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ANALYSIS OF WIND TURBINE ACOUSTIC SIGNALS IN TERMS OF DETECTING AMPLITUDE MODULATION AND FREQUENCY DEVIATION

Marcjanna Czapla[1*] **Tadeusz Wszołek**[1]

[1] Department of Mechanics and Vibroacoustic, Faculty of Mechanical Engineering and Robotics, AGH University of Science and Technology, Poland

ABSTRACT

The phenomenon of amplitude modulation has been subject of numerous scientific studies [1-4]. However, the problem remains of determining the depth of AM's impact on the increase in annoyance of wind turbine noise. The results of this research showing the characteristic features and depth of AM in different frequency bands. In addition, it has been shown that, in the recorded results, modulation (deviation) of the frequency of the modulated band occurs simultaneously with amplitude modulation. Cyclical changes in the density distribution of spectra in time and space have been demonstrated. Examples have been presented show that defined metrics to determine the variability of modulation frequency depending on the observer's position relative to the signal source. One such parameter that can demonstrate objective frequency offset is the popular shimmer indicator.

Keywords: *wind turbine noise, amplitude modulation, modulation depth, frequency modulation.*

1. INTRODUCTION

Exploitation of wind turbines has become an important source of renewable energy worldwide. However, the noise emitted by them has also become a serious problem for residents in nearby areas. One of the factors contributing to the increased annoyance of wind turbine noise is amplitude modulation (AM), caused by the cyclic rapid change in the height of wind turbine blade tips, tonality, and high content of low-frequency components. An additional factor that has been identified is frequency modulation (FM), often accompanying the phenomenon of amplitude modulation. Frequency modulation occurs because of blade movement in variable weather conditions, particularly influenced by wind speed and direction, and the observability of the phenomenon depends on the observation point. However, the dominant source of FM is the occurrence of the Doppler effect, resulting from the cyclic approach and retreat of the blade tip from the observer. Therefore, the phenomenon of FM is particularly noticeable in the transverse axis of the turbine (the most dynamic change in the distance between the turbine blade and the observer). Although numerous studies suggest that amplitude modulation is the main factor contributing to the increased annoyance of noise generated by wind turbines, the extent of its impact on noise annoyance remains unclear [1, 2, 4]. The phenomenon of frequency modulation in the wind turbine noise signal is mentioned in very few studies, and there is a lack of literature reports on the impact of FM on the increase in noise annoyance. Therefore, the focus of this study is on identifying the effect of frequency modulation and providing an initial parameterization of this phenomenon.

2. FIELD MEASUREMENT

Within this study, measurements of wind turbine signals were conducted. One measurement session took place in July, and another in October of 2022. The research object was various turbines of the same type located at a wind farm in the Subcarpathia Voivodeship in Poland. The Łęki Dukielskie wind farm consists of 5 wind turbines with a power output of approximately 2 MW each, totaling 10 MW of electrical power. The annual energy production of the wind farm is estimated to be over 20,000 MWh.

*Corresponding author: mczapla@agh.edu.pl

The measurements were taken at 3 points located approximately 140 meters from the turbine tower. The first point (P1) was situated along the rotor axis, the second point (P2) at a 45° angle, and the third point (P3) perpendicular to the rotor axis. At each position, measurements were conducted at 3 different heights: ground level, 1.5 meters, and 4 meters. During the measurements, the audio signal was recorded in wave format.

3. SIGNAL ANALYSIS

Based on the recorded signals, an analysis was conducted to detect both amplitude modulation (AM) and frequency modulation (FM). Modulation phenomena, including both AM and FM, are widely used as universal tools in information transmission systems in telecommunications and radio technology. Modulation has many advantages in various fields, but in the context of wind turbine noise, amplitude modulation (AM) is one of the factors contributing to increased annoyance of this type of noise. Regarding frequency modulation (FM), there are not many publications that specifically address its occurrence and potential impact on the perception and annoyance of wind turbine noise.

3.1 Amplitude Modulation

Two algorithms were used to detect AM. The first algorithm was developed by the AMWG (Amplitude Modulation Working Group) and is described in their final report published in 2016 [1]. The second algorithm was developed by A. Fukushima and his team [2]. The authors of this study described their work on the utility of the AM detection procedure proposed by AMWG in [7].

3.2 Frequency Modulation

The For the analysis of frequency modulation (FM), an initial analysis was undertaken to demonstrate the occurrence of this phenomenon in the recorded data. The first step of the analysis involved calculating the Short-Time Fourier Transform (STFT). The resulting spectrogram provides a visual representation of the data, allowing for the identification of signal characteristics and the analysis of trends and changes over time. The key step is to select appropriate parameters for the STFT to accurately represent the signal energy at different frequencies while minimizing distortion. Subsequently, bandpass filtering was applied to the signal within the frequency range where deviations in frequency and amplitude were observed (Fig.1).

Within the filtered frequency band, the signal envelope was determined as a matrix of frequency indices over time, which were then rescaled to obtain the corresponding frequency values. From this envelope, the peak-to-peak amplitude and the constant component of the FM signal were calculated. Next, the FFT (Fast Fourier Transform) of the envelope signal from a 60-second sample was computed. The fundamental frequency along with higher harmonics were determined (Fig.2), as well as the amplitude of the signal. In the subsequent step, a sinusoidal signal with the parameters obtained from the FFT analysis was generated and overlaid on the plot with the measured envelope signal (Fig.3). The waveform shown in Fig.3 illustrates the depth and frequency of frequency modulation (deviation). An additional parameter used to assess changes in the depth of FM is Shimmer [5]. The final stage of this analysis involved determining the Shimmer parameter according to the following Eqn. (1):

$$Shimm = \frac{\frac{1}{N}\sum_{i=1}^{N-1}\left|A_0^{(i)} - A_0^{(i+1)}\right|}{\frac{1}{N}\sum_{i=1}^{N} A_0^{(i)}} \cdot 100\% \quad (1)$$

where N is the number of samples in the signal envelope, and $A_0^{(i)}$ represents the instantaneous amplitude value of the signal and the relative frequency deviation in the form of the ratio of amplitude to the "carrier" frequency in percentage (Frequency Deviation coefficient) presented in Table 1.

4. RESULTS

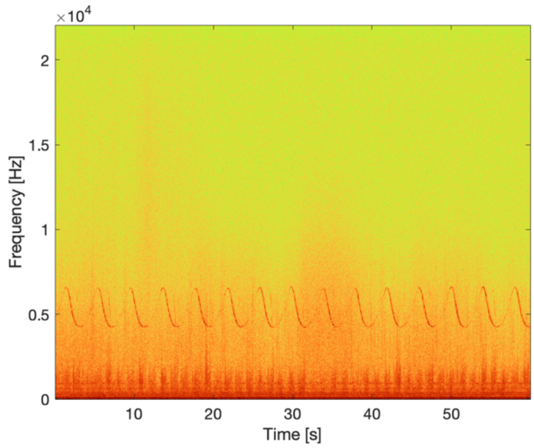

Figure 1. Spectrogram of the recorded signal.

All calculations were performed using the MATLAB package. Below are the obtained results for a 60-second signal sample. The figures present the results obtained from the measurement taken at point P3, which is situated perpendicular to the rotor axis.

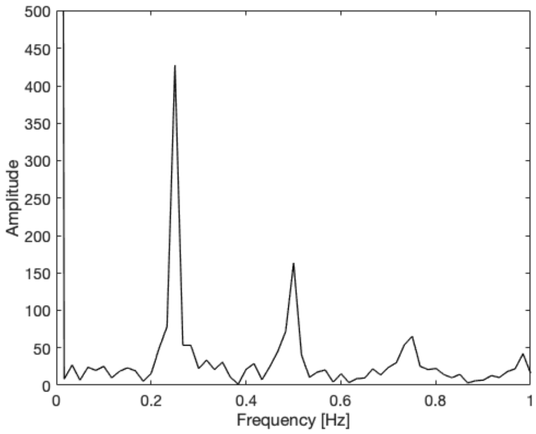

Figure 2. FFT of the signal.

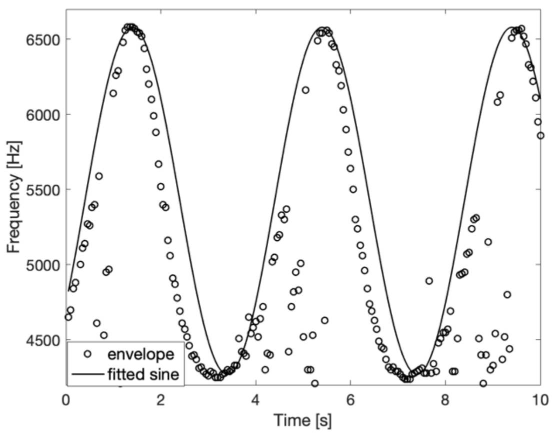

Figure 3. Envelope of a signal with fitted sine – first 10 seconds of a signal.

Table 1 presents the results of the average values and standard deviations of the frequency deviation assessment parameters for the 2 measurement points.

Table 1. Determined parameter values.

	Point	FM deviation [%]	FM Shimmer [%]
Mean	P2	18	5,3
Std. dev.		0,9	0,6
Mean	P3	22	4,7
Std. dev.		0,4	0,77

5. SUMMARY

The focus of the study was to demonstrate that in the acoustic signal from wind turbines, in addition to the widely discussed amplitude modulation (AM), there is also frequency modulation (FM). It was assumed that frequency modulation would be an additional factor, alongside AM, influencing the annoyance of wind turbine noise.

Experimental investigations at the wind farm confirmed the existence of such frequency modulation within the frequency range of approximately 4.2 kHz to 6.8 kHz, with an envelope resembling a sinusoidal signal. The initial analysis of frequency variability revealed some irregularities in the depth of FM and its frequency. The depth of frequency modulation (DFM) was adopted as a measure, which in this case amounted to 22%. Another parameter, Shimmer, indicated the percentage change in the depth of modulation in consecutive cycles, which was 5.3 at point P2 (located at a 45° angle to the rotor axis) and 4.7 at point P3 (perpendicular to the rotor axis).

In the further stages of the study, it is planned to conduct listening tests to examine how the depth of frequency modulation affects the annoyance of noise, particularly in relation to amplitude modulation.

6. REFERENCES

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