of the semi-finished rolled stocks with respect to the nominal thickness on which a continuous group is set up, interstand tension and thickness deviation increases with increasing the thickness – they are decreasing. In the latter case, in the first intervals short term looping are appeared. If the torsional oscillations ("hard" system) are not taken into account, tension and thickness deviation output are by 15 ... 30% less.

Conclusion

The mathematical model of filling 6-stand continuous hot rolling mill group with the strip in the absolute values of the variables was developed. Accounting for torsional oscillations and transportation lag allows establishing the character of formation and improving the accuracy of calculating of the interstand tension and the thickness of the strip, determining the influence on the processes of technological disturbances of the rolled stock thickness and temperature, mismatch in speed mode, etc. The model is also applicable for steady rolling process. The example of calculation for the finishing mill stands 1680 is given in the article.

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Mechanisms of plastic deformation in case of production of thin-walled rolled stock of the special purpose

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