The International Journal of Advanced Manufacturing Technology (2019) 100:673–682
https://doi.org/10.1007/s00170-018-2639-9

ORIGINAL ARTICLE

Experimental analysis of vibration and sound in order to investigate chatter phenomenon in cold strip rolling

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Received: 13 February 2018 / Accepted: 22 August 2018 / Published online: 27 September 2018

Abstract

Chatter is one of the most destructive types of vibration which usually occurs in cold strip rolling at high speeds. There is a minimum critical speed at which chatter mechanism may activate. Once the chatter has occurred, mill vibration is then become unstable. Its distinct sound is the most important sign for operators in order to identify chatter. As soon as chatter happens, the mill and its huge foundation vibrate with a sound as a mobile phone vibration. In these conditions, the only way to avoid hazardous damages is to reduce the rolling speed immediately. This paper is an application of sound analysis for solving chatter problem in cold strip rolling which is supported by experimental data. The results showed that upper housing and backup roll, compared with other parts, are more sensitive to chatter and more appropriate for installation of chatter detection sensors. Frequency analysis of recorded signals showed that at the time of chatter occurrence, dominant frequency in vibration signals of all parts of the stand and sound signal is equal. This frequency is in the range of third-octave chatter. It was also found that from the beginning of acceleration growth to hearing the chatter sound lasts less than 200 μs. Therefore, in the absence of automatic chatter detection systems, chatter sound is the best strategy for detecting and preventing the chatter.

Keywords Chatter · Vibration · Sound · Rolling · Experimental analysis · Signal processing

1 Introduction

One of the main problems of the rolling mills is a phenomenon called chatter. Chatter is a kind of self-excited vibration in which the vibration amplitude increases. Chatter usually occurs in multi-stand cold rolling mills. The incidence of this vibration is potential in certain situations of rolling process parameters, especially at high speeds [1]. Chatter causes unacceptable changes in strip thickness and if not controlled would cause strip rupture and damage to the rolling machine. To avoid chatter, rolling speed is usually kept low. Reduction of production rate to avoid chatter has made this phenomenon not only a technical problem but also an economic problem of rolling mills. Due to the experimental data, this paper has tried to present some concepts about the chatter phenomenon through the simultaneous analyzing of the vibration and sound signals.

All of the research which have been carried out in the field of chatter in rolling can be divided into several different categories. Since chatter is a complex phenomenon, a large number of previous studies have examined the nature of chatter [2, 3]. Lee et al. investigated the various causes of the chatter in cold rolling and physical behavior of the work roll in compact endless rolling [4].

Zhao et al. highlighted that chatter is a self-excited phenomenon resulting from phase delay between strip tension fluctuations and vertical vibration of the work rolls [2]. They described four major mechanisms of third-octave chatter: model matching, negative damping, regenerative, and modes coupling mechanisms in the creation of chatter phenomenon. Niroomand et al. have used wave propagation theory to analyze chatter phenomenon [3]. They found that wave propagation theory, considering dynamic effects, has a higher precision than previous theories and is more effective in the simulation of fifth-octave chatter that occurs at higher frequencies.

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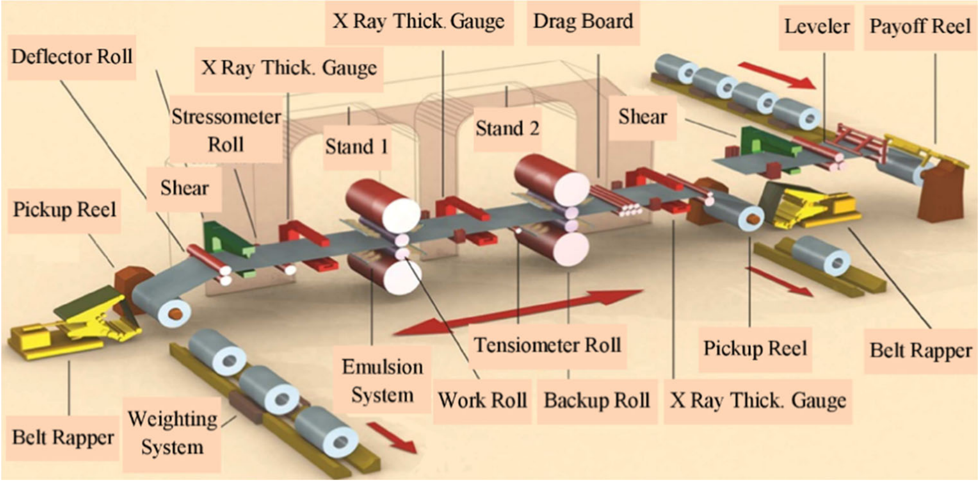
Fig. 1 A schematic of the examined two-stand cold rolling mill



Dynamic modeling of the rolling mills is an open subject in chatter in rolling. These models are powerful tools not only to understand chattering and predicting system behavior but also to feed controlling plants. Concerning the process modeling, nonlinear dynamical responses of the rolling machine are investigated [5, 6]. Also by calculating the stiffness parameters of the mill elements, different structural vibration models are presented [7, 8]. Zeng et al. offered a vertical-torsional-horizontal-coupled vibration model [7]. The results showed that when rolling the thin strip, the system stability boundary may be only enclosed by the critical domains of vertical and torsional vibration modal. Mosayebi et al. calculated the stiffness parameters of different mill elements and proposed a vibration model with two degrees of freedom for a cold sheet rolling mill [8].

Given the important role of lubrication and friction in chatter phenomenon, some researchers have examined the effects of friction on rolling vibration. In the rolling process, when the machine vibrates, the lubrication system is in an unsteady state [9, 10]. Heidari et al. stated that unsteady lubrication models are much precise than simple friction models to simulate friction conditions for chatter in rolling [11]. Considering unsteady lubrication in multi-stand cold rolling mills, they also showed that limiting shear stress is an influential parameter in chatter phenomenon [12]. An intelligent lubrication control system is presented by Fujita et al. for preventing chatter [13]. It is suggested that a hybrid lubrication system, with an actuator for controlling friction coefficient, can prevent chatter in high-speed rolling.

Some other researchers have conducted practical tests. Having laboratory or industrial rolling machines, they have examined the behavior of the system at the time of chatter incidence [14–17]. Brusa et al. tried to find ways to prevent chatter or control it in case it happens. Some of them have led to the installation of chatter detection systems in rolling stands [18]. Through the online processing of vibration signals, they succeeded to detect chatter.

Authors et al., using an industrial cold rolling mill, evaluated the behavior of rolling stands during the chatter [19]. Through installing accelerometer sensors in different points and processing vibration signals, the sensitivity of different parts of the stand is compared with each other. The role of sound in detecting chatter in rolling has been reported in previous studies [20]. Also, the audio signal has been used for chatter detection in turning process [21, 22]. However, due to the difficulties involved in carrying out practical experiments in rolling mills, the chatter sound has not yet been experimentally studied in rolling industries. On the other hand, unlike

Table 1 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)	14,000	14,000
Backup roll and chock mass (kg)	38,000	38,000

Table 2 Properties of the accelerometers

Specification	Value or type
Sensitivity ± 10% (mV/g)	100
Frequency response (Hz)	
± 3 dB	0.5–15,000
± 10%	2.0–10,000
Dynamic range (g)	± 50
Maximum shock protection (g)	5000
Sensing element	PZT ceramic
Sensing structure	Shear mode
Resonant frequency (Hz)	23,000
Mounting torque (N. m.)	2.7–6.8

most of the chatter related research areas, such as vibration of rolling structure and rolling process which can be analyzed using simulation techniques, simulation of chatter sound is simply not possible. Hence, experimental investigation of sound and rolling vibrations is one of the unknown issues which can help researchers in both the academia and the industry to better understand the chatter phenomenon. Meanwhile, development of these findings could lead to new ideas and outcomes to identify and control the chatter in rolling.

The current research aimed at investigation of chatter phenomenon in cold strip rolling from two simultaneous perspectives of sound and vibration. To this end, experimental data of an industrial two-stand cold rolling mill have been investigated. After recording data, through using signal processing techniques, it is tried to achieve technological information which can be used for solving chatter problem in cold strip rolling.

2 Materials and methods

This research is based on the experimental data obtained from an industrial two-stand cold rolling mill. The vibration and sound data have been recorded simultaneously during the rolling process through four accelerometer sensors together with a microphone. A sound and vibration analysis machine was used to record and process the data. The following describes the applied rolling machine, vibration analysis device, and the experimental conditions.

2.1 Rolling machine

Strips are entered into two-stand cold rolling mill in the form of coils with a thickness of usually 2 mm. These coils are the output products of hot rolling that after passing through pickling unit are brought to this unit. In this line, coil, after being opened by payoff reel passes through two four-high mills. The strip passes through stands in a regressive way over two or three passes and undergoes 60 to 90% thickness reduction. The second pass is in the reverse direction. The strip outputted from the second stand in each pass coiled by pickup reel. Each pass's pickup reel plays the role of payoff reel in the next pass. Chatter phenomenon usually occurs in the second and third passes. In these passes, the strip has a higher speed, less thickness, and a higher yield stress. These factors increase the potential for chatter in the strip [2, 7]. The data used in this paper are related to the second pass of the rolling process. Figure 1 shows different parts of this unit schematically.

Properties of mill stands are presented in Table 1.

Table 3 Properties of the microphone

Specification	Value
Sensitivity (dB)	− 43
Frequency response (Hz)	100–16,000
Impedance (Ω)	600

2.2 Sound and vibration measurement and analysis device

To measure vibration and sound, four accelerometers and a microphone were used. Since all of them are attached to one device, their information is fully synchronized and critical moments coincide in all signals. Accelerometers were Internal Circuit Piezoelectric (IPC) type and cylindrical, and capable of measuring acceleration along their axis. Tables 2 and 3 show properties of the used accelerometers and microphone, respectively.

Acceleration and sound signals were received and analyzed using a portable device which is shown in Fig. 2.

Input signals are first filtered by a high-pass filter; then, they are amplified and filtered by a low-pass filter. Next, the analog signal is converted into a digital signal and stored in the hard disk of the device's computer. Figure 3 shows the block diagram of the device.

The high-pass filter is used in order to remove DC offset of the signal. Then automatic gain control block amplifies the signal automatically. In this system, the input signal is multiplied by the number 8 and both the basic amount and the multiplied number are entered into the gain selection block. Depending on the amount of signal, the processor decides to use whether the signal or its multiplied number. Using automatic gain control the system precision increases. Afterward, a low-pass filter is used to eliminate high frequencies and noise and preventing aliasing phenomenon. The next is to convert the analog signal to digital one. Since the output of the sensors is analog while the processing software can be performed only on digital signals, analog signals have to be converted into digital ones. This is done by using a 12-bit

Fig. 2 The portable sound and vibration analysis device

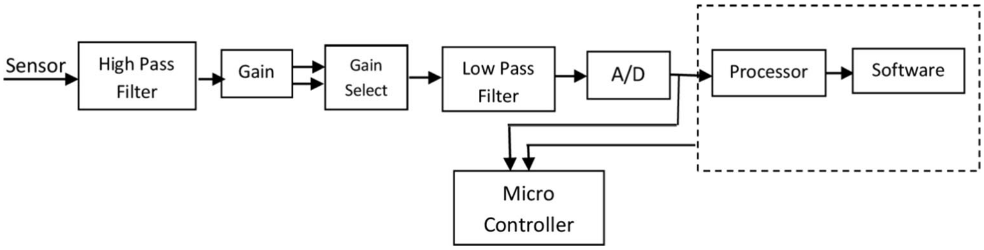


Fig. 3 Block diagram of the sound and vibration analysis device

analog to digital converter. The digital signal is transferred to the device's computer. Using the software installed on the computer, online and offline monitoring and analysis of the data is possible.

2.3 Test conditions

Three of the accelerometers have been placed on the rolls chock and one accelerometer has been placed on the upper housing of the stand. The microphone is also located within a few meters of the stands. Figure 4 shows the conditions of the experiment.

According to the position of the sensors, the recorded data are as follows: vertical vibration of the upper work roll of the second stand (UWR2S)-sensor1, vertical vibration of the upper backup roll of the second stand (UBR2S)-sensor2, vertical vibration of the upper housing of the second stand (UH2S)-sensor3, and vertical vibration of the upper work roll of the first stand (UWR1S)-sensor4.

Rolling conditions are also shown in Table 4. As previously mentioned, the data are related to the second pass of the rolling process. According to the low thickness of the strip at the exit of the second stand, 0.409 mm, there is the possibility of instability at high rolling speeds.

The data are related to when the online chatter detection system has not been active. If the rolling machine is not equipped with a chatter detection system, the only way to detect chatter is through its sound. When the system is unstable, if the vibration amplitude reaches a certain level, a sound similar to mobile phone vibration can be heard. Hearing this sound, operators will reduce rolling speed immediately. When instability rate of the system is not excessive, it regains its stability and chatter will not happen. In this experiment, hearing the sound of chatter, the operator has reduced the rolling speed. However, owing to the high growth rate of vibration, the system failed to maintain its stability and the increase of vibration amplitude leads to the strip rupture. Strip rupture caused some damages to the rolling machine and rolls. Some of the damages caused by the chatter are shown in Fig. 5.

Recording the vibration and sound data during the chatter and before the strip rupture can be useful to analyze the behavior of the rolling system. Hence, despite the damages due to this experiment, the related results are valuable in terms of scientific research. Figure 6 shows the strip speed at the entrance to each stand during the two rolling passes.

As can be seen, the rolling process is done in two passes. In each of the passes, the rolling speed has increased gradually from zero. In the first pass, after reaching a maximum speed, the rolling has continued with this speed for a while. At the end of the first pass, speed is gradually reduced to zero. As the thickness of the strip is high in the first pass, there is no potentiality for chatter occurrence.

After the end of the first pass, an interruption is made in order to set the second pass parameters and provide the situation for the test. Also in the second pass, the speed is increased gradually from zero. With the increase of speed, the system became unstable and chatter was happened at the 730th second. At this moment, hearing the chatter sound, rolling speed was suddenly reduced by the operator. However, owing to the excessive increase of vibration amplitude, the strip was ruptured and rolling was stopped.

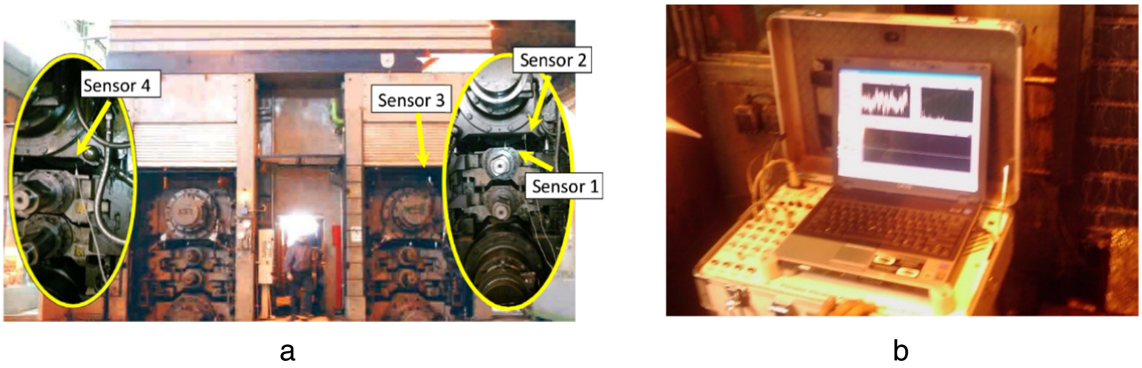


Fig. 4 Conditions of the experiment; **a** sensor positions, **b** online sound and vibration analysis

Table 4 Rolling conditions

Parameter	Stand 1	Stand 2
Backward tension (MPa)	92	165
Forward tension (MPa)	165	96
Rolling force (MN)	6.3	5.9
Yield stress (MPa)	938	1005
Friction coefficient	0.019	0.016
Strip width (mm)	674	674
Entry thickness (mm)	0.905	0.619
Exit thickness (mm)	0.619	0.409

3 Results and discussion

Figure 7 shows acceleration graphs obtained from four accelerometers in each position together with sound pressure obtained from the microphone. These graphs have been drawn in a range of 10 s around the time that chatter has happened. The graphs show the moment of chatter occurrence and continue until the moment of strip rupture. Before drawing the graphs, all signals are filtered by a low-pass filter with cut-off frequency of 200 Hz so that the results may be analyzed in the frequency range of 0 to 200 Hz more clearly.

The moment at which certain events have happened is shown in Fig. 7. It can be seen that the second stand is more sensitive to chatter than the first one. In the second stand, while the vibration of the work roll (1st sensor) has the higher amplitude, vibration growth at the backup roll and upper housing (2nd and 3rd sensors) happened with the further rate. The first time the gradient of the acceleration graph has been positive is considered as the beginning of the chatter. This time, 5.42 s, is detectable on the backup roll and upper housing acceleration graphs. In order to determine the beginning of the chatter sound, the sound pressure data was converted into an audio signal. The simultaneous playback of the sound signal and its adaptation to the sound pressure graph show that the beginning time of the chatter sound is 5.57 s. Since all the accelerometers and microphone are fully synchronized, there is no time delay to detect beginning times. It can be seen that from the beginning of acceleration growth till hearing the chatter sound lasts 0.15 s. Given this short time difference, chatter sound can be used to detect chatter in the absence of online signal processing systems. Furthermore, as the figure shows, the highest sound pressure before rupture at time 9.62 s is 28.67 Pa.

Figure 8 shows the amount of acceleration in each position together with sound pressure in the range of 20 s when the chatter happens. This graph contains events which have happened from a few seconds before the chatter occurrence till after rupture.

There are other specific moments that can be detected in the graph. Strip rupture occurs at 9.99 s. There are some reasons for recognizing this time as the rupture time:

- In a range of 9.99 to 11.4 s, when the rolling is not done normally, vibration is closed to zero.
- Deferent appearance of the acceleration graphs and before and after this time.

At 15.56 s, vibration reaches its maximum amount due to a collision between the strip and stands. That is, at this moment, the stands are affected by a severe stroke and hence vibrate severely.

It can be seen that from the onset of acceleration growth (5.42 s) up to the strip rupture (9.99 s), it takes less than 5 s. This short timeframe reflects the rapid growth of vibration amplitude and high destructiveness of chatter phenomenon.

Frequency spectrums of vibrations and sound in the pre-rupture moments (in the range of 5.5 to 6.5 s) are shown in Fig. 9. Examining this figure, the following information is obtained:

- Chatter frequency has been 126 Hz. This frequency is in the range of the third octave which is known as the most destructive chatter type.
- All sensor positions of both stands at the moment of chatter have a similar dominant frequency vibration of 126 Hz, which is the chatter frequency.

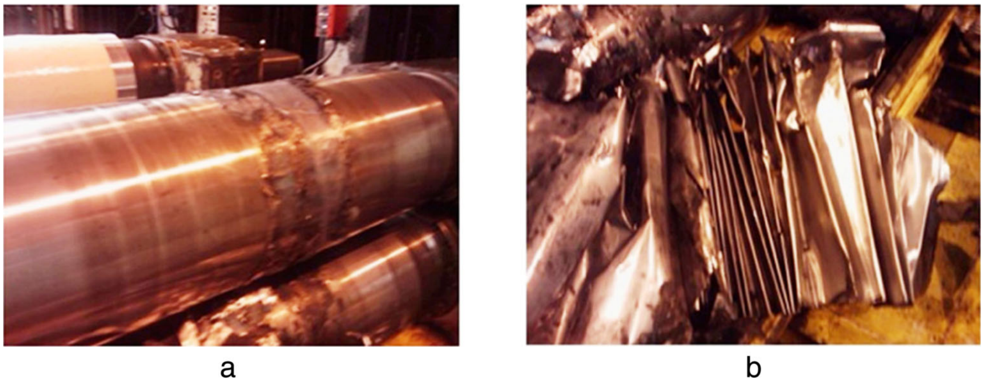


Fig. 5 Damages caused by the chatter; **a** damage to rolls, **b** ruptured strip

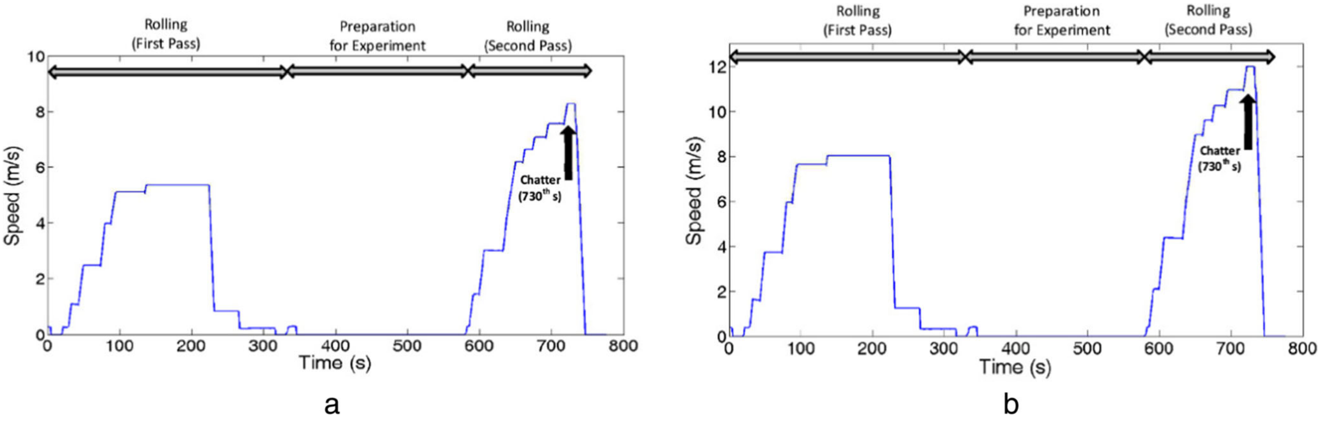


Fig. 6 Strip speed at the entrance to each stand during the two rolling passes: **a** the first stand; **b** the second stand

- At the chatter happening moment, the sound signal has a dominant frequency as same as the vibration signals.

In Figs. 7, 8, and 9, before data analysis, a low-pass filter with cut-off frequency of 200 Hz has been applied to the data. In the following graphs, a band-pass filter has been used in the range of 100–200 Hz. By removing lower frequencies, forced vibration of the system, as well as noises with frequencies below 100 Hz, is removed. Therefore, more precise information about

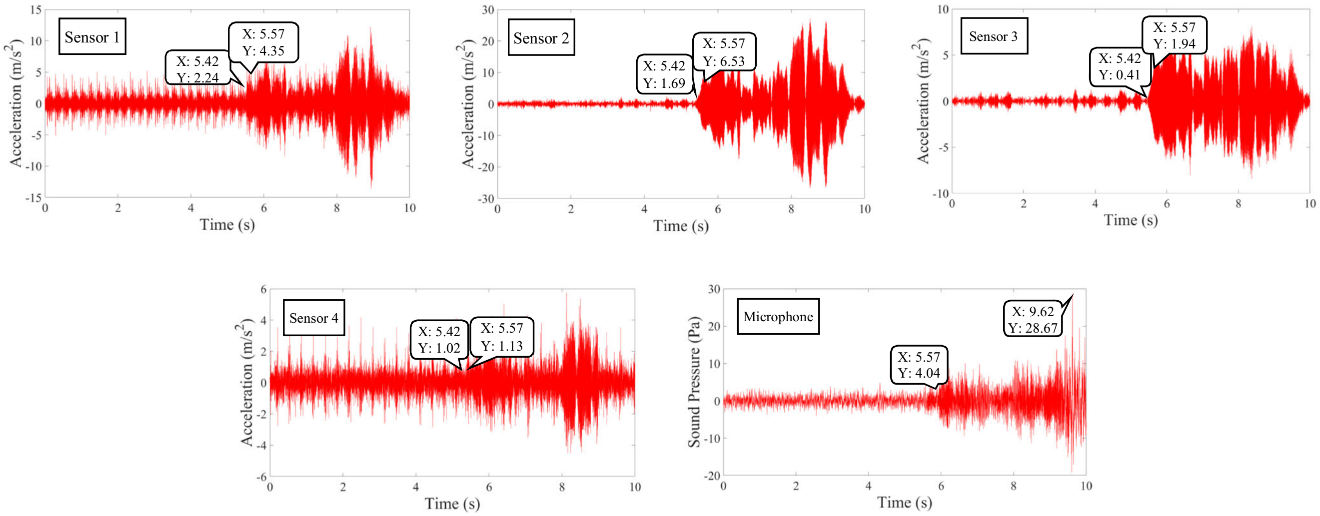


Fig. 7 Acceleration and sound values within a range of 10 s around the time of chatter occurrence after applying 0–200-Hz filter

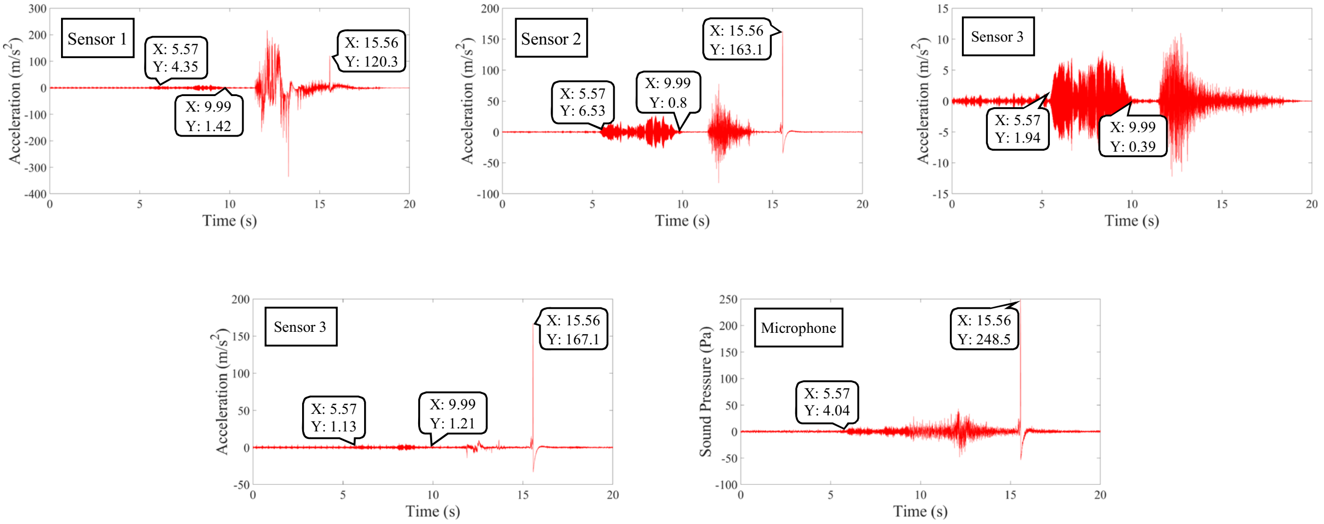


Fig. 8 Acceleration and sound values within a range of 20 s around the time of chatter occurrence after applying 0–200-Hz filter

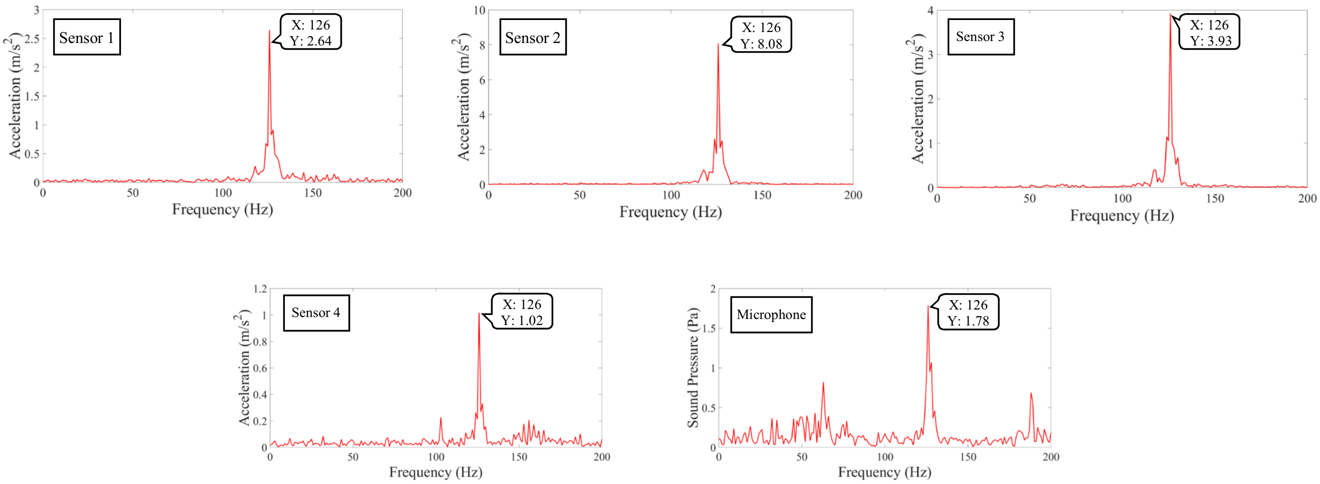


Fig. 9 Frequency spectrum of different signals in the pre-rupture moments

chattering behavior of the system can be provided. Figure 10 shows acceleration in each position together with sound pressure within the range of 10 s around the chatter occurrence after applying a 100–200-Hz filter.

By filtering vibration signals in the frequency range of 100–200 Hz, modular nature of vibrations can be seen clearly in the signals. Modulation is an evidence for the regenerative mechanism of chattering in the mill [6]. Regeneration is the

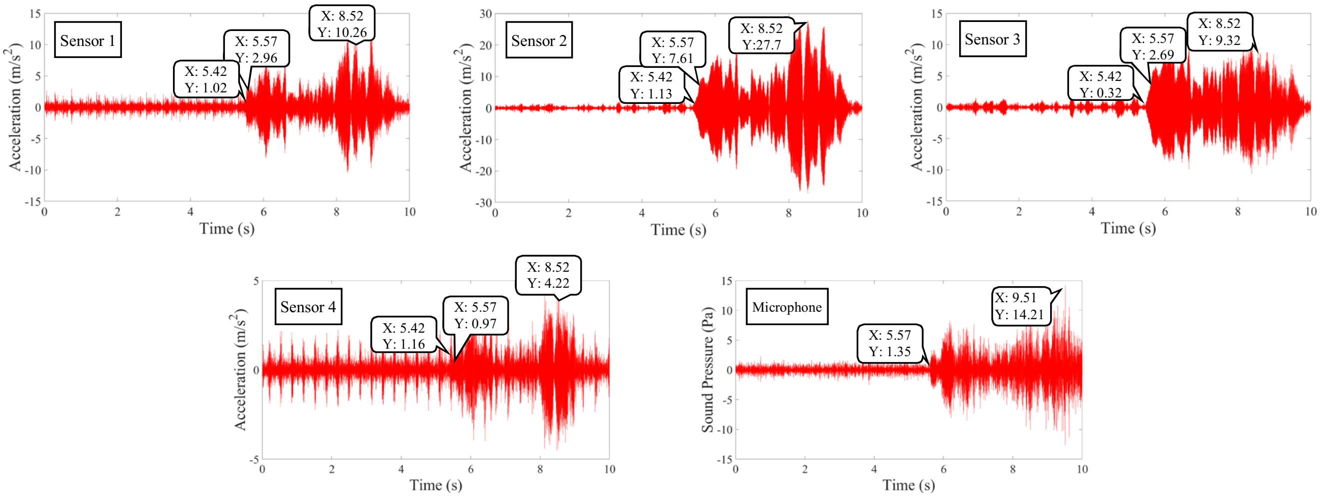


Fig. 10 The values of acceleration and sound in the range of 10 s around the chatter occurrence after applying 100–200-Hz filter

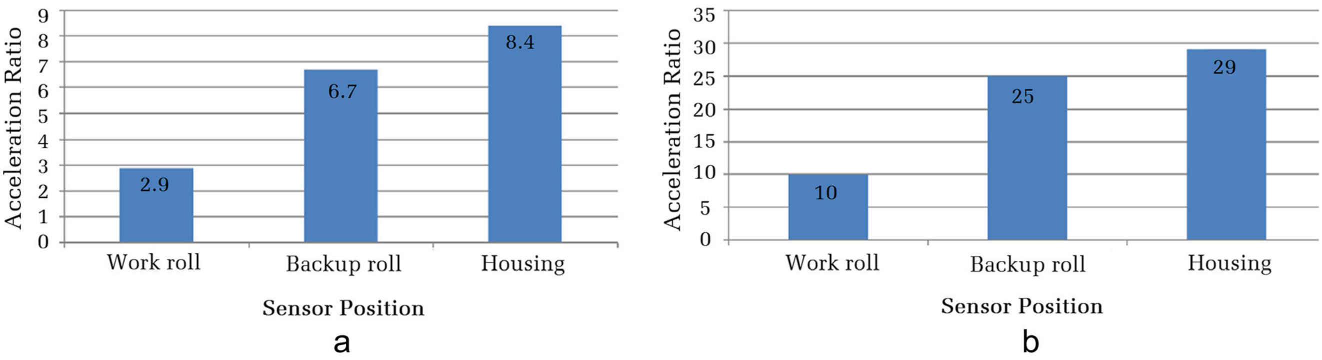


Fig. 11 The ratio of acceleration at different moments to acceleration at the beginning of growth; **a** the moment of hearing chatter sound, **b** pre-rupture moment

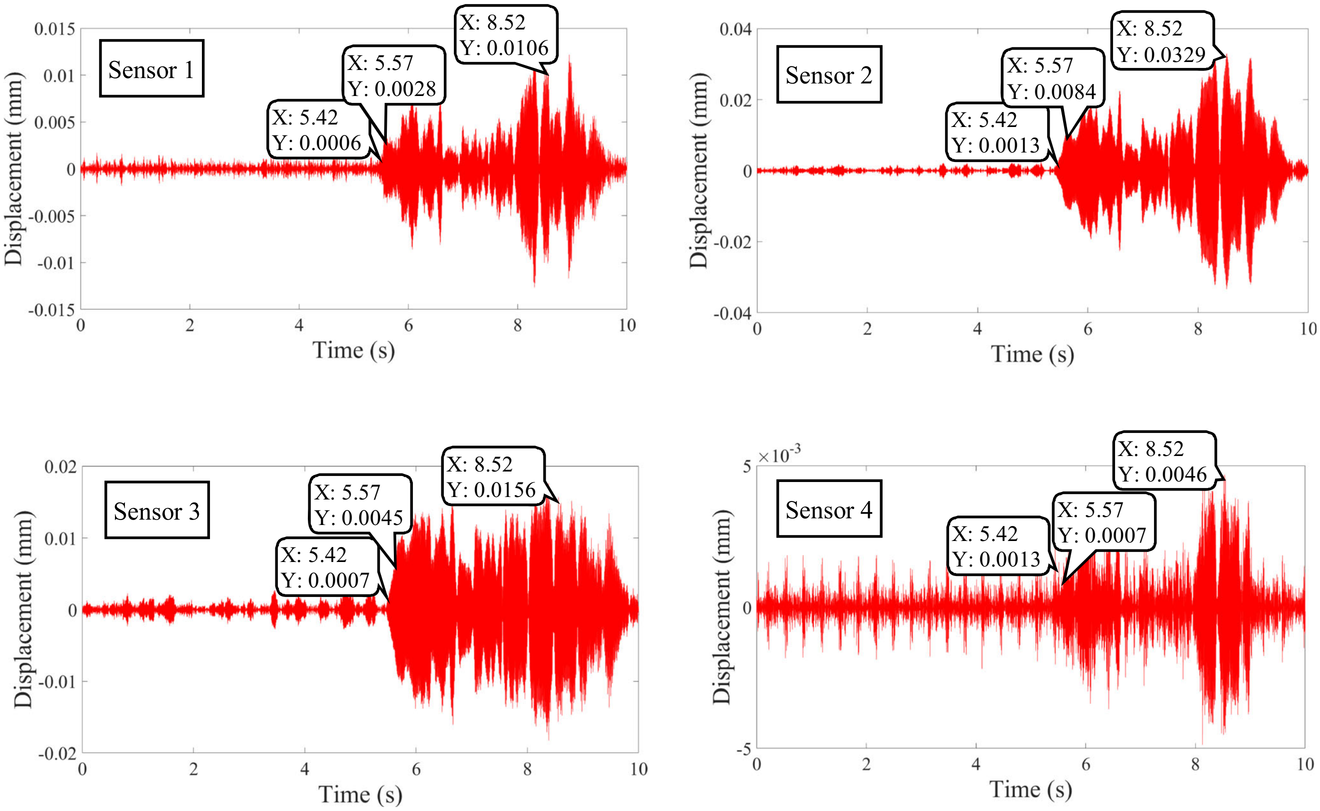


Fig. 12 Displacement in each position within the range of 10 s around the chatter occurrence after applying 100–200-Hz filter

most important mechanism of chattering in multi-stand rolling mills, as the two-stand one studied here.

In order to the quantitative investigation of the sensitivity of different sensor attachment points, the ratio of acceleration amplitude in any sensor of the second stand at the moment of hearing the sound to acceleration amplitude of the same sensor at the moment of acceleration growth onset is calculated and expressed in Fig. 11a. As can be seen, the ratio is 2.9, 6.7, and 8.4 for work roll, backup roll, and upper housing respectively.

In a similar way, the ratio of the maximum acceleration at the pre-rupture moment to the acceleration amplitude at the beginning of acceleration growth is presented in Fig. 11b. The ratio is 2.9, 6.7, and 8.4 in work roll, backup roll, and upper housing, respectively. Thus, it can be observed that the sensitivity of the backup roll to vibration growth is more than the work roll. Similarly, the increase of vibration amount at the time of chatter occurrence is more in the upper housing compared with work and backup rolls. Therefore, the upper housing is a suitable place for the installation of permanent sensors in order to detect chatter.

If the acceleration signal is twice integrated numerically, displacement signal is obtained. The amount of displacement also can contain valuable information. Particularly, the amount of displacement can be compared with the thickness of the strip. Figure 12 shows the displacement in each position

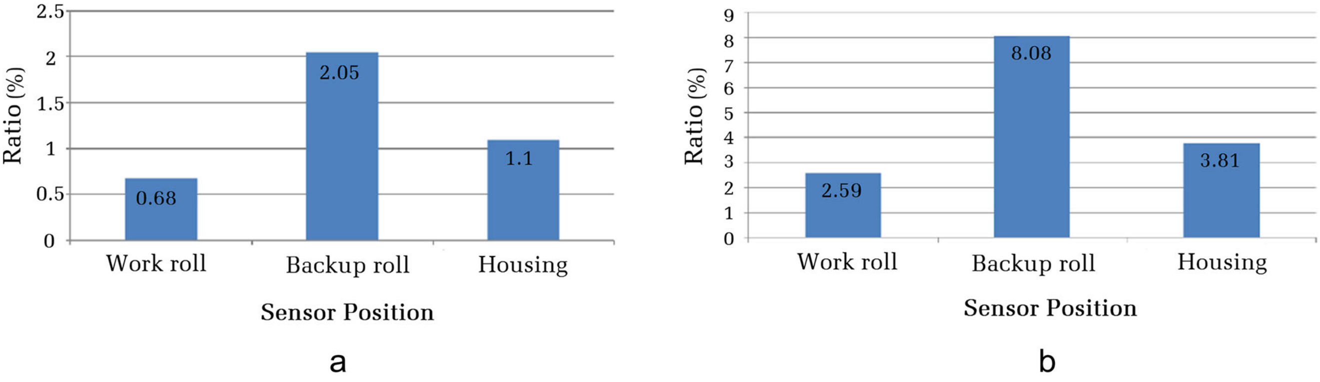


Fig. 13 The ratio of vibration amplitude at different moments of the chatter occurrence to the exit strip thickness; **a** the moment of hearing chatter sound, **b** pre-rupture moment

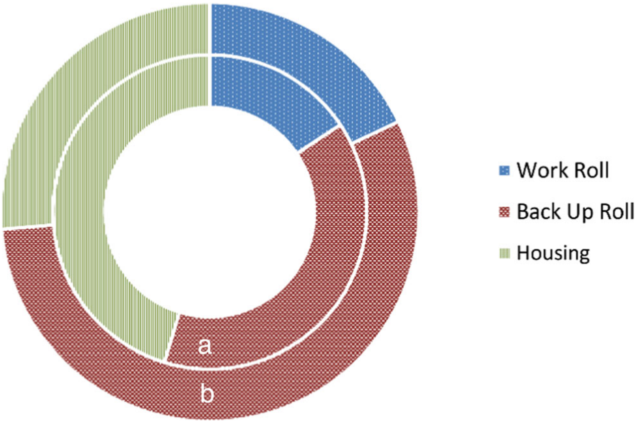


Fig. 14 Comparison of the sensitivity and amplitude of vibration in different positions; a) sensitivity, b) amplitude

within the 10 s around the chatter occurrence after applying a 100–200-Hz band-pass filter to the data.

In this experiment, the thickness of the exit strip from the second stand is 0.409 mm. The ratio of displacement at the moment of hearing the chatter sound to the thickness of the exit strip is shown in Fig. 13a. Moreover, the pre-rupture maximum displacement to the thickness of the exit strip is shown in Fig. 13b.

As seen in Fig. 13, the ratio of displacement at the moment of hearing the chatter sound in the work roll, backup roll, and upper housing to the exit strip thickness is 0.68%, 2.05%, and 1.1% respectively. It is observed that when the vibration amplitude in backup roll is about 2% of the thickness of the exit strip, the chatter sound is heard which is consistent with the results provided by Tamiya et al. [20]. Moreover, as the Fig. 13b shows, the ratio of pre-rupture maximum displacement to the output strip thickness in the work roll, backup roll, and upper housing is 2.59%, 8.08%, and 3.81% respectively. Therefore, in the present case, when the backup roll vibration amplitude is about 8% of the thickness of the exit strip, strip rupture happens.

It should be noted that selecting of the appropriate location for the installation of the chatter detector sensors depends on the sensitivity of the location. In Fig. 14, a comparison between vibration amplitude and sensitivity to chatter is done. Part a shows the ratio of acceleration in any positions of the second stand at the pre-rupture moment to the same value at the moment of acceleration growth. The amplitude of displacement in each position is presented in part b.

As can be seen, the upper housing, despite the lower vibration amplitude than the backup roll, has a higher growth rate. In other words, the upper housing is more sensitive than other parts and is recommended for the installation of chatter detector sensors.

4 Conclusion

Based on the experimental data, recorded from an industrial two-stand cold rolling mill, this paper aimed at examining unstable vibration and chatter sound as well. The results showed that the backup roll and the upper housing are more sensitive to the third-octave chatter than anywhere else. Thus, these positions, especially the stand's upper housing, are appropriate for the installation of the sensor to detect the chatter. However, since it takes only 0.15 s from the onset of acceleration growth to the hearing of the chatter sound, chatter sound is a good solution for the detection of process instability in the absence of automatic chatter detection systems. Review of the recorded values indicated that the ratio of displacement at the moment of hearing the chatter sound to the exit strip thickness in the work roll, backup roll, and upper housing in the present case is 0.68%, 2.05%, and 1.1% respectively. Moreover, the ratio of maximum displacement before strip rupture to the exit strip thickness in the work roll, backup roll, and upper housing is 2.59%, 8.8%, and 3.81% respectively. At the moment of chatter occurrence, the dominant frequency in vibrational signals of all parts of the stand as well as the sound signal was found to be 126 Hz. This frequency is in the range of the destructive third-octave chatter. Given the fact that from the beginning of the acceleration growth to the strip rupture lasts less than 5 s for this typical case, the danger of this phenomenon becomes more apparent. The existence of modulation in vibrational signals is an indication of regenerative chatter according to the multi-stand rolling mill.

Acknowledgments The authors express their gratitude to the experts of cold rolling mill unit in Mobarakeh Steel Company for their efforts and cooperation.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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