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Experimental Research of the AMWG Algorithm for Assessing Amplitude Modulation in Wind Turbine Noise

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Abstract The operation of a wind turbine (WT) is characterized by fluctuations in sound pressure amplitude associated with the passage of the propeller blade through the tower. Amplitude Modulation (AM) is one of the factors that contributes to the increased annoyance of wind turbine noise. The phenomenon of AM is currently the subject of research in many research centers around the world in the context of a parametric assessment of its impact on annoyance. Despite the development of many methods to measure the AM of a WT noise, there is no commonly accepted method. This paper discusses the most crucial factors that stimulate the phenomenon of AM and the implementation in the MATLAB environment of the algorithm to find the frequency and depth of AM proposed by the Amplitude Modulation Working Group (AMWG). The results of verification of the developed algorithm as well as the measurement results of the frequency and depth of modulation for two measurement samples of a 2 MW wind turbine are presented.

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

1. Introduction

The problem of wind turbine noise appeared in the 1980s, and its result was the undertaking of works aimed at explaining the mechanism of noise generation, propagation, and, on the other hand, its impact on the environment and assessment methods, as well as related legal regulations.

One of the first documents to broadly describe the issue of the impact of wind turbine noise on the environment is the report of the WG ESTU-R-97 Working Group of 1996 "The Assessment and Rating of Wind Turbine Noise" [1]. This document includes descriptions of the noise generation phenomenon, measurement methods, as well as suggested limit values and conditions in which they should be applied. Also consider possible benefits of installed wind turbines as a circumstance in which the noise limit value can be increased by 2 dB. In general, the limit values should refer to noise in the environment (outside), and at night, additionally also inside buildings as protection against waking up and sleep disturbances. The noise assessment should consider the background noise from the wind and the noise from the turbine should be limited to 5 dB above the background noise, but in quiet areas the L_{A90} level should not exceed 35-40 dB. At wind speeds greater than 12 m/s at a height of 10 m, the evaluation should not be carried out [1]. The above provisions were the basis for formulating detailed provisions on the definition of noise limit values, considering other legal conditions.

This document does not mention neither the modulation of amplitude nor the increase in the content of low-frequency components in the final assessment of wind turbine noise. On the other hand, wind turbine noise tests showed residents complaining about its annoyance, describing annoying sounds as rumble, whistling and thumping, despite slight exceedances of the limit values [2]. One of the reasons for these complaints was the presence of modulation of the amplitude. As a result, an AMWG [3] was established at the Institute of Acoustics in the UK, whose task was to develop a method to measure and parametric evaluate the impact of AM on the noise nuisance of wind turbines [3]. According to the AMWG, amplitude modulation is a regular periodic fluctuation of the noise level with a frequency related to the speed of passage (next to the tower) of the turbine blades, perceived as whistling, rumbling and thumping. The essence of the measurement of amplitude modulation consists of measuring the multispectral in 1/3 octave bands in the range from 50 to 800 Hz, divided into three overlapping bands with a width of 50-200 Hz, 100-400 Hz and 200-800 Hz. The multispectral is measured in 100 millisecond steps in 10-second windows (100 spectra). The resulting amplitude envelope is subject to FFT analysis in the range up to 5 Hz with a resolution of 0.1 Hz to cover the fundamental frequency of the modulation and the second and third harmonics of this frequency. With a rotational speed of 20 RPM (60 propeller passes next to the tower), the fundamental frequency will be 1 Hz and the later harmonics will be 2 Hz and 3 Hz. Typically, the rated speed of 2 MW turbines is several revolutions per minute, so the fundamental frequency will be slightly less than 1 Hz. The modulation depth in each 10-second window is the difference between the levels of L_5 and L_{95}.

However, the approach presented by the AMWG was not widely recognized, even in the UK, where the independent INWG group raised objections to the method [4], accusing of not checking and testing the method, and not finding cause-and-effect relationships. There are also reservations about overcomplicating the method in terms of metrology. Although in the literature there are other approaches to measuring AM (Amplitude Modulation) and assessing its impact on noise nuisance, presented, e.g., in the works of P. Virjonen et al. [5] or R. Makarewicz [6] It was assumed that the AMWG algorithm to calculate AM may be the basis for further modification and development of a more objective method for measuring and assessing AM noise from turbine wind power. It is worth adding that the phenomenon is not there anymore, for example, in the ETSU R 97 tests [1], as well as tests in tests at work [7], as well as in research and tests also in wind tests in Poland [8].

Therefore, as part of the work, an implementation of the AMWG algorithm in the MATLAB environment with an extension to the low-frequency band was developed, verified based on noise measurement data from a 2 MW wind turbine.

2. Assumptions for the Implementation of the AMWG Algorithm

The algorithm described in the AMWG report [3] was implemented using the MATLAB [9] package tools of the MathWorks company. The method described above runs on the recording of the equivalent sound level of the A-weighted equivalent. However, the input data for this work was the sound pressure time waveforms saved in wave format. This method of selecting input data will allow for a more flexible approach in the future and the possibility of introducing virtually any modification in the next stages of work.

The basic time interval needed on which the analysis is based is the measurement of 10 minutes. The program reads successively the files recorded during the measurement session. Then it is scaled, the scaling factor is read from the wav file, and then, according to the steps described in the [10] manual, the whole signal is multiplied by this factor. The next step is to create the splMeter System object ™ [11] to determine the spectrum in 1/3 octave bands (from 25 to 800 Hz) in 100 millisecond steps. As a result, after running wave file data through created system object, we obtained a multispectral which is the input data for finding the fundamental frequency and the depth of amplitude modulation.

A wave file with 10-minute interval measured and scaled as described above is divided into 60 frames of 10 s each. The data in the wave file are a record of the sound pressure over time (Figs. 1 and 5). In every frame, 100 L_{Aeq} values (in 100-ms step) were found (calculated by SplMeter) in four frequency bands, summed for 7 each. In addition to the three frequency ranges (50-200, 100-400, 200-800 Hz) mentioned in the report, the range of 25-100 Hz has also been proposed. An additional band was proposed to check whether the algorithm could handle low-frequency detection, since, as noted by Van Renterghem [12], the phenomenon of modulation of amplitude increases the annoyance, especially in the low-frequency range.

In a 10 s interval, the signal envelope is found, smoothed with a third-degree polynomial (Figs. 2 and 6). The power spectrum is calculated from the temporal envelope of the signal. The power spectrum shows the power as the mean square of the amplitude on each frequency line. As follows:

$$S = \frac{|F\{x\}|^2}{n^2}, \tag{1}$$

where $F\{x\}$ is the output of DFT and n is the number of samples in the time series (n = 100). The spectrum is determined with a resolution of 0.1 Hz (Figs. 3 and 7) in the range up to 5 Hz. The spectrum searches for local maxima in the frequency range from 0.4 Hz to 1.0 Hz, as the basic modulation frequency, which is also the frequency of the propeller blade passage. The limits of the frequency search range are related to the rotational frequency of the turbine. Therefore, values that exceed the assumed limits are automatically rejected. Then, following the method proposed in the AMWG report, a prominence check is carried out, aimed at figuring out the fundamental modulation frequency from the local maxima found and checking the ratio of the power of the fringe (potential f_0) to the average power level of the pair of adjacent fringes found above and below the potential fundamental frequency f_0 and away by 0.1 Hz. Criteria for considering higher harmonics have also been proven. When the efficiency condition is satisfied and the fundamental frequency is found, the search for harmonics that are multiples takes place. While the above criteria are met, the temporal envelope of the signal is reconstructed, since the identified harmonic components (Figs. 4 and 8). The reconstruction of the signal is performed by the Inverse Fourier Transform (IFFT), keeping the information about the amplitude and phase of the input signal. It is also important at this stage to figure out the statistical levels L_5 and L_{95}, after subtracting which the modulation depth was obtained.

The results of the algorithm implemented in this way are presented by a matrix in which the identified (or empty cell, if not found) are recorded: fundamental frequency (fulfilling the validity condition >4), harmonic components (if they meet the condition >1.5). The validity of the data obtained in this way is checked. A 10-minute period is considered valid when 50% of the samples (30 out of 60 frames) have the fundamental frequency determined in one (all) of the four analyzed frequency bands. When the analyzed time interval is important, the 90th percentile is determined (Tab. 1-2).

3. Results

This paper presents the results of sample samples obtained during in situ measurements that meet the validity condition. The object of the research was a Vestasy V90 turbine with a power of 2 MW, the figures included were obtained from the analysis for two microphone positions. In the first case, the measurement distance was exactly 150 m (Fig. 1-4 and Tab. 1), in the second case, the distance was 250 m (Figs. 5-8 and Tab. 2). In both cases, the measurement was carried out on a plate (ground, with a single shield according to IEC 61400-11). Tables 1 and 2 present the results for the frequency bands analyzed. The results contain the correctly found fundamental frequency and harmonic components that meet the above-mentioned criteria. As described in the report [4] the AM values in the output of the algorithm are aggregated to provide a single value. The determined output is the 90th percentile of valid data, which is the amplitude modulation evaluation for a 10-minute period. This single value is presented in tables below (Tabs. 1 and 2) as well as the mean and standard deviation for comparison.

Table 1. Measurement at 150 m behind the turbine on the plate (ground).

Frequency range [Hz]	Quantity	Fundamental frequency [Hz]	Second harmonic [Hz]	Third harmonic [Hz]	Modulation depth [dB]
25-100	90th percentile	0.88	1.60	2.10	3.10
	Average	0.70	1.40	2.00	2.20
	Std. Deviation	0.09	0.22	0.27	0.70
50-200	90th percentile	0.80	1.60	2.37	2.70
	Average	0.70	1.50	2.30	1.80
	Std. Deviation	0.09	0.18	0.21	0.60
100-400	90th percentile	0.80	1.40	2.40	2.20
	Average	0.70	1.40	2.40	1.60
	Std. Deviation	0.08	---	---	0.50
200-800	90th percentile	0.80	---	---	2.10
	Average	0.70	---	---	1.60
	Std. Deviation	0.10	---	---	0.40

Table 2. Measurement at 250 m on the side of the turbine on the plate (ground).

Frequency range [Hz]	Quantity	Fundamental frequency [Hz]	Second harmonic [Hz]	Third harmonic [Hz]	Modulation depth [dB]
25-100	90th percentile	0.80	1.54	1.80	3.80
	Average	0.70	1.50	1.80	2.40
	Std. Deviation	0.07	0.10	---	1.50
50-200	90th percentile	0.80	1.56	2.10	3.20
	Average	0.70	1.50	2.10	2.20
	Std. Deviation	0.06	0.12	---	1.30
100-400	90th percentile	0.80	1.60	---	3.80
	Average	0.70	1.60	---	2.60
	Std. Deviation	0.05	---	---	0.80
200-800	90th percentile	0.70	1.40	---	4.80
	Average	0.70	1.40	---	3.50
	Std. Deviation	0.04	---	---	0.90

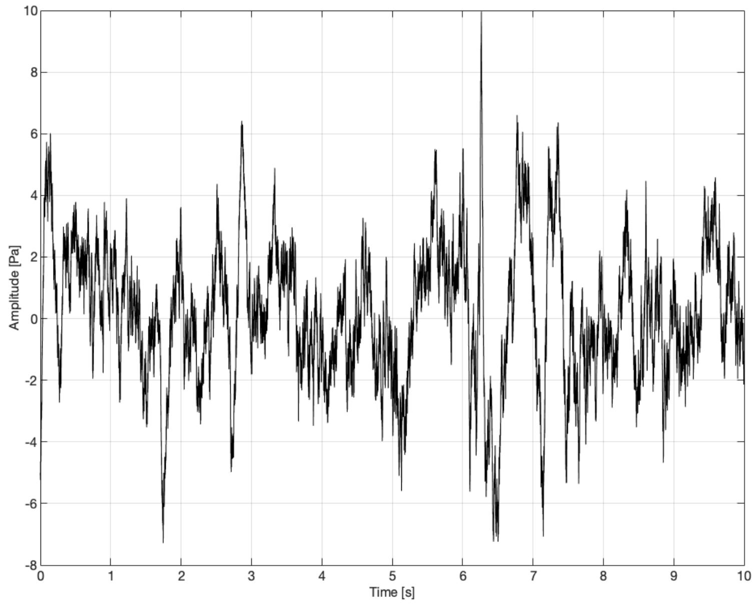

Figure 1. Time series of the recorded signal in the 10-second frame - measurement at 150 m behind the turbine on the plate.

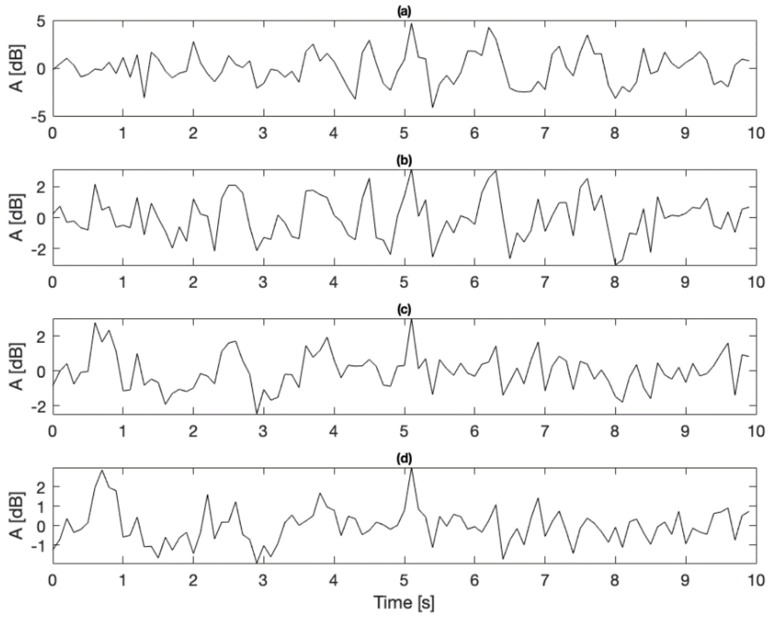

Figure 2. Envelope of the signal from the 10-second frame in the analyzed frequency band a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, d) 200-800 Hz frequency range - measurement at 150 m behind the turbine on the plate.

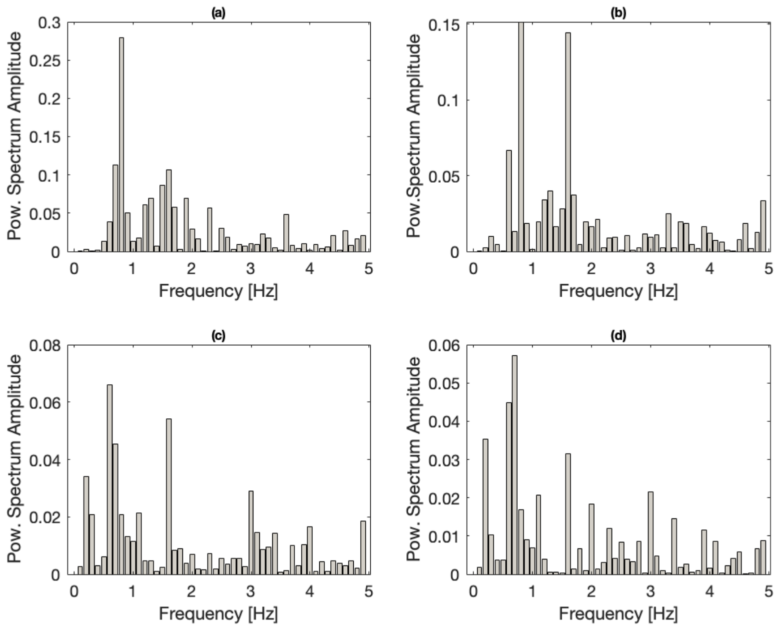

Figure 3. Power spectrum for a 10-second block a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, d) 200-800 Hz frequency range - measurement at 150 m behind the turbine on the plate.

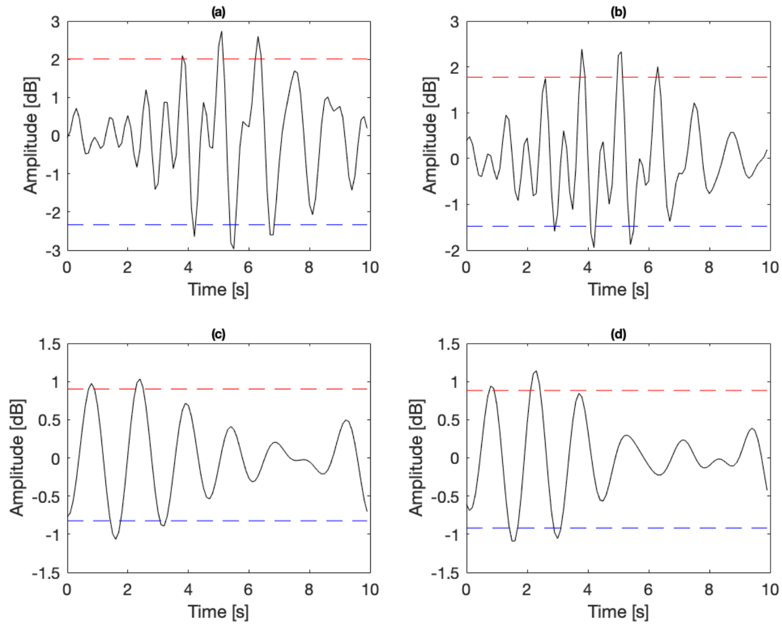

Figure 4. Reconstructed time series with added L_5 (red) and L_{95} (blue) a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, d) 200-800 Hz frequency range - measurement at 150 m behind the turbine on the plate.

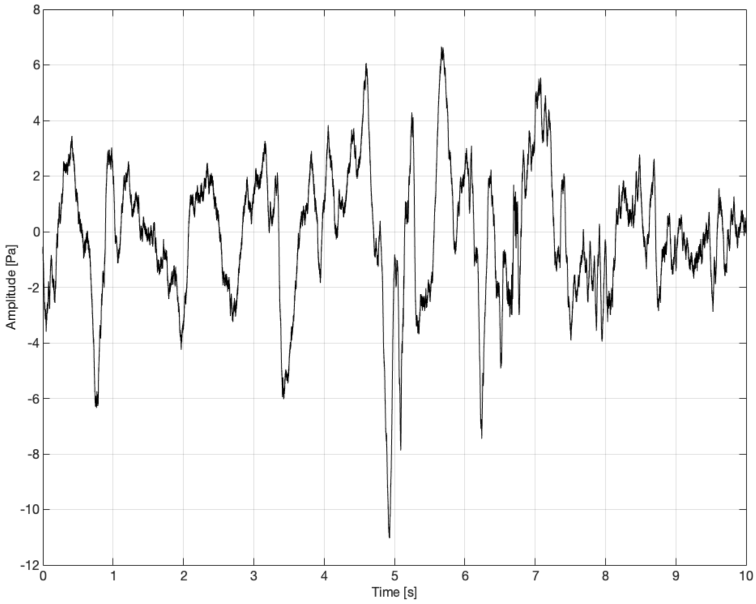

Figure 5. Time series of the recorded signal in the 10-second frame - measurement at 250 m on the side of the turbine on the plate.

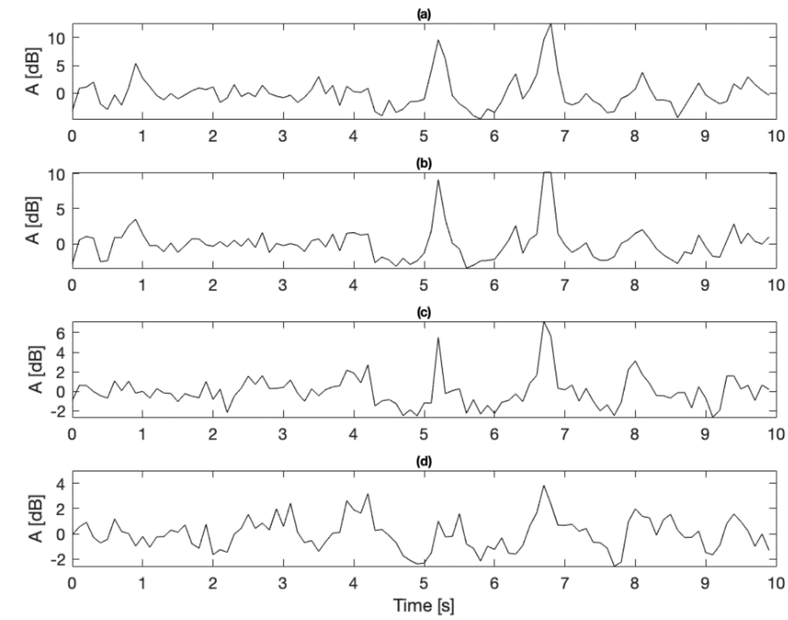

Figure 6. Envelope of the signal from the 10-second frame in the analyzed frequency band a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, d) 200-800 Hz frequency range - measurement at 250 m on the side of the turbine on the plate.

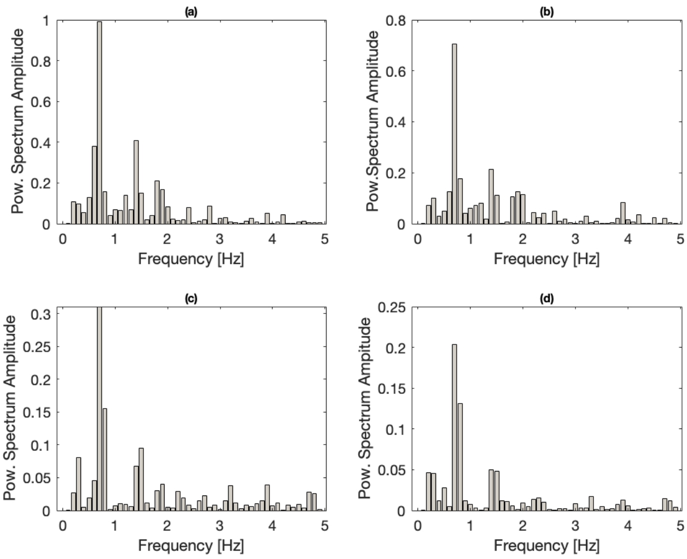

Figure 7. Power spectrum for a 10-second block a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, d) 200-800 Hz - measurement at 250 m on the side of the turbine on the plate.

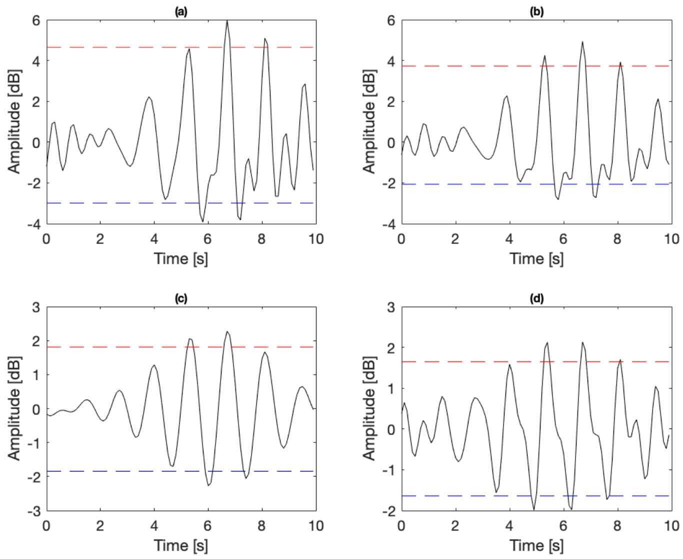

Figure 8. Reconstructed time series with added L_5 (red) and L_{95} (blue) a) 25-100 Hz, b) 50-200 Hz, c) 100-400 Hz, c) 200-800 Hz frequency range - measurement at 250 m on the side of the turbine on the plate.

4. Analysis

This paper presents the results for two selected 10-minute-long measurement samples recorded in the vicinity of a 2 MW wind turbine. From the point of view of the adopted algorithm, these are samples containing valid data, which means that more than 50% of the data have found the fundamental frequency that meets the prominence check criterion in each of the 4 analyzed frequency bands. Half of the data are at least 30 out of 60 values determined from 10 s blocks. For the samples presented, the mean fundamental frequency was approx. 0.7 Hz (Tab. 1-2). The 90th percentile values are indicative, as such output data are described in the AMWG report. The spread of the mean value is small in each of the four analyzed frequency bands; it is smaller than 0.1 Hz; that is, it does not exceed the resolution value with which the frequency spectrum is determined for the 10 s block from which the fundamental frequency is determined.

Correct identification of the fundamental frequency does not always imply finding the next harmonics. Most often, one of the harmonics (2nd or 3rd) is found correctly. Both are found in individual cases. It can be noticed that the values of the components in the two lower bands (25-100 and 50-200 Hz) are easier to name than in the other ones. In the 200-800 Hz band it is difficult to name the higher harmonic (3rd).

5. Summary

The work focuses on the implementation and verification of the usefulness of the AMWG algorithm [3] in determining the depth of modulation of the amplitude, which is useful in assessing the noise annoyance from a wind turbine. The algorithm in question, implemented in the MATLAB environment, was extended in the range of low frequencies to the band from 25 Hz to 800 Hz, and the search band for the fundamental frequency of modulation and its higher harmonics was narrowed to the closest vicinity of the propeller blade transition frequency, which increased the effectiveness of detecting this harmonic. The use of envelope smoothing in the 1/3-octave bands (in the range of 25 to 800 Hz) with the function of the third-degree polynomial increased the efficiency of fundamental harmonic detection.

The efficiency of the algorithm was tested for two 10-minute measurements. Wave samples recorded in the vicinity of a 2 MW turbine at 150 and 250 m. In both cases, despite the poorly visible and dynamically changing modulation (Figs. 1 and5), it was possible to determine the waveforms of these modulations with the fundamental frequency and the first and/or second harmonic or modulation depth.

The summary of the measurement results is presented in Tables 1-2, for distances of 150 m and 250 m, respectively. The modulation depth changes dynamically in the range from about 1 dB to nearly 5 dB, so in the harmless range (acc. to AMWG below 2 dB) and in the range of increased annoyance - above 2 dB.

As a continuation of the work, it is planned to develop the algorithm with the lowest frequency range, including infrasound frequencies, and listening tests of the impact of modulation depth on the change of noise annoyance of wind turbines in the low frequency range.

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Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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