

SELF EXCITED VIBRATIONS IN FOUR-HIGH ROLLING MILLS CAUSED BY STOCHASTIC DISTURBANCE OF FRICTION CONDITIONS ON THE ROLL-ROLL CONTACT SURFACE

SUMMARY

In this paper an probabilistic model of the friction phenomena on the work-back up rolls contact surface has been presented. It has been shown that such character of the disturbance in distribution of zones with static and kinetic friction. can be regarded as one of the sources of self-excited vibrations appearing in the system consisting of a rolling mill and a strip.

Keywords: rolling mill, friction phenomena, self-excited vibrations

SAMOWZBUDNE DRGANIA WALCAREK KWARTO POWSTAJĄCE W WYNIKU STOCHASTYCZNEGO CHARAKTERU ZABURZEŃ SIŁ TARCIA NA POWIERZCHNI KONTAKTU WALCÓW ROBOCZYCH I OPOROWYCH

Przedmiotem pracy jest probabilistyczny model opisujący zaburzenia rozkładu sił tarcia na powierzchni kontaktu walców roboczych i oporowych walcarki kwarto. Analiza tego modelu wskazuje, iż taki charakter tarciaowego sprzężenia obu walców może być przyczyną wzbudzenia w układzie drgań o charakterze samowzbudnym.

Słowa kluczowe: walcarki, drgania, drgania samowzbudne

1. INTRODUCTION

The explanation of the source and character of self-excited vibrations in four-high temper rolling mills in the frequency range 500–700 Hz that lead to chatter marks on the steel strip surface is still an open question.

The assumptions made in the analyses carried out to date should be given critical consideration (Nesler and Cory 1993, Hoffman and Aigner 1998, Hardwick and Dunlop 1999, Zhong *et al.* 2002).

This applies especially to the neglecting of the influence of the plane motion of the rolls, which as one can expect can provoke transverse vibrations of the rolls resulting from a coupling with cyclic changes of the strip tension. Additionally, by taking into account the frictional coupling of the work- and back-up rolls one can expect the displacements of the rolls along the strip axis to depend on this coupling, too.

The analysis of the motion of the rolling mill system taking place in the plane perpendicular to the axes of the rolls is motivated by the following two questions:

- 1) Is the neglecting of the horizontal motion of the work- and back-up rolls justified?
- 2) Is it necessary to account for possible slips between the work- and back-up roll when performing vibration analysis?

2. PROBABILISTIC MODEL OF THE FRICTION PHENOMENA ON WORK-BACK UP ROLLS CONTACT SURFACE

The analysis of the self excited vibrations in four-high rolling mills has been done by considering a spring-mass model

of the system (Fig. 1) in which – in the opposite to the previous work (Nesler and Cory 1993, Hoffman and Aigner 1998, Hardwick and Dunlop 1999, Zhong *et al.* 2002) plane motion of the rolls and stochastic nonlinear function describing the friction phenomena on the work-back up roll contact surface has been assumed.

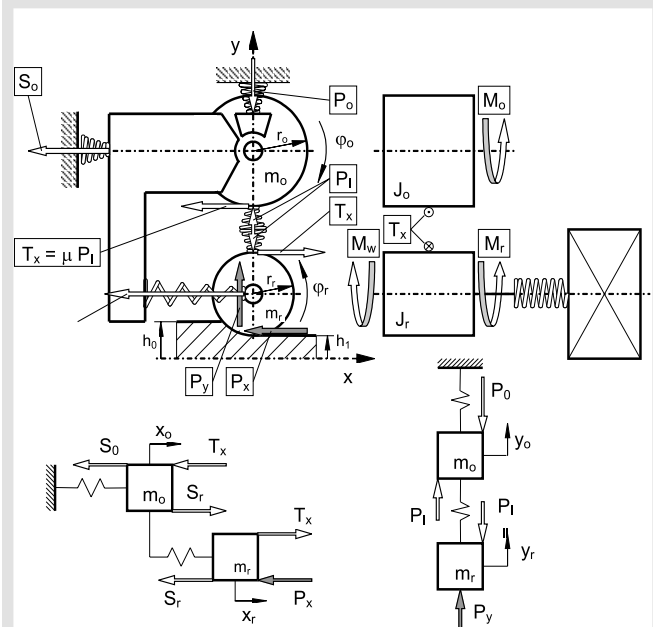


Fig. 1. Spring-mass model of the four-high rolling mills with the driven work rolls described by six nonlinear ordinary differential equations. Both the rolling mill configuration and the metal deformation process are assumed symmetrical about the rolling axis

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Additionally, it has been assumed that:

- The mass of the strip is negligible compared to that of the rolls.
- The strip thickness is sufficiently small compared to the radius of the work rolls, which justifies the use of the Tselikov method (Tselikov and Grishkov 1970) applicable to the cold-rolling process of thin bands.
- Both the rolling mill configuration and the metal deformation process are assumed symmetrical about the rolling axis.
- There is a close analogy between the friction phenomena taking place between the driven back-up- and stationary work roll (configuration used in some skin-pass mills) and those between the driven work roll and the stationary back-up roll (typical quarto mills).

The equation of the system motion have the form:

$$\begin{aligned}
 m_o \frac{d^2 x_o}{dt^2} &= S_r - S_o - P_l \mu \\
 m_o \frac{d^2 y_o}{dt^2} &= P_l - P_o \\
 J_o \frac{d^2 \varphi_o}{dt^2} &= P_l \mu r_o - M_o \\
 m_r \frac{d^2 x_r}{dt^2} &= P_l \mu - S_r - P_x \\
 m_r \frac{d^2 y_r}{dt^2} &= P_y - P_l \\
 J_r \frac{d^2 \varphi_r}{dt^2} &= M_r - M_w - P_l \mu r_r
 \end{aligned} \tag{1}$$

where:

$x_o, y_o, (x_r, y_r)$ – coordinates of back-up (work roll) axes respectively,

$\varphi_o (\varphi_r)$ – angle of rotation of the back-up (work) roll,

μ – coefficient of friction between the rolls,

S_o – reduced horizontal reaction acting on the back-up roll bearing,

S_r – reduced horizontal reaction between work and back-up roll,

P_o – resultant of pressures of back-up roll bearings acting on adjusting screws,

P_l – vertical reaction of the work roll acting on the back-up roll,

$P_l \mu = T_x$ – horizontal reaction of the work roll acting on the back-up roll,

P_x, P_y – horizontal and vertical components of the metal pressure on the work roll,

$M_w (M_o)$ – resistance torque due to friction in work (back-up) roll neck,

M_r – driving torque of the work roll (from the power system).

The values of P_y, M_w and those of forward and back tension stresses are non-negative. The formulas defining the loads on the work roll have been derived by modifying the equations described by Tselikov (Tselikov and Grishkov 1970), taking into account the following observations about the rolling process (Świątoniowski 1996):

1. The dependence of the location of the neutral point (a place with zero relative velocity of the roll with respect to the metal being processed) on the magnitude of the forward and back tension suggests there exists a relationship between the velocity of the work roll surface and the reaction of the processed metal. This can be further related to the friction condition that exists on the roll-roll contact surface between the work – and back-up rolls.
2. The dependence of the friction between the work- and back-up rolls on the relative velocity of their surfaces suggests that vibrations with frequencies 500–700 Hz can originate and be sustained as a result of the frictional condition on the roll-roll contact surface (see Fig. 2).

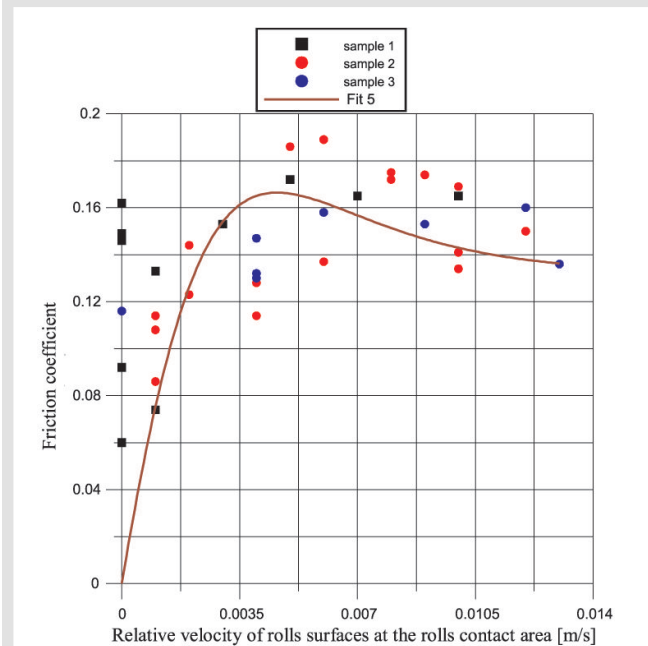


Fig. 2. Friction coefficient vs. relative velocity of the rolls (1, 2, 3 – series of experiments making on the laboratory mill)

The first of the above observations results in relationship (2) between the position of the neutral point c and the back and forward tension, and subsequently leads to the dependence of the loads on this quantity, as expressed by equations (2), (3), (4), (5) and (6).

$$l_d = \sqrt{2r_r (h_0 - h_1)} \tag{2}$$

$$c = \left(h_0 \ln \frac{\sigma_o - \sigma_p}{\sigma_1 - \sigma_n} + l_d \mu_m \right) \frac{h_1}{h_1 - h_0} \tag{3}$$

$$\frac{P_x}{B} = 2h_1\sigma_n - 2h_o\sigma_p +$$

$$E \int_0^t \left[\frac{v_o(\tau)}{L_0^2(\tau)} - \frac{h_1 l_d + (h_o - h_1)c}{h_o L_0^2(\tau) l_d} r_r \frac{d\phi_r}{d\tau} + \frac{1}{L_0^2(\tau)} \frac{dx_r}{d\tau} \right] d\tau + \quad (4)$$

$$-E \int_0^t \left[\frac{h_1 l_d + (h_o - h_1)c}{h_1 L_0^2(\tau) l_d} r_r \frac{d\phi_r}{d\tau} + \frac{1}{L_0^2(\tau)} \frac{dx_r}{d\tau} - \frac{v_1(\tau)}{L_0^2(\tau)} \right] d\tau$$

$$\frac{P_y}{B} = \frac{(\sigma_o - \sigma_p) h_o}{\mu} \left\{ \exp \left[\frac{\mu_m (l_d - c)}{h_o} \right] - 1 \right\} +$$

$$+ \frac{(\sigma_1 - \sigma_n) h_1}{\mu} \left\{ \exp \left[\frac{\mu_m c}{h_1} \right] - 1 \right\} \quad (5)$$

$$\frac{M_w}{B} = \frac{(\sigma_o - \sigma_p) h_o}{\mu_m^2} \cdot$$

$$\cdot \left\{ \exp \left[\frac{\mu_m (l_d - c)}{h_o} \right] (h_o + c \mu_m) - (h_o + l_d \mu_m) \right\} + \quad (6)$$

$$+ \frac{(\sigma_1 - \sigma_n) h_1}{\mu_m^2} \left\{ \exp \left[\frac{\mu_m c}{h_1} \right] (c \mu_m - h_1) + h_1 \right\}$$

where:

- B – width of strip,
- l_d – contact arc length,
- μ_m – coefficient of friction between material and the work roll,
- c – vertical coordinate of the neutral cross section,
- E – Young's modulus,
- h_o, h_1 – half of the strip thickness entering and leaving the rolls,
- v_o, v_1 – material velocity in the input and output cross section of the roll gap,
- σ_o, σ_1 – the yield stress at the roll gap input and output, respectively,
- σ_p, σ_n – back and forward tension stress, respectively,
- t – instantaneous time of observation,
- L_0 – instantaneous length of the strip in front of the rolling mill.

The second of the above observations follows from the experimental fact that the work- and back-up rolls work in a stable and stationary regime even though there is a difference of velocities at their contact point (Fig. 2).

The above experimental data have led to the assumption that the coefficient of friction of the matching surfaces increases with the relative velocity until it (most probably) saturates. It stabilizes at this level or falls and stabilizes at a lower level.

Using these results it has been assumed that the probability that the unit friction force $t = p\mu(\Delta v)$ exceeds its extremely boundary conditions and slip occurs increases with relative displacement Δs , which is proportional to the instantaneous relative velocity Δv (p – unit pressure force).

Also, a normal probability distribution has been assumed, which is described by the function:

$$P_1 = erf \left(\frac{\Delta v}{\sigma_r} \right) \approx \frac{\exp \left(\frac{2.40528 \Delta v}{\sigma_r} \right) - 1}{\exp \left(\frac{2.40528 \Delta v}{\sigma_r} \right) + 1} \quad (7)$$

where σ_r – standard deviation of the density function describing the probability of the appearance of boundary friction conditions leading to slipping at all points of the contact surface (i.e. relative displacements between work and back up roll in macro scale).

The unit friction force t – corresponding with the conditions of relative displacement (in macro scale) – on the roll-roll contact surface can assume one of the following forms:

1. The friction force, further referred to as static friction, which is the maximum friction force not related to slips of contacting bodies at a contact point. This definition of static friction assumes that the experimentally verified (see Fig. 2) showing the experimental data of the friction coefficient and their approximating function) velocity difference Dv is possible without breaking the contact as a result of local deformation of the metal in the neighbourhood of the contact point.
2. The friction force referred to as kinetic friction, when contact is broken at the contact point and the bodies slip.

Both forms of the friction forces are calculated as the pressure force multiplied by the corresponding coefficient of friction: μ_s – for static friction and μ_k – for kinetic friction ($\mu_s > \mu_k$).

The roll-roll slip contact surface is divided between these two types of boundary friction. Assuming that the probability P_2 of the kinetic friction taking place at all points of the contact surface increases with the relative velocity Δv , the probability $1 - P_2$ of the appearance of static friction must decrease correspondingly.

$$P_2 = erf \left(\frac{|\Delta v|}{\sigma_k} \right) \approx \frac{\exp \left(\frac{2.40528 |\Delta v|}{\sigma_k} \right) - 1}{\exp \left(\frac{2.40528 |\Delta v|}{\sigma_k} \right) + 1} \quad (8)$$

where σ_k – standard deviation of the density function describing the probability of the appearance of kinetic friction at all points of the contact surface.

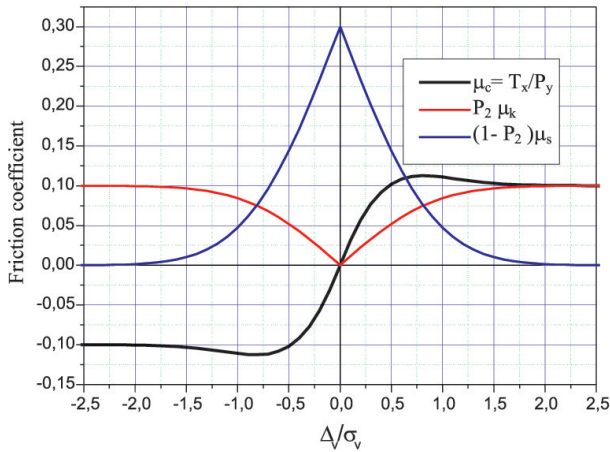


Fig. 3. Friction coefficient μ as well as fraction related to static and kinetic friction vs instantaneous relative velocity Δv

The above discussion leads to the following formula, which enables the calculation of the friction coefficient on the roll-roll contact surface as well as friction forces T_x applying to the back up roll – accounting for different velocities of the work- and back-up roll (Fig. 3):

$$\mu = \mu_c = P_1 [P_2 \mu_k + (1 - P_2) \mu_s] \quad (9)$$

$$T_x = \mu P_l = P_l \operatorname{erf} \left(\frac{\Delta v}{\sigma_r} \right) \cdot \left\{ \operatorname{erf} \left(\frac{|\Delta v|}{\sigma_k} \right) \mu_k + \left[1 - \operatorname{erf} \left(\frac{|\Delta v|}{\sigma_k} \right) \right] \mu_s \right\} \quad (10)$$

In relationship (10) standard deviations are bounded by inequality $\sigma_r \geq \sigma_k$ which leads to the conclusion that saturation of boundary friction – corresponding with relative displacement (in macro scale) – at all points of the roll-roll contact surface may occur with greater relative velocity Δv than decay of static friction.

The decrease in the compressive deformation in the distance between the respective centers of the back-up roll and the work roll is given (Yarita *et al.* 1980) as follows:

$$\Delta y = \frac{P_l w}{B \pi} \left[\frac{2}{3} + \ln \left(\frac{4r_r}{b} \right) + \ln \left(\frac{4r_o}{b} \right) \right] \quad (11)$$

The expression of b is based on Hertz's contact stress theory:

$$b = 2 \sqrt{\frac{P_l}{B} \frac{2w}{\pi} \frac{r_r r_o}{r_r + r_o}} \quad (12)$$

$$w = \frac{1 - \nu_r^2}{E_r} + \frac{1 - \nu_o^2}{E_o} \quad (13)$$

where:

- Δy – deformation in the distance between centers of back-up roll and work roll,
- b – width of flattened contact area,
- ν_r, ν_o – Poisson's ratios for work roll and back-up roll,
- E_r, E_o – modulus of elasticity for work roll and back-up roll.

Analytical form of the function $P_l = f(\Delta y)$ have been obtained applying power function as the approximation of the equation (11).

3. COMPUTER SIMULATION OF THE MODEL AND DISCUSSION OF RESULTS

The simulation of the model has been done applying typical parameters of the industrial rolling mill system (Roberts 1997) (Tab. 1).

Table 1

Parameters of the rolling mill and the strip used in numerical simulations

Rolling mill layout	Parameters	five stands continuous
Material being processed	entry thickness h_0	1.6÷4.8 mm
	exit thickness h_1	0.2÷3.2 mm
	strip width b	600÷1600 mm
	coil mass	25÷50 Mg
Technical specifications of a rolling mill	type of rolling mill	four-high
	work rolls diameter	475÷610 mm
	back-up rolls diameter	1220÷1520 mm
	total power	20000÷25000 kW
	roll velocity (max)	21÷30.5 m/s

Since the back and forward tension depends – among the others – on the metal roll gap input and output velocities, it has been assumed that by presenting a dependence of the frequencies of changes of these velocities on the friction condition between the work- and back-up rolls it will be possible to show that these conditions can lead to unstable vibrations of the mill-strip system.

The simulation results of the friction condition are shown in plots of the friction coefficient vs. the relative velocity of the work- and back-up roll surfaces at their contact point (Fig. 4), whereas the influence of this condition on the metal velocity is illustrated on the corresponding power spectral plots (Fig. 5).

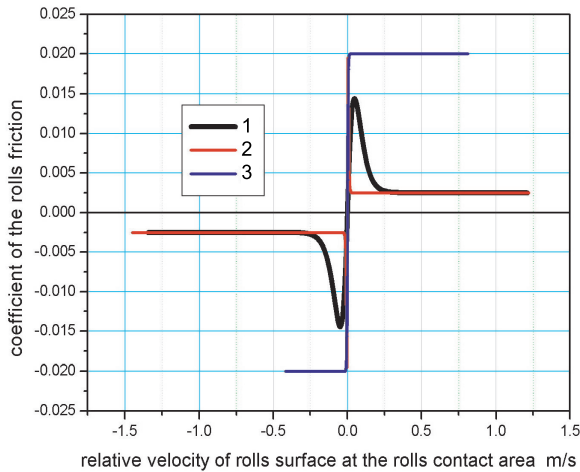


Fig. 4. Friction coefficient vs. the relative velocity of the work-back up roll surfaces at their contact point calculated by formula (4) for different simulations of the relations between μ_s and μ_k (1, 2, 3)

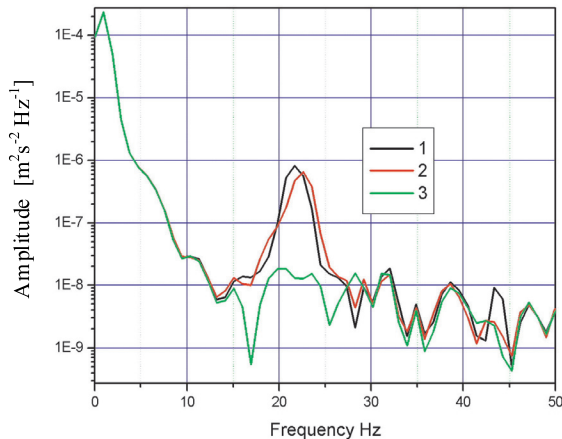


Fig. 5. Power spectrum of the velocity of the metal entering the roll gap (1, 2, 3 – series of simulations)

The power spectrum displays two local maximums. The first one appears at a frequency around 1 Hz, which corresponds to the assumed harmonic back tension frequency. It appears that the position of this peak does not depend on the friction condition between the rolls. The second maximum appears for the natural frequency close to that of the torsional vibration of the work roll (20 Hz) and can shift by 2.5 Hz (about 11%). Together with the frequency, the power of vibration changes, too.

In the part of the spectrum with higher frequencies in Figure 6 one can observe many local relatively small maximum which are more or less shifted relative to each other depending on the friction condition between the back-up- and the work roll.

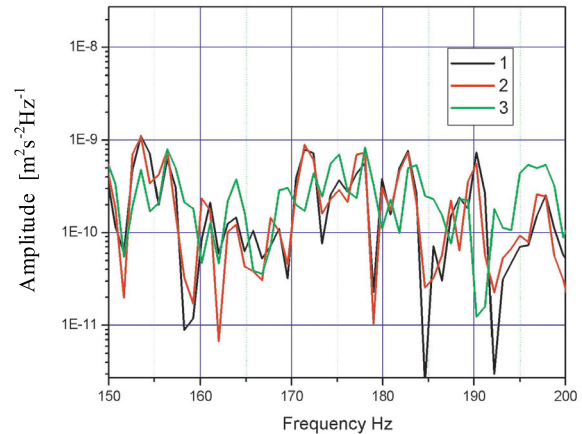


Fig. 6. Power spectrum of the strip velocity in the range of high frequencies of velocity change (1, 2, 3 – series of simulations)

Referring to the previous results (Świątoniowski and Bar 2003), which indicate a chaotic behaviour of the rolling mill vibrations, it is understandable that such character of the friction phenomena on the roll-roll contact surface leading to even such a small disturbance of the strip velocity can be regarded as one of the sources of self-excited vibrations of the system.

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