This study investigates acoustic processes that occur during the flow of air around the blade segment of a wind turbine. The issue of aerodynamic noise generated by wind turbines is one of the factors that hinders the widespread implementation of wind turbines. Noise reduction is possible by changing the design of the turbine blade to influence the aerodynamic processes during the flow of air around it.

This paper reports an experimental study on the possibility of reducing the aerodynamic noise of wind turbines by modifying the trailing edge of the blade. An original methodology of acoustic experiments in an anechoic chamber is described; the results of experimental studies are given.

Two different modifications of serrated trailing edges of the blade with the NACA0012 aerodynamic profile have been considered: a flat serrated edge and a three-dimensional serrated edge. The results from aerodynamic noise measurements of the prototypes of the blade segments were compared with the noise from the basic original sample. Acoustic measurements were carried out in the range of flow speeds: 7.5–20 m/s and angles of attack 0–15°.

The results demonstrated that both configurations of the serrated trailing edge make it possible to reduce the level of aerodynamic noise compared to the base segment. It was found that the noise reduction occurs at relatively small angles of attack (0–5°) and moderate flow speeds (up to 15 m/s). In the specified range of parameters, the reduction of aerodynamic noise occurred due to a decrease in the sound pressure level in a certain frequency range by up to 4 dB. The segment with flat serrations turned out to be somewhat more effective in terms of noise reduction in the low-frequency range.

Results of this work could be used when designing new generation wind energy systems with reduced noise levels, as well as other aerodynamic devices

Keywords: aerodynamic noise, wind turbine blades, acoustic experiment, Fourier analysis, passive methods

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EFFECT OF WIND TURBINE BLADE TRAILING EDGE MODIFICATION ON AERODYNAMIC NOISE

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1. Introduction

The fight against climate change and sustainable development require the active implementation of renewable energy sources. Wind power, as a renewable source of "green" energy, is rapidly developing worldwide, providing electricity generation without the use of fossil energy resources [1]. The transition to sustainable energy systems is especially relevant in the context of Russia's war against Ukraine, during which the aggressor is systematically attacking the country's civilian and energy infrastructure [2].

Wind power generation amounted to more than 2,300 TWh worldwide in 2024, and the potential of wind energy is promising compared to fossil fuel reserves [3]. The use of wind energy is not only a significant contribution to addressing the urgent need for alternative energy sources, but it also increases economic and environmental sustainability. However, the development of wind power plants is associated with the need to overcome a number of economic, political, and technical challenges. In particular, one of these challenges is noise pollution associated with wind farms. Aerodynamic noise generated by turbine blades is a factor that negatively affects both the ecosystem and the quality of life and health of people living or working near wind turbines. Aerodynamic noise from wind turbine blades differs from other sources of noise in the environment due to its specific acoustic characteristics and is more annoying than other sources of noise around [4].

The physical mechanisms of noise generation during the rotation of turbine blades are analyzed in detail in [5]. One of the most significant sources of acoustic radiation is the trailing edge of the blade, in the zone of which the interaction of turbulent flow structures with the surface occurs. Therefore, most methods for reducing blade noise are based on the attenuation of turbulent vortices and the effect on the boundary layer.

One of the most effective and relatively simple approaches to noise reduction is the use of blades with modified trailing edge geometry [6]. In particular, the use of serrated trailing edges, which should destroy large turbulent vortices that arise, is promising. Currently, determining rational configurations of such edges is a pressing task for designers of both wind turbines and fans, engine turbines, copters, etc. [7, 8]. This requires the study of aerodynamic and acoustic processes during the flow of air around the turbine blade and optimization of the geometry of turbine blades [9].

2. Literature review and problem statement

In [10], a comprehensive experimental study of the effect of a flexible trailing edge of an airfoil on noise generation is reported. It is shown that such edges suppress tonal noise caused by laminar boundary layer instability. However, the question of the effect of flexibility on aerodynamic efficiency (lift-to-drag ratio) remains open, which is important for assessing the practical feasibility of such modifications.

In [11], the effectiveness of trailing edge serrations as a passive noise reduction method on a simplified model of a turbomachine blade was assessed using computer simulation. The results demonstrate that serrations reduce broadband noise, especially at high frequencies. However, the cited study is limited to an idealized flat plate model.

In [12], a numerical study of the influence of the geometry of the wavy trailing edge serrations (length and waveform) on the aeroacoustic characteristics of a propeller operating at low Reynolds numbers was conducted. The study showed that sinusoidal serrations can provide a significant noise reduction (up to 6 dB) without a significant loss of aerodynamic efficiency. The results of a similar numerical analysis of the design of uneven sinusoidal trailing edge serrations are reported in [13]. Both papers demonstrate that the modification of the trailing edge contributes to noise reduction, especially in the complex low-frequency range. However, the authors' conclusions are based exclusively on numerical modeling and require experimental validation. It should be noted that computer modeling methods currently allow for sufficiently high-quality parametric studies of the influence of the geometry of the aerodynamic profile of a turbine blade on acoustic processes, as shown in [14]. At the same time, physical experiments remain both an important tool for validating numerical results and a powerful research tool in their own right.

In [15], the results of an experimental study on the influence of trailing edge serrations on the aerodynamic efficiency and flow structure on a scaled model of a wind turbine are described. According to the results of anemometric measurements, it was found that the presence of serrations causes a slight decrease in the power factor but contributes to a significant decrease in the drag coefficient. The work did not conduct acoustic measurements, which does not make it possible to assess the compromise between a small loss of power and potential noise reduction. In addition, the study was conducted on a scaled model, so it remains an open question how these aerodynamic effects would manifest themselves on a full-size turbine under real atmospheric conditions.

The experimental methodology and parametric study of the influence of the geometry of the teeth on the trailing edge of the blade on aerodynamic noise are reported in [16]. The authors demonstrated the dependence of noise characteristics on the geometry of the trailing edge and provided recommendations for choosing a tooth design to reduce broadband noise. At the same time, the study of noise of blade profiles in wind tunnels requires careful isolation of engine noise and is associated with the difficulties of ensuring the similarity criteria between the model and the full-scale blade. In addition, in the case of blowing a stationary model, the influence of centrifugal forces that arise during the rotation of a real blade and affect the flow structure near its surface is not taken into account.

Therefore, the use of a serrated trailing edge of the blade is an effective means of reducing aerodynamic noise. For small and medium-sized turbines, in which tonal noise prevails, the rotation of the blades significantly affects the formation of turbulent vortices and acoustic fields, which complicates the assessment of the effectiveness of serrated edges. At the same time, the issue of the optimal geometry of such modifications remains insufficiently studied, especially under conditions of real flow, which requires further research, in particular experimental.

3. The aim and objectives of the study

The aim of our work is to experimentally assess the impact of various modifications of the serrated trailing edges of the wind turbine blade on the level of aerodynamic noise generated. The results will contribute to solving the problem of noise pollution during the operation of wind turbines, which is one of the limiting factors for the widespread implementation of wind technologies.

To achieve this aim, the following objectives were accomplished:

– to determine the full spectrum of acoustic radiation of the basic segment of the turbine blade with the NACA0012 profile;

– to perform a comparative analysis of the equivalent noise level from turbine blade segments with different trailing edge modifications;

– to investigate the spectral characteristics of noise for various modifications of the blade segments.

4. Methodology of the study

The object of this study is the acoustic processes that occur during the flow of air around the segment of a turbine blade of a wind power plant.

The principal hypothesis of the research assumes that the use of serrated trailing edges of the turbine blade makes it possible to destroy turbulent structures and influence the intensity of acoustic radiation. In this case, the noise level depends on the geometric features of the serrations.

Experimental studies were carried out with blade segments, but not with full-scale turbine blades. The blade segments had a symmetrical NACA 0012 profile, other types of profiles were not considered.

A number of assumptions were adopted, namely:

– due to the use of end plates on the models, three-dimensional effects associated with the final phenomena of flow and vortex formation are not significant;

– the initial level of turbulence in different experiments did not differ significantly;

– aerodynamic noise reflects only the interaction of the turbulent boundary layer with the trailing edge;

– the influence of reverberations and reflections from the outer walls is minimal, due to careful sound insulation.

The original acoustic experiment methodology [17] was used in our work, which, unlike the known methods in wind tunnels, makes it possible to one to study processes with segment models close to real sizes and take into account the effect of blade rotation. Acoustic measurements were carried out in a special anechoic chamber, the walls of which are lined with sound-absorbing material. The room contained an experimental setup with a turbine blade segment model fixed at a given angle of attack. The general scheme of the experimental setup is shown in Fig. 1.

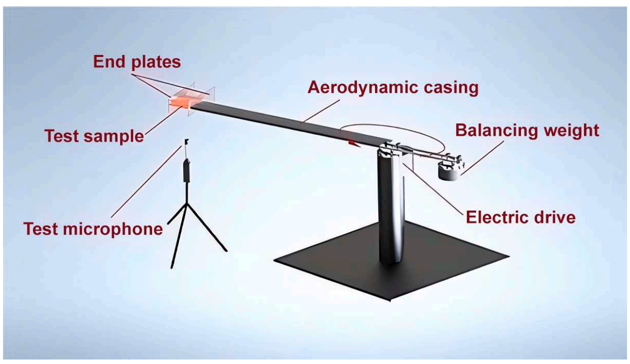


Fig. 1. Experimental setup diagram

During the rotational movement in the horizontal plane, acoustic characteristics were measured using an SV 971A1 sound level meter with an ACO SV 7152 microphone, which was located at a certain distance from the trajectory of the model. The sound level meter and microphone had proper metrological verification. To separate the aerodynamic noise of the model from background noise and noise of the installation itself, appropriate measurements were carried out in a room without a working installation and with the installation turned on without a model. The organization of experimental studies met the requirements of the DSTU GOST ISO 5725-1:2005 standard regarding repeatability and convergence of measurement results.

Three models of blade segments with an aerodynamic profile of NACA 0012 were manufactured using the 3-D printing method. The original model, without serrations (Fig. 2, *a*), served as the base blade segment for comparison. A blade containing a flat serrated insert (type 1 serrations) is shown in Fig. 2, *b*. A third model had three-dimensional serrations formed in the segment body, as shown in Fig. 2, *c* (type 2 serrations). The test segments were designed to take into account the rotation of the blade during the experiment: the Reynolds number was maintained constant over the span, the leading edge of the segment was oriented along the radius of rotation (passing through the center of rotation) to prevent flow skew, and the required angle of attack was provided by spatial rotation of the segment using special variable elements (Fig. 2, *d*).

For the analysis of acoustic signals, the Fast Fourier Transform (FFT) algorithm was used, which makes it possible to switch from the time domain to the frequency domain with a resolution of 12 Hz. This allowed us to isolate the spectrum of aerodynamic noise caused by the movement of the blade model from the total signal, which also contained background components.

For the quantitative assessment of aerodynamic noise, the sound pressure level SPL (dB) was used according to the frequency distribution. To assess the overall noise level, the equivalent noise level L_{eq} (dB) was used as an indirect indicator, which is defined as the energy-averaged value of the sound pressure from the experimental setup and characterizes the total acoustic energy of the signal. However, the spectrum of aerodynamic noise covers a wide frequency range, within which the fluctuations differ in physical and psychoacoustic significance. Therefore, a frequency weighting filter was used for the correct comparison and interpretation of the measurement results. It is known that such filters simulate the real sensitivity of the measuring system or human hearing to different frequencies. Fig. 3 shows a diagram of the frequency characteristics of various filters according to ANSI 1.43 standards and the international standard IEC61672-1 [18].

In Fig. 3, the Z-filter (linear weighting) is used to determine the physical energy of an acoustic signal in the full frequency range without taking into account psychoacoustic effects. The B-filter is used for comparative analysis of the mid-frequency region of the spectrum, which partially corresponds to the conditions of human noise perception at moderate volume levels. The A-filter is used to estimate the equivalent noise level taking into account the sensitivity of human hearing to frequency, which makes it possible to interpreting the results in the context of acoustic comfort. Therefore, the filters are used to estimate both the physical and psychoacoustic characteristics of aerodynamic noise.

To estimate the noise spectra, a fast Fourier transform is used, according to which signal $X[k]$ in the frequency domain is represented as

$$X\left[k\right]=\sum_{m=0}^{M-1}x\left[m\right]\cdot e^{-\mathbf{i}2\pi\frac{km}{M}}, \tag{1}$$

where $k=0,1,\ldots,M-1$, is the index of FFT point, M is the length of the analyzed window (number of FFT points), $x[m]$ is a discrete time signal, $\mathbf{i}$ is an imaginary unit, the frequency index k corresponds to frequency $f_k=\frac{kf_s}{M}$, f_s is the discretization frequency, which is equal to 12 Hz.

From (1) we determine the amplitude $\left|X\left(k\right)\right|$ and arg $X[k]$. In the time domain, the total signal obtained as a result of measurements is determined from

$$x\left(t\right)=s\left(t\right)+n\left(t\right), \tag{2}$$

where $s(t)$ is the usable signal (model noise) that needs to be separated, $n(t)$ is the background noise measured separately under similar conditions, but without the model.

In the frequency domain we have

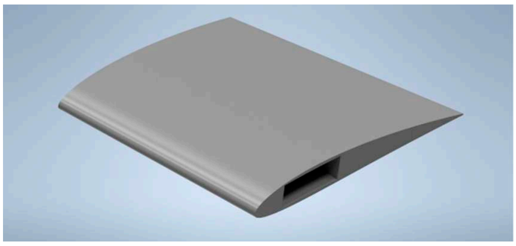
$$X\left(f\right)=S\left(f\right)+N\left(f\right). \tag{3}$$

We obtain the estimate of the cross signal spectrum $S(f)$ through spectral subtraction

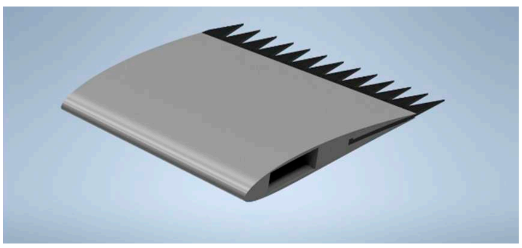
$$|S(f)|^2 = \max\left(|X(f)|^2 - \alpha|N(f)|^2, 0\right), \quad (4)$$

where α is the noise power estimation compensation coefficient $0 \le \alpha \le 2$. Spectrum reconstruction taking into account the phase is

$$S(f) = |S(f)| \cdot e^{\mathrm{i} \arg X(f)}. \quad (5)$$



a



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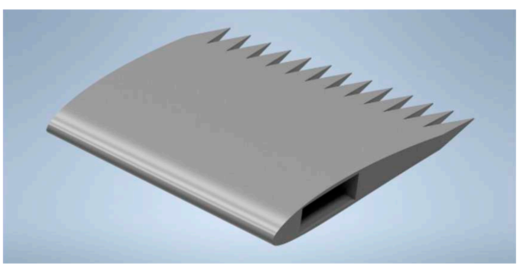
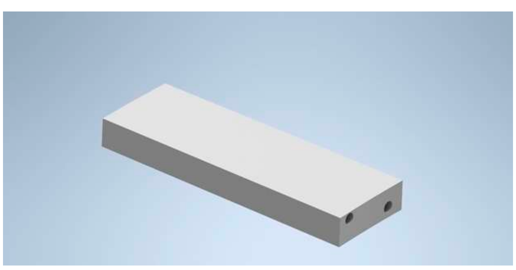


c



d

Fig. 2. Variants of modification of the serrated blade edge: *a* – original (without serrations); *b* – serrations of type 1; *c* – serrations of type 2; *d* – special element that provided a given angle of attack

After purifying the spectrum, the inverse Fourier transform is applied for time domain

$$s[n] = \frac{1}{M}\sum_{k=0}^{M-1} S(k) \cdot e^{\mathrm{i} 2\pi \frac{kn}{M}}. \quad (6)$$

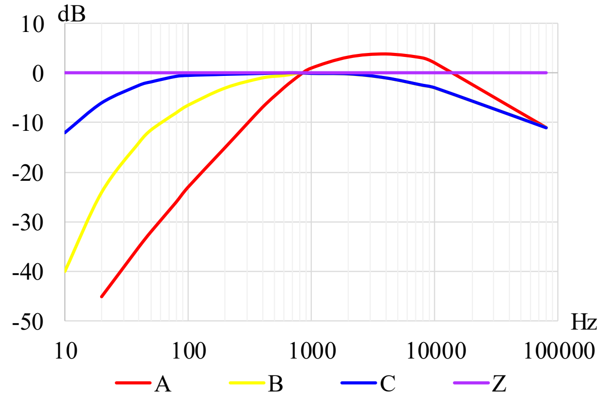


Fig. 3. Types of weighing filters for determining L_{eq} [17]

The real time is expressed as $t = n/f_S$. Expression (6) makes it possible to obtain a cleaned signal. The power spectral density is converted into sound pressure level SPL according to the following expression

$$SPL(f) = 10 \cdot \lg\left(\frac{|S(f)|^2}{p_0^2}\right), \quad (7)$$

where $p_0 = 20$ μPa is the reference pressure value for air. For the time domain reduction of random fluctuations, the spectra are averaged over several independent observation intervals

$$SPL = 20\lg\left(\frac{p_{rms}}{p_0}\right), \quad (8)$$

where $p_{rms}^2 = \frac{1}{M}\sum_{j=0}^{M-1} s[n]^2$. For integral noise estimation, a weighted average noise level is used

$$L_{eq} = 10\lg\left(\frac{1}{M}\sum_{m=0}^{M-1}\frac{s^2[n]}{p_0^2}\right). \quad (9)$$

The described methodology was used to study the characteristics of aerodynamic noise from blades with different trailing edge modifications. To reduce the influence of random factors, data averaging was performed on the noise spectrum measurement results. The obtained data were averaged over 20 observation intervals obtained from 3 consecutive measurements. The convergence of the averaged results was achieved after 7 measurements.

5. Results of experimental assessment of aerodynamic noise under the influence of various modifications of the edges of the wind turbine blade

5. 1. Studying the aerodynamic noise levels of the blade segment with the NACA0012 profile

The first series of experiments was conducted to study the general physical picture of acoustic radiation with the original NACA0012 profile. The results of these experiments form a comparative base. The experiments were conducted for angles of attack (AoA): 0–15° with a step of 2.5°, and linear velocities in the range of 10–20 m/s. Fig. 4 shows the spectra of aerodynamic noise for the specified range of determining parameters.

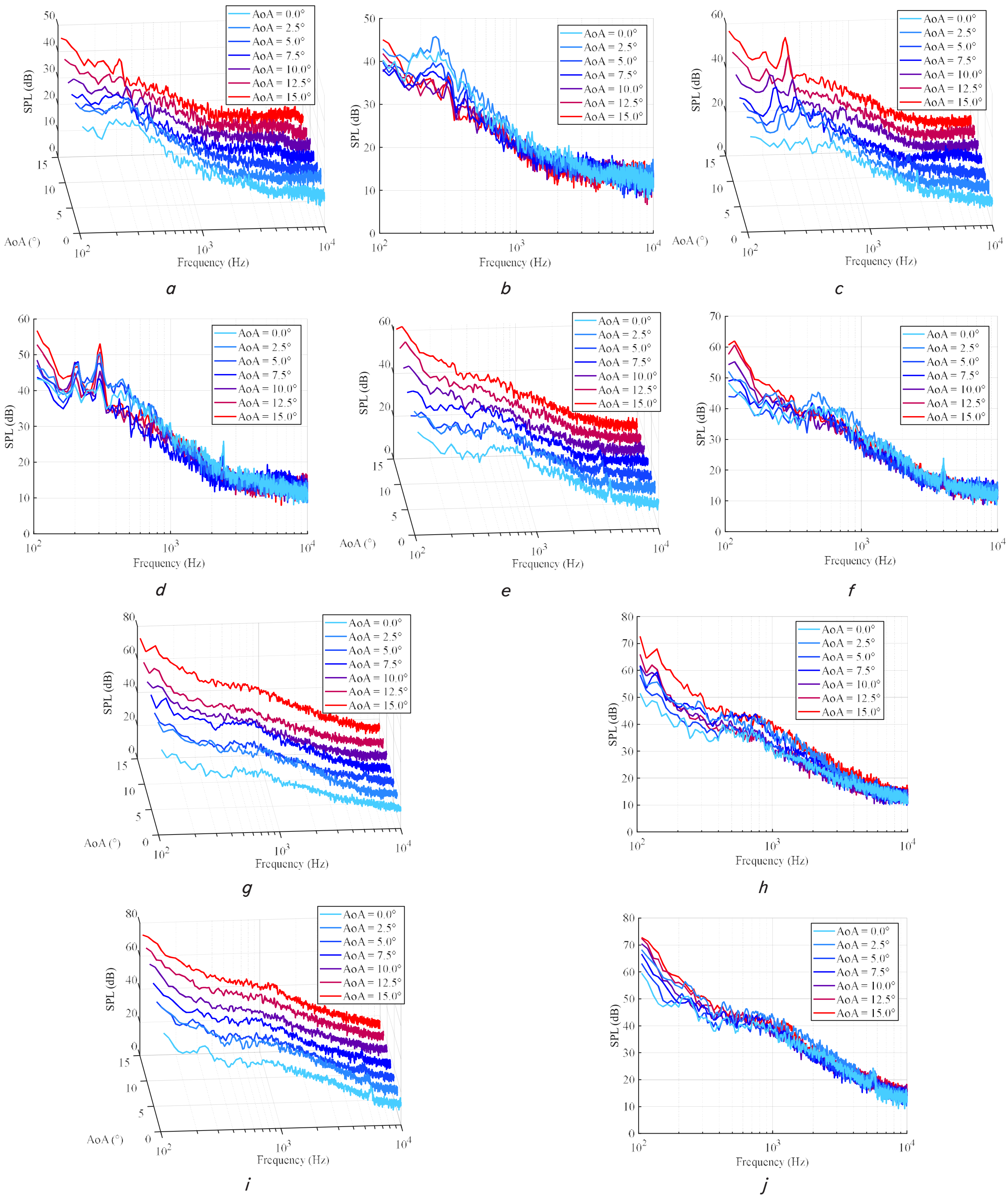


Fig. 4. Spectral structure of aerodynamic noise of the NACA0012 profile: *a, c, e, g, i* – three-dimensional SPL spectra; *b, d, f, h, j* – corresponding narrowband slices for each speed; *a, b* – U = 10 m/s; *c, d* – U = 12.5 m/s; *e, f* – U = 15 m/s; *g, h* – U = 17.5 m/s; *i, j* – U = 20 m/s

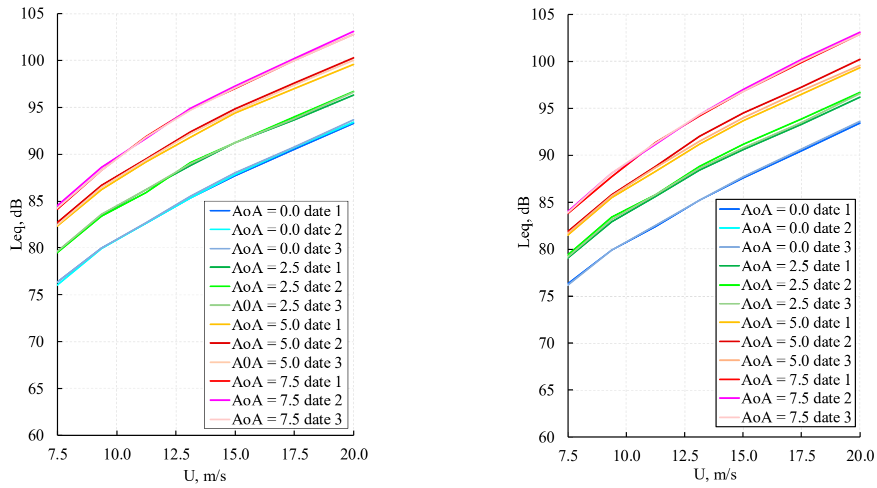
The left part of Fig. 4 shows three-dimensional (3D) spectra, which gives an overall picture of the evolution of the spectrum with the flow parameter and makes it possible to determine the region where the tonal peaks occur, and how they shift with changing velocity and AoA. The right part shows flat (2D) spectra, which allows for a detailed comparison of individual slices and energy distribution.

5. 2. Comparative analysis of the equivalent noise level from turbine blade segments with different trailing edge modifications

Experiments to determine acoustic parameters for the same parameters were conducted on different days in order to ensure reproducibility of the results. The results for the reproducibility of results in the form of curves of the equivalent noise level (filter A) are shown in Fig. 6.

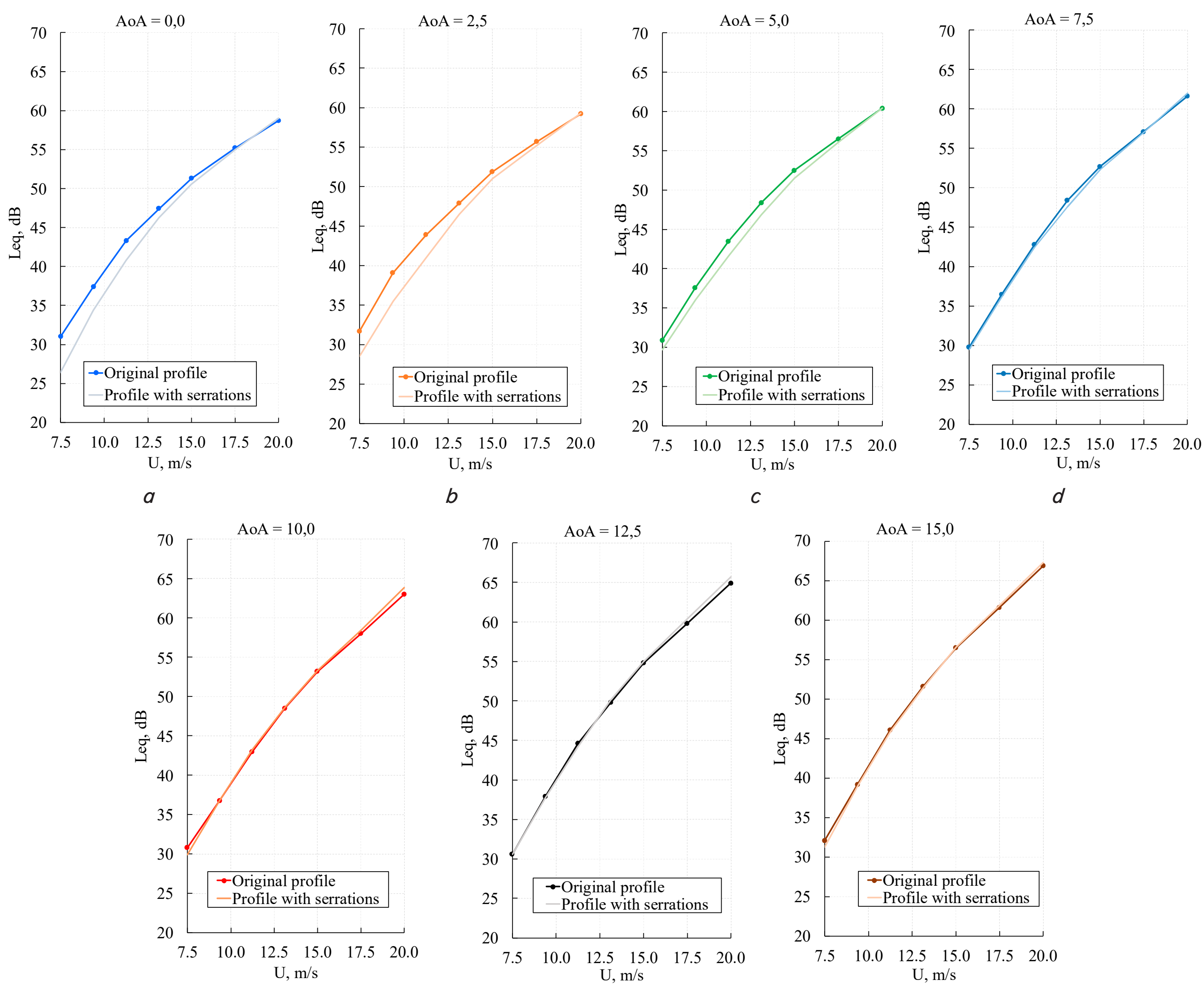
As shown in Fig. 5, the difference between the series does not exceed 1 dBA, which indicates the reliability of the experimental methodology. A comparison of the noise from the original profile with the noise of the profile with a modified trailing edge of type 1 is shown in Fig. 6, where the effect of angle of attack and speed on L_{eq} is illustrated (filter A is used).

Our results were obtained using the A-weighting filter, as the most sensitive one.



a *b*

Fig. 5. Repeatability of aerodynamic noise research results: *a* – basic sample; *b* – with type 1 serrations



e *f* *g*

Fig. 6. Equivalent noise level (L_{eq}, Filter A) for segments with the original NACA0012 profile and the NACA0012 profile with type 1 serrations: *a* – AoA = 0°; *b* – AoA = 2.5°; *c* – AoA = 5°; *d* – AoA = 7.5°; *e* – AoA = 10°; *f* – AoA = 12.5°; *g* – AoA = 15°

5. 3. Results of investigating the spectral characteristics of aerodynamic noise of blade segments of different modifications

Fig. 7–10 show the results of investigating the sound pressure level depending on the frequency for the full range of angles of attack and speeds, for the original blade segment and modified with both types of serrations.

Therefore, our experimental results make it possible to analyze the influence of different types of serrations on the trailing edge of a blade segment on its acoustic radiation.

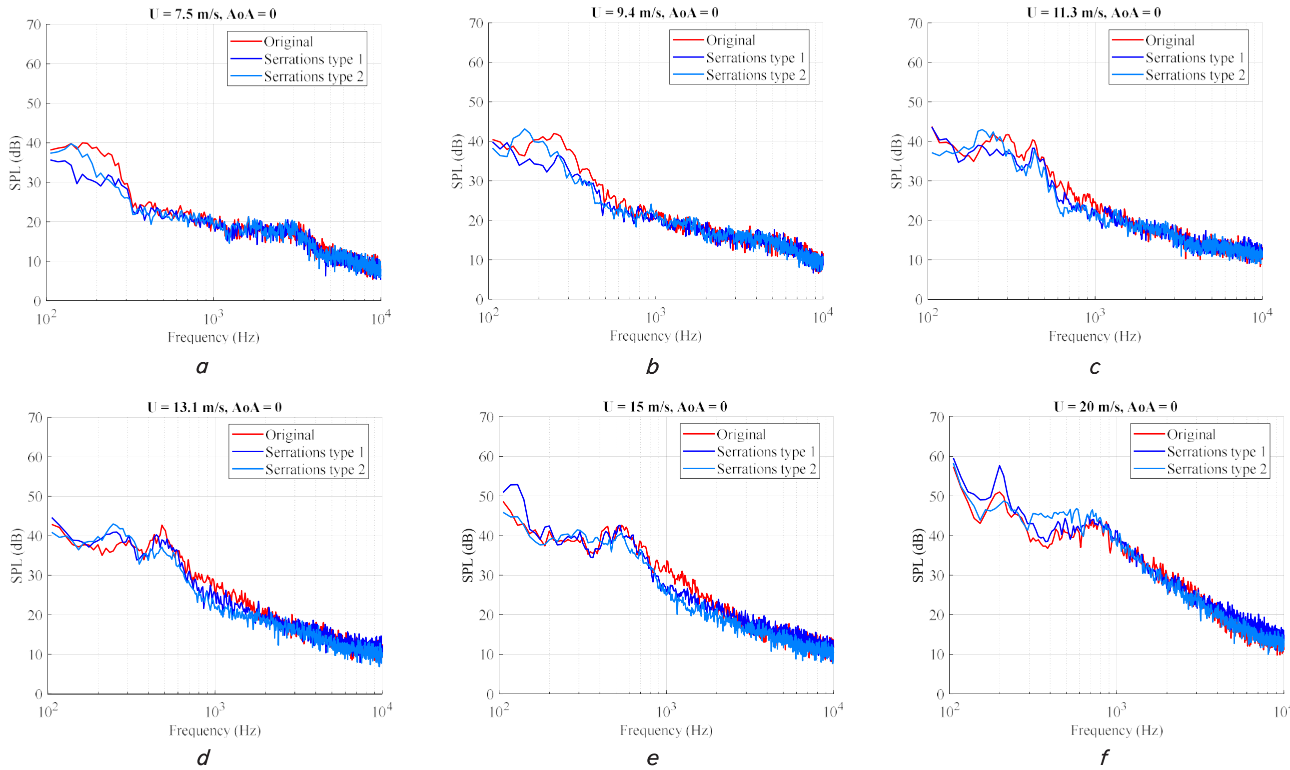


Fig. 7. SPL dependence on frequency for AoA = 0°: *a* – *U* = 7.5 m/s; *b* – *U* = 9.4 m/s; *c* – *U* = 11.3 m/s; *d* – *U* = 13.1 m/s; *e* – *U* = 15 m/s; *f* – *U* = 20 m/s

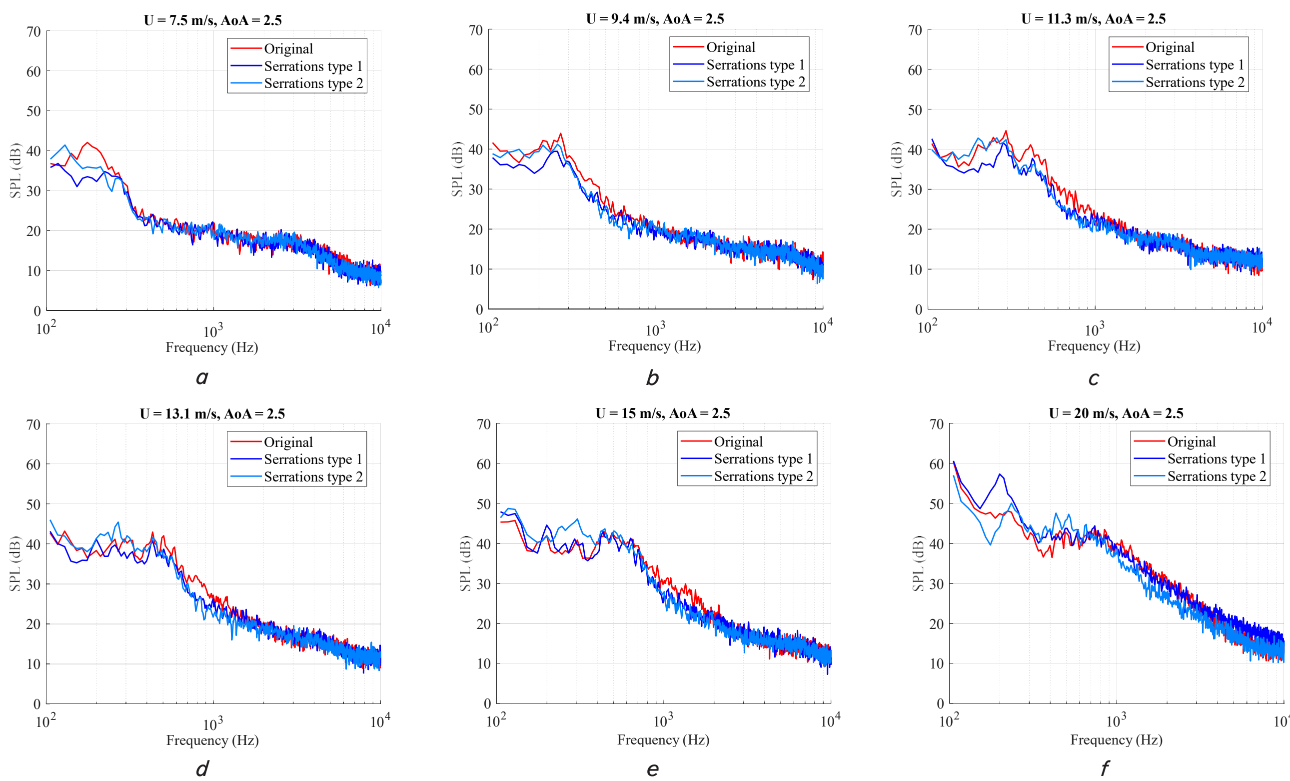


Fig. 8. SPL dependence on frequency for AoA = 2.5°: *a* – *U* = 7.5 m/s; *b* – *U* = 9.4 m/s; *c* – *U* = 11.3 m/s; *d* – *U* = 13.1 m/s; *e* – *U* = 15 m/s; *f* – *U* = 20 m/s

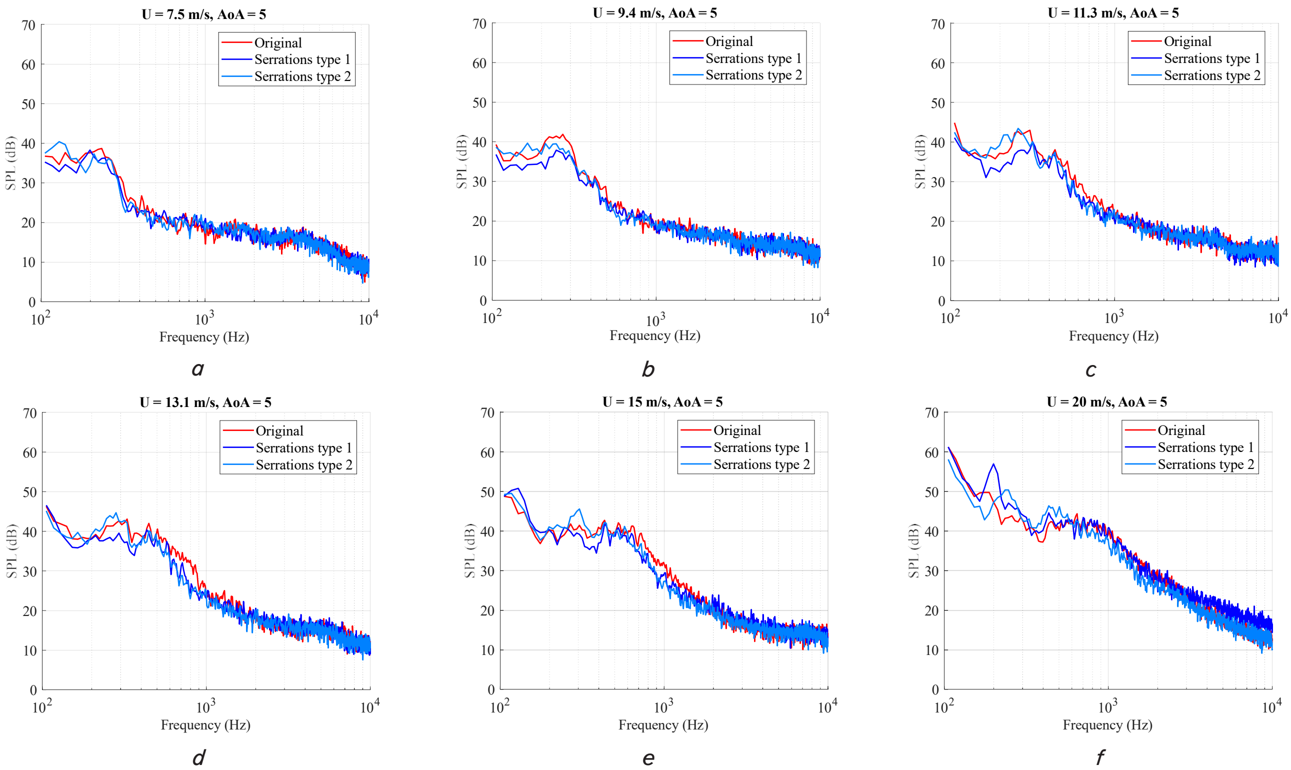


Fig. 9. SPL dependence on frequency for AoA = 5°: *a* – U = 7.5 m/s; *b* – U = 9.4 m/s; *c* – U = 11.3 m/s; *d* – U = 13.1 m/s; *e* – U = 15 m/s; *f* – U = 20 m/s

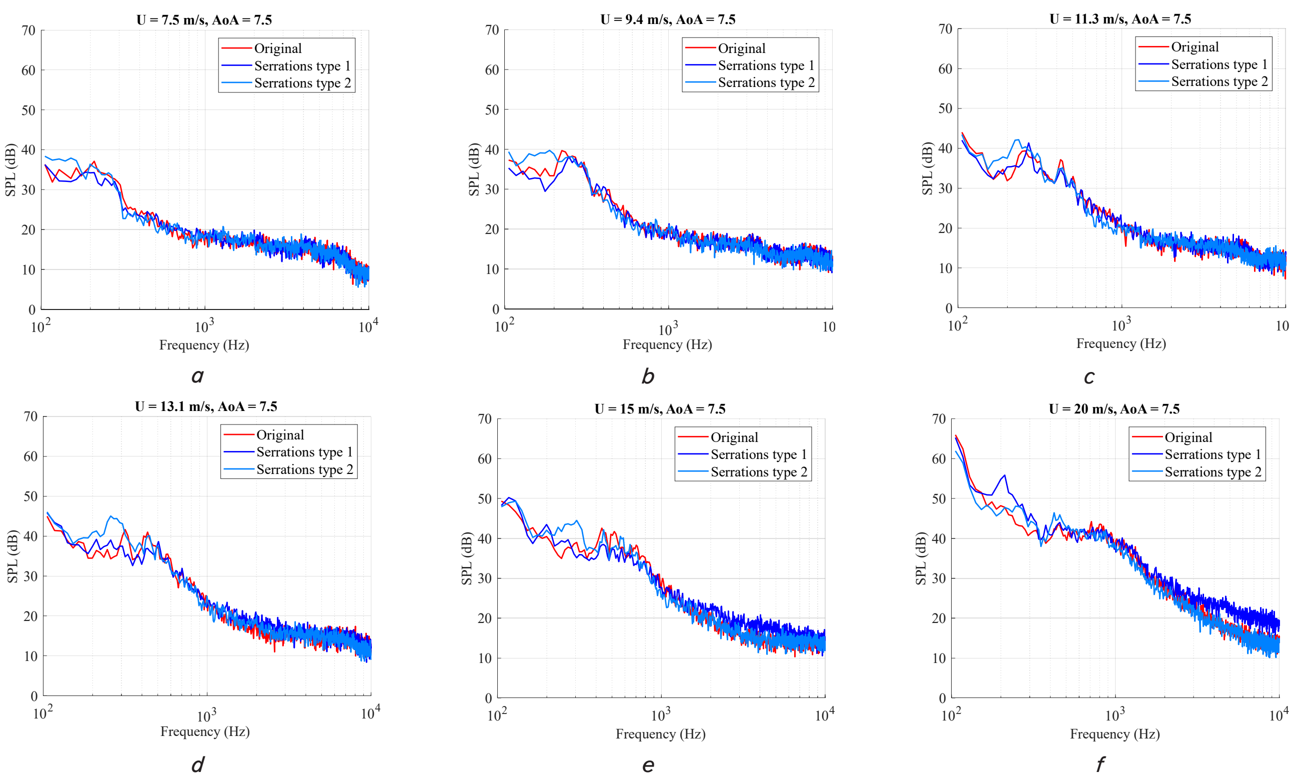


Fig. 10. SPL dependence on frequency for AoA = 7.5°: *a* – U = 7.5 m/s; *b* – U = 9.4 m/s; *c* – U = 11.3 m/s; *d* – U = 13.1 m/s; *e* – U = 15 m/s; *f* – U = 20 m/s

6. Discussion of results of investigating the aerodynamic noise of turbine blade segment models

Our results allow for a comprehensive assessment of the influence of the geometric modification of the trailing edge of the NACA0012 profile on the acoustic characteristics of the flow under conditions typical of wind turbine blades. The SPL spectra for the original profile (Fig. 4) show that the noise level increases with increasing speed and angle of attack, which is explained by the increase in turbulence and noise intensity with an increase in these parameters. The obtained spectra (Fig. 4, 7–10) are mostly broadband in nature.

The curves of the equivalent noise level demonstrated in Fig. 5 for the base sample and the sample with serrations of type 1 demonstrate that the discrepancy between the series of measurements does not exceed 1 dB; therefore, the results are reproducible.

A comparative analysis of the equivalent noise level of the original profile and the modified one with serrations of type 1 (Fig. 6) was performed with an A-weighting filter, which is sensitive to mid-frequency and tones. The analysis reveals that the noise reduction effect is observed only at small angles of attack (0–5°) and moderate flow velocities (up to 15 m/s). Outside the specified ranges of angles of attack and velocities, the curves for the original and modified profiles practically coincide.

Analysis of acoustic radiation spectra for the original segment and modified models of both types (Fig. 7–10) showed a decrease in sound pressure in the low-frequency range for all angles of attack when using modified profiles. The effectiveness of such a reduction depends on the speed and type of serrations on the trailing edge. The greatest reduction was observed at angles of attack up to 5° (Fig. 7, 8), by 3–6 dB depending on the speed regime. Serrations of type 1 demonstrate better efficiency in the low-frequency range and speeds up to 13.5 m/s, while in the high-frequency range, this type of serrations shows an increase in noise level at high speeds. This result demonstrates the importance of the geometric factor. At AoA > 10°, the difference between the basic and modified profiles practically disappears, which is explained by the transition of the flow into a deep turbulent separation and a change in the dominant noise generation mechanisms. The interaction of such turbulent vortices with the edge is a determining factor in the generation of broadband noise. At higher speeds and larger angles of attack, and correspondingly higher Reynolds numbers and more intense turbulent processes, the advantages of serrations are reduced. It is likely that at high speeds more intense and large-scale noise sources may prevail, making the effect of serrations less noticeable.

Spectral analysis confirms the reduction of the noise level mainly in the low and mid-frequency ranges (up to 2 kHz), which corresponds to a decrease in the energy of the broadband component associated with the vortex structures at the trailing edge.

The experimental results reliably demonstrate a tendency to reduce broadband noise in the low-frequency range when using a serrated trailing edge, but their validity is limited to the range of flow regimes around the blade segments determined in the experiment. Our results apply only to one NACA0012 profile, which is symmetrical and cannot be directly transferred to other types of profiles or blades with different aerodynamic loading.

The results do not demonstrate a clearly pronounced effect of modifications on the tonal components of noise, which requires further research. Also, further studies should be aimed at finding the optimal trailing edge design that could effectively suppress noise pollution in a wider range of determining parameters. At the same time, such design should provide an effective balance between noise reduction and aerodynamic performance of the blade.

7. Conclusions

1. The full spectrum of acoustic radiation of the basic segment of the NACA 0012 profile, without modification of the trailing edge, has been studied. The original acoustic experiment methodology was used for our study, which, unlike common studies in wind tunnels, makes it possible to simulate the rotational motion of the blade under modes close to natural conditions. A qualitative and quantitative picture of the growth of the equivalent noise level with increasing flow velocity and angle of attack was obtained. Acoustic radiation is formed mainly due to the interaction of the turbulent boundary layer with the trailing edge. In the range of small angles of attack (AoA up to 5°) and low speeds, tonal components occur. The results of investigating the original blade segment create a basis for comparison and study of the influence of modifications of the trailing edge.

2. The influence of modification of the trailing edge of the blade on the equivalent noise level has been determined. The results of experiments with an A-weighting filter showed that modification of the trailing edge of the NACA 0012 profile in the form of serrations contributes to a reduction in noise level up to 4 dB(A) compared to the original profile. This effect is most noticeable at small angles of attack and moderate flow speeds (10–15 m/s), when noise is formed mainly due to the interaction of turbulent boundary structures with the trailing edge.

3. The spectral characteristics of noise for blades with basic and modified edges have been studied. It was shown that the considered modifications of serrations (flat and three dimensional) make it possible to selectively reduce the level of aerodynamic noise in the low-frequency range. The blade with serrations of type 1 turned out to be somewhat more effective in the low-frequency range, while in the high-frequency range such serrations demonstrate an increased noise level compared to the basic one. Promising for the possible use of serrations to reduce aerodynamic noise is the range of small angles of attack (up to 5°) and moderate flow velocities (up to 15 m/s), in which a local reduction of broadband noise in the low-frequency region is observed.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Serhii Aleksieienko: conceptualization, methodology, verification, supervision; **Andrii Dreus:** writing and editing, formal data analysis; **Lilia Nakashydze:** experimental research; **Vitalii Derbaba:** administration, resource management; **Serhii Zolotarenko:** experimental research.

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