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Definition of Fill Level of Ball Mill Based on Vibration Acceleration Signal

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Abstract

The paper is devoted to the study of the relationship between the vibration accelerometer signal and the fill level of a ball mill. It was established that there is a direct correlation between the vibration level of the front support of the mill drum and the amount of material being ground in the mill. A low vibration level corresponds to a high fill level of the mill. Two methods of processing the vibration accelerometer signal to obtain a fill level signal using a moving window are proposed. In the first method, the frequency spectrum is built and the maximum is determined in a specific frequency range. The second method consists in calculating the integral of the modulus of the vibration acceleration signal during the time of the moving window. The operation of each method is demonstrated based on the experimental data of vibration acceleration signals during the work of two ball mills at operating conditions.

Keywords: ball mill; vibration acceleration signal; frequency spectrum; moving window; experimental data; fill level.

1. Introduction

A ball mill is a complex control object, since there are mechanical, heat exchange and aerodynamic processes taking place in it with a large number of interrelated parameters. The main production characteristic of the mill is its productivity, namely the amount of ground material per time unit. The productivity of the mill depends on the fill level, i.e. the amount of material in the mill drum during grinding.

For reliable and efficient operation of a ball mill, it is very important to maintain the fill level at an optimal value, since too low a fill level leads to inefficient use of energy consumed by the mill, as well as to rapid wear of the internal armor of the mill [1]. Too high a fill level leads to a blockage of the mill, when a large amount of material rotates in the drum with the balls, but there is no grinding process in the mill. This is an emergency situation when the mill should be stopped in order to clean it and restart it. This situation can be prevented by measuring the fill level and maintaining it at an optimal value. Therefore, measuring the fill level is an extremely important process for ensuring reliable and efficient operation of a ball mill.

There are no direct methods for measuring the fill level of the mill, so indirect measurement methods are used in practice, namely, determining the fill level based on the vibration acceleration signal or the acoustic signal of the mill operation. In addition, during the operation of the ball mill other parameters are also measured, i.e. the air mixture temperature at the mill outlet, the differential pressure across the mill drum and the active power consumed by the mill electric drive. These parameters are used to control the mill operation, as well as to protect against emergency situations.

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2. Goal of the paper

The goal of this paper is to analyze the vibration acceleration signals during the operation of ball drum mills under operating conditions and also to present the methods for processing these signals to determine the variation of the fill level of the mill (filling with the material) with a constant amount of ball charge.

3. Analysis of recent publications

Studies of the acoustic signals of ball mills, as well as vibration acceleration signals during ball mill operation, are presented in publications [2]-[9]. In [2], a method for processing the acoustic signals for determining the grinding fineness of calcined alumina in a small ball mill is presented. In [3], [4], the acoustic signals of a ball mill for different fill levels and rotation speeds are analyzed using a sound signal model and the discrete element method. In [5], the results of processing the acoustic signal of the mill using machine learning models are presented.

Since the acoustic signal, besides the useful information, often contains additional noise and sounds from other equipment, a more effective signal for determining the fill level of the mill is the vibration acceleration signal. In [6], a method for collecting and processing vibration signals using sensors installed on the outer surface of the mill drum, as well as on the supports of the front and rear bearings of the mill drum is presented. In [7], a method for determining the characteristics of the ground material based on the vibration accelerometer signal installed on the surface of the mill drum is presented. In [8], a method for determining the mill load based on the vibration accelerometer signal using the Adaptive Chirp Mode Decomposition (ACMD) method and the Standardized Variable Distance Classifier (SVD) method is presented. And in work [9], a method of processing the signal from an accelerometer using a Hampel filter to eliminate noise, as well as Fast Fourier Transformation (FFT) to construct the spectral density (PSD).

In the publications mentioned above, a great deal of attention is paid to the processing of signals from the operation of ball mills in laboratory conditions and there are no results of signal analysis in operating conditions.

4. Presentation of research results

4.1. Analysis and processing of vibration acceleration signal for the first mill

The vibration acceleration signals were recorded using a sound card for two ball mills under operating conditions. ABC117-03 vibration accelerometer was installed on the front support of the mill. The parameters of the recorded vibration acceleration signal file for the first mill are as follows:

File name:	Mill_1.wav
File size:	64.9 MB
Bit rate:	1536 kbit/s
Sample rate:	96000
Total samples:	34028800
Duration:	354.4667 s
Bits per sample:	16

The vibration acceleration signal was imported into Matlab using the “audioread” command [10]. The results are presented in Fig. 1.

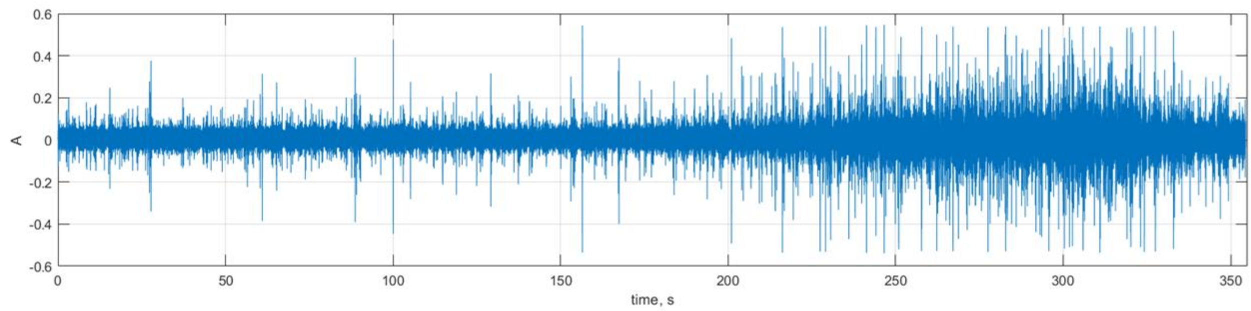

Fig. 1. Imported vibration acceleration signal.

Fig. 1 shows that in the first part of the recorded signal the amplitude is smaller than in the second part of the signal. This means that the fill level of the mill with material is higher for the first part of the recorded signal, and in the second part the fill level (the amount of material in the mill) decreases.

To process the vibration acceleration signal, it is proposed to use a moving window. The signal within the moving window is processed with application of the following two methods:

- fast Fourier transform;
- integral of the modulus of the vibration acceleration.

We need to select the size of the moving window to process the signal. The technique for defining the optimal size of a moving window is presented in [11]. As a result of applying this technique to the signal from the file "Mill_1.wav", it was found that the optimal value of the moving window size is 400 ms. The window movement step is chosen to be 200 ms.

According to the first method of the vibration acceleration signal processing, the frequency spectrum was built for each position of the moving window with application of "fft" command [12]. The result of building the frequency spectra for the first five positions of the moving window is presented in Fig. 2.

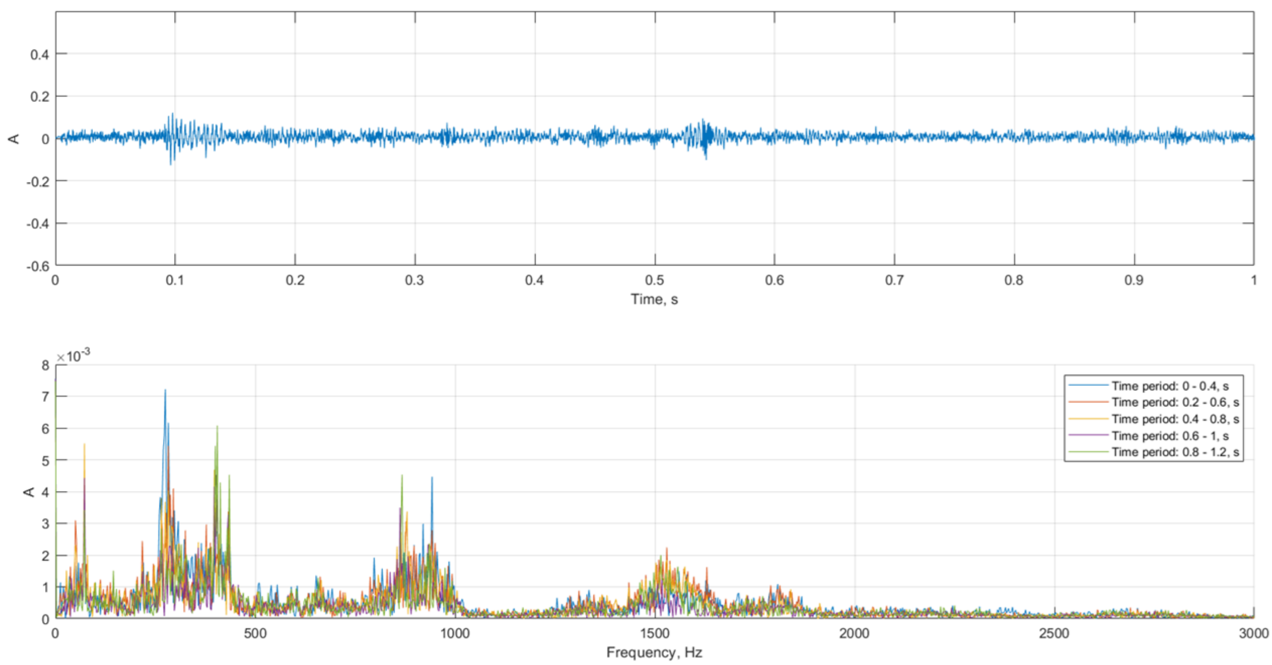

Fig. 2. Beginning of the vibration acceleration signal and the first five frequency spectra.

We can see from Fig.2 that the frequency spectrum has several ranges where there is useful signal. These are the following ranges: from 200 to 500 Hz, from 750 to 1100 Hz and from 1300 to 2000 Hz. To determine the vibration level using the first method, the maximum of the frequency spectrum in the frequency range from 750 Hz to 1100 Hz was selected.

Variation of the vibration level according to the first method of the vibration acceleration signal processing with application of the moving window is presented in Fig. 3. The obtained values were smoothed using a moving average filter (causal) with a smoothing window size of 20 s, which contained 101 samples of the vibration level signal. The delay of the smoothed vibration level signal with respect to the non-smoothed signal is 10 s. A causal filter was chosen to smooth the signal, since this type of filter can be used to process the vibration acceleration signal in real time.

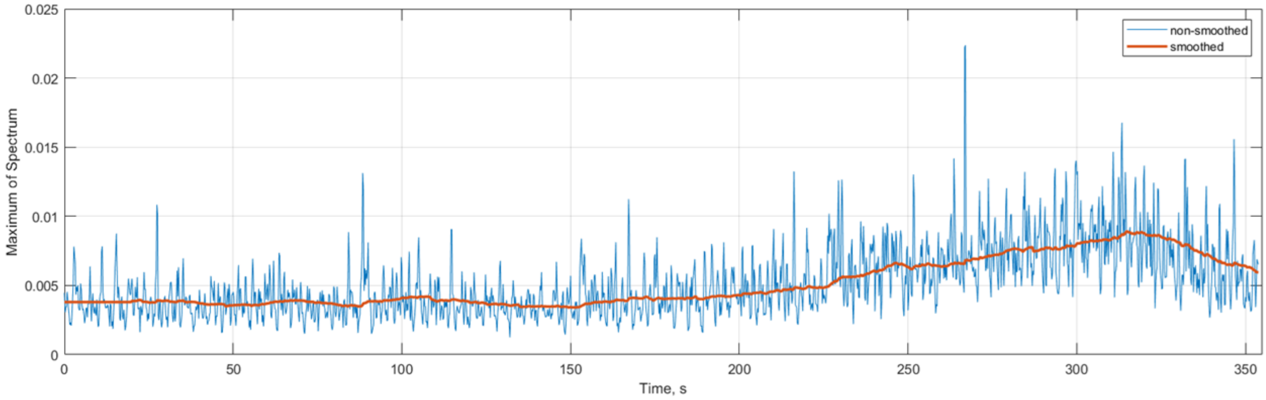

Fig. 3. Variation of the vibration level defined by the first method
(maximum of the frequency spectrum in the frequency range from 750 Hz to 1100 Hz).

To calculate the variation of the fill level of the mill on the basis of the vibration level (smoothed), the following assumptions were made: the fill level signal starts at the value of 90%; the fill level signal decreases to the minimum value of 60%. Calculation of the fill level was made by means of the following formula:

$$y = \frac{(x_0 - x)\cdot\Delta y}{\max(x) - x_0} + y_0, \tag{1}$$

where y is the fill level of the mill; x is the vibration level (smoothed); x_0 =0.0038 is the initial value of the vibration level; Δy = 30 is the range of fill level variation; y_0 = 90 is the initial value of the fill level.

The result of defining the fill level of the mill on the basis of the vibration acceleration signal with application of the first method is presented in Fig. 4. This figure shows that from the beginning to 200 s, the amplitude of the vibration acceleration signal and the fill level of the mill remain approximately at a constant value. Between 200 s and 320 s, the vibration acceleration amplitude increases, and the fill level decreases. After 320 s, the vibration acceleration amplitude decreases, and the fill level increases.

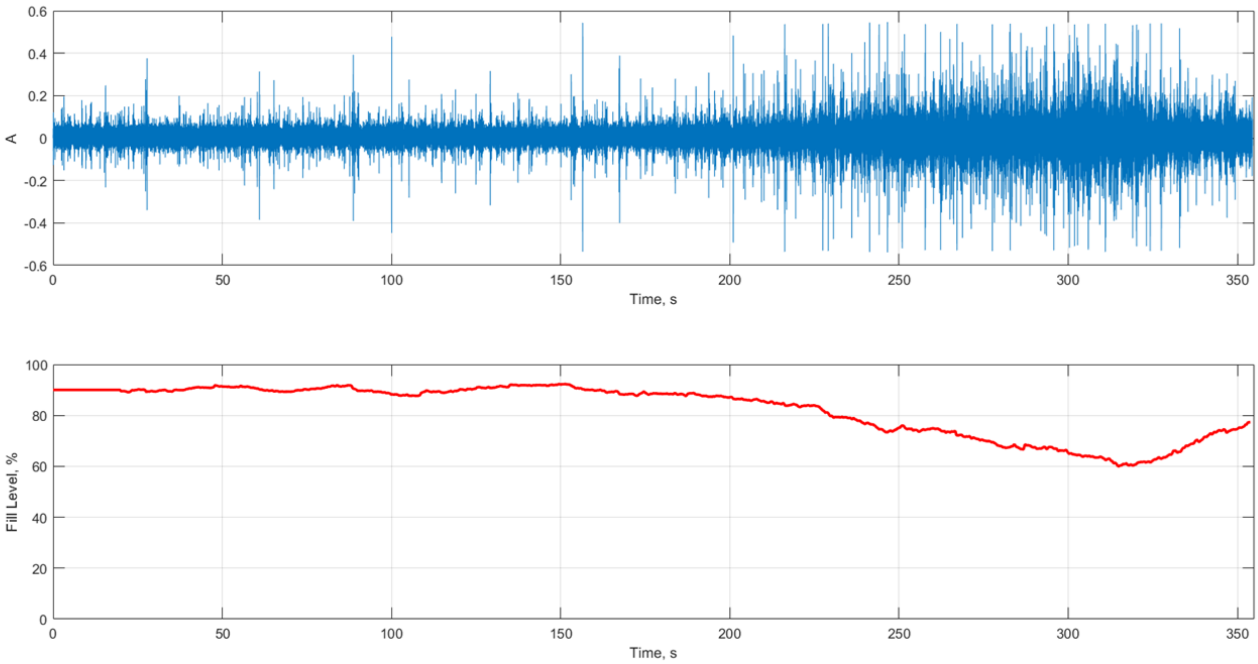

Fig. 4. Vibration acceleration signal and variation of fill level of mill defined by the first method.

Now we will apply the second method of the vibration acceleration signal processing, i.e. the integral of the modulus of the vibration acceleration over the duration of the moving window. The window size is again taken to be 400 ms, the window movement step is 200 ms.

For each position of the moving window, the integral of the modulus of the vibration acceleration signal was calculated using the "cumtrapz" command [13]. The result of calculating the variation of the integral for the first five positions of the moving window is presented in Fig. 5.

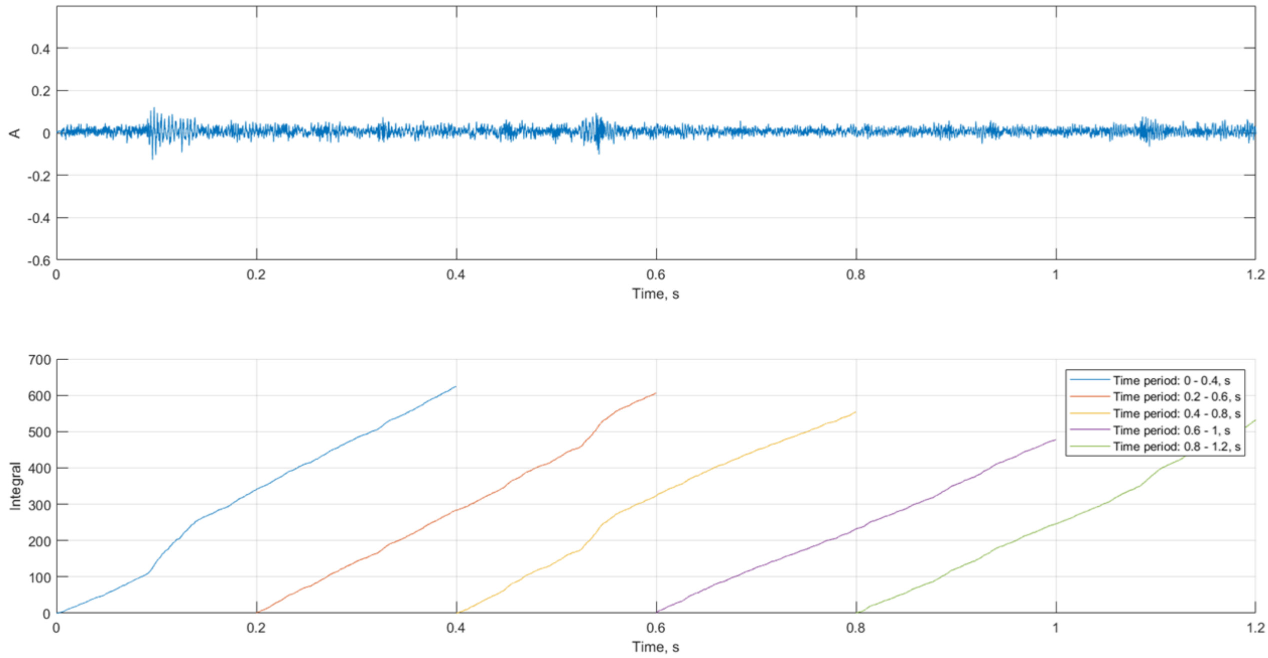

Fig. 5. Beginning of the vibration acceleration signal and variation of the integral for the first five positions of the moving window.

Variation of the vibration level defined by the second method is shown in Fig. 6. The obtained values were smoothed using a moving average filter (causal) with a smoothing window size of 20 s, which contained 101 samples of the vibration level signal. The delay of the smoothed vibration level is 10 s with respect to the non-smoothed vibration level.

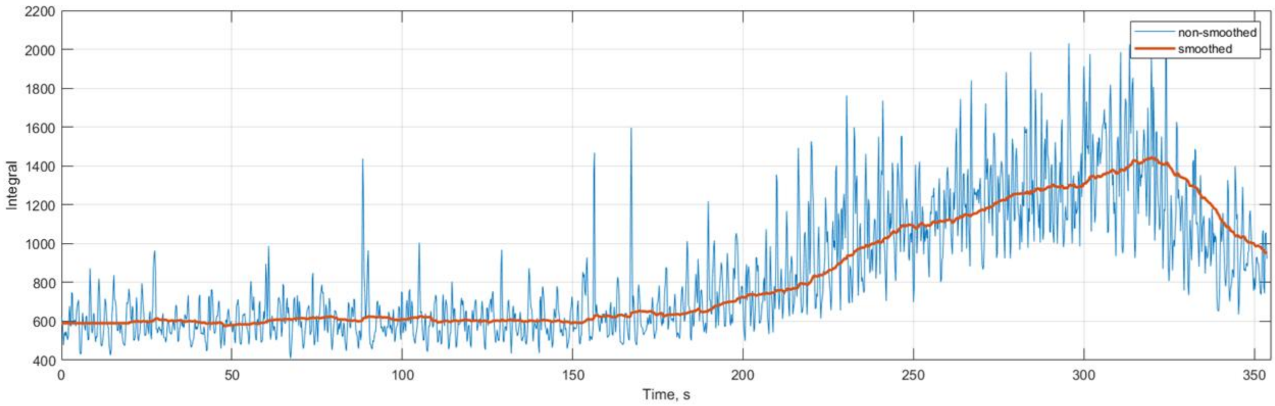

Fig. 6. Variation of the vibration level defined by the second method
(integral of the modulus of the vibration acceleration).

To calculate the variation of the fill level based on the second method, the same assumptions were made as for the first method (initial value of the fill level is 90% and minimum value of the fill level is 60%). Formula (1) was used for calculation. The value of x_0 was taken equal to 590. The result of defining the fill level of the mill on the basis of the vibration acceleration signal with application of the second method is presented in Fig.7.

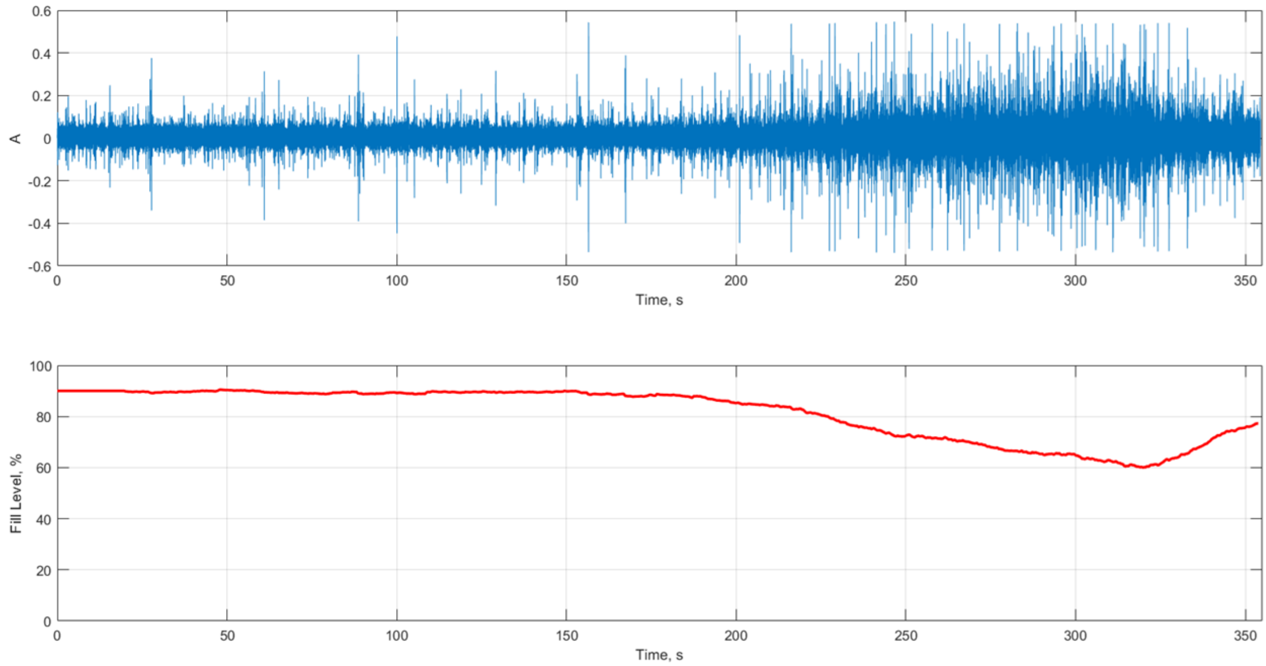

Fig. 7. Vibration acceleration signal and variation of fill level of mill defined by the second method.

We can see from Fig. 7 that from the beginning to 200 s, the amplitude of the vibration acceleration signal and the fill level of the mill remain approximately at a constant value. Between 200 s and 320 s, the vibration acceleration amplitude increases, and the fill level decreases. After 320 s, the vibration acceleration amplitude decreases, and the fill level increases.

Based on the comparison of the fill level signal obtained by the second method with the signal obtained by the first method, it can be concluded that the signal obtained by the second method (Fig. 7) is smoother than the signal obtained by the first method (Fig. 4).

4.2. Analysis and processing of vibration acceleration signal for the second mill

Now we will analyze and process the vibration acceleration signal for the second ball mill. The parameters of the recorded vibration acceleration signal file for the second mill are as follows:

File name:	Mill_2.wav
File size:	77.2 MB
Bit rate:	1536 kbit/s
Sample rate:	96000
Total samples:	40500480
Duration:	421.8800 s
Bits per sample:	16

The file “Mill_2.wav” was processed in the same way as the file “Mill_1.wav”. The size of the moving window was set to be 400 ms, the window step was 200 ms. According to the first method of signal processing, the maximum of the frequency spectrum was calculated in the frequency range from 950 Hz to 1800 Hz. The values of the vibration level were smoothed using a moving average filter (causal) with a smoothing window size of 20 s. The following assumptions were made to calculate the variation of the fill level: the fill level signal starts at the value of 80%; the fill level signal decreases to the minimum value of 10%.

The calculation of the fill level signal with application of the first method (maximum of the frequency spectrum in the frequency range from 950 Hz to 1800 Hz) was made using formula (1), where the following values of constants were taken: x_0 = 0.0045, Δy = 70, y_0 = 80. The results of processing “Mill_2.wav” file with application of the first method are presented in Figures 8 – 11.

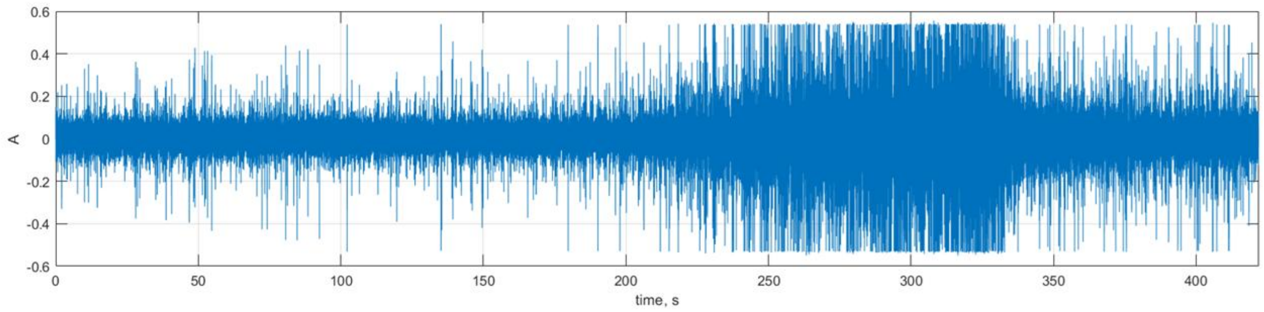

Fig. 8. Imported vibration acceleration signal for the second mill.

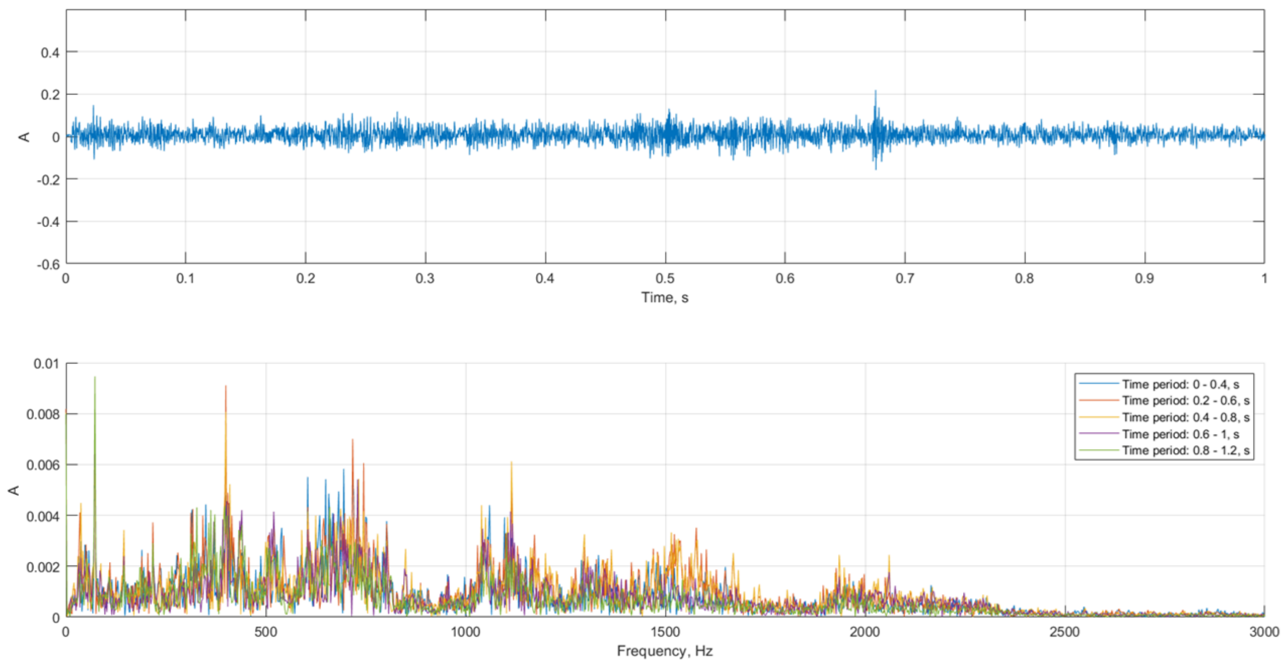

Fig. 9. Beginning of the vibration acceleration signal and the first five frequency spectra.

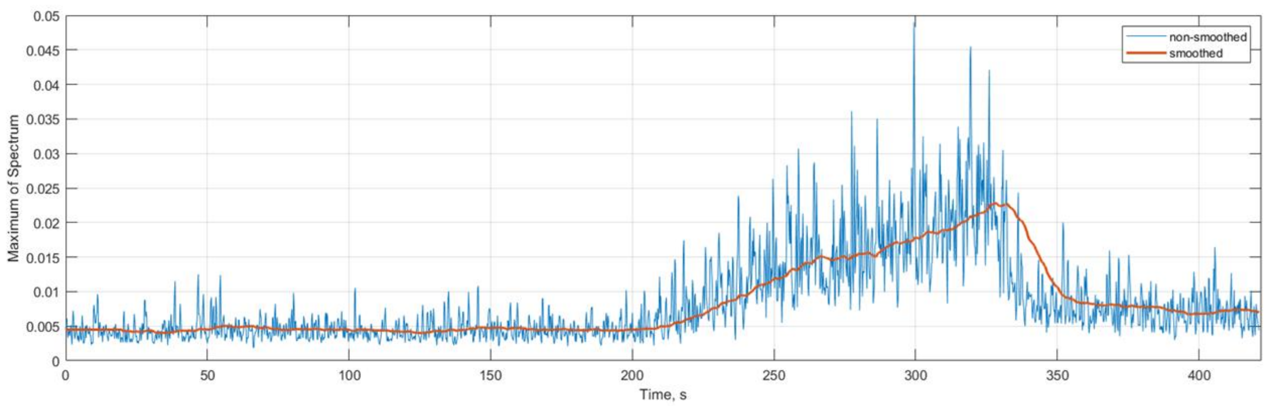

Fig. 10. Variation of the vibration level defined by the first method
(maximum of the frequency spectrum in the frequency range from 750 Hz to 1100 Hz).

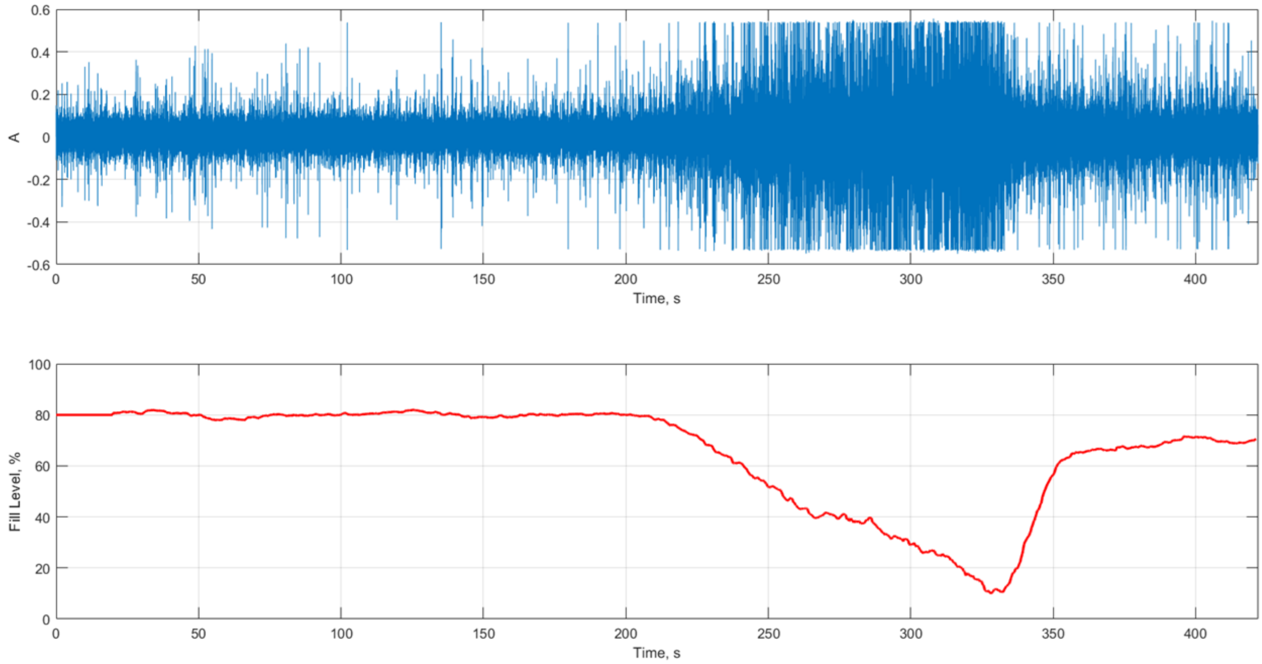

Fig. 11. Vibration acceleration signal and variation of fill level of mill defined by the first method.

The calculation of the fill level signal by the second method (integral of the modulus of the vibration acceleration signal over the time of the moving window) was made using formula (1), where the following values of constants were taken: $x_0 = 885$, $\Delta y = 70$, $y_0 = 80$. The result of processing "Mill_2.wav" file by the second method is presented in Fig. 12.

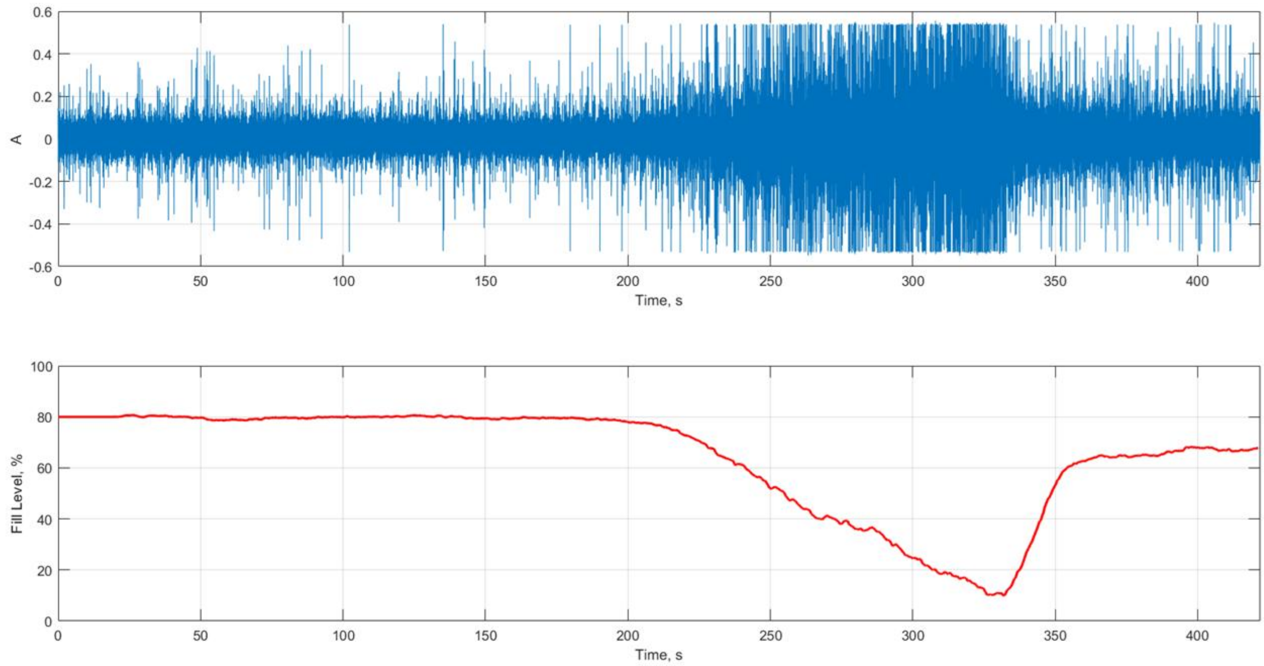

Fig. 12. Vibration acceleration signal and variation of fill level of mill defined by the second method.

Based on the comparison of the results obtained by the first and the second method, for the second mill we can draw a similar conclusion as for the first mill: the fill level signal obtained by the second method (Fig. 12) is smoother than the signal obtained by the first method (Fig. 11). By comparing the results for files "Mill_1.wav" and "Mill_2.wav", the following conclusions can be made:

- the frequency spectra of the signals in these files are slightly different, therefore, for the file "Mill_1.wav" the maximum was calculated in the frequency range from 750 Hz to 1100 Hz, and for the file "Mill_2.wav" – in the frequency range from 950 Hz to 1800 Hz;
- the initial value of the amplitude in the file "Mill_1.wav" is slightly smaller than that in the file "Mill_2.wav", therefore the initial fill level for the first mill was set to a higher value than for the second mill;
- the increase in the amplitude of the vibration acceleration signal in the file "Mill_1.wav" is less significant than in the file "Mill_2.wav", therefore the fill level signal for the file "Mill_1.wav" changes by a smaller amount than for the file "Mill_2.wav".

5. Conclusion

As a result of the study, it was found that the vibration level of the front support of the ball mill is directly correlated with the amount of material being ground in the mill. The higher the vibration level, the less material is in the mill and vice versa. Two methods with application of a moving window are proposed to process the vibration acceleration signal during the operation of the ball mill. The first method consists in building the frequency spectrum using the fast Fourier transform and subsequent determination of the maximum in a specific frequency range. The second method consists in calculating the integral of the modulus of the vibration acceleration signal during the time of the moving window.

Based on the experimental data for two ball mills, each of the two proposed methods was tested. The results show that the fill level signal obtained by the second method is smoother than the signal obtained by the first method. In addition, it should be noted that to obtain the fill level signal by the second method, less computational resources of the controller are needed than for the signal obtained by the first method, since the calculation of the integral of the modulus of vibration acceleration is a simpler algorithm than building the frequency spectrum with subsequent determination of the maximum in a specific frequency range.

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Визначення рівня наповнення кульового барабанного млина на основі сигналу віброприскорення

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Анотація

Стаття присвячена дослідженню зв'язку між сигналом віброакселерометра та рівнем наповнення кульового барабанного млина розмелюваним матеріалом. Встановлено, що є пряма кореляція між рівнем вібрації передньої опори млина та кількістю матеріалу, що розмелюється у млині. Низький рівень вібрації відповідає високому рівню наповнення млина. Запропоновано два способи опрацювання сигналу віброакселерометра для отримання сигналу рівня наповнення із застосуванням рухомого вікна. У першому способі виконується побудова частотного спектру та визначення максимуму в певному діапазоні частот. Другий спосіб полягає у розрахунку інтеграла модуля сигналу віброприскорення за час рухомого вікна. Продемонстровано роботу кожного способу на основі експериментальних даних сигналів віброприскорення під час роботи двох кульових барабанних млинів.

Ключові слова: кульовий барабанний млин; сигнал віброприскорення; частотний спектр; рухоме вікно; експериментальні дані; рівень наповнення.