VIBRATION MONITORING SYSTEM AND THE NEW METHODS OF CHATTER EARLY DIAGNOSTICS FOR TANDEM MILL CONTROL

I.Y. PRIHOD'KO (PhD), P.V. KROT (PhD), K.V. SOLOV'YOV, E.A. PARSENYUK
Sheet Rolling Mills Department, Iron and Steel Institute, Ukraine National Academy of Science, Dnipropetrovs'k, Ukraine.

P.P. CHERNOV (PhD), V.A. PIMENOV (PhD), A.P. DOLMATOV (PhD), A.V. KHARIN
Novolipetsk metallurgical combine (NLMC), Lipetsk, Russia.

ABSTRACT

Real-time vibration monitoring and diagnostics system is developed and supplied for the 5-stand 4-h tandem cold rolling mill 2030 NLMC. Mechanism of chatter regeneration due to high frequency strip thickness variation and stands synchronization in the tandem rolling mills are considered. Methods for chatter passive damping and active suppression are considered. Work rolls hydraulic bending system influence on bearings vibration and chatter is discussed. The new methods are used for the 3rd octave chatter early diagnostics and model based mill control.

INTRODUCTION

High frequency vibration or "chatter" is a well known phenomenon for the different types of rolling mills. But it is most important for the cold rolling as the final metal treating operation. As it noted in references (1,20) it is not the problem specific to rolling mills. The chatter periodic marks exist on the railways surface, during the materials treating operations (grinding, drilling, and cutting) where friction forces interact with the spring elements of mechanical equipment.

Nowadays the only reliable method to reduce amplitude of chatter vibration in the rolling mills and to avoid strip breakages is the speed reducing. In the different mills the required speed drop which enough for chatter canceling before strip break is about 50-250 m/min depending on current speed level, mill type and rolling conditions. Such method reduces maximum mill operating speed.

Frequent repairing of the mechanical equipment elements (spindles, couplings, gears, winding reels, tension rollers, bearings and rolls) may be effective only till to certain limit when the cost expenditures begin to restrict the whole mill efficiency. Often chatter vibration affects strip surface and rolls by periodic marks (see Fig. 1) which may cause mill "roaring" even for 600-700 m/min rolling speed. Depending on rolling speed and vibration source chatter marks period may varies from 100-140 mm to 20-30 mm. It corresponds to main frequencies (modes) 100-120 Hz in the 3rd octave and 500-600 Hz in the 5th octave respectively.

a) b) c)

Fig. 1 Chatter marks: a) backup roll; b) strip (period 140 mm); c) strip (period 20 mm)

Modern chatter research and developments for cold rolling and temper mills are carrying out in the several directions:

- stationary vibration monitoring and diagnostics systems installing;
- methods and devices for passive and active vibration damping in the rolling stands;
- methods for non contact periodic marks control on the rolls and strip;
- rolls grinding process and machines optimization;
- methods for mill speed and other rolling parameters control using vibration signals;
- methods for mill equipment diagnostics.

Among the other companies supplying specialized chatter monitoring systems are such as *Vold Solution Automation* (USA) with the *"QuartzGrind"* (for rolls grinding process) and *"QuartzMill"* (for rolling mills), *AMTRI* (UK) with the *"AVAS"*, *IAS - Industrial Automation Systems* (Australia) with the *"VIDAS chatter monitor"*, *SMS Demag* (Germany) with the *"MIDAS"* and *SensorScript (*former *Pemtech)* (USA) with the *"ChatterMD"*.

Some of those companies supply vibration dampers for the rolling mills and rolls grinding machines. Vibration history archives for every coil and trends viewing for spectrum amplitude in the different frequencies of mechanical elements are the most required functions of chatter monitoring systems.

The chatter monitoring systems allow mill operators to be sure in manual control, relaxed and keep mill speed close to possible upper limit for current mill condition. The most known method for chatter and strip breaks prevention is on-line spectrum analysis in certain frequency range including main chatter frequency and giving the alarm signal for mill speed reducing when the spectrum amplitude overcome limit value (one or three levels). The advanced vibration monitoring systems give the automatic alarm signal to the mill control system. As the chatter amplitude arises quickly (less then 0.5-1.0 second) mill operators try to set 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 and vibration amplitude forecasting in the rolling mills.

THEORETICAL APPROACHES TO CHATTER SIMULATION

The friction forces between the treating tools and material (including rolled strip) has the nonlinear relation with many factors: machine design, lubrication conditions, rotating speed and others. Therefore such kind of instability is usually considered and called as self-excited (2) or parametric vibrations (3,4). This point of view reflects nonlinear or periodic system parameters changing. On the other side numerous external periodic sources which exist in the rolling mills may cause instability too when its frequencies match with the system natural ones.

A large number of mathematical models were designed to determine the causes of this phenomenon for the mechanical systems and for rolling mills too. All known approaches can be classified according to some common features.

Some of the authors pointed to the original chatter excitation causes beyond the strip and work rolls contact zone. Their investigations concern rolls, gears and other mill details vibration kinematics frequencies. They matched it with the chatter frequency. They stated that chatter marks on the rolls and strip are the result of resonance in the mill due to integer number of defect wave length along the rolls circumference. These models are represented in references (5,6,7,8). Other authors investigated frequencies of the elastic rolls and strip displacement as a possible source of chatter. They matched different system modes frequencies with the chatter frequency.

The electric drives and control system parameters are considered in reference (9). Author builds a stable rolling area in the domain of the stand electrical drive parameters. The friction and slipping velocity relation linearization was admitted. The electrical drive stability is discussed in references (10,11,12) too. Linear models and the transfer function method are frequently used for the complete mill dynamic describing including drives and mill automatic control system, roll stack and strip in the tandem mill (13). The linear models do not allow chatter investigating for the real plant conditions as the friction in the contact zone is a non linear force.

The next group of publications concerns the contact friction and emulsion instability as a source of vibrations (14,15). Some authors (16,17,18) successfully investigated the rolls grinding process influence on the strip chatter marks and mill vibration. They showed exact relation between usually invisible rolls surface defects after grinding and chatter vibrations in the rolling mills. Dampers and speed range control for grinding machines are proposed to avoid those causes of chatter.

The authors mentioned in reference (19) and others try to describe the positive feed-back in the mill as a linear system. The authors tried to find the mill vibration self-excitation condition due to contact friction linearization.

For the mechanical systems dynamics description the Lagrange method and equation is the most widely known approach. As it considered that the strip and rolls relative slipping appears during chatter it is necessary to assign Raleigh dissipation function in accordance with the Lagrange method. This function should describe friction forces relation with the rolling strip and work rolls relative slipping velocity and allow integrating the Lagrange equation in the definite form. Everyone before strive to define non linear friction and relative speed formulas which contain the drop zone with the "negative friction". The well known Van-der-Pole and Raleigh dissipation function formulas allow describing non damped self-excited vibrations in the system.

The new theoretical approach which allows avoiding Raleigh function by using the moving system of coordinates is described in works (20,21). The energy balance method for the moving strip kinetic energy and distributed friction forces work was used instead of the Lagrange equation. Strip back and forward tensions work are taken into account too. The nonlinear positive feedback as the cause of chatter was described and method for model based rolling mill control proposed.

It is worth to note that in the last numerous publications (22-32) during the last years authors already leaved hopes to treat chatter problem with the simple linear models as it was before. But the paradox appears. The sophisticated nonlinear models need more number and accurate parameters determination. Firstly, there are no practical methods for on-line accurate determination of the analytical dissipation function in the rolling mills moreover for the different frequency ranges. Secondly, non linear models may give absolutely unexpected in the reality results due to bifurcations at the bound of stability as it concerns high speed rolling mills.

All mentioned above difficulties for determined models initiated statistical approaches to chatter research. Some authors proposed the chaotic oscillations models for chatter investigation (33) because the rolling mills are the non conservative systems in fact.

The chatter early recognition has more development in the metal treating machines control than in the rolling mills. It is known some methods for chatter vibration prediction in drilling and cutting (34). Authors of those work used ARMA (*Auto Regression Moving Average*) model and controller. The real-time monitoring system is described which determines system damping factor and main mode frequency. Designed method was tested in the rig and showed well enough results in chatter forecasting (about 2 s before chatter onset). As the some kind of statistical approach the neural networks or fuzzy logic controllers were used to control drive line chatter vibrations (35).

PREVIOUS PRACTICE OF CHATTER RESEARCH

Since 70th years of last century the Iron and Steel Institute (Ukraine National Academy of Science, Dnipropetrovs'k) fulfilled numerous research projects related to the different dynamics problems in the tandem cold rolling and temper mills of the Magnitogorsk (Russia) and the Temirtau (Kazakhstan) plants. The dynamic processes in the drive lines were the main subject of theoretical and experimental research. The other chatter researches at the Cherepovets «Severstal'» plant (Russia) are also analyzed (36,37).

Drive torque oscillations and load balance regulator.

It was experimentally discovered in every rolling mill that the rolls eccentricity (preferably backup rolls) cause in mechanical drives large (50-70 %) torque periodic variation and much less (3-5%) drive electrical current oscillations when the mill speed was kept in the resonant ranges.

The strip product and rolls in some investigated mills at Magnitogorsk plant (Russia) were affected by chatter marks. It was analytically obtained conditions of chatter appearing depending on rolling parameters (torque, speed), teeth's wear and drives load balance regulator design. When the drive load for one roll is much less (20-30%) than for another roll then teeth couplings begin to work in a so called «shock mode» when system becomes parametrically excited by the elasticity periodic changing and beating. The rubber spindle coupling was proposed to eliminate teethes vibration influence on strip surface quality. Load balance design was corrected by feeding impact not only to upper but to lower drive too. As it following from the current chatter vibrations research such measures may have effect only in transient period of mill speed changing.

Rolls eccentricity compensation system.

Almost all modern rolls eccentricity compensation systems do not take into account phase conditions in the neighboring stands of tandem mill in the low frequency range of rolls beating. Compensation systems work independently in every stand taking as input back tension signal in every stand and using Automatic Gage Control cylinders for rolling force changing. Chatter research in the 2030 mill NLMC showed that the three middle stands №2, 3, 4 demonstrate the same phase in low frequency range (2-4 Hz) of backup rolls beating. But the stand №5 shows out of phase oscillations in this domain as working in mode «C» with constant rolling force. Therefore mill control and eccentricity compensation system may be used to reduce phase matches between stands to avoid 3rd octave chatter.

Rolls preparing process.

In the 1-stand temper mill at Temirtau plant (Kazakhstan) periodic oscillations were discovered during the finishing work rolls gritting operation. The unbalanced rotating drum caused periodic surface hardness and then chatter marks appearing on the work rolls in the temper mill. Gritting machine design (belt coupling and drum) was improved and chatter marks were eliminated.

Shocks wear and backlashes between stand housing and rolls shocks.

Next serious problem which was investigated and can not be eliminated completely in the rolling mills are the backlashes. It always exists between the rolls shocks and stand housing. Some companies proposed hydraulic liners or flat cylinders to restrict horizontal and vertical shock moving during chatter vibration. But such approach make worse strip thickness control and does not helps during 5th octave chatter as it not related with the large displacements of masses in the rolling stands. Method proposed which implies work rolls shocks back shift (instead forward) in the stand housing. Also method allows calculating rolling parameters in the mill setup procedure to avoid horizontal shocks vibration (36) due to possible changing of stand entry and exit tension difference during rolling.

Winding reels dynamics.

In some 1-stand reversing mills the coils beating compensation systems are installed. Unfortunately, majority of other mills often demonstrate interaction between the coils on the reels and first or last stands. It mostly appears when the backup rolls diameters in the last stands equal to coil diameter. Then tension begins to oscillate with the backup rolls rotating frequency while the coil diameter will change enough to cancel such kind of resonance. Another type of resonance observed in the temper mills involves reels drive line torsion oscillations with the natural frequencies or harmonics of coil rotating frequency.

Time-frequency diagrams are the most suitable means for long term process spectrums analysis in the complex drives of rolling mills (38). The two coils compared which were rolled in the 2030 tandem mill NLMC to the different winding reels (see Fig. 2). One reel (№2, further) had problems with the coil supporting rollers. It was diagnosed successfully by the stand №5 exit tension analysis. Beside it approximately 15-20% cases of chatter occurred under the constant mill speed at the end of coils when the coil and stand №5 backup rolls diameters became equal (about 1600 mm). Such cases were identified and tension oscillations avoided due to mill speed control.

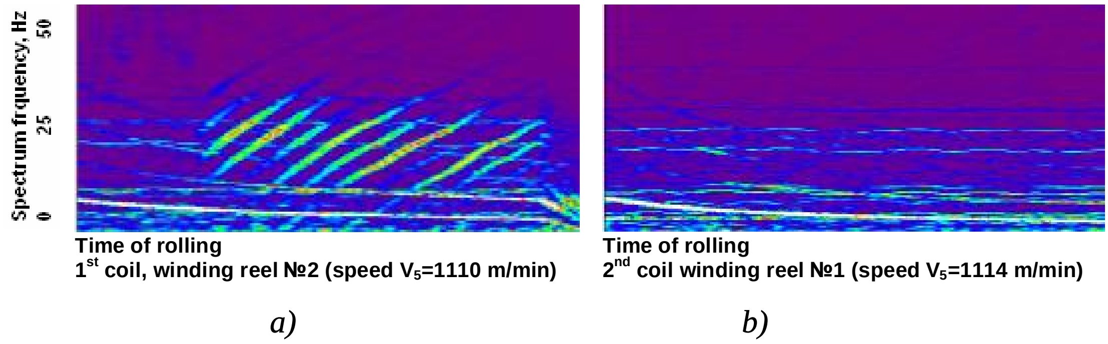


Fig. 2 – Time-frequency diagrams for the stand №5 exit tension signal in the 2030 tandem mill NLMC: a) – reel №2 (further, had problems with rollers); b) – reel №1 (hither).

Chatter and emulsion.

It was proved by many investigators before that some problems with chatter may occur due to improper emulsion feeding or contact conditions (). Among them are:

- too high temperature and pressure in the contact zone;
- too high rolling speeds;
- low emulsion concentration or bad quality;
- sprays malfunctioning and emulsion deficiency in some zones along the rolls.

It is enough difficult to make diagnosis for all those factors but it should be done to exclude its influence for sure. Even a little dry or semi-liquid friction zone along the strip and rolls contact will produce disturbance in a very wide range of frequencies. It will cause excitation of all natural modes of the roll stack in the stand.

In references (13,14) analytically shown the possibility of self-excited periodical temperature changing in the contact zone during vertical rolls vibrations. Emulsion temperature may rich upper limit when it dissociates. The conditions for vibration excitation and chatter frequency (about 120 Hz) for rolling conditions in the tandem mill 2030 NLMC were determined.

Recent analysis about emulsion concentration influence was carried out by data represented by the NLMC Engineering Center. All samples were taken at the same time in the morning and in the evening.

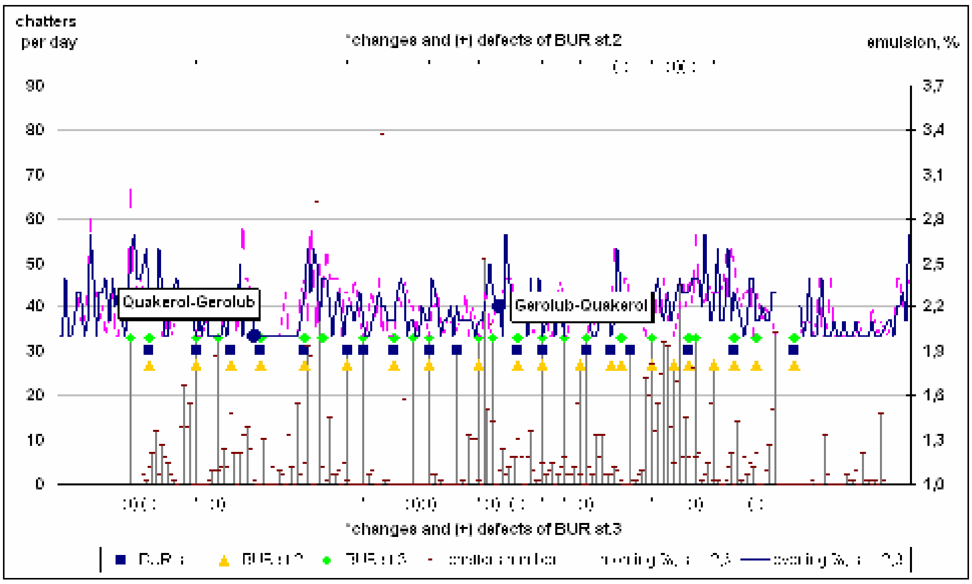


Fig. 3 – Chatter dependence on emulsion concentration (%) in stands 1, 2, 3 of 2030 mill NLMC

As it following from Fig. 3 there is no evident relation between the emulsion type, its concentration and chatter occurrence in the 2030 tandem mill NLMC. Chatter has rather dependence on backup rolls defects which are also marked on the Fig. 3. But this graph told us rather about not correct method of research (seldom emulsion sampling) than about absence of relation. Research in that direction is continuing further.

Chatter features overview in the 2030 tandem mill NLMC.

The main features of chatter phenomenon for investigated 5-stand 4-h tandem cold rolling mill 2030 NLMC are the following:

- only 3rd octave chatter occurs in all stands of this mill;
- backup rolls affected by chatter marks very seldom and only in the last 5th stand;
- work rolls affected by chatter marks never before;
- rolls grinding process is quite right, there are no surface defects after grinding;
- chatter occurs only for thin strips (exit thickness less then 0.8-0.9 mm);
- strip width has less importance on chatter occurrence;
- strips affected by visible chatter marks very seldom;
- hidden periodic thickness variations are 2-4 μm for 20 mm and 10-90 μm for 140 mm;
- "dangerous" speed depends on backup rolls surface defects and varies 600-1400 m/min;
- work rolls hydraulic bending system increases vibration levels in the stands;
- when chatter occurs mill speed drop under manual control is usually 100-200 m/min;
- strip breaks did not occur due to chatter for the last years.

Recent numerous chatter observations and research allow to formulate idea about it nature in the 2030 NLMC and possibly in the other tandem mills. It concerns rather the vibration amplification mechanism then the initial sources of vibrations which are almost all discovered before.

CHATTER SYNCHRONISATION IN THE TANDEM MILLS

As it known in the rolling mills always observed low frequency (5-15 Hz) natural or forced oscillations in the drive lines and in the roll stack. It is more for backup rolls and less for work rolls frequencies (first or second harmonics of rolls rotation frequency). Although the low frequency such oscillations cause disturbance in the strip and rolls contact zone. The slow rolling force changes may cause high frequency chatter amplification in the 3rd or 5th octave under the certain phase conditions between neighboring stands.

Chatter vibration in the four last stands 2030 tandem mill is shown in the Fig. 4a. Stands №2, 3, 4 are synchronized within low frequency range (backup rolls rotation). Stand №5 is always out of phase with the other stands (see envelop lines). Stand №5 also out of phase (see Fig. 4b) in the high frequency range too (about 118-120 Hz which is the main chatter frequency for this mill). Therefore even very high vibration level in the last stand №5 of mill 2030 NLMC almost never cause the whole mill chattering excluding the seldom cases when backup rolls already affected by chatter marks.

Synchronization phenomenon is the basic physical feature of the several mechanical oscillators (stands) interacting by the elastic connecting link (strip). Usually all stands of one tandem mill have very close main frequency of vertical vibrations. For the different mills main frequency of 3rd octave chatter varies from 90 Hz to 150 Hz. Synchronization in the tandem mills as the source for chatter vibration arising should be considered in several aspects.

Strip thickness variation and chatter regeneration.

The coil rolled under the normal vibration levels at the mill speed about 1000 m/min was taken and strip samples profile measured. In the Fig. 5 short strip sample profile (0.5 m) shown. Modern measuring devices in the mills do not able to detect such high frequency thickness variation. The whole picture of strip thickness along the coils was obtained in the inspection machine where strip moving speed was less than 60-120 m/min (maximum speed is 300 m/min). There are three thickness variation periods which correspond respectively to: 1) backup rolls rotations; 2) main frequency of vertical stand vibration; 3) bearings and teeth couplings vibrations.

It was fulfilled dynamics simulation with the spring-mass mathematic models for the twin drive lines (see Fig. 6a) and 4-high stands (see Fig. 6b) with the proper rolling parameters of the 2030 tandem mill. Model vibration signal and strip exit thickness variation is shown in the Fig. 7 for different time scale but for the same mill speed 1200 m/min. Distance between the stands for this mill is 4 750 mm. When the frequent pulse series are superposing stand is later to dissipate disturbances and chatter amplification sets up. During this process low frequency vibration beating also appears (see Fig. 7b).

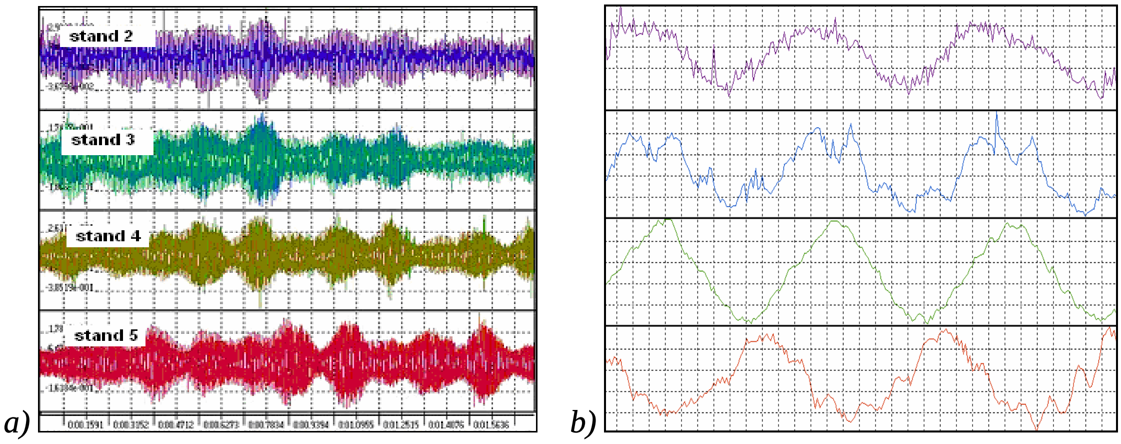


Fig. 4 - Tandem mill 2030 NLMC chatter vibration and stands №2-5 synchronization: a) backup rolls beating phases; b) chatter main frequency phases in the stands

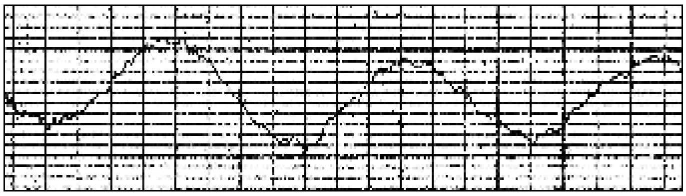


Fig. 5 – Strip profile which was rolled under the normal vibration levels (without chatter); Scales: 20 mm – horizontally; 2 mm – vertically

Frequency spectrum and envelop line for strip periodical thickness pulse sequence is shown in the Fig. 8a. Parameters of thickness variation series sequence are as following:

- **Td** – pulse series period (backup rolls diameter and stand speed dependent) (4.2 Hz);
- **T** – pulses period (main chatter frequency) (125 Hz);
- t - pulse duration (defects width 120-160 mm or 20-30 mm) (200 Hz);
- **dt** – signals sampling rate (spectrum width) (1000 Hz).

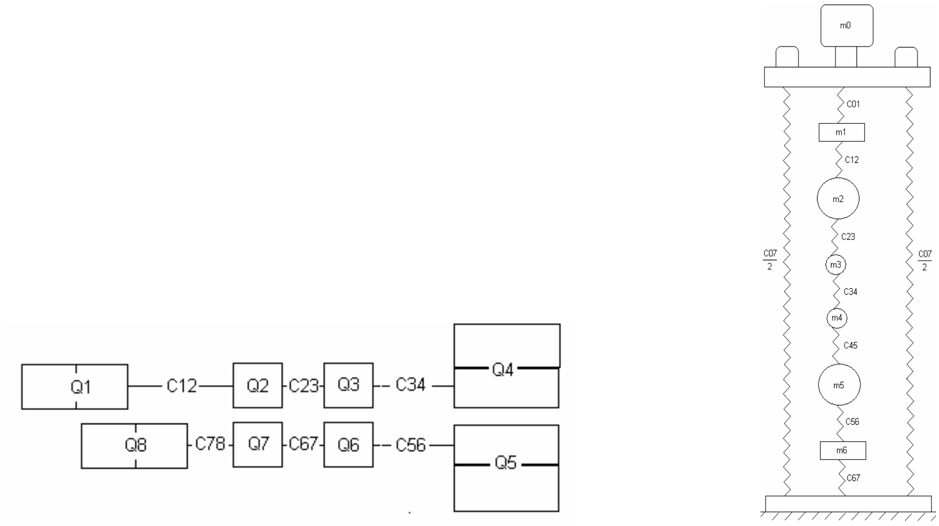
Measured chatter vibration spectrums for stands №2-5 are shown in Fig. 8b. Such picture is characteristic for every chatter case. There are always 3-5 harmonics during the rolls stack resonance in the main frequency (about 120 Hz). In mechanics for all known impacts and systems only two ones may produce such response spectrum:

1) linear systems output for pulse sequence input;
2) non linear system output for periodical (sinusoidal) input.

Both reasons may have place in the mill. The first one already exists (thickness variation) as it shown above. The second reason may appear in two cases:

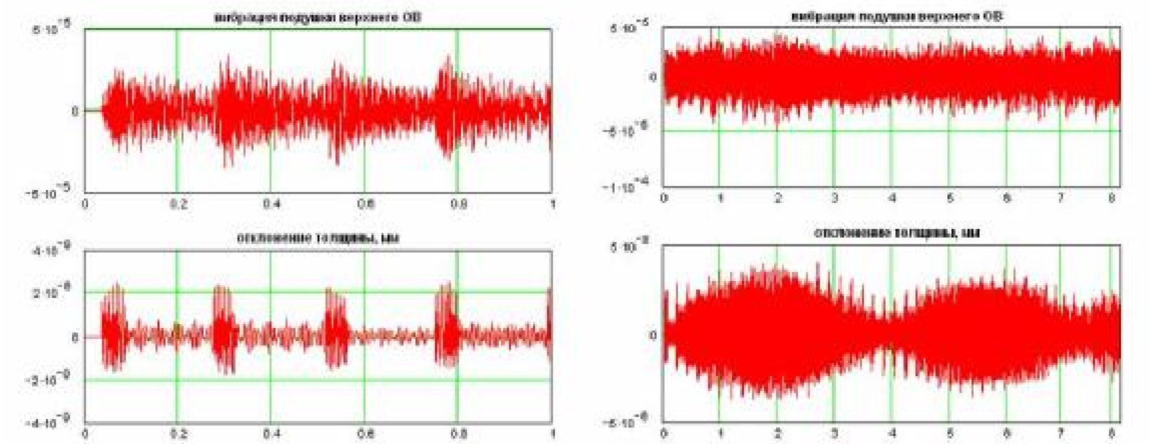
2.1) rolls slipping in the contact zone;
2.2) backlashes opening in the stand between the housing and rolls shocks.

As it concerns the first chatter amplification reason the high frequency thickness measurement function was designed in the vibration monitoring system (described below). So that to clear up second reason some additional measurements and sensors are testing in the mill now.



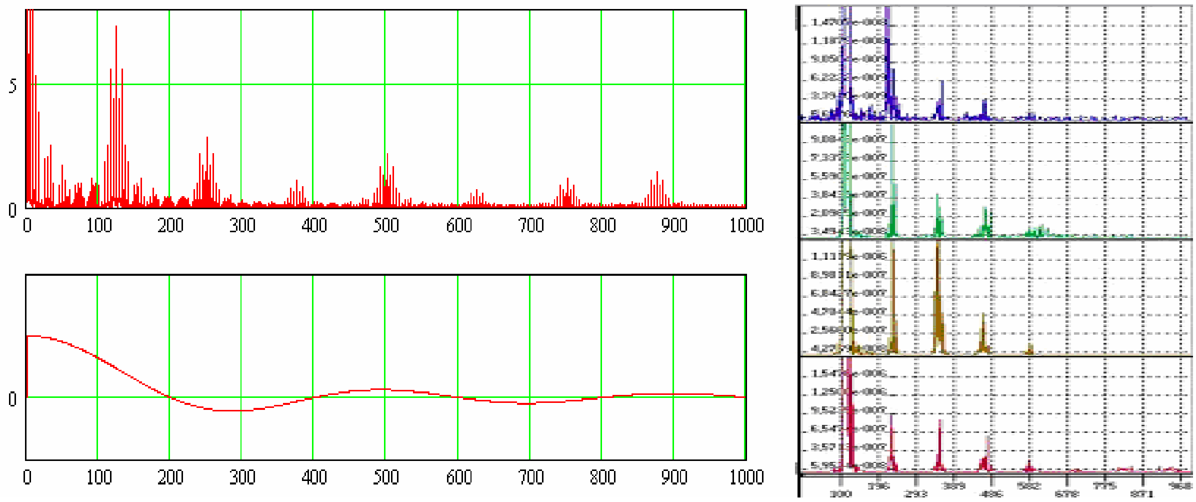
a) *b)*

Fig. 6 – Spring-mass model a) work rolls drive lines; b) 4-high stand



a) *b)*

Fig. 7 – Model vibration signals under the mill speed 1200 m/min: (vibration - upper graphs), (exit thickness variation – lower graphs); a) time scale - 1 s; b) time scale - 8 s



a) *b)*

Fig. 8 – a) model spectrum and envelop line of upper backup roll shock vibration;
b) measured signals spectrums during chatter for stands №2-5 (downstream)

Stands and strip damping properties.

It is noted in many chatter investigations before that it occurs rather for thin and hard strips (39). It is related with the strip dissipation properties. The more strip section size and more its plastic deformation in comparison with the elastic deformation determines possible energy dissipation of the rolls stack during the vertical oscillations. Spring-mass system hysteresis loop width depends on rolling parameters. In the tandem mills last sands always have narrower hysteresis loop than the previous ones and more sensibility to chatter as the rolling speed increases to the exit of mill.

Stands dissipation coefficient may be calculated during the strip breaks when the rolls stack oscillates for some time without strip in the rolls bite. It was done and decrement time about 0.3 s obtained. For the mill rolling speed 1200 m/min (20 m/s) the distance 4.75 m between stands will be passed in 4.75/20 = 0.2375 s. So the last stands after some speed limit will not be able to dissipate energy after previous impacts. And vibration amplitude will rise. Such nature of resonance vibrations called «regenerative» chatter in some publications (40). Backup rolls abnormal eccentricity and thickness variation phase matching will increase mill sensitivity to chatter.

CHATTER DAMPING METHODS

It is impossible due to rolling process nature to avoid strip hardening or to increase strip thickness greatly in the last stands of the tandem mills. Therefore one of the main directions for chatter problem solving is mill equipment dissipation ability improving. Some methods and devices are described below.

Vibration passive damping devices.

The *IAS* company (Australia) proposes damping devices (*VIP – Vibration Inhibition Piston*) which installing in the upper backup rolls balancing system (41). As it reported by designers such devices allow to increase mill speed by 25-30%.

Vibration passive damping is widely used in different machines. But it has some particularities in the rolling mills. Dampers efficiency directly depends on its ability of tuning to the resonance frequency. In general purpose machines main natural frequency varies insignificantly (±1-2 Hz). But the chatter frequency in the rolling mill may vary in the wide range (±20-25 Hz) or even changes octave. Therefore dampers should be installed in the stand carefully taking into account what kind of chatter (3rd or 5th octave) is observed preferably.

More reliable are the hydraulic liners installed between the rolls shocks and stand housing (42). However this method may cause thickness control system problems as it restricts rolls vertical moving. It was proposed in the tandem mill 2030 NLMC to test the special polymer liners for the work rolls shocks as the mean to prevent its horizontal moving due to tension changes (43).

Active suppression methods.

Active chatter suppression methods are quite popular now in the research publications (44) and patents (45). This method of damping includes the additional source of energy (preferably hydraulics) and some device which produces regulated periodic force in the rolling mill stands. There are several modifications of such approach.

1) Periodic rolling force changing in AGC cylinders through the separate servo-valve like the eccentricity compensation system. But it is difficult to compensate rolls moving with the 120 Hz chatter main frequency as the usual AGC pass band restricted by 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 is implied close to contact zone. The very little force is enough to compensate work rolls vibration.

4) Some kind of previous methods was proposed in the mill 2030 NLMC for chatter prevention. Method includes protection valve installed in the hydraulic system close to work rolls bending cylinders. It acts as the non linear element when vibration amplitude overcomes some limit. Protection valve may work separately or by the signals from the vibration monitoring system

(preferable). The tandem mill stands hydraulic block and rolls shocks section is presented in Fig. 9.

The main problem to use active damping methods is the absence of reliable high frequency hydraulic valves and exact damping force phase regulation methods. Even a little mistake in phase regulation may cause worse situation in the mill than before. In any case the vibration monitoring system is needed to produce valve control signals.

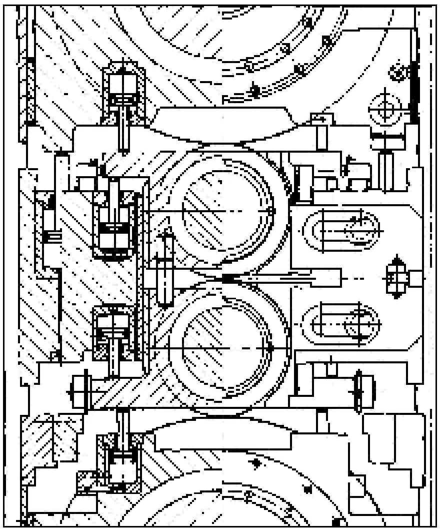


Fig. 9 – Tandem mill 4-h stand hydraulic block and rolls shocks section

There are some patents where proposed to install passive and active dampers in the tension rollers supporting elements. Natural frequency of passive supporting roller may be regulated by the stiffness (46) or mass (47) and it should be a little bit more than the chatter frequency (chatter is in the left part of roller resonance peak). Also active damping may be fulfilled by the additional drive for roller vertical vibration inducing (48). Such devices may be quite efficient as the strip tension is the link for stands synchronization in the tandem mill (49).

ROLLS HYDRAULIC BENDING SYSTEM AND BEARINGS VIBRATION.

It is well known fact that rolls bearings in the stands without bending system (in the roughing stands of hot rolling mills) serves twice longer than in stands with rolls bending. It became clearer as the Fig. 10 shows work rolls shocks deformations calculated for 900 kN «positive» (up) and 450 kN «negative» (down) maximum bending forces.

The periodic wear marks observed on the rolls necks and even in the fixed details of morgoil backup rolls bearings (see Fig. 11) for every investigated rolling mill. Shocks deformation lead to bearing defects influence and vibration level increasing.

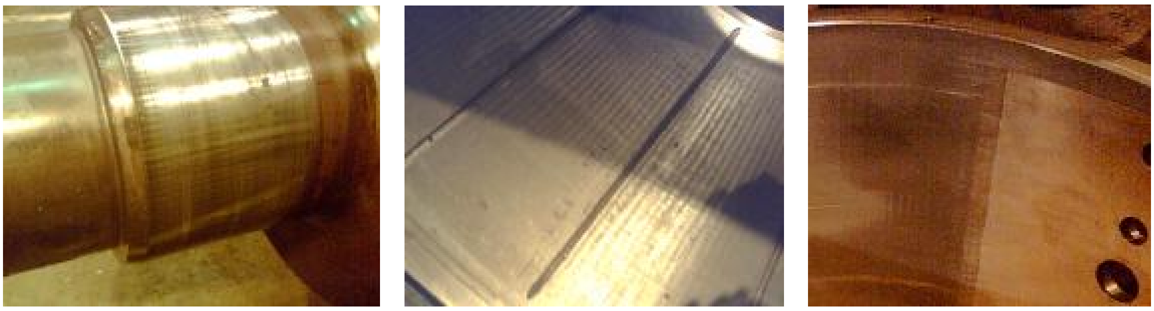
Beside it calculations with the mathematical model (see Fig. 12a) give enough wide ranges of natural frequencies for the positive forces in the range of +10…+100% (in the graph legend 1.0 means +50% relative force level). That helps to understand difficulties with chatter identification during mill working as the natural frequencies shift remarkably.

Statistical data processing showed that the available maximum mill speed is dependent on rolls bending forces in all three last stands.

It was fulfilled experiments without strip and the rolls bending force changing in the stands №3 (has only positive bending) and №4 (has both bending) at the 600 m\min speed. Vibrations levels (RMS) measured are shown in the Fig. 13. Vibration begins to increase after +50% bending force level in the stand №3 and it has smoother curve in stand №4. So it is preferable for the thin strips rolling at the high mill speeds to have such rolls profiles so that was no need to keep more than 50% bending forces in the last stands.

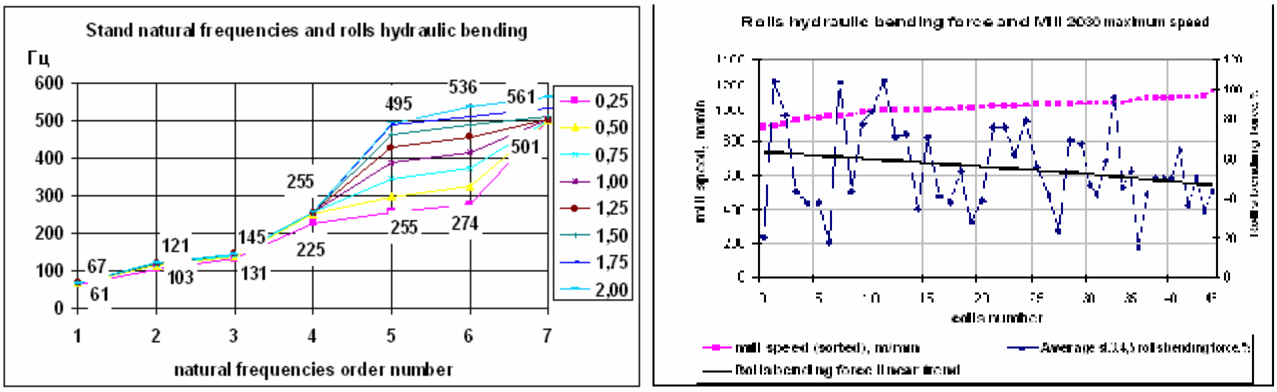
a) b)

Fig. 10 – Work rolls shocks deformation under the maximum bending forces: a) «Positive» (up) 900 kN force; b) «negative» (down) 450 kN force



a) b) c)

Fig. 11 – Periodic wear marks on the rolls neck and in the elements of backup rolls bearing



a) b)

Fig. 12 – a) Stand natural frequencies changing ranges due to rolls bending system; b) Available tandem mill speed and average three last stands bending force

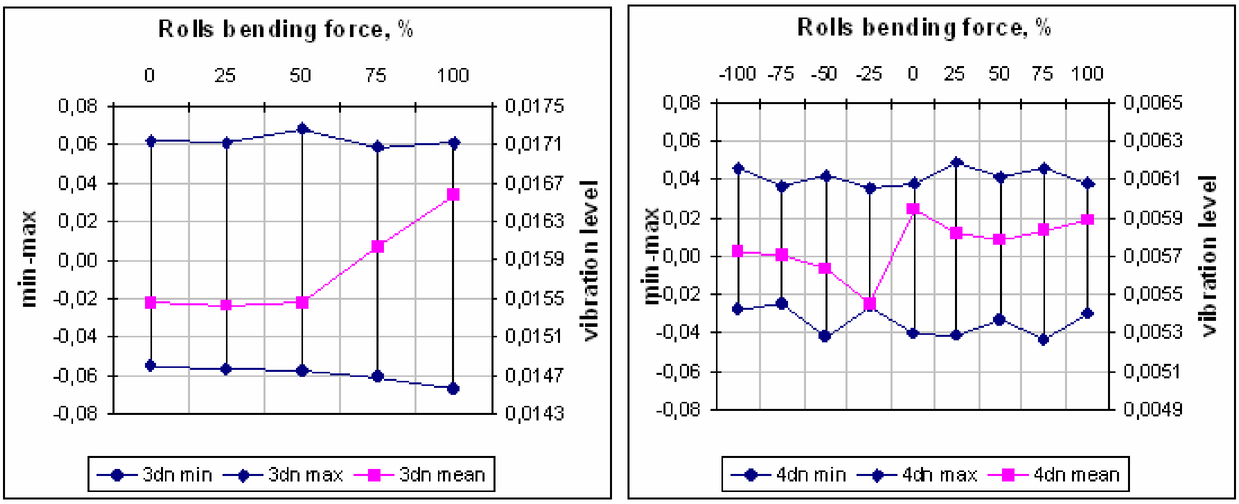


Fig. 13 – Rolls bending force influence on vibration levels in the mill 2030 stands №3, 4

VIBRATION MONITORING SYSTEM DESIGN

The first chatter monitoring system was installed in the 2030 NLMC tandem mill in 90th yet. It was designed by plant people and collected analog signals from the hydraulic pressure sensors in the automatic gauge control system. This system provided mill operators with the three level alarm signals and fulfilled automatic mill speed reducing when chatter occurred (50).

In the 2003 *"ALSTOM"* company updated mill automatic control system and the *IAS* Company (Australia) installed *"VIDAS chatter monitor"* with the 6 channels for vibration control and some additional channels for rolling parameters logging. Sensors installed in the three last stands №3, 4, 5 on the top and bottom backup rolls shocks on the rolls service side.

It was necessary to improve monitoring system for such functions including: mechanical mill parts diagnostics, additional rolling process on-line calculated parameters monitoring (neutral angle value, high frequency strip thickness variation, balance of horizontal forces on work rolls shocks) which have influence on mill vibration. Also the needs of new methods for chatter early diagnostics and mill speed automatic control initiated the newly vibration monitoring system research and development (51). For rolls defects and chatter marks diagnostics additional sensors was installed in the stands №1, 2. The new system is designed with account of all known before features (19,38).

The vibration monitoring system research and development project included:

- mathematical models design and identification for stands synchronization research;
- stands and drivelines investigation, natural and kinematic frequencies determining;
- rolling technology inspection for chatter possible causes discovering;
- development and suppling vibration monitoring and diagnostics system;
- mill automatic control system influence research;
- methods development for chatter early diagnostics and mill automatic control;

Stands and drive lines kinematics frequencies tracing.

Separately upper and low work rolls drives angle speed and drive loads signals are obtaining by the monitoring system from the mill automatic system.

For suitable kinematics analysis in the monitoring system was developed color scaled time-frequency diagram. As an example for stand №5 of mill 2030 NLMC Fig. 14a shows gearbox teeth frequency trace during rolling speed changing. The main stand natural frequency is observed there as horizontal line. Backup rolls beating intervals repeated in the spectrum amplitude changing.

Such the outlying drive lines elements as overload protection teeth couplings between motors and gearboxes are well hearing by the sensors on the backup rolls shocks (service side). So the wear of such elements even far from rolls is important for stand excitation during chatter. Also the gearbox couplings frequency is very loud in the signals on the stands. But the spindles teeth couplings although the closest to stand elements are visible in the spectrum only before repairing term (with large wear). It was discovered stand vibration amplitude increasing for speeds where bearing frequencies match with main chatter peak in the spectrum (115- 120 Hz).

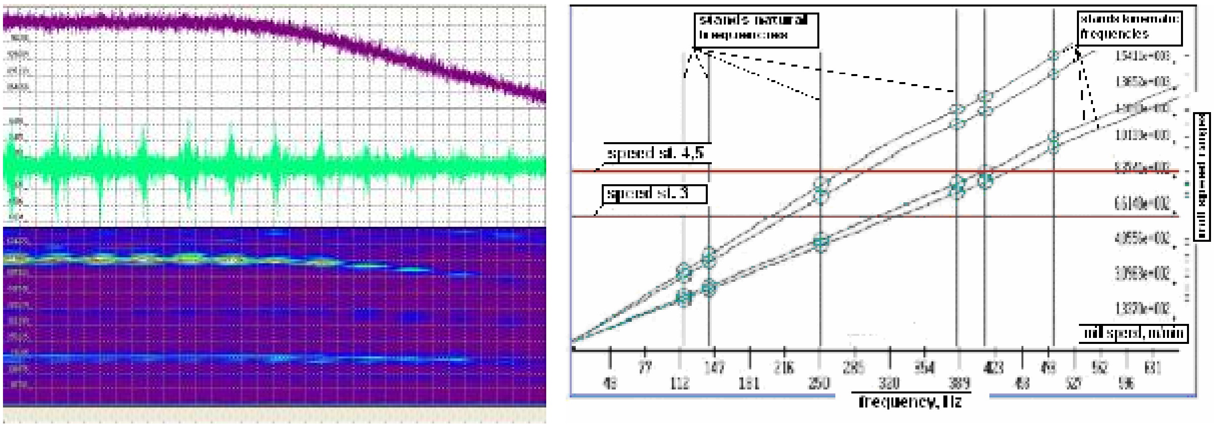
Vibration levels increase when some kinematical and natural frequencies match. For suitable avoiding of resonance speed ranges it was designed mill frequency diagram (see Fig. 14b). Operating mill even in higher speed may be less dangerous for chatter. Successive passing of such speed ranges may be done manually by mill operators in assistance with the designed tool.

Vibrations records statistical processing.

Vibration monitoring system fulfills current data logging in two modes (two file types):

- high frequency (about 10 kHz) alarm mode when chatter occurs;
- low frequency (about 5Hz) continuous mode for every coil.

High frequency files allow to make spectrum and correlation analysis of such quick processes like automatic speed control. Low frequency files allow fulfilling overall shocks bearings defects and rolling condition analysis by the vibration average level and in all kinematics frequencies amplitude. The example of such analysis for stand №3, 4, 5 is shown in Fig. 15. Step like lines correspond to backup rolls changes in all mill stands №1-5 (upstream).



a) *b)*

Fig. 14 - a) Kinematical frequency tracing example (gearbox teeth coupling in stand №5); b) Frequencies diagram for mill operator on-line speed ranges choosing

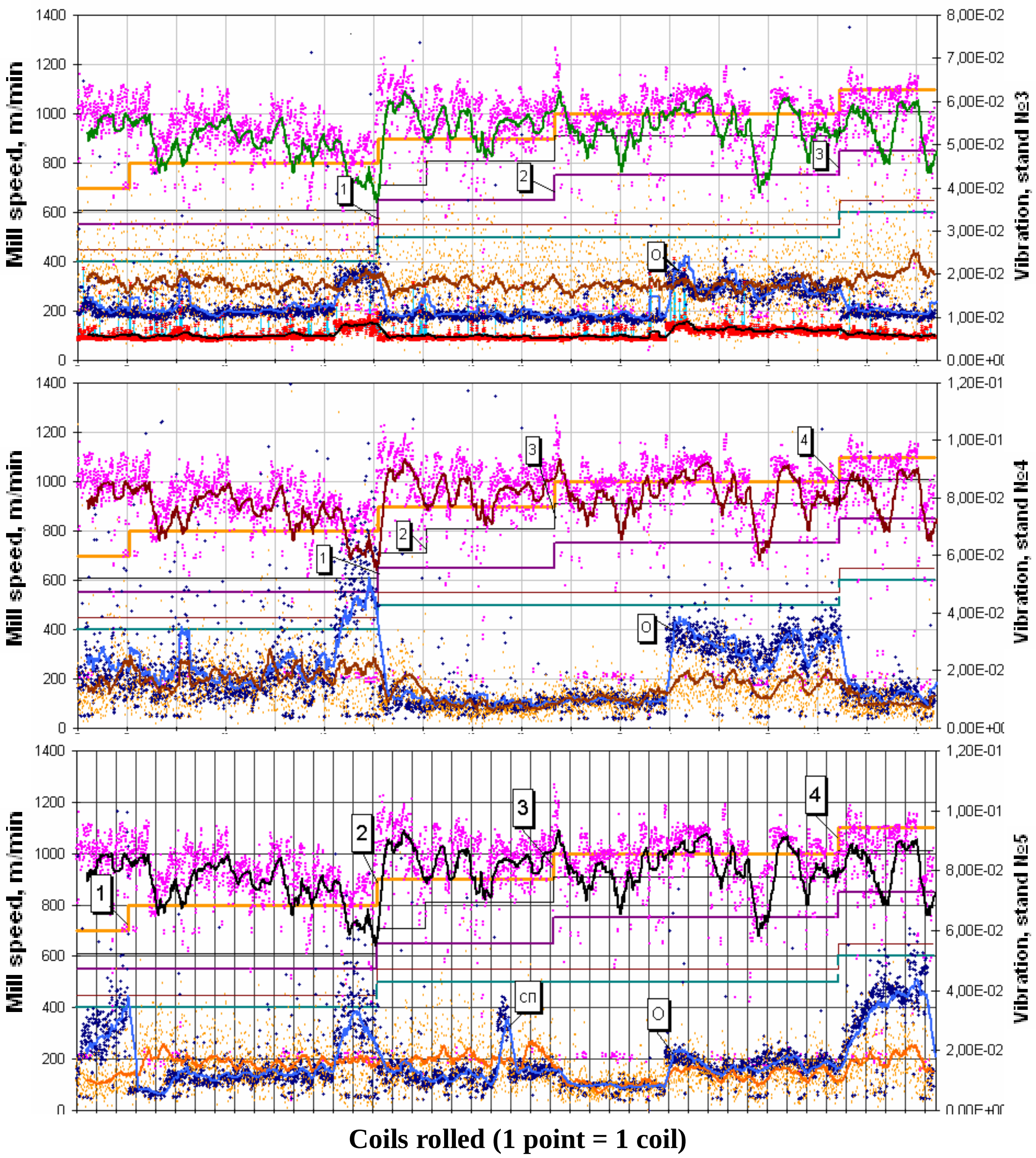


Fig. 15 – Vibration data files statistical processing

The signs in the rectangular frames on graphs in the Fig. 15 show some trouble events in the mill ("o" - strip break, "1, 2, 3, 4" – backup rolls surface defects, "cn" – work roll bearing crash). All point lines smoothed by the usual moving average filters in order staff could make a decision about mill speed (the very upper lines) and the other sources of vibration trends interrelation. As an example the backup rolls frequency amplitude (yellow-brawn curves) along with overall vibration levels (blue curves) in the stands are quoted. Diagnosis may be fulfilled by the comparison of those values for some time. If rolls beating spectrum component is small but overall level is high it means that rolls have surface defects. When was the work roll bearing crash in stand №5 it had no effect backward but rolls defects in the previous stands affect the last stands.

Rolling process parameters control.

Rolling parameters on-line control in the vibration monitoring system allows to determine some dynamics conditions which lead to mill instability. First condition is when epy neutral angle shifts beyond the contact zone (rolls slipping). Second condition is when the work rolls shocks begin horizontal beating. Both instabilities caused by tension oscillations in conjunction with the other rolling parameters.

The other reliable method to achieve more high rolling speed is the tension levels decreasing in the last stands. Decreasing tension forces make weaker links between stands. In order to clear up the efficiency of such method for chatter prevention the series of experiments were carried out in the tandem mill 2030 NLMC. Specific tensions between stands №2-5 were from 130-150 kN/mm^2 to 90-100 kN/mm^2. For strip thickness 0.5-0.6 mm available mill speed was increased by 50-100 m/min without chatter occurring. But with tension 100 kN/mm^2 for stands №4-5 strip lost stability and the rolls surface was damaged. Hence method has technology restrictions.

Work rolls shocks horizontal forces balance control.

Work rolls shocks horizontal moving appear when the both tension forces and rolling force horizontal component (due to work rolls shifting in the stand) balance violated. Backlashes opening and rolls shocks begin vibrate in the stand housing which further lead to chatter in the tandem mill. To prevent such dynamic effect the vibration monitoring system controls horizontal forces balance and gives alarm signal when it violated in any stand (52). This method is more suitable than the hydraulic liners mentioned above as it does not interacts with the AGC system.

Measuring the high frequency strip thickness variation.

As it mentioned above the high frequency strip thickness variation appears in the mill even during the normal rolling conditions (without chatter). Thickness wave amplitude may overcome standard deviation and cause product rejection by customers. It was assumed that the last stand vertical vibrations have most influence on strip thickness variation. Therefore method for such quick periodical defects measuring was designed based on vibration signals in the last stand.

It is necessary to know exact phases between backup and work rolls moving as the accelerometers mounted on the backup rolls shocks. Four sensors were used for temporary measurements in every roll shock and analytical relations were obtained which allow thickness calculating by the vibration signals. As the 3rd octave vibration occurred for the most cases the upper and low rolls move in phase.

Method includes accelerometers signals filtering, double integration and some additional operations which allow obtaining accurate results. Then method accuracy checked by the direct strip samples thickness measurements. Hydraulic work rolls bending system influence also been taken into account and the bending forces signals had been inputted into the vibration monitoring system.

CHATTER EARLY DIAGNOSTICS METHODS AND MILL CONTROL

Tandem mill vibration spectrum analysis showed that the main chatter frequency peak (100-120 Hz) has many side bands peaks ($\pm k \cdot f_{BUR}$, k=1,2…5) which usually corresponds to backup rolls rotation frequency harmonics (see Fig. 16). Right before chatter onset interrelation between the main peak and side bands peaks changes. In the time domain vibration signals demonstrate amplitude modulation effect.

It was proposed algorithm for on-line chatter conceiving diagnostics and tandem mill control. It allows chatter determining earlier than by known spectrum amplitude method (53). Some other additional phase conditions are taken into account for more reliable prediction.

The new methods give an opportunity to build automatic control system for rolling mills speed optimal control. When chatter amplitude is small yet the speed drop value may be less than 10 m/min and it is enough to prevent further vibration increasing (see Fig. 17). In this way average mill speed increases and maximum available speed too (see Fig. 18, Fig. 19).

Tandem mill 2030 NLMC automatic control efficiency parameters quoted in the Table 1 and in the Fig. 20 for several months. First mill work period taken April-June 2006 under the manual control and it is compared with the period July-September 2006 under the automatic mill speed control by the new methods from monitoring system.

Tandem mill 2030 NLMC automatic control efficiency parameters. Table 1

Absolute mill efficiency parameters	Manual control				Automatic control			
	April	May	June	Average	July	August	Sept.	Average
Average mill speed, m/min	862	901	895	**886**	1010	1006	926	**980**
Maximum mill speed, m/min	1137	1159	1197	**1165**	1274	1244	1257	**1258**
Speed drop value, m/min	107	94	39	**80**	13	60	92	**55**
Relative mill efficiency parameters	**Manual control**				**Automatic control**			
Average speed increasing, %	-	-	-	-	13,91	13,51	4,45	**10,62**
Maximum speed increasing, %	-	-	-	-	9,41	6,78	7,90	**8,03**
Speed drop values decreasing, %	-	-	-	-	-83,75	-25,00	15,00	**-31,25**

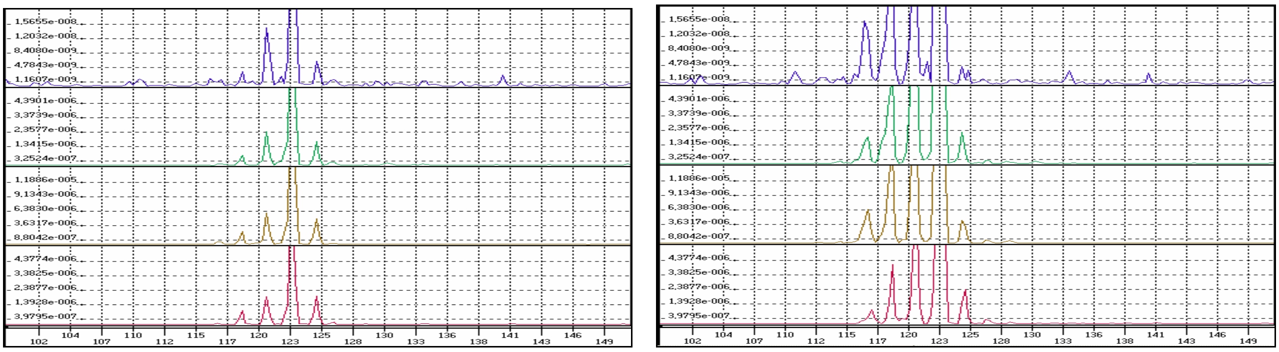
The general expression about vibration monitoring system interposition (taking into account tandem mill operator’s opinion) is as following:

- reliable early chatter diagnostics (90% cases, not later than 3-5 s before chatter onset);
- minimal available speed drop value under the automatic mill control (10-30 m/min);
- quick mill speed restore after speed drop;
- strip periodical defects reducing caused by chatter vibration;
- rolls chatter marks reducing;
- average and maximum mill speed increasing.

It was noted in the past that right after every mill «roaring» operators could not rich previous speed level. It may be related with the temporary rolls surface affecting by chatter marks which disappear later after 1-2 coils rolling. So the automatic mill control helps to avoid large vibration amplitudes and provides quick speed restore.

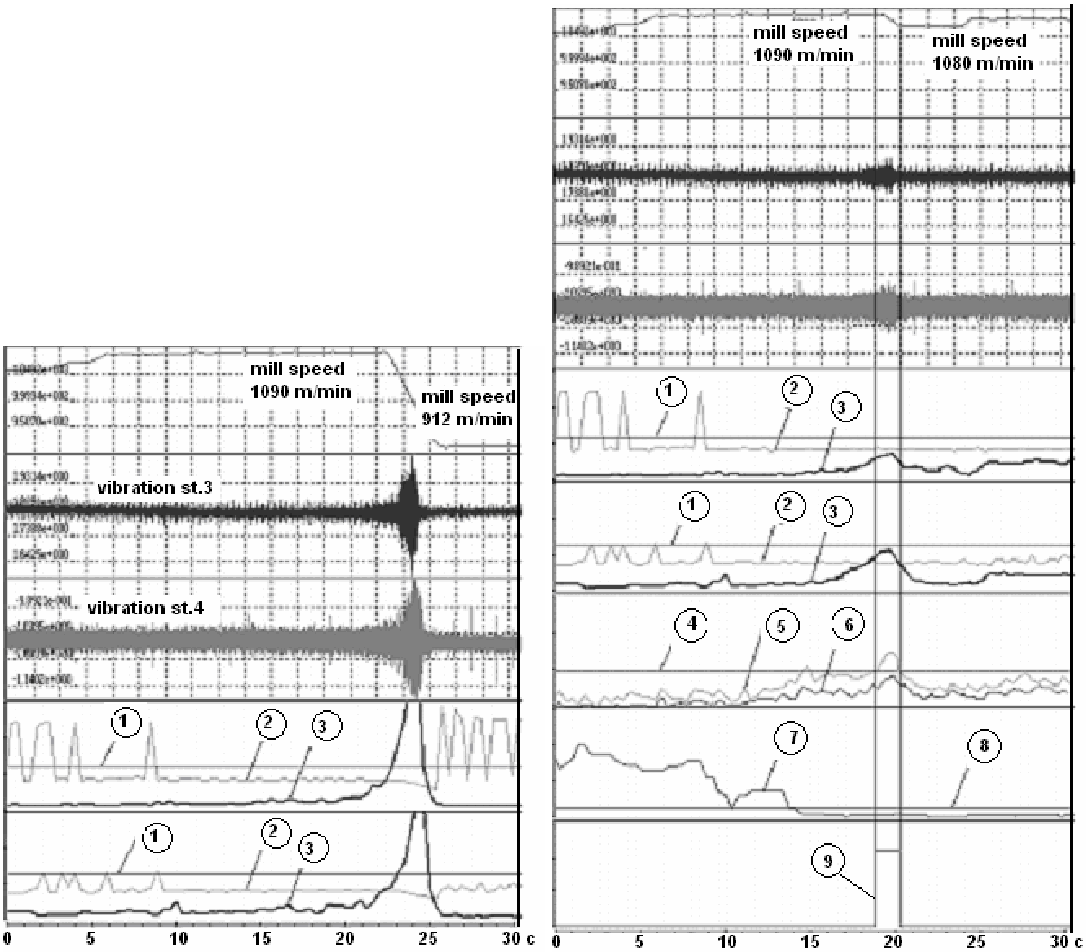
Automatic mill control estimation should be done with taking into account accelerometers malfunctioning from the 15th August to the 8th September 2006 when sensors in stands 2up, 4up, and 5dn were restored (changed). Nevertheless vibration monitoring system continued mill control but with less efficiency. It proves reliability and stability of new methods for chatter diagnostics and most important for mill automatic control.

Also sensors failures initiated the self diagnostics function development in monitoring system. The evident cables and sensors damages (dead short) are possible epyto discover by the standard means embedded to the signal conditioning blocks. But the detailed signals analysis during the system hidden malfunctioning is almost impossible by the mill staff.



a) *b)*

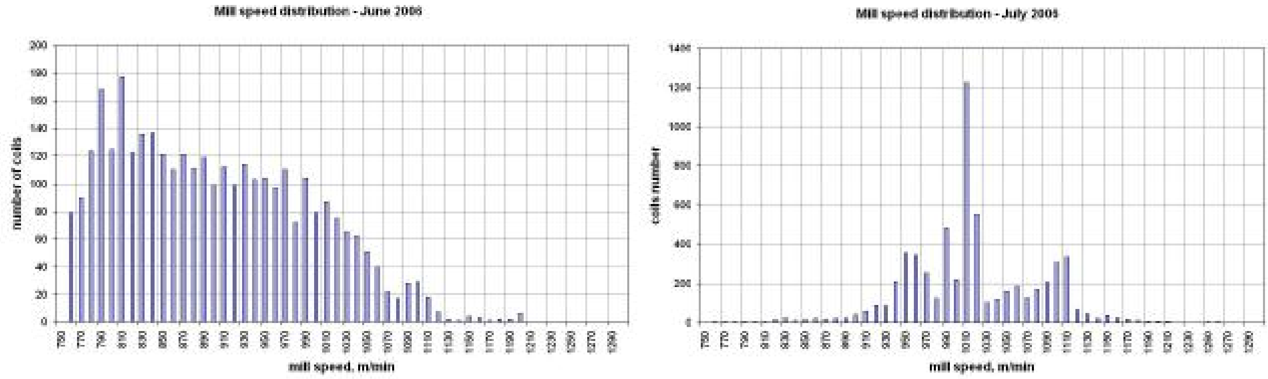
Fig. 16 – Chatter main peak and side band peaks in the vibration spectrum (stands 2,3,4,5):
a) under the normal vibration levels;
b) during vibration levels rising



a) *b)*

Fig. 17 – Chatter early diagnostics and tandem mill 2030 NLMC speed control:
a) manual control by the mill operator and visual chatter control (stands 3, 4);
b) automatic control by the signal from vibration monitoring system;

1 – spectrum amplitude alarm level; 2 – spectrum peak frequency; 3 – spectrum current level; 4 – chatter index №2 alarm level; 5, 6 – chatter index №2 current levels for stands 3,4; 7 – chatter index №1 current level; 8 – chatter index №1 alarm level; 9 – mill speed control signal



a) *b)*

Fig. 18 – Tandem mill 2030 NLMC speed distribution:
a) under manual control (June 2006) by the operator;
b) under automatic control (July 2006) by the vibration monitoring system

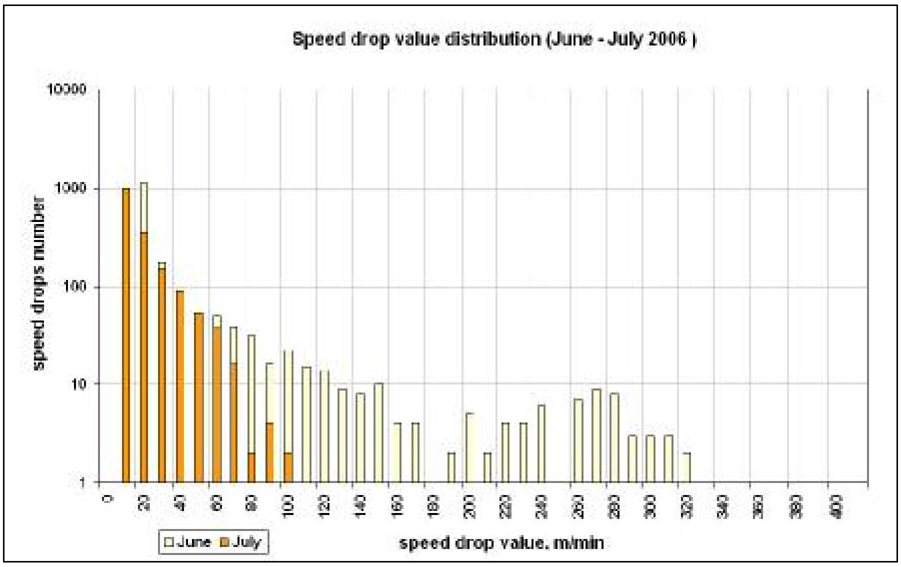


Fig. 19 - Tandem mill 2030 NLMC speed drop value distribution:
a) June – under manual control; b) July – under automatic control

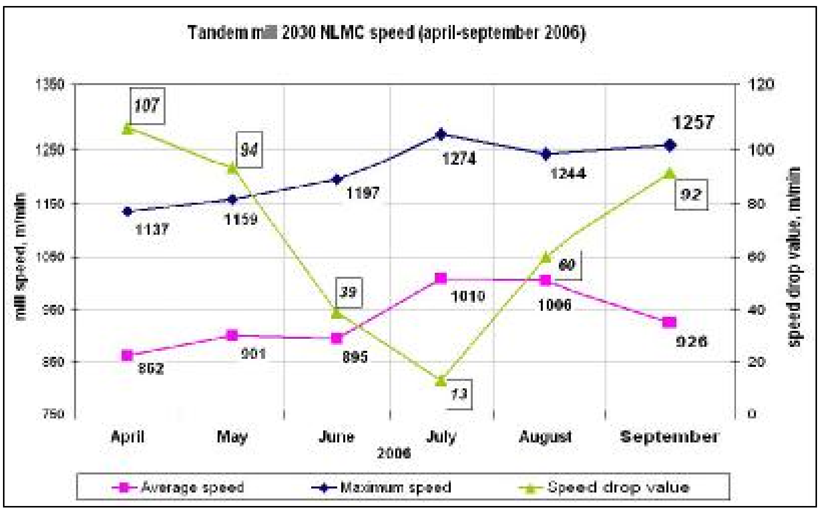


Fig. 20 – Mill speed automatic control efficiency estimation

SUMMARY

1. Extensive chatter vibration research has been carried out in the 5-stand 4-high tandem mill 2030 NLMC and practice of many different causes is discussed. The high frequency strip thickness variation is considered to be more credible and measurable cause for chatter in the tandem mills.

2. Thickness variation appears in the strip as during vibration resonance so under the normal rolling condition and vibration levels (without chatter). Chatter amplifies due to vibration phase matching and synchronization between neighboring stands as in the low so in the high frequency range.

3. Thickness variation pulse impact mathematical simulation on the spring-mass 4-high stand model shows response vibration modulation which is very close to the measured signals in the mill. The main chatter frequency harmonics are characteristic for vibration spectrum.

4. Strip damping properties in the contact zone play the most remarkable role for the chatter vibration energy dissipation. As the strip reduction schemes is restricted by rolling technology the chatter damping methods and devices are proposed to reduce vibration amplitude in the last stands.

5. Rolls hydraulic bending system and bearings vibration is investigated and way to avoid its influence proposed (rolls profiling).

6. Vibration monitoring system is developed for chatter diagnostics in the tandem mills. System features include all previously known tools and some newly developed ones. Rolls and bearings diagnostics is available in the system. The new function for high frequency strip thickness variation measuring is developed.

7. The new methods for chatter early diagnostics are developed and used for tandem mill automatic control. Mills efficiency statistical analysis for three months period showed that new system increases: maximum available mill speed – by 11%, average mill speed – by 8%. Strip and rolls defects decreased significantly as the stands vibration not exceeds low levels at high speeds.

8. The next step of the automatic control system development is the other rolling parameters control (stands reduction scheme, tension forces) along with the mill speed variation.

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