811. Frequency analysis of chatter vibrations in tandem rolling mills

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Abstract. Chatter in high speed tandem mills affects the quality of the product and the production rate of the rolling mill. It may also cause damage to mill components and strip rupture. To monitor chatter generation within the rolling mill, it is highly recommended to use online chatter detecting systems. This paper presents a set of guidelines to optimal control and prevention of chatter in rolling mills. Investigation is based on experimental results of the third octave chatter in a two-stand tandem rolling mill. Online vibration monitoring system that was used has provided different acceleration signals from various components of the rolling stand. Acceleration signals have been analyzed by a vibration analysis toolbox. Frequency analysis and signal processing techniques were used for examining the vibration data. From frequency spectrum analysis it is found that the prominent frequency in the vibration spectrum of the upper backup roll is the most significant one. It is demonstrated that the upper backup roll and top housing are more sensitive to chatter than the work rolls and they are suitable locations for installing the permanent acceleration sensors for chatter warning system.

Keywords: frequency analysis, vibration, rolling, chatter, experiment.

1. Introduction

Cold rolling is the most vital process in manufacturing flat sheet products. During the cold rolling of thin metal sheets, undesired mechanical vibrations, generally referred to as chatter, are often generated. It usually lowers the surface finish of the sheet and in some cases causes gauge variation. It may also cause severe damage to the rolling mill and strip rupture under extreme conditions [1]. Chatter is characterized by a very sudden occurrence [2] and was called "ghost vibration" by the operators of the milling plants [3].

It has also been found that as mill speeds are increased the system goes to instability [1, 4-10]. As the need for low-cost and high-quality products increases, prevention of chatter phenomenon becomes an important task in the rolling industry.

Chatter has three predominant types: torsional, third octave and fifth octave [6, 10-12]. Typical frequencies of torsional chatter occur between 5 and 25 Hz. The third octave chatter, in which the vibration frequency is usually in the range of 100-250 Hz, often occurs in cold rolling of thin strips. The main feature of this chattering is that the strip thickness greatly fluctuates. The fifth octave chatter, usually occurs in the range of approximately 500-700 Hz, displays no measurable gauge variation, but the alternating light and dark lines can be shaped in roll or strip surface. According to frequency dependency nature of chatter, frequency analysis of this phenomenon is a useful way to detect and suppress it.

Several theoretical research studies have been conducted to model chatter vibrations in rolling [1, 6, 9-11, 13]. Consequently a large number of mathematical models for the rolling process have been established with various degrees of simplification. In these studies it is attempted to understand the causes of chatter without using extensive experimental tests. Many researchers reported enough experimental findings in this respect [6, 14-18] and they will be used in this study.

Several approaches have been made to provide significant insights into the chatter phenomena and are used to investigate control methods for suppression of instability in this process [1, 16, 18, 19]. As a result, advanced chatter monitoring instruments were implemented. The frequency analysis of the rolling mills is presented in some articles to be used to predict the dynamic behavior of rolling stands [3, 15, 20]. The influence of friction on chatter is studied and the conclusions are reported in the literature [6, 21-23]. It is found that either too low or too high friction leads to system instability and there must be optimum conditions for the friction where chatter can be prevented [6, 22].

An effective signal processing method can provide more evident information from vibration signals. Thus, there is a considerable interest in vibration analysis and signal processing in this area [14, 15, 17, 24-26].

Investigation of the dynamic behavior of cold rolling mills is the main objective of this research. It is sought to understand the nature of chatter phenomenon experimentally. Accordingly, online tandem mill instrumentation and advanced chatter monitoring equipments were used. Frequency analysis of measured data is carried out. In order to improve the presented results, signal processing algorithms were applied to vibration data. Finally, some guidelines for a better detection and suppression of chatter in rolling mills are presented.

2. Different mechanisms of third octave chatter

Four significant mechanisms for the third octave chatter that have been defined up till now are model matching, negative damping, mode-coupling and regenerative [10-12, 27-31].

In the model matching mechanism the single-stand rolling mill becomes unstable because of the overall negative damping and spring coefficients generated by the coupling of the rolling process and mill structure [11, 12]. The coupling of the rolling process model and the mill structure model combines the components from both models and the resulting single-stand chatter model may possess completely different behaviors. That is, the combination of two stable systems may produce an unstable system if the two systems are not well-matched. The model matching effect usually does not lead to instability of a single-stand rolling mill in the practical range of the rolling process parameter settings [11, 12].

Negative damping is possibly the most direct cause leading to the onset of third octave mode chatter in a single-stand rolling. As pointed out in many literature sources [10, 11, 21, 22, 32] tension variations caused by mill vibrations generate roll force variations which, in turn, induce further vibrations, and thus can be viewed as a negative damping effect. It should be noted that the negative damping mechanism is different from the model matching mechanism, in the sense that the model matching instability is purely a result of the interactions between the rolling process and the mill structure of a single stand in a tandem mill configuration, while the negative damping mechanism is caused mainly by variations of the strip tension. The coupling of two or more of the principal modes of vibration of the mill may also be responsible for dynamic instability of the rolling process. This mechanism is named mode coupling. Such instability is possible in machining operations, depending on the principal modal directions and the direction of the cutting forces [33]. Paton and Critchley [34] showed experimentally that the work rolls do indeed vibrate in the horizontal direction as well as in the vertical direction. In order to investigate this, Yun et al. [10] presented a multi-modal chatter model by combining the multi-modal structural model and the model of the rolling process.

Regenerative effect is an important factor which may lead to instability in a rolling tandem mill [6, 10, 11, 21]. The regenerative effect in rolling can be found in the following way: the vibration at the current stand causes a variation of the strip velocity at entry; this velocity variation then, through inter-stand interactions, immediately affects the upstream stand and causes a gauge variation, which after a time delay enters the current stand again. That is, the strip thickness variation that influences the rolling process is generated by the same stand at a prior time.

3. Experimental equipment

This paper relates to the experimental investigation of third octave chatter on a two-stand tandem mill unit of Mobarakeh Steel Company (MSC). Fig. 1 shows a view of this unit.

Fig. 1. Two-stand tandem mill unit of Mobarakeh Steel Company

Incoming coils of this unit are often 2 mm in thickness. They open up and pass through two 4-high stands two or three times. Usually thicknesses of the strip were reduced by 60 to 90 percents depending on desired thickness. Outgoing strip from the second stand in any pass is coiled by a coiler machine (Pickup reel). The pickup reel of the previous pass plays role of the pay-off reel for the current pass which is in the reverse direction of the previous pass. In practice in this mill, chatter usually occurs in the second stand during the third pass.

Rolling control instrumentation in two-stand tandem mill unit consists of tens of analog and digital signals, all connected with a data collection system (IBA). All rolling conditions are recorded in this system and can be used online or offline. To evaluate the status of the rolling system in chatter conditions, rolling speed was increased for the moment. This is done by the operator via online monitoring system which is shown in Fig. 2.

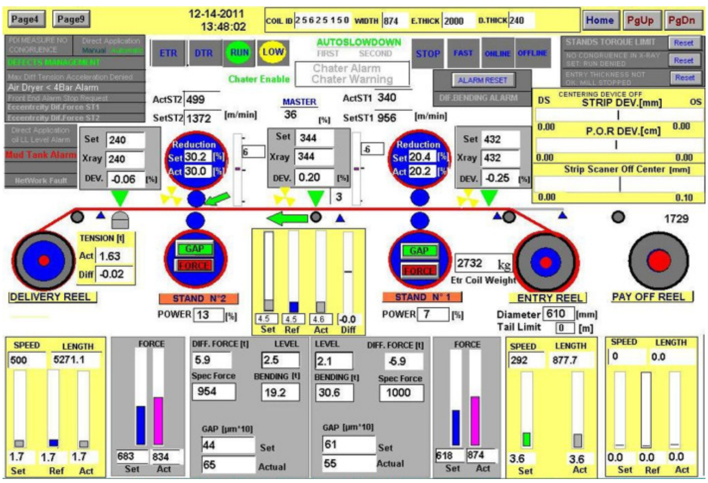


Fig. 2. Online monitoring system to control the rolling process

In this study, two different experiments were conducted for analyzing the rolling vibrations. In each case four magnetic accelerometers have been installed on the chocks of the rolls and stand housings. Accelerometers which were used in the experiments were cylindrical in shape and were able to measure acceleration merely in the direction parallel to their axis. The accelerometer positions in each case are shown schematically in Fig. 3.

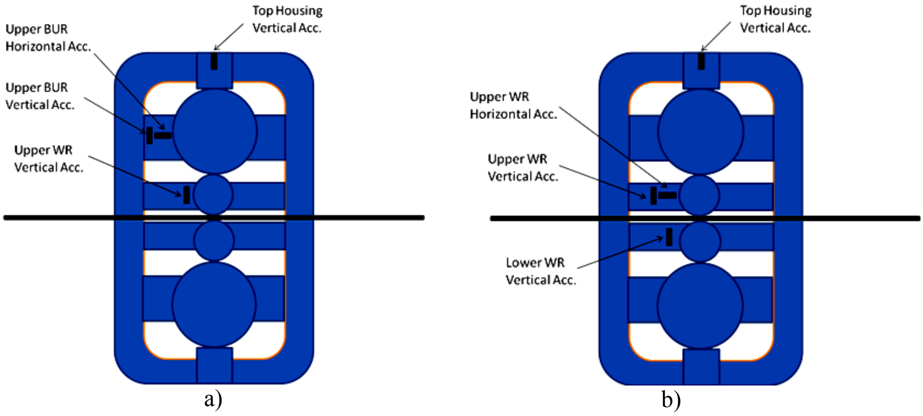
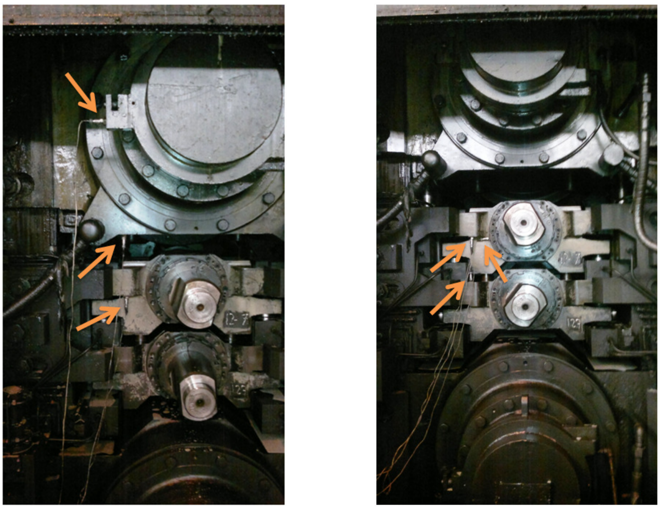


Fig. 3. Schematic view of accelerometer positions: a) first experiment, b) second experiment

In any experiment number of portable accelerometers was limited to three. In addition, the stand is equipped with a permanent accelerometer which is fixed on top housing. As it can be seen, the vibrations that have been measured in the first experiment are: vertical acceleration of the upper work roll, vertical and horizontal accelerations of the upper backup roll and vertical acceleration of top housing. In the second experiment the following vibrations have been measured: vertical acceleration of the lower work roll, vertical and horizontal accelerations of the upper work roll and vertical acceleration of top housing. Fig. 4 shows how the accelerometers were mounted on rolling stand in practice.



a) b)

Fig. 4. Installation of accelerometers on chocks: a) first experiment, b) second experiment

Rolling conditions in the first and second experiment are presented in Tables 1 and 2 respectively. Mill stand configuration is shown in Table 3.

Acceleration signals have been analyzed by a Portable Vibration Analysis Toolbox (PVAT). Fig. 5 shows a view of the PVAT system.

Table 1. Rolling conditions in the first experiment

Parameter	Stand 1	Stand 2
Backward tension (MPa)	93	148
Forward tension (MPa)	148	80
Rolling force (MN)	6.1	6.8
Yield stress (MPa)	1047	1090
Critical rolling speed (m/s)	10.82	17.82
Friction coefficient	0.0092	0.0099
Strip width (m)	0.842	0.842
Entry thickness (m)	$444 \cdot 10^{-6}$	$340 \cdot 10^{-6}$
Exit thickness (m)	$340 \cdot 10^{-6}$	$220 \cdot 10^{-6}$

Table 2. Rolling conditions in the second experiment

Parameter	Stand 1	Stand 2
Backward tension (MPa)	96	144
Forward tension (MPa)	144	77
Rolling force (MN)	6.8	7.8
Yield stress (MPa)	1024	1068
Critical rolling speed (m/s)	10.8	16.1
Friction coefficient	0.012	0.011
Strip width (m)	0.818	0.818
Entry thickness (m)	$537 \cdot 10^{-6}$	$399 \cdot 10^{-6}$
Exit thickness (m)	$399 \cdot 10^{-6}$	$280 \cdot 10^{-6}$

Table 3. Parameters of mill stand configuration

Parameter	Stand 1	Stand 2
Distance to previous reel or stand (m)	5.675	4.725
Distance to next reel or stand (m)	4.725	6.6
Work roll radius (m)	0.245	0.245
Backup roll radius (m)	0.675	0.675
Work roll and chock mass (kg)	14000	14000
Backup roll and chock mass (kg)	38000	38000

Fig. 5. Portable Vibration Analysis Toolbox (PVAT)

The signals received from accelerometers were high-pass filtered, amplified, low-pass filtered, digitized and transmitted to a computer. Fig. 6 shows the block diagram of the vibration analysis toolbox.

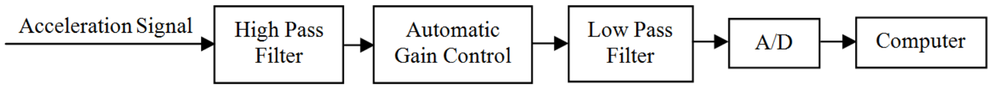
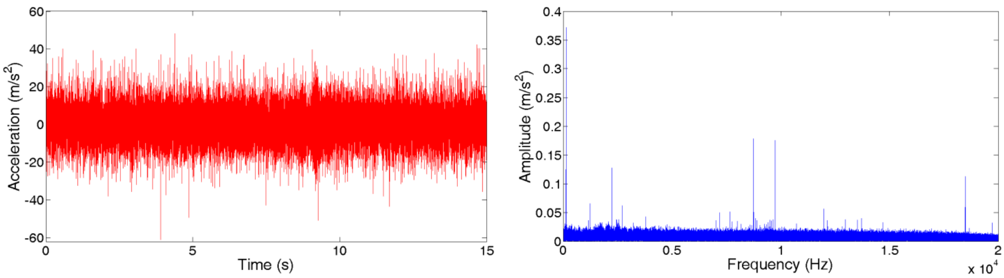


Fig. 6. Block diagram of the vibration analysis toolbox

High-pass filter eliminates the DC value of the sensor output. Then the Automatic Gain Control (AGC) block amplifies the signal for resolution enhancement, automatically. Then a low-pass filter is used for anti-aliasing. Next, the analog signal is converted to digital signal using a 12-bit analog to digital (A/D) converter. The digital signal is transmitted to a computer. Finally, it is analyzed and monitored by means of proper software packages.

4. Regenerative chatter, dominant mechanism in industry

As mentioned earlier, regenerative chatter is the most important cause of instability in the tandem rolling mills. It can be evaluated by investigating the measured acceleration signals of rolling stands. Fig. 7 shows the vertical vibration of upper backup roll and its Fast Fourier Transform (FFT) spectrum when chatter occurs.



a) b)

Fig. 7. Vertical vibrations of the upper backup roll when chatter occurs (Original signal):
a) acceleration signal, b) FFT spectrum

Since the sampling frequency is 51200 Hz, the original signal does not show the chatter properly. It can be seen that frequency spectrum has several local maximum at high frequencies, while the third octave chatter occurs in the frequency range of 100-250 Hz. Therefore, the increase in the amplitude of the vibrations cannot be observed in this figure.

Chatter occurrence can be observed if the original signal is filtered with a low-pass filter. Therefore a low-pass filter with a cut-off frequency of 2 kHz is applied to acceleration signal. Fig. 8 shows the filtered acceleration signal and its FFT spectrum, respectively.

The increase in the amplitude of the vibrations due to chatter can be seen in Fig. 8a. Fig. 8b shows that the prominent frequency in this range is 137 Hz that lies within the range of third octave chatter. If a 100-200 Hz band-pass filter is used, results will be similar to Fig. 9.

Regenerative chatter can be clearly seen in these figures. Observation of the phenomenon of modulated vibration in Fig. 9a shows that the regenerative chatter has occurred. It confirms that the regenerative chatter is the most important cause of instability in the tandem rolling mills. This mechanism occurs prior to other mechanisms in the tandem rolling mill under study.

Note that the vibrations plotted on the Fig. 9a are a selected part of total vibration of the upper backup roll. Acceleration domain in this figure meets a peak approximately 9 seconds after the selected start. From zero to 9 seconds the rolling speed is constant in such a high speed that the system is susceptible to chatter. It could be concluded from the acceleration domain which is increasing. At this time the operator has reduced the rolling speed to avoid chatter. We name this peak time of the acceleration domain the Acceleration Peak Time (APT).

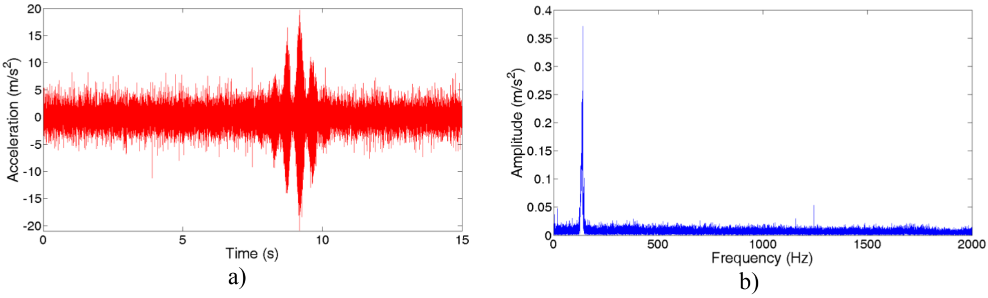


Fig. 8. Filtered signal of the vertical vibrations of the upper backup roll when chatter occurs (Cut-off frequency = 2 kHz): a) acceleration signal, b) FFT spectrum

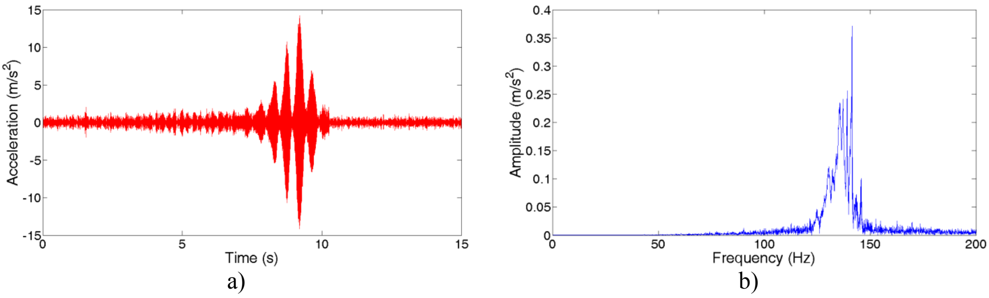


Fig. 9. Filtered signal of the vertical vibrations of the upper backup roll when chatter occurs (Band-pass frequency: 100-200 Hz): a) acceleration signal, b) FFT spectrum

5. Frequency analysis of vibration signals

In this section the frequency behavior of different positions in the stand around the APT, will be evaluated. Therefore, the FFT spectrum of each signal in a period of time containing chatter is studied. Frequency analysis for each sensor is presented as a waterfall diagram.

5.1. The first experiment

Waterfall diagram of the vibration signals in the first experiment are shown in Fig. 10. In this diagram, the FFT spectrum corresponds to ten one-second time interval are shown.

This figure indicates the FFT spectrum of vibration signals from seven seconds before the APT to two seconds after the APT. In this figure, the 8th second indicates the moment of occurrence of the chatter peak. To draw this graph, the acceleration signal is filtered. For this purpose a low-pass filter with a cut-off frequency of 1 kHz is used.

Fig. 10a shows that the amplitude of chatter frequency starts to increase about two seconds before the APT and reaches to its maximum value at APT. However it can be observed that there is no significant difference between the amplitude of chatter frequency and the amplitude of other frequencies. It is concluded that chatter does not cause severe instability in vertical vibrations of upper work roll. Upon the occurrence of chatter rolling speed is reduced by the operator in order to prevent the strip rupture. Reducing the rolling speed reduces the vibration. Also, the amplitude of chatter frequency will be reduced more than the amplitude of other frequencies. Frequency spectrum of the ninth and tenth seconds indicates that the chatter frequency (141 Hz) is not the prominent frequency hereinafter.

Fig. 10b demonstrates that the amplitude of chatter frequency starts to increase about six seconds before the APT and reaches to its maximum value at APT. However, it can be observed that there is a relatively significant difference between the amplitude of chatter frequency and the amplitude of other frequencies. It can be inferred that chatter causes more instability in the horizontal vibrations of the backup roll than the vertical vibration of the work roll. Frequency spectrum of the ninth and tenth seconds indicates that the chatter frequency vanishes from frequency spectrum by reducing the rolling speed.

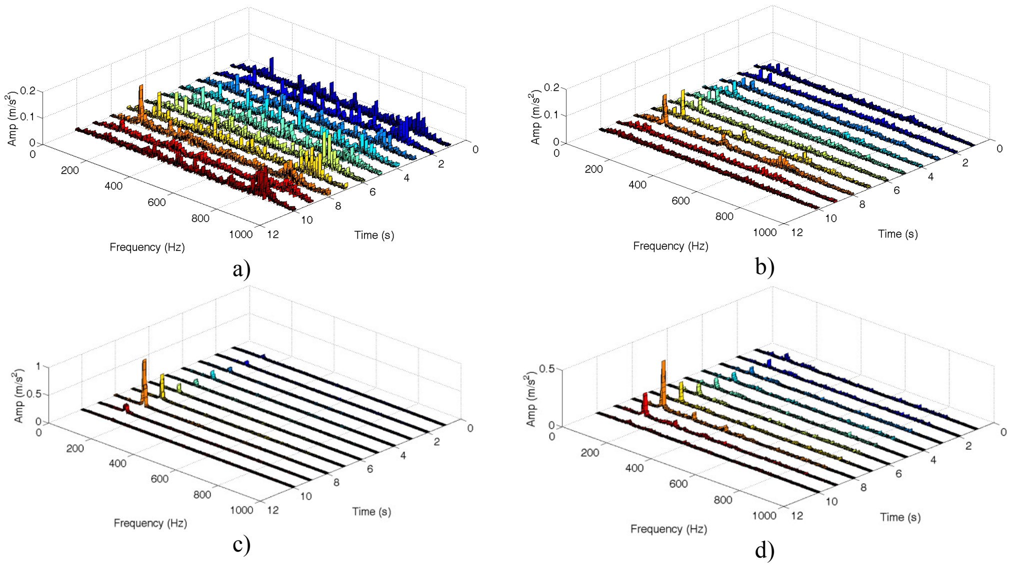


Fig. 10. Waterfall diagram of vibration signals in the first experiment:
a) vertical vibration of the upper work roll, b) horizontal vibration of the upper backup roll,
c) vertical vibration of the upper backup roll, d) vertical vibration of top housing

It is clear from Fig. 10c that the frequency of chatter is the prominent frequency from the beginning and its amplitude is being increased continuously. Difference between the amplitude of chatter frequency and other frequencies is very significant in this case. It is obvious that the backup roll is much more sensitive to chatter than the work roll, so backup roll is more suitable for detection and prediction of chatter in rolling.

It can be observed in Fig. 10d that top housing is highly sensitive to chatter, the same as the backup roll. It also detects the growth of chatter frequency from beginning.

5.2. The second experiment

Waterfall diagrams of the vibration signals in the second experiment are shown in Fig. 11.

It can be seen from Fig. 11a that the amplitude of chatter frequency starts to increase about four seconds before the APT, but it converts to prominent frequency one second before the APT. In the case of Fig. 11b frequency spectrum has big amplitudes in the region of high frequencies. These frequencies are larger than chatter frequency even one second before the APT. But at the APT, chatter frequency is the prominent frequency in the frequency spectrum. From Fig. 11c it is clear that lower work roll is less sensitive to chatter instability. It does not detect the chatter even one second before it. Only at the APT, it shows chatter frequency in its frequency spectrum. It can be seen from Fig. 11d that same as the first experiment top housing shows great sensitivity to chatter. Chatter frequency is the prominent frequency from about five seconds before APT. It can be determined that the top housing is more sensitive to chatter than upper and lower work rolls.

Therefore it can be concluded from these two experiments that the order of sensitivity to chatter in a rolling stand is as follows: the backup roll, top housing, upper work roll and then the lower work roll.

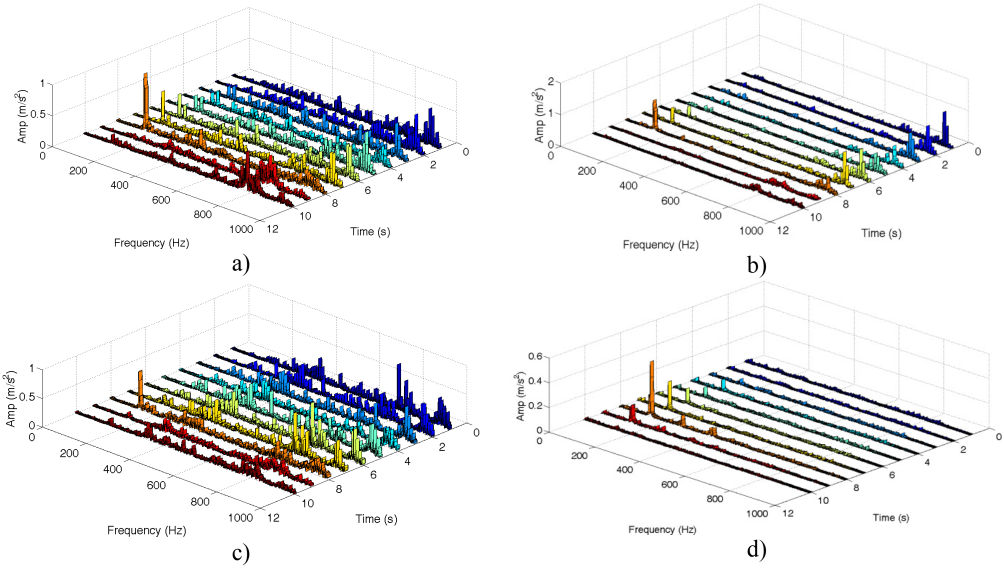


Fig. 11. Waterfall diagram of the vibration signals in the second experiment:
a) vertical vibration of upper work roll, b) horizontal vibration of upper work roll,
c) vertical vibration of lower work roll, d) vertical vibration of top housing

6. Chatter detection technicalities

If chatter is detected before degrading strip quality or damage on the mill, any undesired detriment can be prevented by reducing the rolling speed. This is essential to avoid strip and stand damage. Therefore it is very important to select suitable position for installing acceleration sensor for chatter detection. It is shown in the previous section that different positions of stand have different mode and sensitivity to chatter phenomenon. Therefore, the vibration behavior of each sensor position must be analyzed carefully.

6.1. The first experiment

Fig. 12 shows the variation of prominent frequency of the acceleration signal over time at each position. To draw this diagram, the frequency spectrum of each signal is analyzed in an interval of 35 seconds. The 26th second of this graph indicates the APT. Before analyzing the acceleration signal, a low-pass filter with a cut-off frequency of 500 Hz is applied to data. By studying this graph, the frequency behavior of each signal from several seconds prior to a few seconds after chatter can be analyzed.

This graph highlights the following main results. Firstly, prior to the start of divergent chatter vibration each signal has its own prominent frequency. The prominent frequency is about 180 Hz for the vertical vibration of the upper work roll, 101 Hz for the horizontal vibration of the upper backup roll, 142 Hz for the vertical vibration of the upper backup roll and 144 Hz for the vertical vibration of top housing. It should be noted that the chatter frequency is calculated to be 141 Hz in the first experiment. Secondly, at the time range of the divergent chatter vibration, the prominent frequency of all signals is equal to the chatter frequency. Thirdly, various sensors detect the chatter at different moments. For example, the upper work roll detects chatter about two seconds before it occurs. The prominent frequency of the horizontal vibration of the upper backup roll converts to chatter frequency about six seconds before it occurs. While the prominent frequency of the vertical vibration of the upper backup roll and the vertical vibration of the top housing is equal to the chatter frequency from the beginning. Upon the occurrence of chatter (second 26 in Fig. 12), rolling speed is reduced by the operator in order to prevent the strip rupture. Due to sudden decrease in rolling speed, the system was not stable for some time. A small decrease in the chatter frequency from 141 Hz to 137 Hz can be seen in the above figure immediately after speed reduction due to changing the rolling conditions.

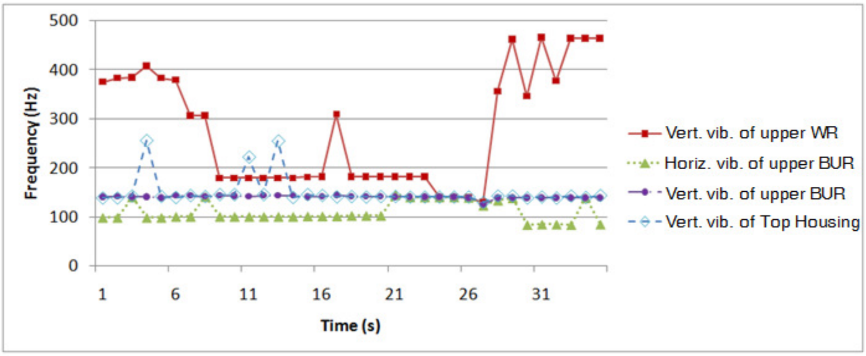


Fig. 12. Variation of prominent frequency of the acceleration signals over time

It can be determined from Fig. 12 that the upper backup roll has a major contribution towards the chatter phenomena. Frequency of the third octave chatter detected in this experiment is approximately equal to the vibration frequency of the backup roll.

Fig. 13 shows the ratio of the amplitude of chatter frequency to RMS value of amplitude in frequency spectrum over time for each signal. Before analyzing the acceleration signal, a low-pass filter with a cut-off frequency of 500 Hz is applied to the recorded data.

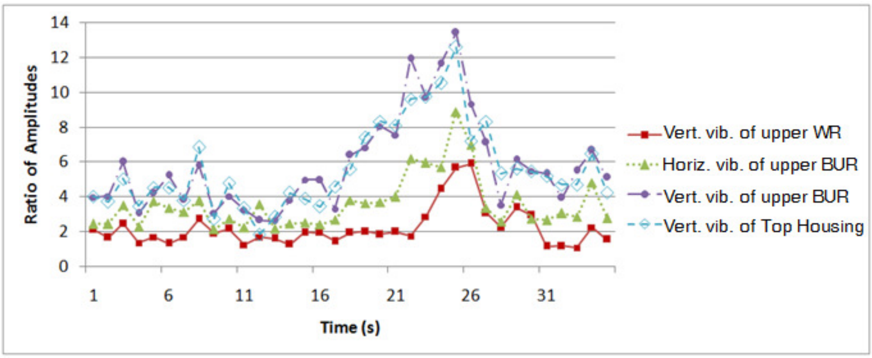


Fig. 13. Ratio of amplitude of chatter frequency to RMS value of amplitude in frequency spectrum

Also in this figure, the 26th second shows the APT. It can be observed that the ratio of amplitudes is increased when chatter occures. This ratio varies from one signal to another. The ratio is larger in the signals of the vertical vibration of the upper backup roll and the vertical vibration of the top housing. The moment that this ratio starts to increase is another important consideration by looking at this figure. This time is shorter the signals of the vertical vibration of the upper backup roll and the vertical vibration of the top housing. So it can be concluded that these signals are more sensitive to rolling chatter.

Fig. 14 shows the variation of RMS value of acceleration over time for each signal. First a low-pass filter with a cut-off frequency of 500 Hz is applied to the recorded data.

By examining this figure, the value of acceleration at stability and instability time of the system is observed. At stability (before and after of chatter occurrence) upper work roll vibrates with high amplitude. But it has small increase when chatter happens. Vibration of the upper backup roll is smaller than that of the upper work roll when system is stable; while it vibrates severely upon chatter, especially in vertical direction. The top housing vibrates slowly at the time of stability and greatly at the chatter time.

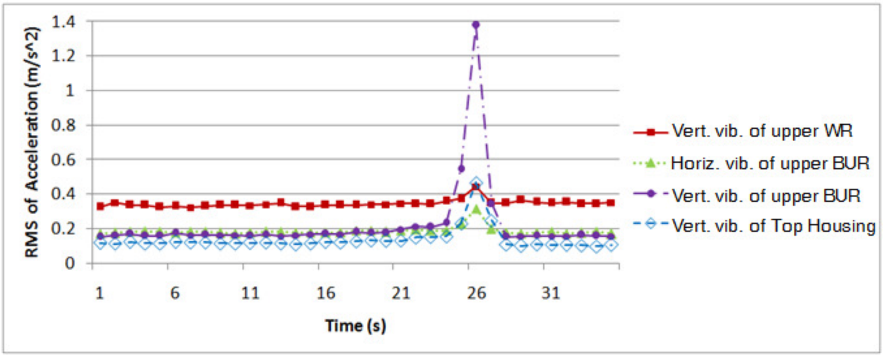


Fig. 14. RMS value of acceleration signals

It can be concluded from Figs. 12 to 14 that the upper backup roll is highly sensitive to rolling chatter. Also, the top housing is relatively sensitive to chatter. So upper backup roll and top housing are suitable positions to install acceleration sensors for chatter detection.

6.2. The second experiment

Fig. 15 provides the variation of prominent frequency of the acceleration signals over time at each position in the second experiment. The 26th second of this graph indicates the APT. Before analyzing the acceleration signal, a low-pass filter with a cut-off frequency of 500 Hz is applied to the recorded data.

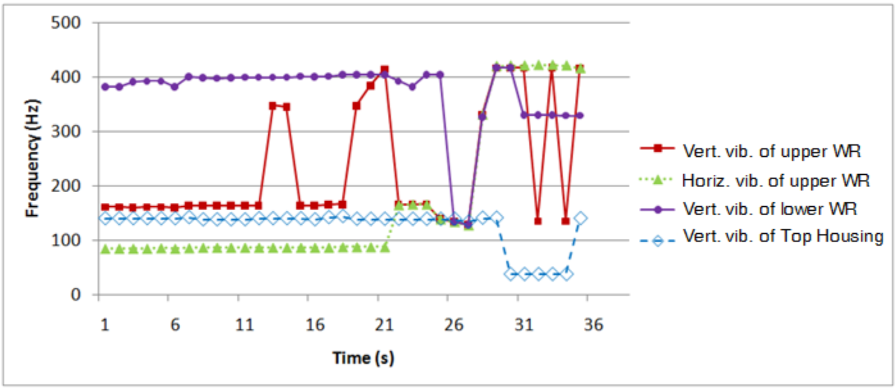


Fig. 15. Variation of prominent frequency of the acceleration signals over time

The prominent frequency is about 163 Hz for the vertical vibration of the upper work roll, 87 Hz for the horizontal vibration of the upper work roll, 400 Hz for the vertical vibration of the lower work roll and 139 Hz for the vertical vibration of the top housing. It should be noted that the chatter frequency is 139 Hz in the second experiment.

At APT, the prominent frequency of all signals is equal to the chatter frequency. The upper work roll detects the chatter about four seconds before the chatter occurs. The lower work roll does not detect chatter before and its prominent frequency converts to chatter frequency exactly at APT. The prominent frequency of the vertical vibration of top housing, similar to the first experiment, is equal to chatter frequency from the beginning.

Fig. 16 shows the ratio of amplitude of the chatter frequency to RMS value of amplitude in frequency spectrum over time for each signal. Before analyzing the acceleration signal, a low-pass filter with a cut-off frequency of 500 Hz is applied to the recorded data.

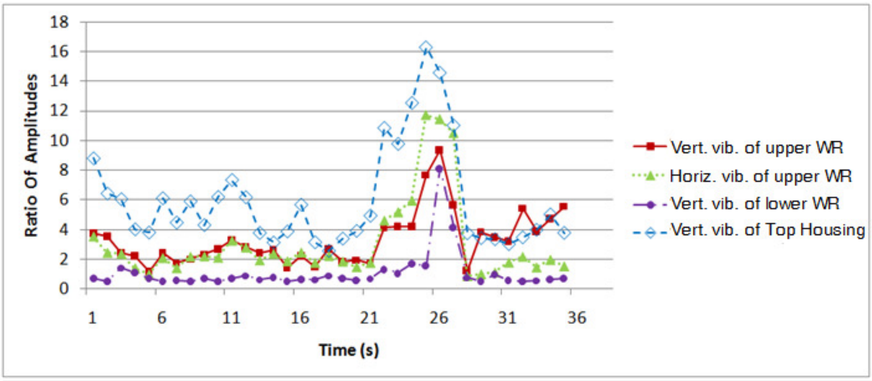


Fig. 16. Ratio of amplitude of chatter frequency to RMS value of amplitude in frequency spectrum

Also in this figure, the 26th second shows the APT. The signal of the vertical vibration of the top housing has the largest ratio at APT, because the top housing is highly sensitive to rolling chatter.

Fig. 17 shows the variation of RMS value of acceleration over time for each signal. First, a low-pass filter with a cut-off frequency of 500 Hz is applied to the recorded data.

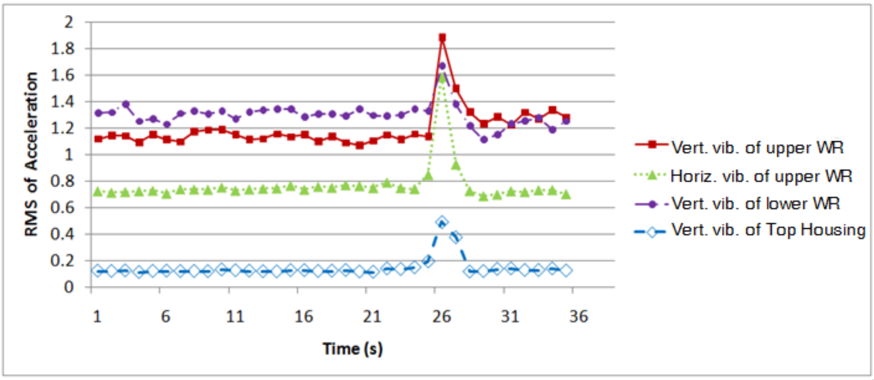


Fig. 17. RMS value of acceleration signals

It is evident that the RMS value of signals varies from one signal to another. The top housing has the minimum value in the time of stability, but its value grows strongly when chatter occurs. Whereas the lower work roll has the maximum value of acceleration when system is stable and has minimum growth at the instability time.

It can be concluded from Figs. 15-17 that the top housing is more sensitive to chatter than the work rolls. According to results of the first and second experiment, upper backup roll and top housing have high sensitivity to chatter and are suitable positions to install permanent acceleration sensors for chatter detection.

7. Conclusion

In this article the vibration analysis of a two stand tandem mill is presented. Vibration monitoring and chatter detecting systems were used to analyze the rolling stand. Using the experimental data, several analyses were performed to quantify the correlation of rolling instability with vibration of various components of the mill stand. The results reveal the importance of signal processing of vibration data and confirm their efficiency. It is demonstrated that the upper backup roll is highly sensitive to rolling chatter. It has a major contribution towards the chatter phenomena and the third octave chatter occurs in its vibration frequency. It is shown that the upper backup roll detects the chatter several seconds before its occurrence. Also the top housing is relatively sensitive to chatter. Hence the upper backup roll and the top housing are more sensitive to chatter than the work rolls and they are suitable positions for permanent acceleration sensors installation for chatter detection. The results can be a very effective tool for controlling rolling mills to achieve maximum production rate and product quality. It is recommended to apply finding of this research for improving the automatic warning system in tandem rolling mills.

8. Acknowledgments

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