REGENERATIVE CHATTER VIBRATIONS CONTROL IN THE TANDEM COLD ROLLING MILLS

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Chatter vibrations were investigated for the high speed 5 stand 4-h tandem cold rolling mill 2030 of the NLMC. Real-time chatter vibration monitoring and diagnostics system was developed and supplied for that mill. The tension forces oscillations and the chatter regeneration due to strip thickness variation is discussed. The new methods of the 3rd octave chatter early diagnostics were developed and model based mill control improved. Methods are based on stands synchronization control and the tandem mill resonance avoiding due to a speed and other rolling parameters variation of small amplitude. Work rolls hydraulic bending system influence on the bearings vibration and chatter modes is discussed. Methods and devices for chatter damping are represented briefly.

Keywords: chatter vibrations, control, regenerative effect, damping

Introduction

Since 1970th chatter vibration in the high speed cold rolling and temper mills is a phenomena still intensively investigated because it significantly (20-30%) reduces annual plant productivity and strip quality. The most advanced tendencies in this domain of research were discussed in Ref. [1] and other papers. But some aspects, namely, regenerative chatter and its control was not reported. Stands interaction by the strip tension was analyzed but not from the view point of mill control. Also stands synchronization due to roughness and thickness variation in the tandem mills was not investigated as an explicit cause of chatter amplification. Chatter research in the tandem (5 stands) cold rolling mill 2030 of the NLMC allowed us supplying an automatic system. This work is devoted to minimizing impacts and new chatter control methods development.

1 Chatter Studies

The high speed tandem cold rolling and temper mills are complicated machines with the Many-Input-Many-Output (MIMO) structure. Modern strategies of its control based on adaptive models including fuzzy logic algorithms, neural nets for parameters prediction to meet customer's very high demands on steel strips flatness, roughness and thickness tolerance (±5 μm). Conventional Automatic Gauge Control (AGC) system sensors and actuators are not able to control high frequency chatter vibrations because its effective pass band is less than 10 Hz (hydraulic AGC). Therefore in practice the only effective way to control chatter is speed fast drop by the vibration signals being monitored in special purpose systems. But the frequent speed drops reduce mill productivity and strip quality.

Monitoring the speed related (kinematical) sources is a usual approach to the vibration problem solving in any rotating machines and in the rolling mills too. Resonances appear when the natural frequencies coincide with the speed related disturbance. Parametric resonances are also included to that area of research (tooth couplings, roll bearings etc.). Methods of such vibrations control assume avoiding resonance ranges during plant operation. But for tandem mills the number of possible sources of vibration is very big and different elements may have more or less importance in a short period of time (work rolls changes every 3-4 hours). Beside it a large variation of mill natural frequencies and modes exits under the working conditions. Therefore such approach is rather useful for rotating equipment diagnostics off-line than for real-time mill automatic control. Nevertheless many cases of chatter elimination reported based on mill maintenance improving.

Lubricant degradation as a vibration source under the high duty conditions has been investigated by many authors. Narrow contacts (10-15)×(1000-2000) mm of strip and both work rolls (WR) are the only places where the biggest part of power (up to 10 MW) from electric motors is being transferring by the friction to metal for its elasto-plastic deformation in every stand. Therefore even smallest disturbance in contact friction conditions under the high loads in stands (10-15 MN) may produce impulsive impacts with the wide band spectrum. Consequently it excites all natural frequencies of the mill stands in the range of 1000-1500 Hz for the high rolling speeds 18-25 m/s (in the last stand). The obvious methods were reported for emulsion concentration control (increasing) by the vibration signals in the stands. Beside the emulsion very high cost, mill cooling system could not able to vary concentration quickly (time of response 20-40 min) so it can not be used for fast chatter control. Nevertheless mills show sensitivity (less robustness) to that parameter and stands cooling system set-up before rolling may be optimized. In Ref. [2] it has been shown by simulation and experiment that in tandem mill for the 2 neighboring stands exists optimal friction factor (not low and not high) for minimal mill susceptibility to chatter.

Friction factor nonlinear dependence on relative speed of contacting bodies slipping is a well known mechanism of instability in mechanics. Usually it is considered that for the real rolling conditions and lubricants parameters a minimum value of friction factor is about 5 m/s speed and hence could not cause instability at higher speeds.

During mill operation backup rolls (BUR) and WR with the unavoidable local defects (e.g. spalling) may produce the same wide band impacts as the slips in contact. If the frequency of some source of vibration at the certain speed accords to roll circumference length the periodic defects (chatter marks) may appear on the BUR (Figure 1a). It is well known fact that to the end of BUR service time (7-10 days) when the surface defects accumulated the probability of chatter increases significantly. It should be divided the chatter marks from rolling and grinding processes. The chatter marks after grinding almost invisible on roll (Figure 1b) and could be cleared up only by chock test.

a) 

b) 

Figure 1: Chatter marks on the backup rolls after rolling (a) and grinding (b)

Such roll being installed in the mill behaves like speed related source and excites chatter at certain frequency. Vibration diagnostics allows to reduce structural resonances in the grinding machines but reliable device (preferably optical) is required for hidden chatter marks recognition (ΔRa = 1-3 μm) and grinding process control. The tuned vibration absorbers (designed by the AMTRI Company, UK) are also effective means to avoid grinding chatter marks.

2 Chatter Control Problems

Because of chatter amplitude arises enough quickly (0.3-0.5 s) mill operators try to set vibration monitoring alarm levels as close to normal level as it possible. But it frequently cause wrong alarm signals as the rolls and strip size change from coil to coil. As it follows from the known publications and patents there are no systems which provide chatter early diagnostics (5-8 s before chatter on-set) and vibration amplitude forecasting in the tandem rolling mills. The main questions for chatter control are as following (motivation of research):

- How to detect chatter earlier (by 5-8 s) than it comes to visible amplitudes?
- How to control chatter with the stands interaction in the tandem mill?
- How to damp chatter by the impacts of small amplitude (1-2%)?
- How to feed and where to mount actuators with respect to mill design?

Taking into account all above mentioned the following problems are discussed.
1) Natural frequencies and modes deviation in a multi-body roll stack.
2) Friction factor and rolling speed nonlinear relation.
3) Feedback loops and stands synchronization in the tandem mill.
4) Chatter regeneration due to thickness variation.
5) Vibration passive damping devices and active control methods.

2.1 Natural frequencies and modes deviation of mill stack

In papers some divergence exists in roll stack spring-mass models schemes for chatter simulation. It depends not only on the stands different design: 4-h, 6-h, 20-h (cluster mills), but on the chocks and rolls assigning as lamped masses and springs. The only feature that accurate models have to exhibit is the symmetry modes of upper and lower sets of rolls at the main frequencies of 3rd and 5th octave chatter for certain mill (Figure 2a). Chatter in 3rd octave appears only for thin strips when the upper and lower pairs of rolls move symmetrical about the strip plane. Symmetrical modes were discussed by many authors but the strip properties and WR bending system influence on modes deviation has not been enough studied. Calculations have shown that modes frequencies may vary significantly (Figure 2b).

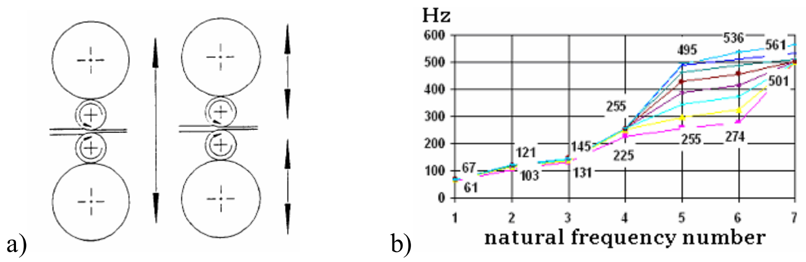

Figure 2: Chatter vibrations modes (a) and WR bending influence (b)

Vibration measurements in tandem mill 2030 have been carried out with the accelerometers being mounted on every of WR and BUR chocks. Thin (0.6 mm) and thick (1.0 mm) strips have different modes of stack movement. Thin strip rolling corresponds to main node in the roll bite but thick strip stiffness shifts node out of rolls and strip contact. Such result may be obtained by simulation only if to suppose not symmetrical stack model (upper housing included as lamped mass). Thick strip stable rolling was available at the high speed without chatter. Mill had the same technical condition and almost the same rolling parameters (steel type, width, rolls, loads, specific tensions, coolant amount etc.). There are some reasons for such behavior.

1) Even with a little output thickness deviation (Δh=0.4 mm) strip mechanical properties (hardening and yield stress) varies significantly (20-30%). It influences on damping properties of steel strip in the roll bite. Harder strip corresponds to less damping.

2) WR bending influences only on high frequency modes No. 5…7 (Figure 2b) therefore thin strip periodic thickness or surface roughness could cause stands interaction and tandem mill excitation. Strip variable stiffness in the roll bite may be considered as a parametric excitation in the stands. Some papers published on this theme. Experiments with the mill drives rotation under the working loads and speeds without strip in stands have shown that vibration signals exhibit another patterns. But during rolling as strip come from previous slow stands to faster further ones the main parametric resonance condition (frequency of excitation twice more than natural one) is impossible to be fulfilled.

2.2 Friction factor and rolling speed nonlinear relation

Dynamic model for chatter research includes parameters of technology and lubricant: $\mathbf{t_{MAX}}$ - ultimate temperature of oil flash, $\mathbf{K_T}$ – roll surface temperature by speed relation factor, $\boldsymbol{\nu_{50}}$ – initial viscosity (at 50°C), **Ra** – WR surface roughness, $\boldsymbol{\varepsilon}$ – strip relative reduction, $\mathbf{k_S}$ – type of oil factor (synthetic or natural), $\mathbf{t_R}$ – current temperature of roll surface. Calculations have shown that only roll surface temperature ($\mathbf{t_R}$) may shift minimum of friction factor toward the higher speeds (up to 15 m/s). But all other parameters variation cause only up and down shift of friction factor minimum value. This particularity was not reported before. During the long coils rolling time (4-5 min) of thin strips (0.3-0.8 mm) when chatter mostly occurs the rolls temperature may exceeds the limit of oil degradation (150-200°C) and causes instability in most loaded last stands of mill. Therefore as the WR temperature being varied has influence on friction factor and instability it may be considered as bifurcation parameter. The rolls coolant amount varying and lubricants parameters optimization is one of the methods to control chatter. Work rolls temperature on-line control by pyrometers is not reliable so heat transfer model based observers are required for mill control. As a rule vibration is initiated in stands No.3-4 where the high loads and speeds lead to the most duty lubrication conditions.
In order to identify contact friction instability and strip stiffness (hardening) the vibrations spectrums in the different stands shown in Figure 3. There are three different patterns in every stand.

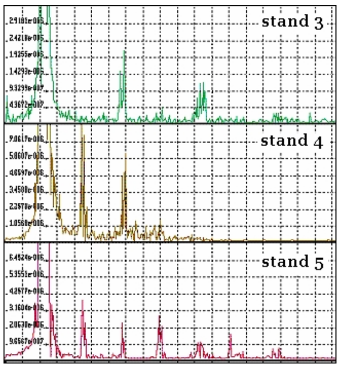

Figure 3: Chatter vibrations spectrums in the stands No.3-5

Friction tangential forces and deformation normal forces determine strip stressed condition and its nonlinear stiffness as an elasto-plastic element in the roll stack. Type of nonlinearity in the roll bite and its nature may be determined by the harmonics of main frequency. It is known that cubic nonlinearity give odd harmonics (stand No.3) and quadratic relation causes even harmonics (stands No.4-5). Odd harmonics are rather related with the strip hardening (like cubic curve) and friction nonlinearity rather shows even harmonics (curve with minimum). So that to separate nonlinearities the two or three axis sensors should be used in the mill. Horizontal axis corresponds to friction forces.

2.3 Feedback loop and stands synchronization in the tandem mill

Some approaches to chatter research came from the other treating operations (grinding, milling cutting etc.) studies. See detailed overview in Ref. [3].

Feedback loop mechanism in the tandem mills appears because rolling load interacts with strip tension. Tension forces in elastic strip are determined as:

$$T_i = \frac{E \cdot S}{L} \int (V_i / \xi_i - V_{i-1}) dt \, , \qquad (1)$$

where $\boldsymbol{T}$ – strip tension, N; $\boldsymbol{E}$ – modulus of elasticity, MPa; $\boldsymbol{V}$ – strip speed, m/s; $\boldsymbol{\xi}$ - strip elongation factor; $\boldsymbol{L}$ – strip length (distance between the stands), m; $\boldsymbol{S}$ – strip section, m^2; $\boldsymbol{i}$ - stand number; $\boldsymbol{t}$ – time, s. Tension is proportional to the integral of speeds difference and may be explained as a low-pass filter. Hence 90° phase shift between the input and output should appear which is not depends on frequency. Roll stack main mode movements (strip gauge) give additional 90° phase shift so entry and exit tension always oscillate with the 180° phase shift.

It can be shown on the basis of continuity of mass flow through the mill stand during rolling that a change of exit thickness will produce a change in strip speed, assuming entry gauge and exit speed remain constant. Feedback loop gain depends on rolling speed. Thus beyond the speed threshold chatter will appear.

In Ref. [4] using Routh's stability criterion for mill stack linear model, the critical strip speeds at which 3rd octave chatter occurs were obtained. Stability depends on tension response time constant and partial derivative of load by tension. Also mill internal damping is present in criterion. Some authors suggested other stability criterions based on linear models too. Analysis of criterions has shown that it can be used rather for qualitative estimation than for real-time mill control. We consider that tandem mill chatter should be described in terms of chain of coupled oscillators and synchronization conditions. Chatter vibration in the stands No.2-5 of tandem mill is shown in Figure 4a. In Figure 4b main chatter period has shown (about 120 Hz). Stands No.2-4 are synchronous within both low and high frequency but stand No.5 is always out of phase with the other stands because it works in "infinite stiffness" mode of control.

a) b)

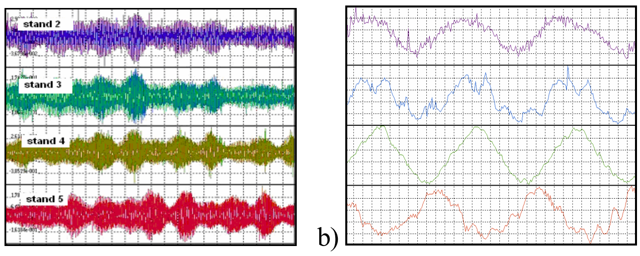

Figure 4: Chatter vibrations in stands No. 2-5

Nonlinear friction and strip stiffness in the contact zone make it difficult whole system analytical analysis. System is described by the parametric differential equations with varying time-delay.

2.4 Strip Thickness Variation and Chatter Regeneration

The modern isotopic gauge meters are too slow (response time about 0.1 s) and are not able to measure high frequency strip thickness variation (waviness periods 20-140 mm) in the tandem mill at the high rolling speeds. In Ref. [5,6] regenerative effects due to strip thickness and roughness variation in the tandem mills has been studied in the dynamic models.

In cutting and other operations Spindle Speed Variation Method is used for chatter avoiding due to regeneration from the previous passes waviness. Tandem rolling mill can not be controlled in such way due to big drives torques transient oscillations (in 2-3 s). Slow mill speed variation will make dynamic situation even worse because of torsional vibration at the low natural frequencies (9-12 Hz) which lay in AGC system pass band.

One of remarkable chatter features noted in every research. During rolling under the normal conditions vibration signals in every stand are always accompanied by the more or less modulations of low (2-3 Hz) frequency (Figure 4). Some authors explained this feature as frequency beating between neighboring stands which have the same design. Other authors explain it as a BUR eccentricity influence, another ones considered it as a tension frequency.

Another explanation may be given of modulation effect. Calculation with the dynamic model has shown (Figure 5) that if to disturb stand by series of periodic impulses (chatter marks on the strip) it will exhibit modulation and after certain threshold will become unstable. Although the twice difference of speeds in stands No.2 and No.5 (Figure 4a) we see the same phases of low frequency modulation. It is impossible to explain this fact if to consider the BUR eccentricities influence as a source of modulation. But it appears possible if to assume modulation as a result of thickness periodic defects accumulation which is not directly speed related and depends on phases of previous stand and current stand vibration. Such nature of resonance vibrations called «regenerative» chatter in publications. BUR abnormal eccentricity will increase mill sensitivity. Therefore even when very high vibration levels occur in the last stand No.5 of tandem mill 2030 NLMC it never causes mill chatter (there is no back action).

a) b)

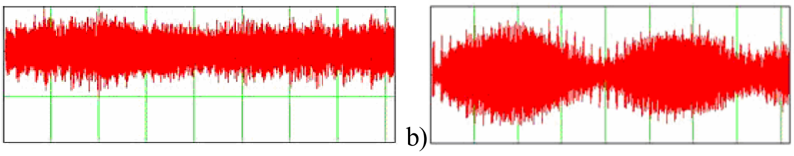

Figure 5: Vibration modulation (a) and thickness variation (b)

During the occasional strip breaks it may be calculated stand's real internal damping by the decrement of transient oscillations. Time of attenuation about 0.3 s is obtained for different stands. For the rolling speed 15 m/s the distance between stands in 4.75 m will be passed in 4.75/15 = 0.3167 s and for 20 m/s in 4.75/20 = 0.2375 s. So the previous stand is stable and last stand is unstable. After speed limit 4.75/0.3 = 15.83 m/s it will not be able to dissipate periodical impacts and vibration amplitude will rise in time even at constant speed.

3 Chatter Control

As the mill speed drop during chatter control reduces productivity the two ways are to solve problem: to control other rolling parameters (tension, reductions) or minimize speed drop value. Experiments proved that specific tension decreasing by 5 N/mm^2 between the stands No.4-5 allows speed increasing by 0.7-0.8 m/s. Relative reduction increasing in stands No.1-2 and it decreasing in the stands No.3-4 allows to bring up mill speed by 0.3 m/s for every 1% of relative reduction decreasing. The second way to improve control is to recognize chatter amplification earlier than it comes to large amplitudes in the stands and thus to minimize speed drops because less vibration requires less control signals.
For the first stage of research "black box" approach has been applied. Cross-correlation matrices of all available for measurement mill parameters (loads, tensions, torques, drive speeds, vibrations) were calculated as time functions and most related parameters were chosen for chatter prediction and mill speed control. For the second stage some additional factors (so called "chatter index") were tested in order to improve the reliability of automatic mill speed control. Coefficient of harmonics (nonlinear distortion), modulation factor and some other indexes were tested on-line in the automatic monitoring system. Band-pass filtering used to improve signals in the desired frequency ranges. Data analysis has shown that vibration signals are more sensible than loads, tensions etc. and most suitable signal for chatter control. Speed impacts reduced from 100 m/min (10%) to 10 m/min (1%) (Figure 6). Notations: 1, 4, 8 – spectrum and indexes alarm levels, 2 - chatter frequency, 3 – amplitude, 5, 6, 7 – chatter new indexes.

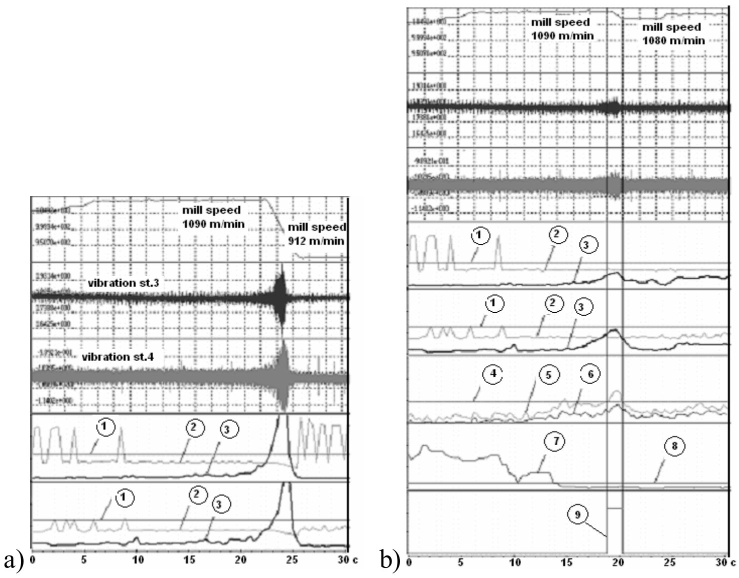

Figure 6: Chatter control by the known (a) and new methods (b)

System has been working since June 2006. Patent is pending on method and system for chatter vibrations early diagnostics and tandem mill control.

3.1 Chatter Damping Methods and Devices

As the upper threshold of rolling speed depends on mill internal dissipation ability then chatter passive damping methods and devices were investigated. Some companies produce polyamide removable liners and pads for rolling stands and chocks. Also thin inflatable hydraulic cylinders used for pressing chocks to mill housing. It allows preventing clearances opening and chocks horizontal vibration when the tension oscillations amplitude is too high. Experiments have shown that only 5-10% speed increasing may be achieved by passive dampers.

Active chatter suppression methods are quite popular now in the research papers and patents. This method of damping includes the additional source of energy (preferably hydraulics) and some devices which produce regulated periodic force in the rolling mill stands. In Ref. [7] additional degree of freedom (DOF) has been introduced for strip vibration phase shifting between stands and reserve of stability increasing in the rolling mill. Some other patents give the same ideas.

Many kind of damping methods were proposed earlier (1985) for dynamics reduction in hydraulic system in the 2030 mill of NLMC and later (2005-2007) for vibration damping. There are several ways for active chatter control.

1) Periodic force changing in AGC cylinders through the fast servo-valves. But it is difficult to compensate rolls moving with the 120 Hz chatter main frequency as the usual AGC pass band restricted by the 10-15 Hz.

2) Periodic force generation in the backup rolls balancing system. Usually it works in the on-off mode. But the same problem appears with the low pass band of servo-valves and big cylinders.

3) Periodic force generation in the work rolls bending cylinders. This method is more effective as the acting force of small amplitude is implied close to contact.

4) One method includes safety valves installed in the hydraulic system close to work rolls bending cylinders. It acts like a non linear element when vibration amplitude overcomes certain limit. Safety valves may work separately or by the signals from the vibration monitoring system (preferable). The tandem mill stands hydraulic block and rolls shocks section are represented in Figure 7.

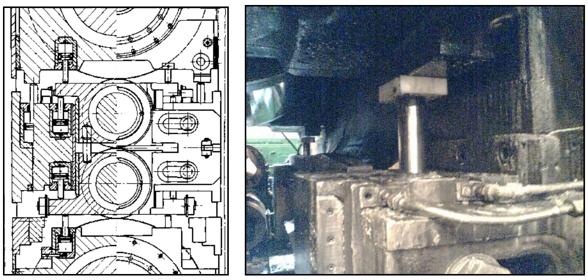

Figure 7: Rolling mill hydraulic system and polyamide damping pad

The main problem in active chatter damping is the absence of reliable high frequency hydraulic valves for exact damping force phase regulation in every of 8 pistons of the stand. Even a little phase divergence under control may cause defects of strip flatness and even worse situation in the mill than before. In any case the vibration monitoring system is needed to produce valve control signals.

Conclusion

- Kinematical sources monitoring is required but it is not effective for control.
- Mill natural frequencies and modes vary under the working conditions.
- Stability criterions based on linear models are not effective for control.
- Work rolls surface temperature is a bifurcation parameter for chatter on-set.
- Chatter frequency harmonics may be used for friction forces diagnostics.
- Chatter vibration modulation in the tandem mills has regenerative nature.
- Stands synchronization control is the most reliable method for chatter control.
- Chatter passive damping devices have no remarkable effect.

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