Volume 10, Number 2, 2024

Technique for Defining the Optimal Parameters of Moving Window at Vibration Accelerometer Signal Processing

Roman Fedoryshyn[a,*], Vasyl Lymych[a], Volodymyr Zagraj[b], Oleh Masniak[a]

[a]*Lviv Polytechnic National University, 12 S. Bandery St., Lviv, 79013, Ukraine*
[b]*Techprylad LLC, 116 V. Antonovycha St., Lviv, 79057, Ukraine*

Received: October 16, 2024. Revised: December 06, 2024. Accepted: December 14, 2024.

Abstract

This paper presents a technique for defining the optimal parameters of a moving window when processing the signal of a vibration accelerometer installed on a ball drum mill as part of the automation system. Time series signals of the vibration acceleration have been synthesized based on the experimental data of frequency spectrums with the application of the inverse Fourier transform. The lower and upper limits for the moving window size have been defined. The frequency spectrum for the time series signal within the moving window has been built by means of the fast Fourier transform method. An optimality criterion has been proposed. This criterion considers the quality of the derived frequency spectrum and the computational resources of the microprocessor system needed for processing the vibration accelerometer signal. The optimal duration of the moving window for the analyzed example is 100 ms. The impact of the time signal sampling rate on the frequency spectrum shape has been studied.

Keywords: vibration accelerometer; Fourier transform; frequency spectrum; time series signal; ball drum mill.

1. Introduction

Processing of the vibration signals is an important part of the procedure for obtaining data on the condition and behavior of mechanical systems. The level of vibration of the technological equipment or its parts is measured by means of an accelerometer. Some changes in the technological process can be defined and certain patterns can be identified on the basis of the vibration signals. One of the examples here is the automation system of a ball drum mill, where the vibration accelerometer is applied to define the level of mill load with the material [1]. As the mill rotates, the balls strike the inner surface of the mill drum, where the material is located, and thus the grinding process takes place. The strikes of the balls excite vibrations that propagate through the mill body. These vibrations are a useful signal, but in addition to the useful signal there is also noise at the input of the vibroaccelerometer, which is caused by the operation of water pumps, shut-off valves, mill bearings, and other technological equipment. The task of the measurement system is to get the useful signal and filter out the noise.

The vibration sensor can be installed in different parts of the mill: on the front bearing support of the mill drum, on the rear bearing support of the mill drum, or on the outer surface of the mill drum (in one or more places). The signal of the vibration sensor installed on the front bearing support contains information about the amount of the material in the inlet part of the mill drum. The signal of the sensor installed on the rear bearing support contains information about the amount of material in the outlet part of the mill. Based on the signals of the vibration sensors installed on the outer surface of the mill drum, it is possible to estimate the distribution of the material along the mill

[*] Corresponding author. Email address: roman.m.fedoryshyn@lpnu.ua

This paper should be cited as: R. Fedoryshyn, V. Lymych, V. Zagraj, O. Masniak. Technique for defining the optimal parameters of moving window at vibration accelerometer signal processing. *Energy Engineering and Control Systems*, 2024, Vol. 10, No. 2, pp. 142 – 152. https://doi.org/10.23939/jeecs2024.02.142

drum. Another way of using vibration sensors is to install them inside the balls. Based on the signals of such sensors, the degree of mill load with the material can be defined [2].

By analyzing the vibrations that occur during the operation of the mill, it is possible not only to determine the level of filling with material, but also to diagnose the condition of the technological equipment and ensure optimization of the grinding process, reduction of energy consumption and minimization of equipment wear [3]. The methods for processing the vibration accelerometer signals affect the operation of the whole mill automation system. Therefore, improving these methods is an important task for ensuring high quality and reliability of the mill automatic control system functioning.

2. Analysis of recent publications

One of the methods for processing the vibration accelerometer signal is the application of a moving window [4]. In [5], 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. For sensors installed on the surface of the mill drum, the window size is chosen to be 4096 samples. And for sensors installed on the bearing supports the window size is 2048 samples at the sampling rate of 19.2 kHz. In [6], a method for determining the characteristics of the ground material based on the signal of a vibration accelerometer installed on the surface of the mill drum is presented. The window size for processing the time series signal here is 10 s. In [7], a method for determining the mill load based on the vibration signal using the Adaptive Chirp Mode Decomposition and the Standardized Variable Distance Classifier is presented. The window size here is set to 1 s. In [8], a window size of 2048 samples at a sampling rate of 20 kHz is chosen for processing the accelerometer signal. In [9], a method for processing the accelerometer signal using the Hampel filter to eliminate noise and the Fast Fourier Transform to get the Power Spectral Density is presented. The window size here is 9000 samples, and the signal sampling rate is 13 kHz.

The abovementioned works describe the methods, tools, and sequence of steps used in processing the vibration accelerometer signal. However, there is no information in these works on how to determine the optimal size of the moving window for processing the vibration accelerometer signal and what the limitations are on the size of the moving window.

3. Goal of research

Defining the optimal size of the moving window when converting a time series signal into a frequency spectrum is an important step to ensure accurate and efficient processing of the vibration accelerometer signal. If the size of the moving window is too small, the obtained frequency spectrum will not correspond to the real frequency spectrum and the quality of the frequency spectrum will be unsatisfactory. Too large a moving window requires more time to process the signal and more memory to store the moving window samples, which leads to the need to increase the computing resources of the microprocessor system. Another factor that needs to be taken into account when defining the upper limit of the moving window size is the rate of mill load change. If the window size is too large, then with a rapid change in the mill load, a significant dynamic error in defining the mill load with the material may occur.

The goal of this work is to develop a technique for defining the optimal parameters of a moving window when processing the signal of a vibration accelerometer installed on a ball drum mill to determine the amount of the material in the mill. To achieve this goal, the frequency spectrums of the vibration acceleration signals should be analyzed for a filled and empty mill. The sampling rate of the time series signal should be chosen. The lower and upper limits for the moving window size should to be defined. An optimality criterion for the size of the moving window should be developed. All these tasks were accomplished by the authors. The results are presented in this paper.

4. Main results of research work

Converting the time series signal of a vibration accelerometer into a frequency spectrum allows improving the efficiency of its analysis, since in this way it is possible to get the useful signal and eliminate the influence of noise. In addition, the amplitude deviations within the useful frequency band become more obvious. To build the frequency spectrum, the fast Fourier transform method [10] implemented by means of the fft command in Matlab [11] has been applied in this work.

The frequency spectrums of the vibration acceleration signal for an empty and filled mill are shown in Fig.1. These frequency spectrums were obtained on the basis of experimental studies [12]. The dependence of the frequency spectrum on the mill load in a three-dimensional space is shown in Fig.2. Fig.1 and Fig.2 show that the more the mill is loaded, the smaller the amplitude of the vibration accelerometer signal and vice versa. The useful signal of the mill load is within the frequency range from 2 to 6 kHz.

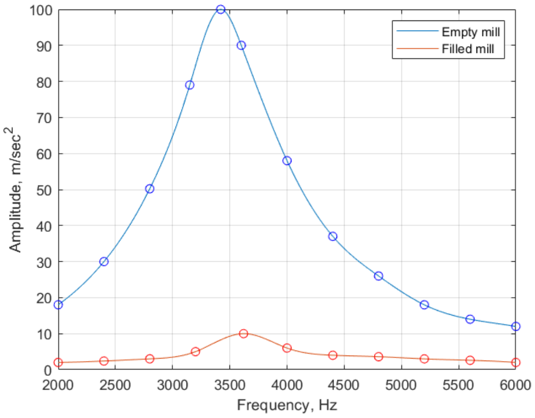


Fig.1. Frequency spectrums of vibration acceleration signal for the empty and filled mill.

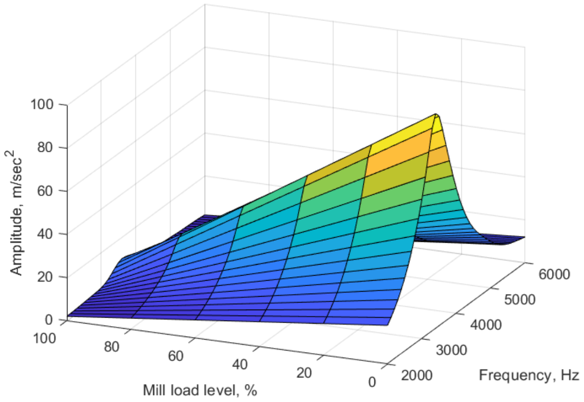
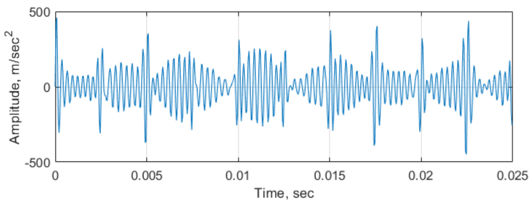


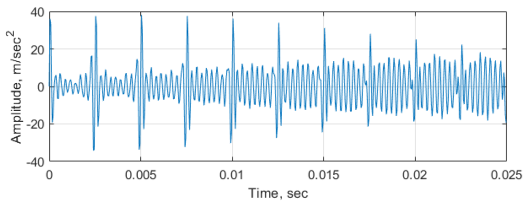
Fig.2. Dependence of frequency spectrum on mill load.

Based on the experimental frequency spectrum points, a time series signal of vibration acceleration has been synthesized using the ifft command in Matlab [13], which performs the inverse Fourier transform. In order to synthesize the time series signal of vibration acceleration, the sampling rate and the number of samples should be set. According to the Nyquist theorem, the sampling rate of the signal should be twice the highest frequency of the continuous signal that needs to be converted into a discrete form [14]. We can see from Fig.1 that the highest frequency of the vibration acceleration signal is 6 kHz. So, for this measurement system, the Nyquist frequency is 12 kHz. According to the recommendations of manufacturers of equipment for measuring the vibration acceleration, it is recommended to set the sampling rate to at least twice the Nyquist frequency [4], [15]. Therefore, the following parameters have been set for synthesizing the time series signal of vibration acceleration:

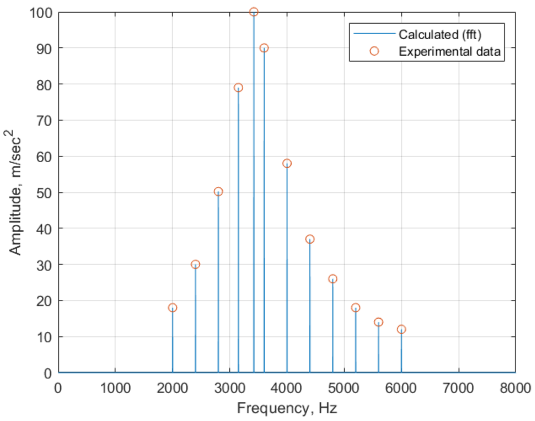
- sampling rate: 24 kHz;
- number of samples: 12000;
- duration of signal: 0.5 sec.



a

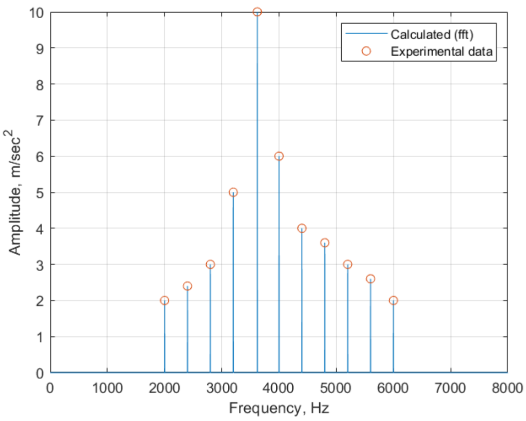


a



b

Fig.3. Time series signal of vibration acceleration (*a*) and its frequency spectrum (*b*) for the empty mill.



b

Fig.4. Time series signal of vibration acceleration (*a*) and its frequency spectrum (*b*) for the filled mill.

The synthesized time series signals of vibration acceleration for the empty and filled mill are presented in Fig.3,*a* and Fig.4,*a*, respectively (the time series signals are visualized in the selected time range from 0 to 0.025 sec). The frequency spectrums for the empty and filled mill are presented in Fig.3,*b* and Fig.4,*b*, respectively (these frequency spectrums are built on the basis of the whole synthesized time series signals with the duration of 0.5 sec). The initial experimental points of the frequency spectrums, on the basis of which the time series signals were synthesized, are also shown in these figures. Fig.3,*b* and Fig.4,*b* show that the frequency spectrums built with the application of the fft command have the form of delta functions for the selected frequencies with amplitudes corresponding to the initial experimental points of the frequency spectrums. This indicates that the inverse and forward Fourier transforms were accomplished correctly.

4.1. Definition of lower and upper limits for the moving window size

Fig.3,*a* and Fig.4,*a* show that the vibration acceleration signal is of cyclic nature and the period of one cycle is 2.5 ms. In order to check how the frequency spectrum will look at different values of the window size (T_{win}), the frequency spectrums of the empty and filled mill were built for the values of T_{win} in the range from 2.5 ms to 500 ms. The results are presented in Fig.5 and Fig.6.

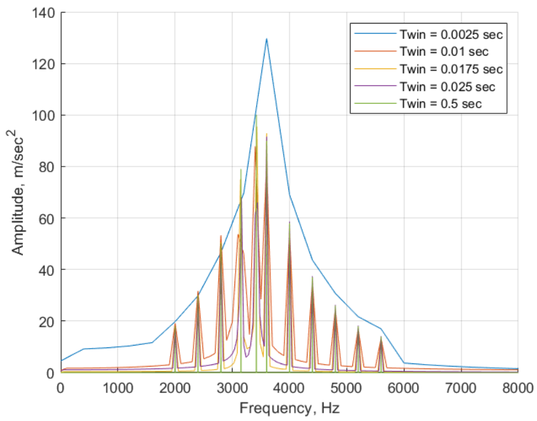


Fig.5. Frequency spectrum at different values of window size (T_{win}) for the empty mill.

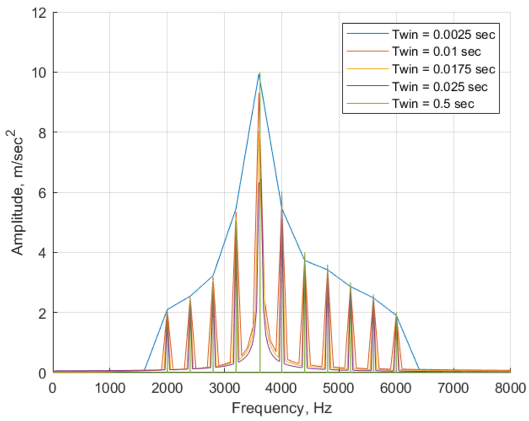


Fig.6. Frequency spectrum at different values of window size (T_{win}) for the filled mill.

We can see from Fig.5 and Fig.6 that at T_{win} = 2.5 ms (period of one cycle of the vibration acceleration signal) the frequency spectrum has the form of a curve that rises up to a certain value, after which it begins to fall down. With an increase in T_{win} value, the frequency spectrum acquires a wedge-shaped form. With a further increase in T_{win}, the width of each wedge decreases and the frequency spectrum approaches the form of delta functions. So, the larger the size of the moving window, the better the quality of the frequency spectrum. At T_{win} = 2.5 ms the quality of the frequency spectrum is unsatisfactory, because the curve of the frequency spectrum has a fundamentally different form than at larger values of the window size. At T_{win} = 25 ms, the frequency spectrum acquires a satisfactory quality. For further studies, we will consider that the lower limit of the moving window size is 25 ms.

In order to define the upper limit of the moving window size, the transient process of mill load variation in time should be analyzed. The transient process curve is presented in Fig.7. It was built on the basis of the results of experimental studies given in [12]. By differentiating the mill load curve, we obtain the load rate of change curve (see Fig.8). In addition, the curve of modulus of load rate of change was built (see Fig.9) and the curve of inverse modulus of load rate of change was built (see Fig.10).

Fig.9 shows that the maximum rate of change of mill load is 2.16 %/sec. This maximum rate of change corresponds to the minimum time period during which the mill load can change by 1% (see Fig.10). In this case, the minimum time period is 462 ms. We will round this value to 450 ms and consider that the upper limit of the moving window size at processing the vibration accelerometer signal is 450 ms.

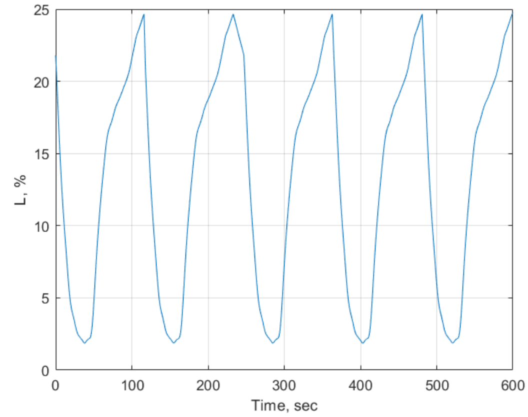


Fig.7. Transient process of mill load variation.

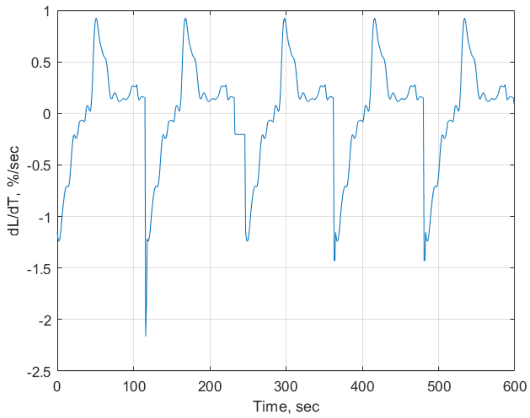


Fig.8. Mill load rate of change.

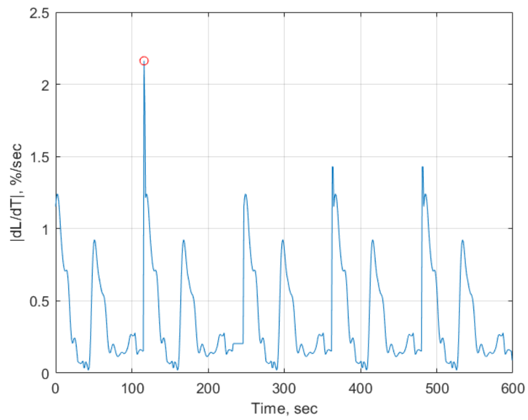


Fig.9. Modulus of mill load rate of change (o – point of maximum rate of change).

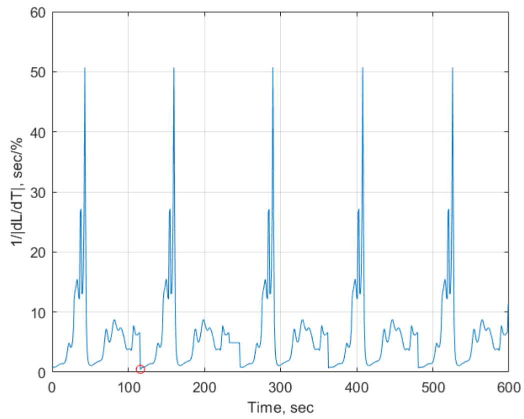


Fig.10. Inverse modulus of mill load rate of change (o – minimum period of time during which the mill load can change by 1%).

4.2. Definition of lower and upper limits for the moving window size

Now when we have the values of the lower and upper limits of the moving window size, we can build the frequency spectrums of the empty and filled mill for the window size in the range from the lower to the upper limit (i.e. from 25 ms to 450 ms). The frequency spectrums are presented in Fig.11 and Fig.12. These figures show that the larger the moving window size, the better the quality of the frequency spectrum. To quantitatively assess the quality of the frequency spectrum, we will calculate the area under the curve of the frequency spectrum for different values of the moving window size (see Fig.13,*a* and Fig.14,a). The smaller the area under the curve, the better the quality of the frequency spectrum.

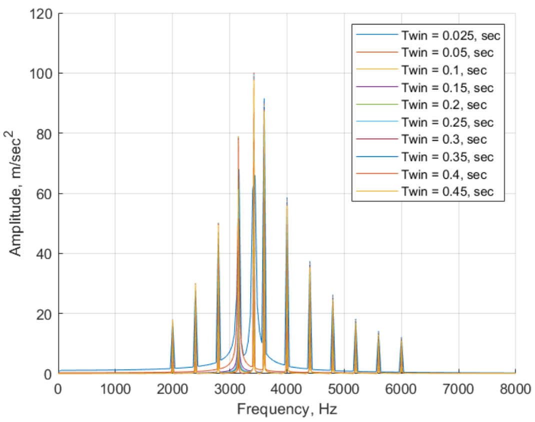


Fig.11. Frequency spectrums at different values of T_{win} for the empty mill.

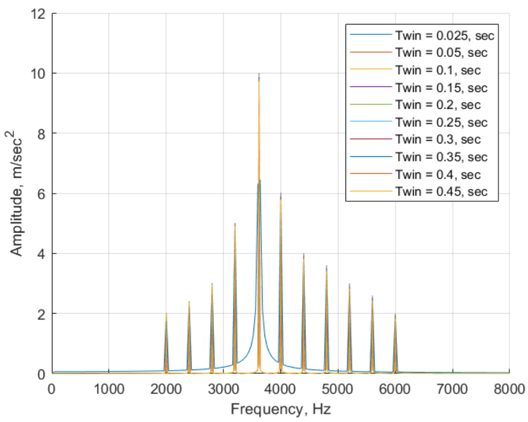


Fig.12. Frequency spectrums at different values of T_{win} for the filled mill.

As the size of the moving window increases, the number of samples in it increases too. As a result, the amount of memory that needs to be allocated in the microprocessor system to store these samples increases, and the time for processing the vibration accelerometer signal within the moving window increases too. To quantitatively assess the impact of the size of the moving window on the requirements for the microprocessor system to increase its resources and performance, we will take the number of samples in the moving window (see Fig.13,*b* and Fig.14,*b*).

To find the optimal size of the moving window, we will calculate the normalized area under the frequency spectrum curve and the normalized number of samples in the moving window using the following formulas:

$$s' = s/\max(s), \qquad (1)$$

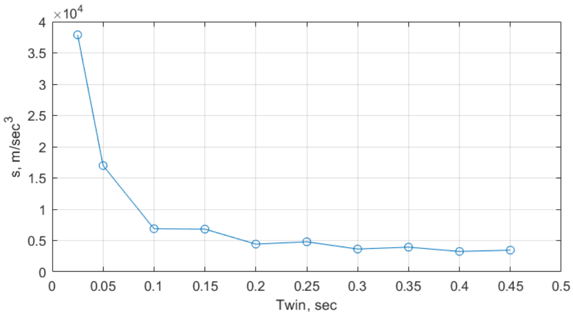
$$n'_{win} = n_{win}/\max(n_{win}), \qquad (2)$$

where s is the area under the frequency spectrum curve, m/sec^3; s' is the normalized area under the frequency spectrum curve; n_{win} is the number of samples in the moving window; n'_{win} is the normalized number of samples in the moving window.

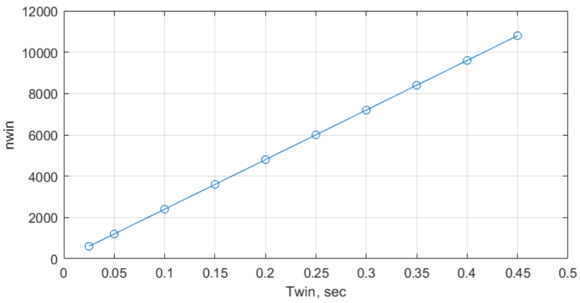
As the optimality criterion for the moving window size, we will take the sum of the normalized values of the area under the frequency spectrum curve and the number of points in the moving window:

$$I = s' + n'_{win}. \qquad (3)$$

This is an integral optimality criterion that takes into account the quality of the frequency spectrum and the impact of the moving window size on the resources and performance of the microprocessor system. The dependence of the optimality criterion and its components on the moving window size for an empty and filled mill is presented in Fig.15 and Fig.16, respectively.

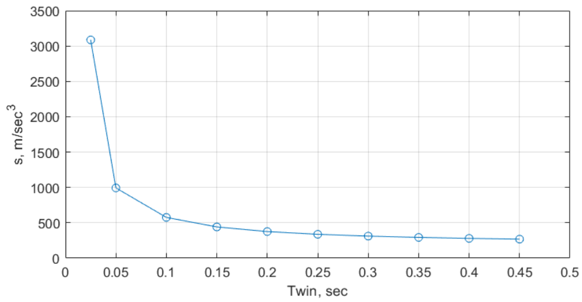


a

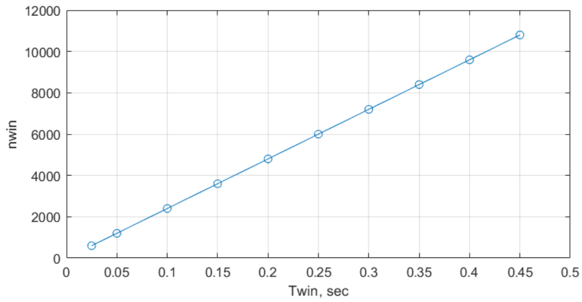


b

Fig.13. Dependence of the area under the frequency spectrum (*a*) and the number of samples in the moving window (*b*) on the size of the moving window for the empty mill.



a



b

Fig.14. Dependence of the area under the frequency spectrum (*a*) and the number of samples in the moving window (*b*) on the size of the moving window for the filled mill.

Fig.15 and Fig.16 show that the minimum value of the optimality criterion for the empty and filled mill is achieved at T_{win} = 100 ms. Thus, we will consider this value as the optimal size of the moving window for processing the vibration accelerometer signal in the automation system of the ball mill under consideration [12].

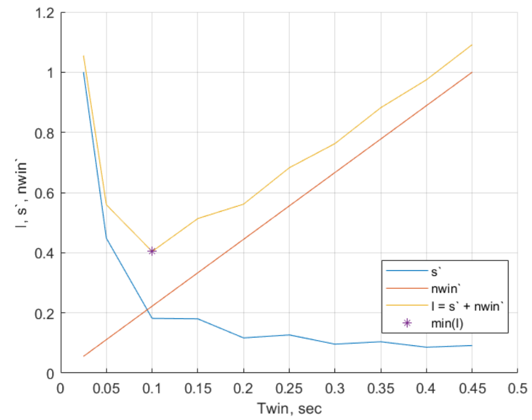


Fig.15. Dependence of the optimality criterion and its components on the size of the moving window for empty mill.

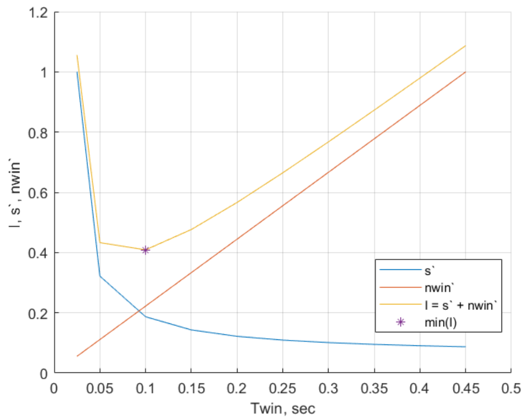


Fig.16. Dependence of the optimality criterion and its components on the size of the moving window for filled mill.

The frequency spectrums of the empty and filled mill for the optimal moving window size (T_{win} = 100 ms) are presented in Fig.17 and Fig.18. We can see from these figures that the quality of the frequency spectrums is high, since the frequency spectrums look almost like delta functions at the points of the selected frequencies, and the amplitudes are equal to the experimental amplitudes, on the basis of which the time series signals of vibration acceleration were synthesized.

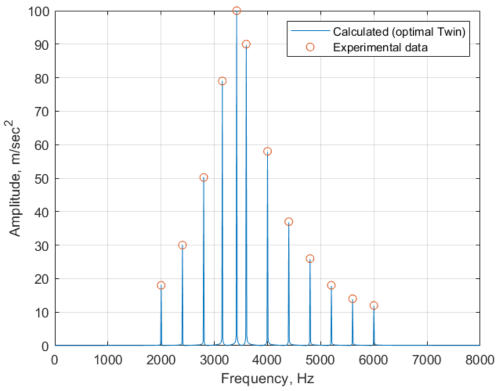


Fig.17. Frequency spectrum of empty mill for optimal size of moving window.

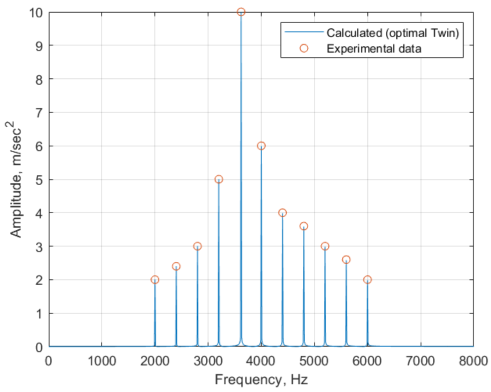


Fig.18. Frequency spectrum of filled mill for optimal size of moving window.

As far as the moving window step is concerned, it depends on the requirements for the accuracy and resolution of the mill load signal. If there is a need to obtain high resolution, the moving window step should be small, e.g. 50 ms for the system under consideration. In this case, the window will move along the time series signal with 50% overlap. During the 50 ms time period, the mill load can change by approximately 0.1% at the maximum rate of change of mill load, which corresponds to high resolution. If there is no requirement for high resolution, then the moving window step can be set at a large value, e.g. 500 ... 1000 ms. In this case, the window with an optimal size will move along the time series signal without overlap.

4.3. Technique for defining the optimal size of moving window

The initial data for defining the optimal size of the moving window when processing the vibration accelerometer signal in the ball mill automation system are the frequency spectrums of the vibration signal for an empty and filled mill, as well as the signal of mill load variation during its operation. The developed technique consists of the following steps:

1) based on the analysis of the frequency spectrums of the vibration acceleration signal, the sampling rate of the time series signal should be chosen (so that it is at least twice the Nyquist frequency);

2) time series signals of the vibration acceleration should be synthesized based on the frequency spectrums for an empty and filled mill;

3) lower limit of the moving window size should be defined (the minimum size of the window at which the frequency spectrum is built with a satisfactory quality for the synthesized time series signal, see 4.1);
4) upper limit of the moving window size should be defined on the basis of the signal of mill load variation during its operation (the minimum period of time during which the mill load can change by 1% at the maximum rate of change of the mill load, see Fig.10);
5) the dependence of the area under the frequency spectrum curve on the size of the moving window should be plotted (see Fig.13,*a*, Fig.14,*a*);
6) the dependence of the number of samples in the moving window on the size of the moving window should be plotted (see Fig.13,*b*, Fig.14,*b*);
7) the normalized values of the area under the frequency spectrum curve and the number of samples in the moving window should be calculated by means of formulas (1) and (2);
8) the integral optimality criterion should be calculated by means of formula (3);
9) the value of the moving window size that corresponds to the minimum of the integral optimality criterion should be chosen.

Defining the optimal size of the moving window according to the proposed technique ensures high quality of frequency spectrum when processing the vibration accelerometer signal, and also makes it possible to minimize the influence of the size of the moving window on the resources and performance of the microprocessor system.

4.4. Impact of time signal sampling rate on the frequency spectrum shape

In order to investigate how the sampling rate of the time series signal of the vibration accelerometer affects the shape of the frequency spectrum, the time series signal was synthesized with different sampling rates, namely 24 kHz, 48 kHz and 96 kHz (the duration of signal was taken equal to 500 ms). The time series signal was synthesized using the ifft command in Matlab based on the experimental frequency spectrum data (Fig.1). The synthesized time series signals for an empty and filled mill are presented in Fig.19 and Fig.20, respectively (time series signals are visualized in the range of time from 0 to 2.5 ms). After that, the frequency spectrum was built at different values of the sampling rate of the time series signal (using the fft command in Matlab). The frequency spectrums for an empty and filled mill are presented in Fig.21 and Fig.22, respectively (these frequency spectrums were built on the basis of the whole synthesized time series signals with the duration of 500 ms).

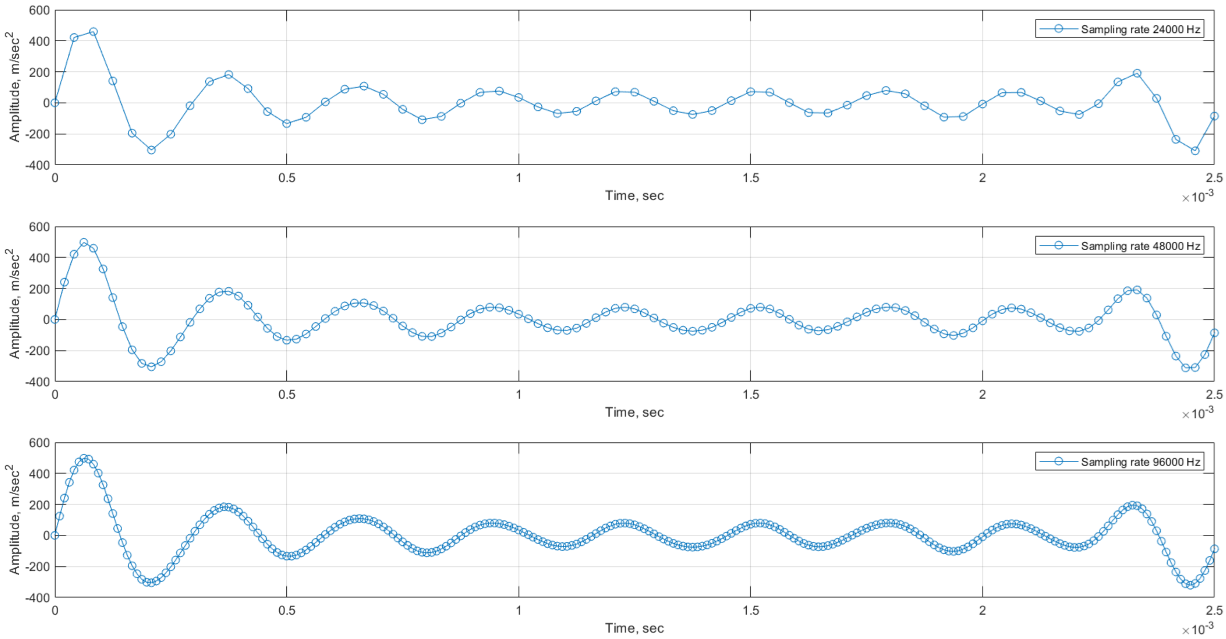


Fig.19. Synthesized time series signal at different sampling rates for the empty mill.

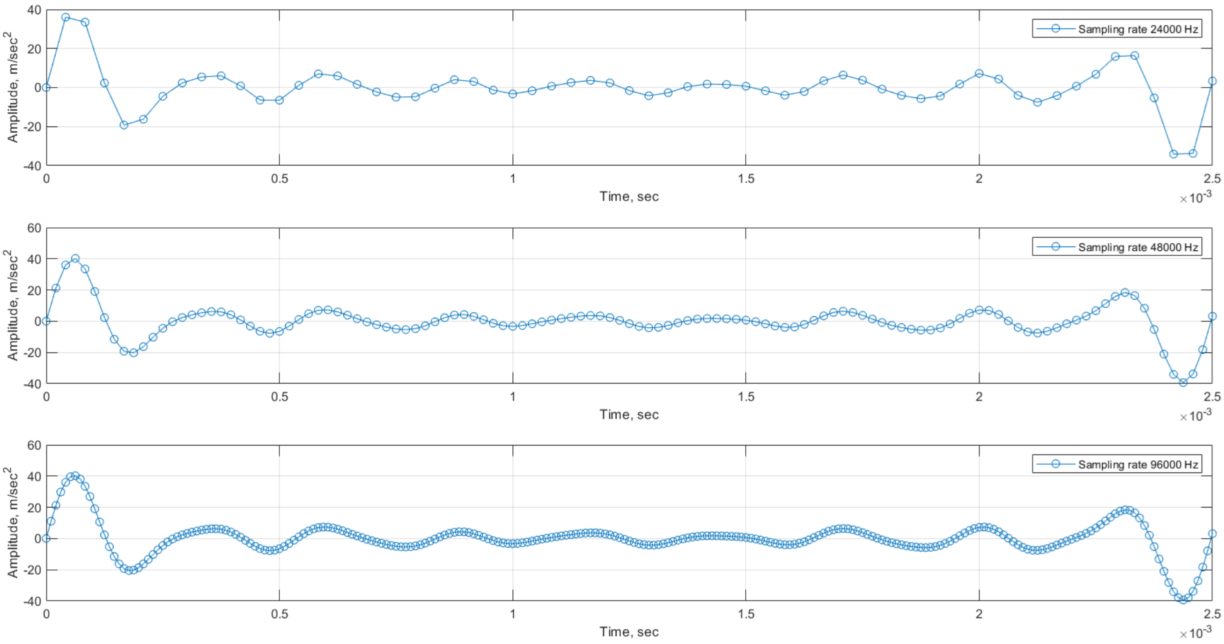


Fig.20. Synthesized time series signal at different sampling rates for the filled mill.

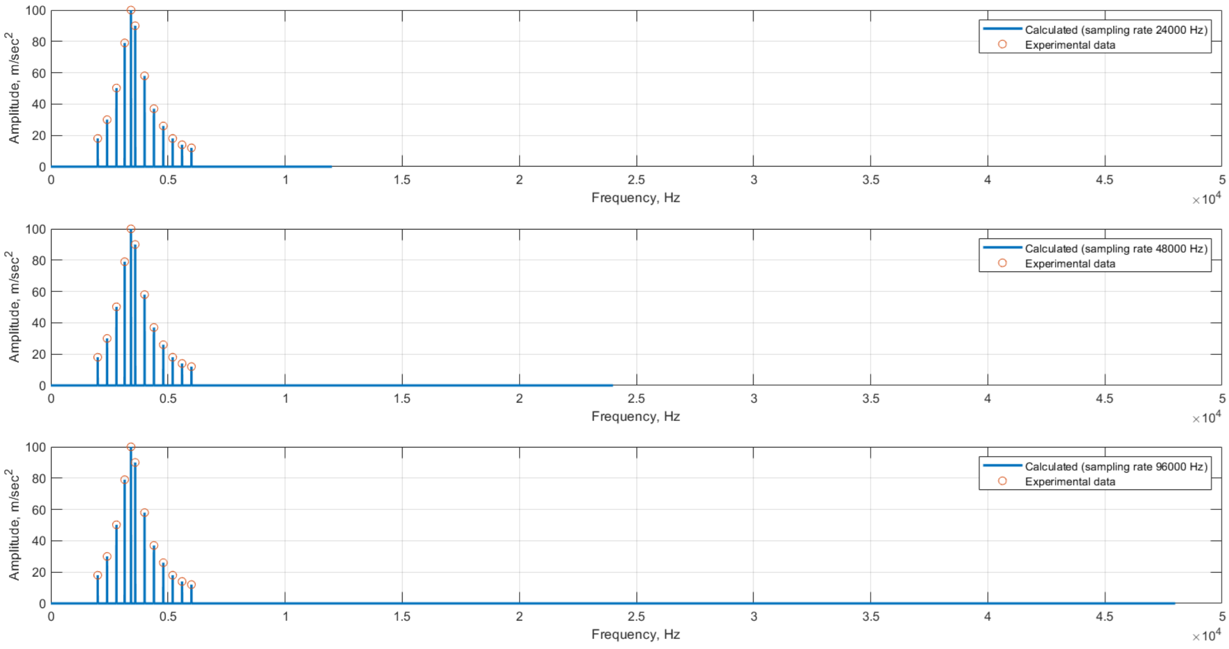


Fig.21. Frequency spectrum at different sampling rates of time series signal for the empty mill.

We can see from Fig.21 and Fig.22 that within the frequency range of the useful signal (from 2 kHz to 6 kHz), the frequency spectrum has the same shape for different sampling rates of the time series signal and it looks like delta functions for the selected frequencies with the amplitudes equal to the initial experimental points of the frequency spectrum. In addition, these figures show that an increase in the sampling rate of the time series signal leads to an increase in the number of zero points of the frequency spectrum outside the range of useful frequencies (in the direction of increasing frequency), and within the range of useful frequencies the shape of the frequency spectrum remains the same. This means that after defining the minimum value of the sampling rate of the time series signal (24 kHz in this example), a further increase in the sampling rate does not affect the shape of the frequency spectrum within the frequency range of the useful signal.

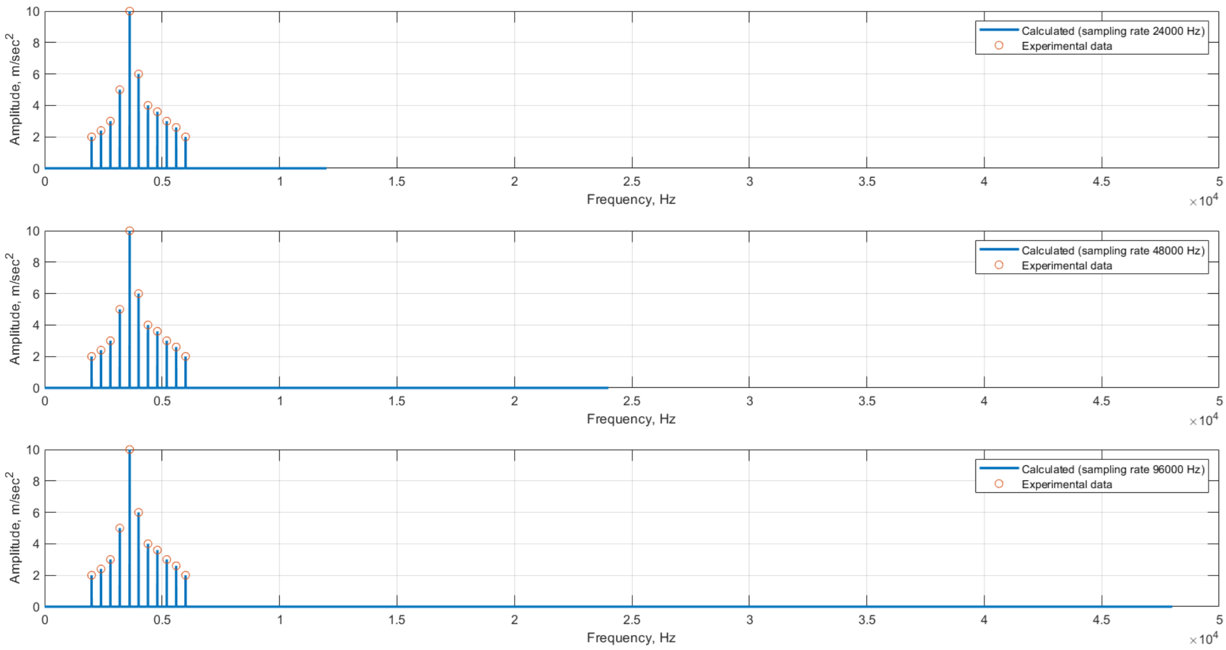


Fig.22. Frequency spectrum at different sampling rates of time series signal for the filled mill.

Thus we can conclude that the optimal size of the moving window (being defined in time units) does not depend on the sampling rate of the time series signal (for sampling rates above the minimum value), because the area under the frequency spectrum curve (s, see 4.2) will remain the same for different sampling rates and the number of samples in the moving window (n_{win}) will change proportionally for different sampling rates, which means that the curves s' and n'_{win} in Fig.15 and Fig.16 will be the same for different sampling rates of time series signal of vibration acceleration.

5. Conclusion

The research found that the size of the moving window when processing the vibration accelerometer signal affects the quality of the derived frequency spectrum in the ball drum mill automation system. Too small a moving window size leads to obtaining a frequency spectrum that does not correspond to the real frequency spectrum and the quality of the derived frequency spectrum is unsatisfactory. In the case of too large a moving window, it is necessary to spend more time on signal processing and involve more memory for storing moving window samples, which leads to the need to increase the computing resources of the microprocessor system. In addition, when defining the upper limit of the moving window size, it is necessary to take into account the rate of change in the mill load with the material. Too large a window size with a rapid change in the mill load can lead to a significant dynamic error in defining the value of the mill load with the material.

The frequency spectrums of the vibration acceleration signal for a filled and empty mill have been analyzed in this work. The sampling rate of the time series signal of the vibration accelerometer has been chosen. The limits for the moving window size have been defined. A technique for defining the optimal size of the moving window has been developed. This technique is based on the integral optimality criterion, which takes into account the quality of the derived frequency spectrum and the influence of the moving window size on the resources and performance of the microprocessor system. The study of the frequency spectrum built for different values of the sampling rate of the time series signal demonstrated that after defining the minimum value of the sampling rate of the time series signal, a further increase in the sampling rate does not affect the shape of the frequency spectrum within the frequency range of the useful signal.

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Методика визначення оптимальних параметрів рухомого вікна для опрацювання сигналу віброакселерометра

Роман Федоришин[a], Василь Лимич[a], Володимир Заграй[b], Олег Масняк[a]

[a]Національний університет «Львівська політехніка», вул. С. Бандери, 12, Львів, 79013, Україна
[b]ТзОВ «Техприлад», вул. В. Антоновича, 116, Львів, 79057, Україна

Анотація

У цій статті представлено методику визначення оптимальних параметрів рухомого вікна при опрацюванні сигналу вібраційного акселерометра, встановленого на кульовому барабанному млині у складі системи автоматизації. На основі експериментальних даних частотних спектрів синтезовано часові сигнали віброприскорення із застосуванням зворотного перетворення Фур'є. Визначено верхню та нижню межу розміру рухомого вікна. Частотний спектр для часового сигналу в рухомому вікні побудовано методом швидкого перетворення Фур'є. Запропоновано критерій оптимальності, який враховує якість побудованого частотного спектру та обчислювальні ресурси мікропроцесорної системи, необхідні для опрацювання сигналу віброакселерометра. Оптимальна тривалість рухомого вікна для аналізованого прикладу становить 100 мс. Досліджено вплив частоти дискретизації часового сигналу на форму побудованого частотного спектру.

Ключові слова: віброакселерометр; перетворення Фур’є; частотний спектр; часовий сигнал; кульовий барабанний млин.