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THE AEROACOUSTICS STUDIES OF THE FLAT PLATES WITH THE TRAILING EDGE MODIFICATIONS

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Abstract

Noise is the one of biggest important problems in our world. The work on these is the subject of many studies all over the world in research centers and commercial laboratories. Solutions to the noise problems are also looked for in nature. The transferring the some solutions from the nature to the engineering is difficult, because it requires multidisciplinary research. There are more and more examples of bionic machines or constructions in the literature. The aeroacoustics also tries to derive examples from nature. For example the owls are unseen, because they fly very quietly. The studies of the physiology and anatomy of these birds revealed that silent flight is the result of several factors - special structure of their feathers.

In the Aeroacoustic Laboratory studies the modifications of the trailing edge of the flat plates were taken. Based on studies of the structure of feathers and wings of owls, cut in the forms the elliptical arcs, rectangular and isosceles teeth has been proposed. For each of the examined plates the tests were conducted for different values of Reynolds number and FFT spectrum was recorded in the whole frequency range. The research showed that the cutting in the regular form of teeth will decrease the level of the acoustic spectrum in a certain frequency range. But in other frequency ranges an increase in the spectrum of the sound pressure was observed. The other forms of the cutting gave the similar acoustical spectrum. Also the aerodynamic parameters were more aligned, for example the velocity distribution behind the serrated flat plate were more leveled than behind the flat plate. These studies suggest that the cutting of the trailing edges of the flat plate contribute to the reduction of aerodynamic noise generated by them.

*Key wods:*owls, bionic, flat plate, aeroacoustics

INTRODUCTION

To minimize the noise emission is an important issue to be considered in the design of future of the airfoils of wind turbines or turbomachinery or aircrafts jet engines. The problem is so important that conducted research around the world devotes much attention to this. Since mechanical noise can be efficiently reduced by well-known engineering methods, the flow-induced noise represents the research focus for further noise reduction. Generally, there are six different sources that independently generate airfoil acoustic emissions: inflow turbulence, turbulent boundary layer trailing edge interaction, separating flow, laminar boundary layer vortex shedding, trailing edge bluntness (von Karman) vortex shedding and tip vortex formation (Brooks et al., 1989). Despite the multidimensional knowledge of the airfoils noise issues the researchers and engineers around the world are still looking for technical solutions to these problems. The natural aspiration of creative engineering became a search for a new original approach to the solution of technical problems and use them. Alternative ways of thinking about sustainable engineering solutions through, or inspired by nature. For example the owls captivate people by their silent flight. These fascinating animals are capable of some amazing physical feats, such as the ability to fly through the air in virtual silence. Their flying style is extremely delicate and their plumage is marvelous. It is precisely a silent flight of the birds of the order strigiformes can be used in technical solutions. Species of these birds have evolved with a number of configurations each with the common characteristic of silent flight. Graham (1934) identified distinctive features that distinguish owl wings from wings of other birds. This design of owls' wings allows them to fly in almost absolute silence (Anderson, 1973). Different parts of their wings and the characteristics of their feathers contribute to their silent flight (Grushka, 1973). Owls have broad wings with large surface areas that help them to float through the air without flapping too much. Less flapping makes less noise. One of the main reasons owls can fly silently is the uniquely designed leading edges of their primary. When most birds fly, turbulence - created when air gushes over the surface of their wings - causes noise. Owls' wings, however, are unique because they reduce noise caused by turbulence. An owl's primary feathers are serrated like a comb. This design breaks down turbulence into smaller currents called micro-turbulences. These soft feathers allow air to pass through which eliminates sound (Hoppitt, 2000). Some people suspect that, as the owls flies, these feathers may also shift sound energy created by the owl's wing to a higher frequency that prey can't hear. Owls' secondary feathers are made up of soft fringes that reduce turbulence behind their wings. The trailing feathers on the back end of the wing are tattered, and the rest of the wing and the legs are covered in downy feathers. As the owl flies, the trailing fringe and tattered feathers break sound waves over the wings as air flows over them.

The reduction of aeroacoustics noise source through the introduction of trailing edge serrations has been conducted by a number of researchers both in the work of theoretical (Howe, 1991a; 1991b; 1998) and experimental (Dassen et al, 1996; Oerlemans et al, 2009; Parchen et al, 1999; Gruber et al, 2010) with trying to explain the bases and sources of the noise of serrated trailing edge. These basic research were often useful to design the new axial fans with reduced noise emissions and the design of future aircraft (Lilley, 2004). But looking at these works, owls technology are still used to reduce noise (eg. aircraft), but it requires a lot of research, both in terms of the biology of these birds as well as the possibility of applying the technique of some of their adaptation. If we look at the owl’s wings we see that they are of a more complex structure than we thought. The previous works showed that wings and flight feathers of owls exhibit specializations on the surface and edges. Firstly, owl wings are bigger in size resulting in low wing loadings that guarantee a slow flight with enough lift reserve to carry heavy weight (prey). The feathers on the wings overlap each other creating a mildly wavy surface (as arcs rather) on the trailing edge. Their detailed structure is more complicated like showed Bachman et al (2007). In technical applications many researchers have focused mainly on studies about the acoustics and aerodynamics parameters of the serrated trailing edge with variable width, height and distance of the teeth. Conducting research on this topic seems to be interesting especially that can it significantly contribute to airfoils noise reduction. For example, Howe’s theory assumes that the scattering process in the generation of airfoil trailing edge noise is the predominant noise source. But the other works proved that such reductions cannot be achieved and suggests that other mechanisms of noise generation are also involved and dominant.

Understanding of the features and mechanisms of noise redution by the serrated trailing edge still requires much research such as study the other geometry of the cuts like those on owl wing or to focus on studies of structural elements present on the wings which can be helpful at the quiet flight (comb, teeth or arcs at the trailing edge). This work focuses on trailing edge noise reduction using different serrations on the trailing edge. It has been shown theoretically by Howe and experimentally, for example by Oerlemans and Parchen, that a significant noise reduction is possible using geometry as a sawtooth. This work may help to understand the mechanism of decrease in noise by this modification. In this paper I have proposed another type of cut-outs, in the form of elliptic curves, like the edge of the wings of an owl, and also as isosceles and rectangular teeth. We described an experimental goal of measuring the acoustic far field and velocity near the field around the trailing edge for the purpose of understanding the mechanisms of noise reduction of the modified trailing edge.

EXPERIMANTAL BAKCGROUND

Experiments were performed in the anechoic room at the Aeroacoustics Laboratory of Institute of Power Energy in Lodz. The anechoic test chamber is cubic, approximately 350m^3 in size and has walls that are acoustically treated with foam wedges providing a reflection free environment (ideally) from 100Hz to 10kHz. The research was performed on the silencer stand test with the outlet to the anechoic room (Fig.1). The outlet was square in cross section with dimensions of 400 mm × 400 mm. The maximum flow velocity of the free jet was 22m/s.

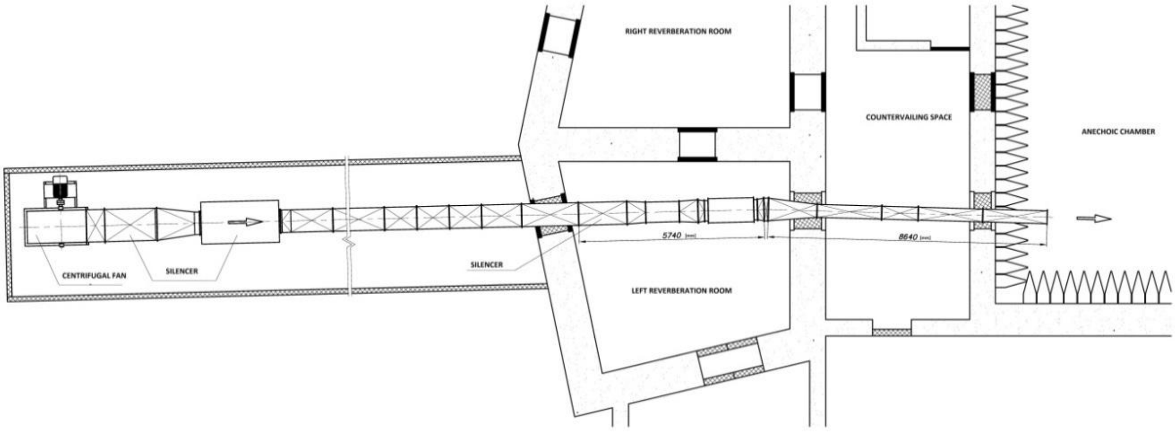

Fig.1. The measuring stand used to study the flat plates.

The ten flat plates were used in this experiment, each of them have a chord of c = 200 mm, a span of s = 400 mm (in flow) and a thickness of d = 2,5 mm, but the nine were with the modification of the trailing edge and one was straight – Fig.2. The geometries cutting of the flat plates are presented on the Fig.3 and summarized in Table 1. The leanding edges of each plate were rounded. The flat plate models were each secured to a housing at zero angle of attack using two side plates and this housing was in turn attached to the contraction flange, as shown in Fig.4. The span of the flat plate models extends beyond the width of the contraction outlet to eliminate the noise produced by the interaction of the flow with the side plates. As shown in Fig.3, two extension plates made from 120mm × 400 mm steel were attached to the contraction flange and aligned with the edges of the contraction outlet. These plates eliminate the noise produced by the interaction of the flow with the sides of researched plates.

To measure the far-field noise, two B&K ½ microphones (model no. 4133) were located in the anechoic room: one above the trailing edge (perpendicular to the direction of the flow) and one behind the trailing edge (in the opposite to the direction of flow). These microphones were positioned at a distance 500mm from the edge. Each of the microphones was calibrated before commencing the acoustic test. To provide isolation from wind noise, wind socks were placed on these microphones. The microphone data from two microphones were collected using a two-channels B&K analyzer 2144 at the same time. Spectra 1/24 octave were measured.

Additionally, the noise behind the different cutting(in the center plane of plates), at the distance 10mm was measured by using the B&K ½ microphone 4190 with tube probe (B&K Kit UA 0040, 2mm diameter and 240mm length) which were connected to preamplifiers and an analyzer SVAN 912. Experiments were performed at one angle of attack $\alpha=0°$. Acoustic measurements were taken at four flow velocities, $\nu_1=2,5$ m/s; $\nu_2=5$ m/s; $\nu_3=10$ m/s; $\nu_4=20$ m/s, corresponding to the Reynolds number: $2,7\cdot10^4$; $5,3\cdot10^4$; $1,1\cdot10^5$;$2,1\cdot10^5$.

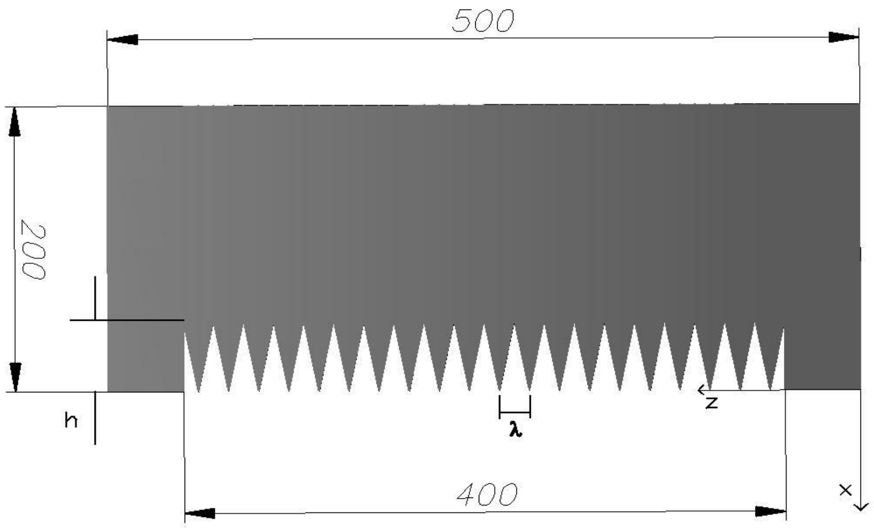

Fig.2. Parameters of the flat plates in [mm].

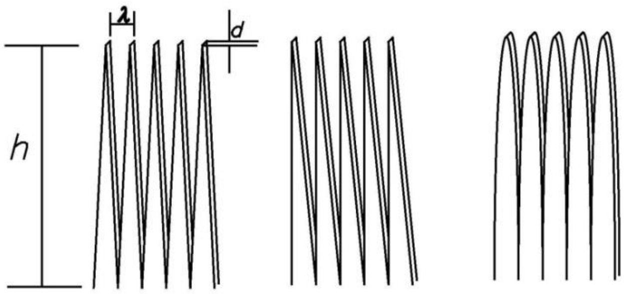

Fig.3. Geometries of cuts on flat plates.

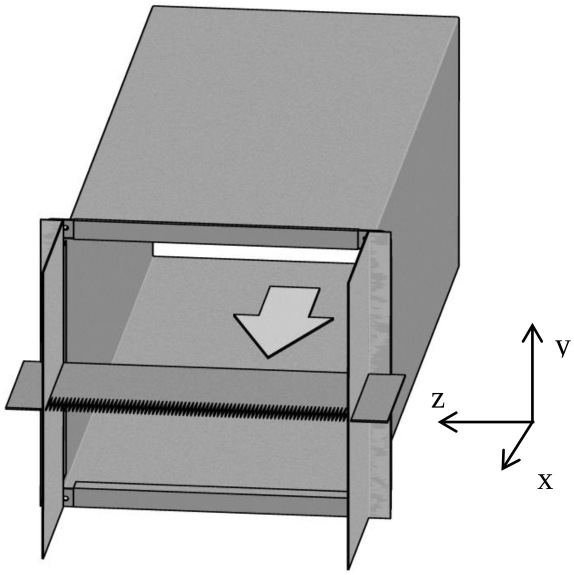

Fig.4. A mounting plate on the outlet.

Geometry of cuts	h [mm]	d [mm]	λ [mm]	λ [mm]	λ [mm]
elliptical arcs	50	2,5	5	10	20
rectangular teeth	50	2,5	5	10	20
isosceles teeth	50	2,5	5	10	20

Table.1. Geometries of cuts as in Fig.2.

The velocities distribution behind the trailing edge of the plates were studied at the two distances – x_1=5 mm and x_2=100 mm. For these investigations a small single probe was used to this with a diameter of 2 mm. The mean velocity in the channel was measured by Pitot probe (8 mm) using log-Chebyshev method. Also the static pressure and temperature in the channel were measured. Measurement of these parameters were performed using pressure transducers, temperature and humidity sensors and recorded and processed by the data acquisition station - SAD-2, equipped with the ADAM modules 4000+, an integrated PC with the application GeniDAQ, equipped with a Visual Basic language (Kopania, 2010). In each measured points in z axis - along the trailing edge of the flat plates, and x axis – at a distance behind the flat plate the data were recording by 10s with resolution 0,1s.

EXPERIMENTAL RESULT AND DISCUSSION

Spectra 1/24 octave the sound pressure level at the top of the trailing edge

Acoustic spectra of the top trailing edge microphone signals are compared with the background noise spectra for an angle of attack of $\alpha=0°$ and all flow velocities. The background noise here was measured by the top trailing edge microphone. But between the registered noise spectra of flat plates and the noise spectrum background is not too great a distance in speeds of ν_1=2 m/s and ν_2=5 m/s. The acoustics spectra of 1/24 octave (SPL spectra) are presented in Fig. 5, Fig. 6, Fig. 7 and Fig. 8, Fig. 9, Fig. 10 at the different speed for the selected flat plate. All figures present the data from 100 Hz to 10 kHz. Additionally on all graphs the small charts were added with the enlarged spectrum in the high frequencies. In this region of frequencies there is a one big peak for the straight flat plate at 330 Hz at ν_2=5 m/s, but it wasn't observed for the plates with the modified trailing edge. This peak is moved to high frequencies at velocities ν_3=10 m/s and ν_4=20 m/s.

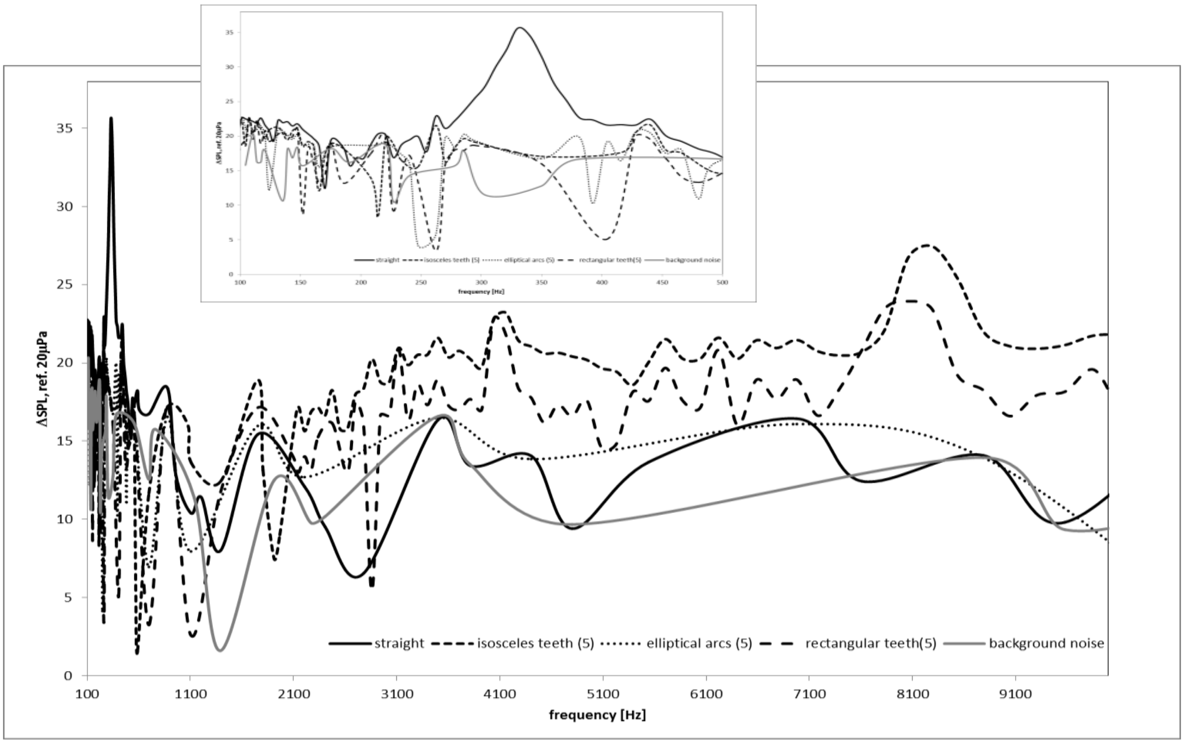

Fig.5. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width of the notches λ=5 mm, in ν_2=5 m/s. In the small picture enlarged spectrum at high frequencies.

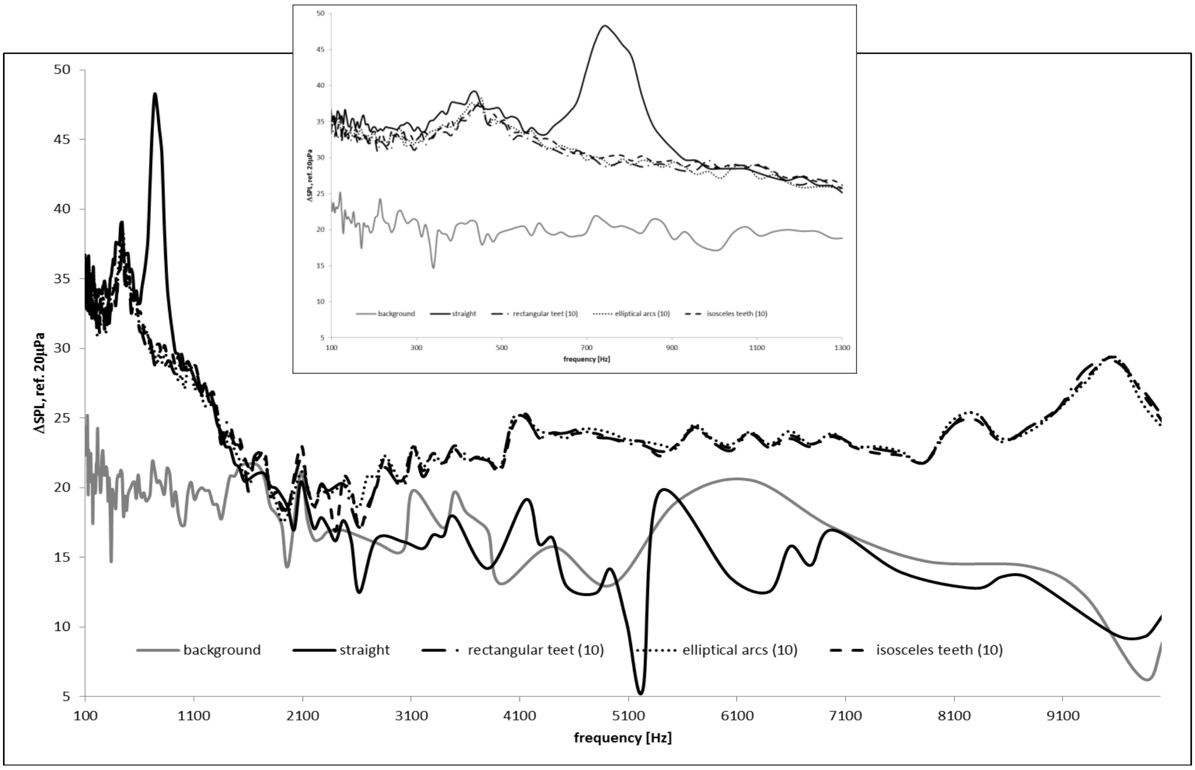

Fig. 6. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width of the notches λ=10 mm, in ν_3=10 m/s. In the small picture enlarged spectrum at high frequencies.

The sound pressure level for the all modified plates at ν_2=5 m/s is reduced between 100 Hz and 1000 Hz, which means that the flat plates with the notches on the trailing edges decrease a sound pressure level in this area. However, above 1000 Hz there is an increased sound pressure level above the spectrum obtained for a straight flat plate. Only the notches as elliptical curves with distances between the peaks λ=5 mm decrease a sound pressure level in a high region of frequencies similar to the straight flat plate. Similar relationships were observed for the tested flat plates at a speed of 10 m/s. But there were two peaks registered at 427 Hz and 739 Hz. Only peak in 739 Hz was cut out by the studied modified plates. But peak 427 Hz is also observed in spectra of the modified flat plate, but it isn't observed in spectrum of the background. Probably this peak is in relation with the noise from the leading edge of the plates or formed as a result of the correlation noise from the leading edge and the edge of the outlet channel.

For the serrated edges at ν_4=20 m/s, the SPL spectra measured by the microphone located above the trailing edge are of equal magnitude and sit well above the background noise level, especially at lower frequencies (Fig. 8, 9, 10). In these cases one can observed the region of frequencies with decreasing the sound pressure level but also with increasing the SPL. As we see from the graphs (Fig. 8, 9, 10) in low frequency bands two peaks you can observe at 440Hz and 1607 Hz for the straight flat plates, but only one at 440 Hz for the modified trailing edge. So the peak at 440Hz must be linked to another source the noise, not from the trailing edge. The second peak at 1607 Hz is very strong and characteristic only for the straight flat plate. This peak is cut out from spectra of sound pressure level of modified plates and decreases noise in this frequency by about 20dB. In the other characteristic bands of the modified flat plates the sound pressure level is reduced by 3-5dB.

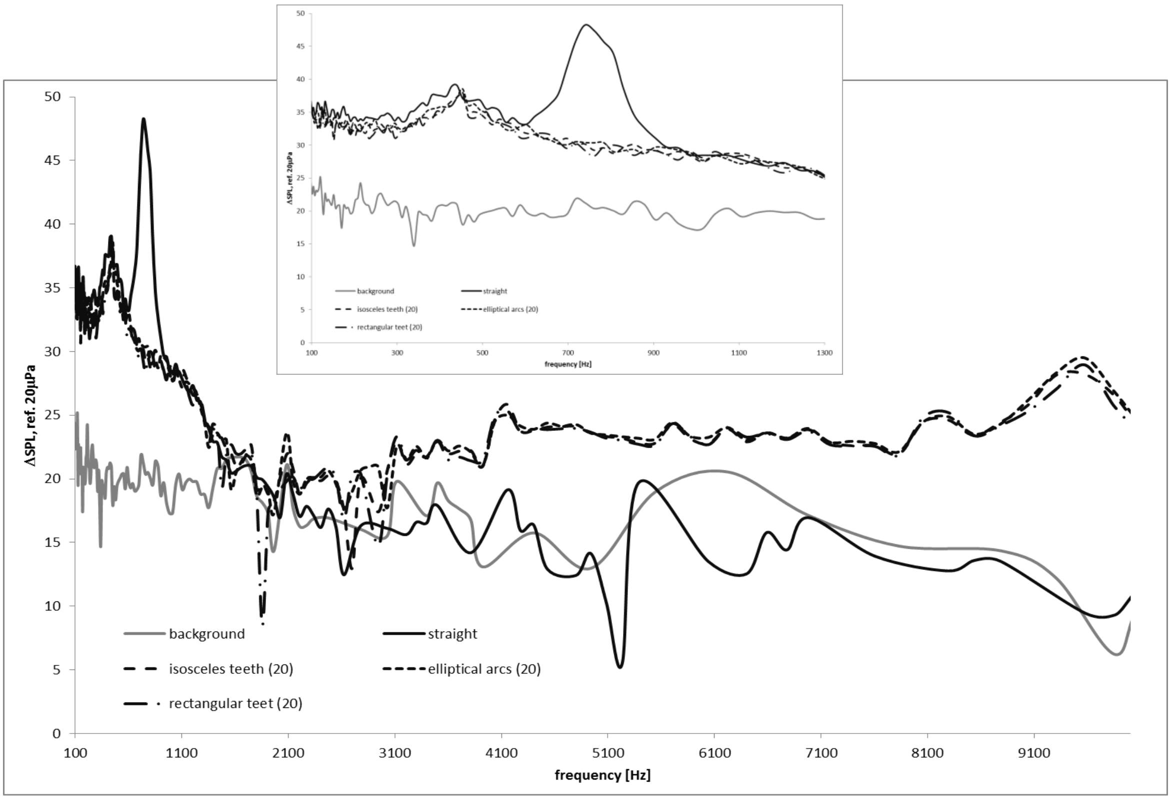

Fig. 7. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width of the notches λ=20 mm, in v_3=10 m/s. In the small picture enlarged spectrum at high frequencies.

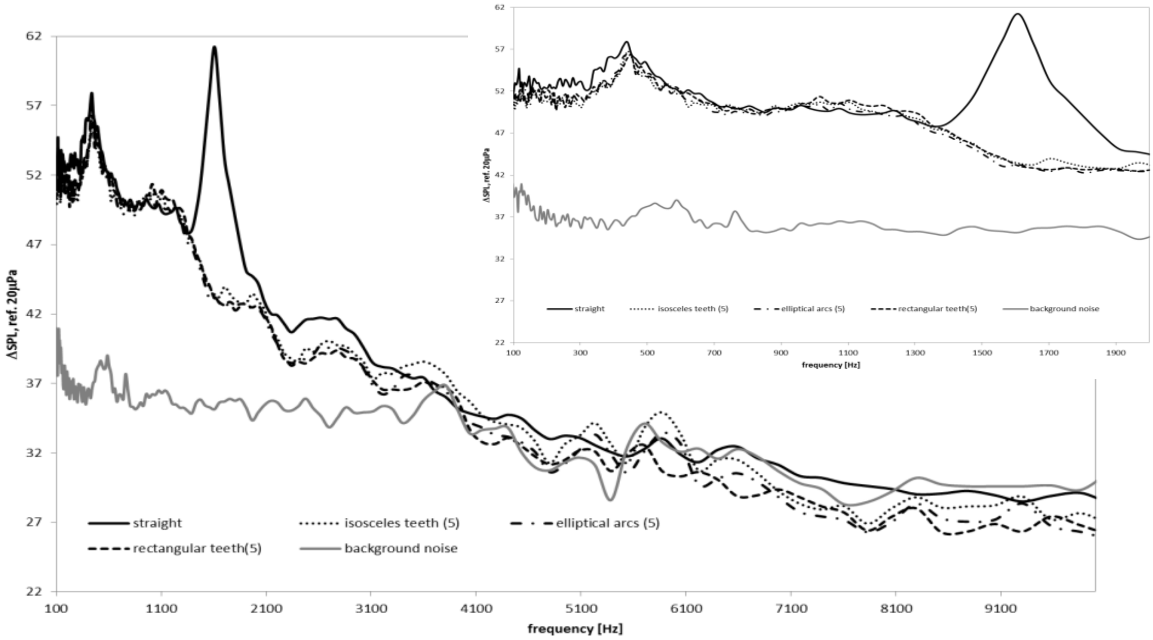

Fig. 8. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width λ=5 mm, in v_4=20m/s. In the small picture enlarged spectrum at high frequencies.

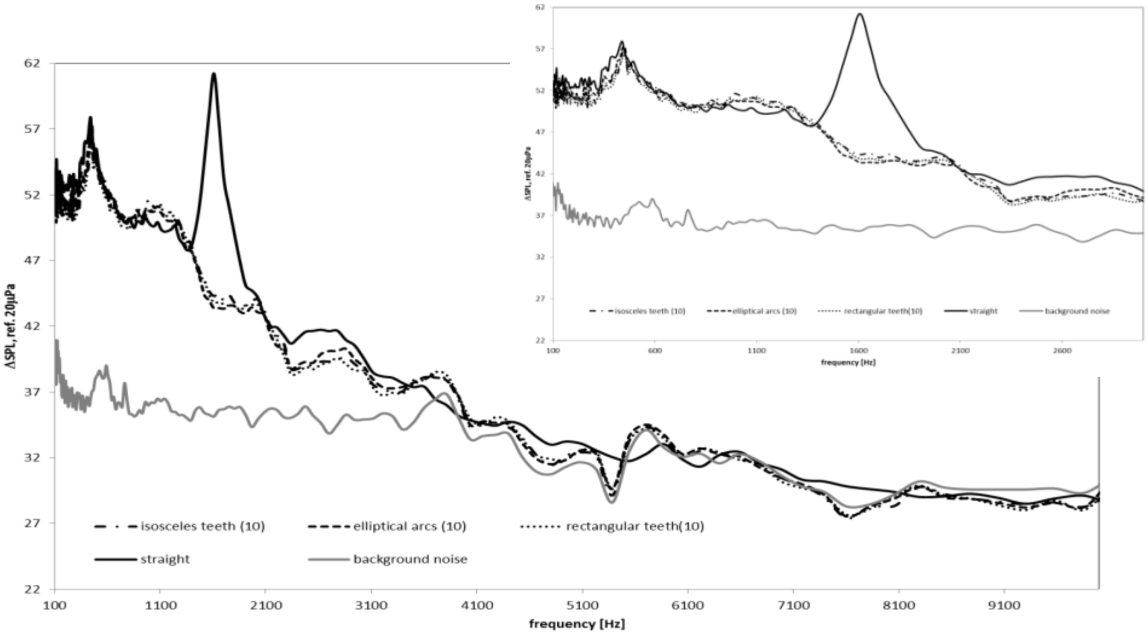

Fig. 9. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width λ=10 mm, in ν_4=20m/s. In the small picture enlarged spectrum at high frequencies.

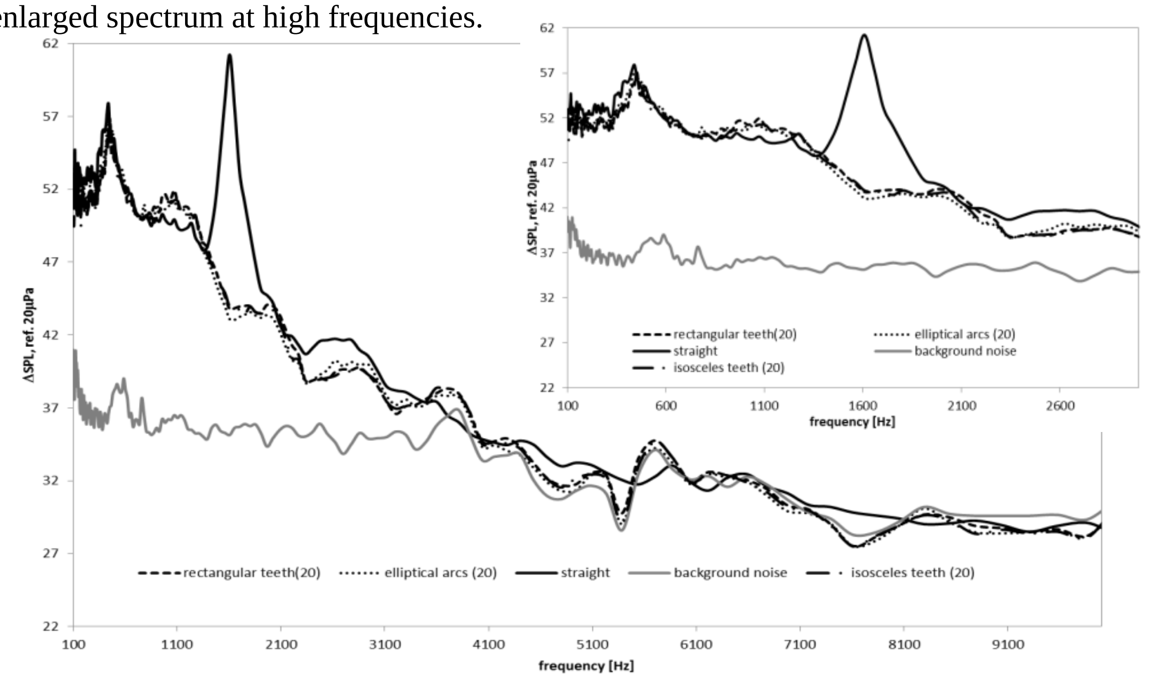

Fig. 10. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width λ=20 mm, in ν_4=20m/s. In the small picture enlarged spectrum at high frequencies.

In Table 3 are presented characteristic frequency bands with an increased or decreased sound pressure level for studied flat plates. For all flat plates studied at low speed (ν_1=2,5 m/s) a decrease inthe sound pressure levels is observed in bands from 100 Hz to 1000 Hz. At speed ν_2=5 m/s flat plates with the gap between the notches λ=5 mm there also occurs a decrease in the sound pressure levels in these region. But for the plates with λ=10 mm and λ=20 mm SPL reduction is observed in the range 250-450Hz. At a speed of ν_3=10 m/s reducing the sound pressure level has been extended to 900-930Hz, while for the speed at 20 m/s spectrum of the sound pressure level for all modified flat plates has an oscillating character. There is a decrease in a sound pressure level in some frequencies and an increase in the other. Increase the sound pressure level for each of the studied flat plates with the modified trailing edge is observed in the higher frequency bands between 1000-10000Hz. No differences were observed in the spectra of noise depending on the geometry of the modified edge of the plate. So in these studied we don't know how the geometry of the notches influences for the acoustic spectra of these plates. Both isosceles teeth, rectangular teeth or elliptical arches give similar levels of sound pressure. But small differences in the spectra observed at lower speeds suggest that elliptical arcs may have an important role in reducing the level of noise generated on the trailing edge of the plate.

Flat plates		top of the trailing edge			
		velocity [m/s]			
		2,5	5	10	20
		[Hz]			
rectangular teeth (λ = 5)	increase	-	1000-10000	2000-10000	Other frequency bands
	decrease	100-2000	100-1000	100-930	100-500; 1300-3300 4000-5000; 6900-7000 9500-10000
elliptical arcs (λ = 5)	increase	-	1000-10000	2000-10000	Other frequency bands
	decrease	100-3500	100-1000	100-930	100-500; 1300-3300 4000-5000; 6900-7000 9500-10000;
isosceles teeth (λ = 5)	increase	3000-10000	1000-10000	2000-10000	Other frequency bands
	decrease	100-1000	100-1000	100-930	100-500; 1300-3300 4000-5000; 6900-7000 9500-10000
rectangular teeth (λ = 10)	increase	4000-10000	1000-10000	2000-10000	Other frequency bands
	decrease	100-1000	250-450	120-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800
elliptical arcs (λ = 10)	increase	4000-10000	1000-10000	2000-10000	Other frequency bands
	decrease	100-1000	250-540	120-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800
isosceles teeth (λ = 10)	increase	4000-10000	1000-10000	2000-10000	Other frequency bands
	decrease	100-1000	250-450	120-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800
rectangular teeth (λ = 20)	increase	4000-10000	1000-10000	2100-10000	Other frequency bands
	decrease	100-1000	260-440	100-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800
elliptical arcs (λ = 20)	increase	4000-10000	1000-10000	2100-10000	Other frequency bands
	decrease	100-1000	260-440	100-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800
isosceles teeth (λ = 20)	increase	4000-10000	1000-10000	2100-10000	Other frequency bands
	decrease	100-1000	260-440	100-900	100-440; 1300-3300 4400-5400; 6500-8000 9500-9800

Table 2. Characteristic frequencies band for the researched flat plates.

Spectra 1/24 octave the sound pressure level behind of the trailing edge in the opposite to direction of flow

Measurement of the sound level of the trailing edge of the flat plates directly in the stream is difficult to perform, due to interference from the flowing stream. So, the measurements were performed at low Reynolds numbers, which allowed observation of increase and decrease the acoustic spectrum in the whole frequency range for the flat plates with cutouts on the trailing edges. All these data are summarized in Table 4, some illustrated in Fig.11, Fig.12 and Fig.13. Generally, for all studied flat plates at low speed (ν_1=2 m/s) a decrease in the sound pressure levels in bands from 100 Hz to 1000 Hz is observed. Exception is a flat plate with the isosceles teeth on the trailing edge, which gives a strong signal throughout the researched frequency range. But also at this speed, the plates with the elliptical arcs and rectangular teeth give a lower acoustic signal than the straight flat plat in the whole range of frequencies.

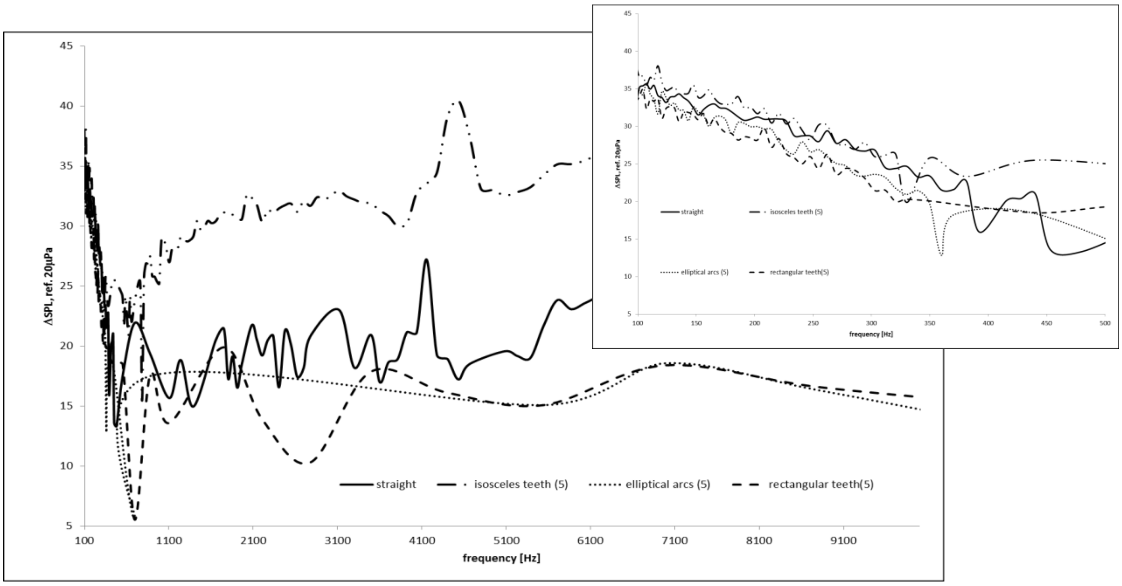

Fig. 11. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width λ=5 mm, in ν_1=2,5m/s. In the small picture enlarged spectrum at high frequencies.

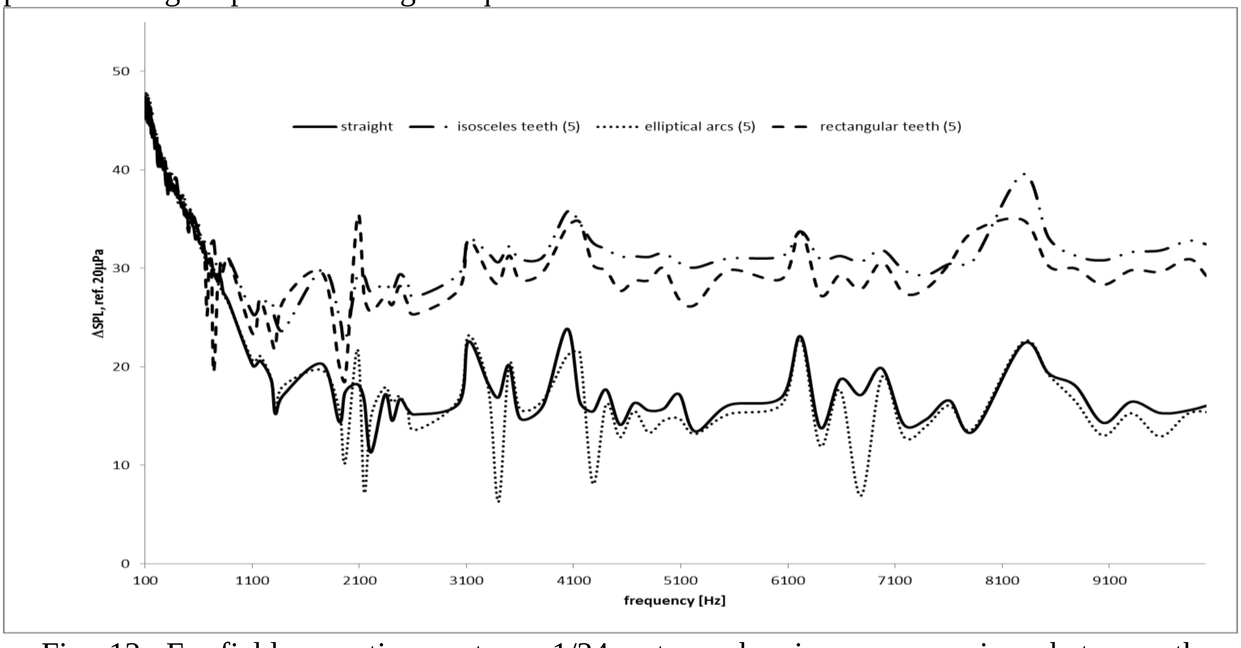

Fig. 12. Far-field acoustic spectrum 1/24 octave showing a comparison between the straight flat plate and the serrated trailing edge with width λ=5 mm, in ν_2=5m/s.

For the studied modified flat plates with λ=5 mm, at speed ν_2=5 m/s, we didn't observe the decrease of the acoustic spectrum. The acoustic signal in this region was at the same level for all flat plates. But also the exception is the flat plate with the elliptical arcs only with λ=5 mm on the trailing edge, which giving a similar acoustic signal like the straight flat plate. The other studied flat plates with the wider gap give the increase sound pressure level between 700-10000 Hz.

Flat plates		behind of the trailing edge velocity [m/s]			
		2,5	5	10	20
		[Hz]			
rectangular teeth (λ = 5)	increase	1100-2100	700-10000	3000-4000 9000-10000	3600-4400 5200-6400 8000-8500
	decrease	100-1000	-	100-150; 1200-1700 6700-8600	100-400 1300-2000
elliptical arcs (λ = 5)	increase	1100-2100	700-10000	3000-4000 9000-10000	3600-4400 5200-6400 8000-8500
	decrease	100-1000	-	100-150 1200-1700 6700-8600	100-400 1300-2000
isosceles teeth (λ = 5)	increase	100-10000	700-10000	3000-4000 9000-10000	3600-4400 5200-6400 8000-8500
	decrease	-	-	100-150; 1200-1700 6700-8600	100-400 1300-2000
rectangular teeth (λ = 10)	increase	1000-10000	700-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	100-400	300-700	100-150 1200-1700 6700-8600	100-500 1100-2000
elliptical arcs (λ = 10)	increase	1000-10000	700-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	100-1000	500-700	100-150 1200-1700 6700-8600	100-500 1100-2000
isosceles teeth (λ = 10)	increase	1000-10000	700-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	100-400	500-700	100-150 1200-1700 6700-8600	100-500 1100-2000
rectangular teeth (λ = 20)	increase	1000-10000	830-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	400-1000	500-720; 780-800	100-150 1200-1700 6700-8600	100-400 1100-1800
elliptical arcs (λ = 20)	increase	1000-10000	830-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	400-1000	500-720; 780-800	100-150 1200-1700 6700-8600	100-400 1100-1800
isosceles teeth (λ = 20)	increase	1000-10000	830-10000	3000-4000 9000-10000	3300-6700 7200-10000
	decrease	400-1000	500-720; 780-800	100-150; 1200-1700	100-400 1100-1800

Table 3. Characteristic frequencies band for the researched flat plates.

At speed of v_3=10 m/s and v_4=20 m/s spectrum acoustic of the studied flat plates are highly oscillatory. There are visible reductions of the spectra in the lower and middle frequency bands.

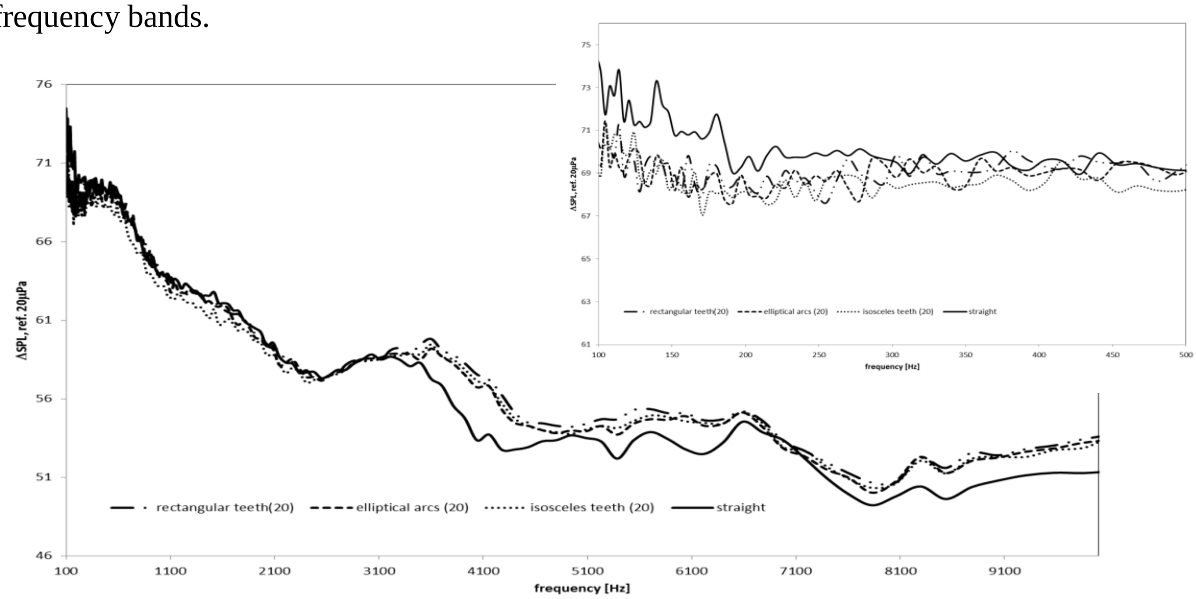

Fig. 13. Far-field acoustic spectrum 1/24 octave showing a comparison between straight flat plate and serrated trailing edge with width λ=20 mm, in v_4=20m/s. On the small picture enlarged spectrum at high frequencies.

At speed v_3=10 m/s the lower sound pressure level from 6700-8600 Hz for some modifies plates was also observed. At speed v_4=20 m/s a decrease in the sound pressure level in the lower (100-500 Hz) and center (1300-2000 Hz) frequencies bands was observed. The increase in the acoustic spectrum of the studied flat plates are observed above 3000Hz. Also in this case there weren't differences between the sound pressure level depending on the geometry of the trailing edge - isosceles teeth, rectangular teeth or elliptical arches. Small differences for the flat plate with the elliptical arcs on the trailing edge in the noise spectra observed at lower speeds, suggest, that elliptical arcs may have an important role in reducing the level of noise generated on the trailing edge of the plate.

Analyzing the spectra of the pressure level for each of the flat plates at all speeds, the sound pressure level was calculated as a single-value according to the relation (1) and the results are summarized in Table 4.

$$\Delta SPL_{1/24} = 10 \cdot \log(\frac{1}{N}\sum_{i=1}^{N} 10^{0,1 \cdot L_{pAi}}), \qquad (1)$$

where, N - appropriate frequency band from range 100-10000Hz; L_{pAi} – sound pressure level in the appropriate frequency band in 1/24 octave. Frequencies for which the acoustic signal was unmeasurable (especially at low speeds) were cut from the spectra.

It's noticeable that in the case of lower speeds the total value of sound pressure level is higher for flat plates with the modification of the trailing edge than to the straight flat plate. In these cases there is too small energy change for the acoustic energy. It may also suggest that the notches on the trailing edges of the blades did not reduce the total sound level in the case of small velocity, as is suggested in the literature. The exception are the flat plates with the rectangular teeth and elliptical arcs with λ= 5mm, which have lower sound pressure levels than the straight flat plate. However, at this stage of research we cannot explain this phenomenon. Analyzing the single-value sound pressure level for the tested flat plates, it can be said that the apparent effect of the noise reduction is for the speed at ν_4=20 m/s. Therefore cutting the trailing edge of the flat plates can reduce the aerodynamic noise at higher flow velocities. However, oscillatory nature of the studied acoustics spectra, indicates that the cutting act as resonators, according to Howe's theory, regardless of their type. You also cannot tell which cuts are best. For any of them, there was no significant relationship in these studies.

Flat plates	top of the trailing edge				behind of the trailing edge			
	velocity [m/s]				velocity [m/s]			
	2,5	5	10	20	2,5	5	10	20
	ΔSPL [dB]				ΔSPL [dB]			
straight	17,11	17,11	23,69	51,24	28,31	39,32	52,34	67,29
rectangular teeth (λ = 5)	14,79	18,37	30,32	49,39	28,92	39,86	52,10	66,57
elliptical arcs (λ = 5)	13,40	18,37	31,43	49,30	30,10	39,78	51,96	66,27
isosceles teeth (λ = 5)	18,75	20,11	35,40	49,16	33,32	40,60	51,47	66,49
rectangular teeth (λ = 10)	20,60	21,49	30,23	49,34	28,29	38,61	51,29	65,80
elliptical arcs (λ = 10)	19,93	21,48	30,84	49,77	28,26	39,91	51,63	65,69
isosceles teeth (λ = 10)	20,48	21,75	30,84	49,60	28,34	40,27	52,07	66,06
rectangular teeth (λ = 20)	20,40	21,76	30,52	49,54	28,01	39,33	51,60	66,14
elliptical arcs (λ = 20)	20,24	21,52	30,96	49,89	28,52	39,71	51,93	65,97
isosceles teeth (λ = 20)	21,04	21,61	30,53	49,42	28,92	39,42	51,17	65,59

Table 4. Energy averages [dB] for each of the studied flat plates.

FFT analysis around cuts

The FFT noise spectrum behind the cuts at the distance of 10mm was measured by using the ½ microphone with a micro tube probe (2mm diameter and 240mm length) which allowed the collection of acoustic signal around cutting. The noise reduction ΔSPL was calculate by equation (2):

$$\Delta SPL = 10 \cdot log_{10}\left(\frac{\Phi_0(x,\omega)}{\Phi(x,\omega)}\right), \qquad (2)$$

where $\Phi_0(x,\omega)$ is the noise spectra for the straight flat plate, $\Phi(x,\omega)$ is the noise spectra for the notches flat plates (Gruber, 2010) at the appropriate frequencies. Figures 14 and 15 present the noise reduction ΔSPL for the each studied flat plates with modified trailing edge at ν_1=2,5 m/s and ν_4=20 m/s. Strong oscillations can be seen in these figures due to interference between the root and the tip of the serrations for these plates. The frequency of these peaks is independent of the spatial periodicity of serrations.

Observed the reduction of spectrum below 0 indicates that at these frequencies the sound pressure level of straight flat plate is larger than the flat plates with the modified trailing edge. In the Fig. 13 and Fig. 14 it can be seen that the reduction in sound pressure level takes place in specific frequency bands alternating with an increase in the spectra in other frequency. The amplitude of these spectrum increases with increasing width of the gap between the tip of cutting especially for the plates with the trailing edge as an elliptical arcs. It was observed at low speeds ν_1=2,5 m/s and ν_2=5 m/s. The modifications of the trailing edge as rectangular teeth also reduce the sound pressure level. But only the trailing edge as isosceles teeth with distances between the top of the teeth λ=5 mm decreases the sound pressure level, while for λ=10 mm and λ=20 mm showed an increase SPL at higher frequencies. At higher frequencies and at the low speeds were also observed oscillation spectrum above and below 0 in the low frequencies, but so strong.

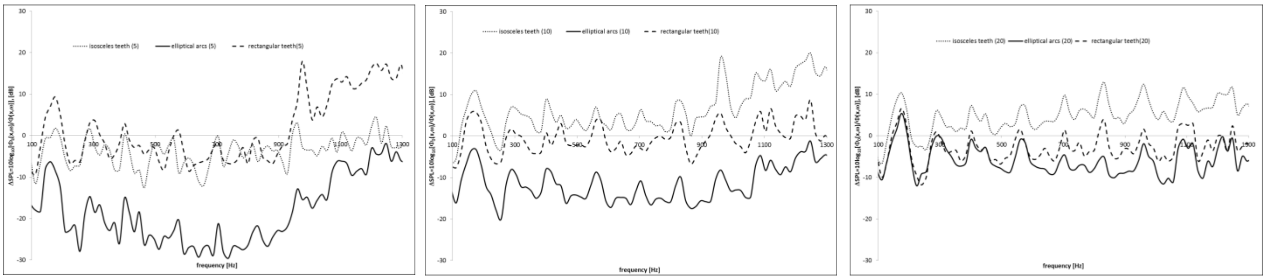

Fig.14. Possible noise reduction for notches flat plates at ν_1=2,5 m/s.

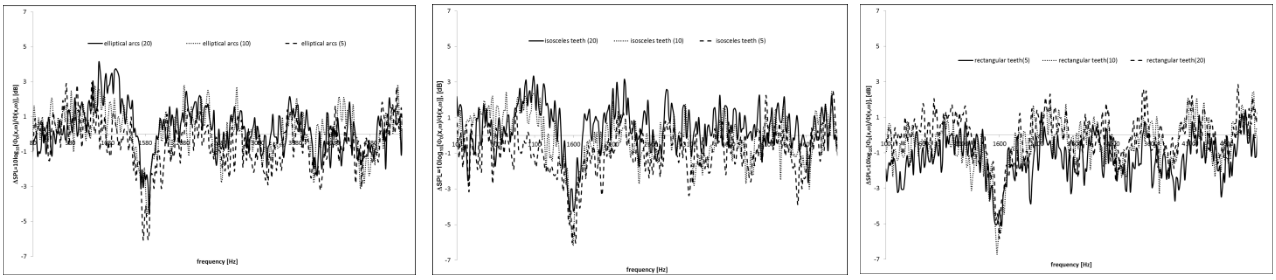

Fig. 15. Possible noise reduction for notches flat plates at ν_4=20 m/s.

At higher speeds, ν_3=10 m/s and ν_4=20 m/s spectra are highly oscillatory. There was a strong reduction of the spectra in the 1300-1800Hz, in the region, where there was a peak 1607 Hz for a straight flat plate absent in the spectra of modified plates. The largest decrease in this region was observed for plates with ellipses and isosceles teeth at the trailing edge with of λ=5 mm. The smallest decrease was observed for plates with λ=10 mm and λ=20 mm. In the case of plates of the trailing edge with rectangular teeth also a decrease in the level of sound pressure level, in total spectrum, was highest for λ=5 mm. But the largest reducing SPL at 1600Hz was for the plates with λ=10 mm. However, at high speeds it is difficult to say what kind of cuts best reduce noise compared to a flat plate.

Aerodynamic studies behind the trailing edge of the flat plates.

Also the dynamic pressure distributions behind the trailing edges of the studied plates were analyzed in the two distances of 5 mm and 100 mm. The Fig. 16 shows the distribution of dynamic pressure behind the plates with cutting with λ=5 mm, λ=10 mm and λ=20 mm in velocity ν_1=2,5 m/s. But Fig. 17 shows the distribution of velocity behind the plates with notches λ=5 mm in velocity ν_4=20 m/s. The distribution of pressure along the z axis (from edge to the center of the plate) was studied. For the straight flat plane a large fluctuations of pressure and velocity can be seen. At one point the pressure was measured for 10 s. By this time pressure on this point vary considerably from positive to negative values. On the graph the area along the z axis with the negative pressure can be seen, which means that normal vectors has opposed direction. Almost sinusoidal nature of the curve proves the formation of large vortices behind the edge of the plate. Energy dissipation is significant. Large speed variations are also observed at ν_4=20 m/s.

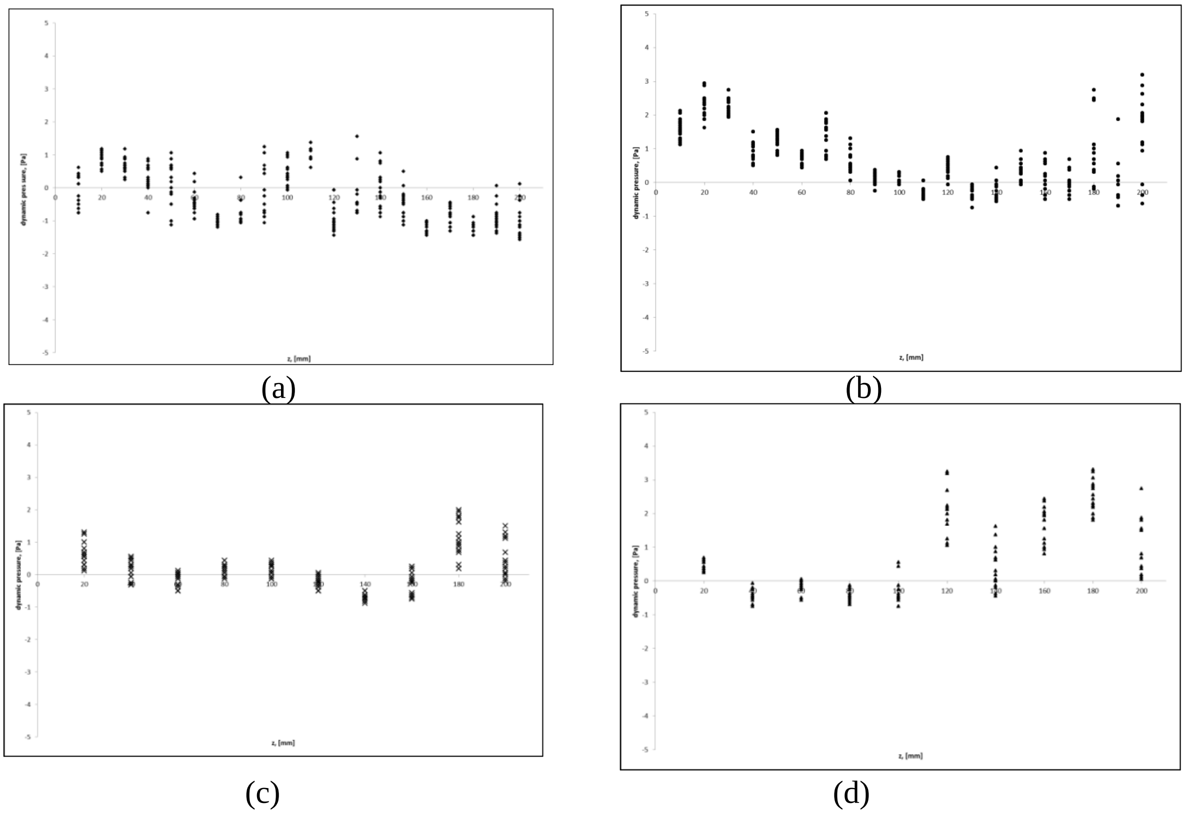

Fig. 16. The distribution of dynamic pressure at ν_1=2,5 m/s at a distance of 5 mm behind the flat plate: straight (a) and with the isosceles teeth on the trailing edge with λ=5 mm (b), λ=10 mm (c) and λ=20 mm (d).

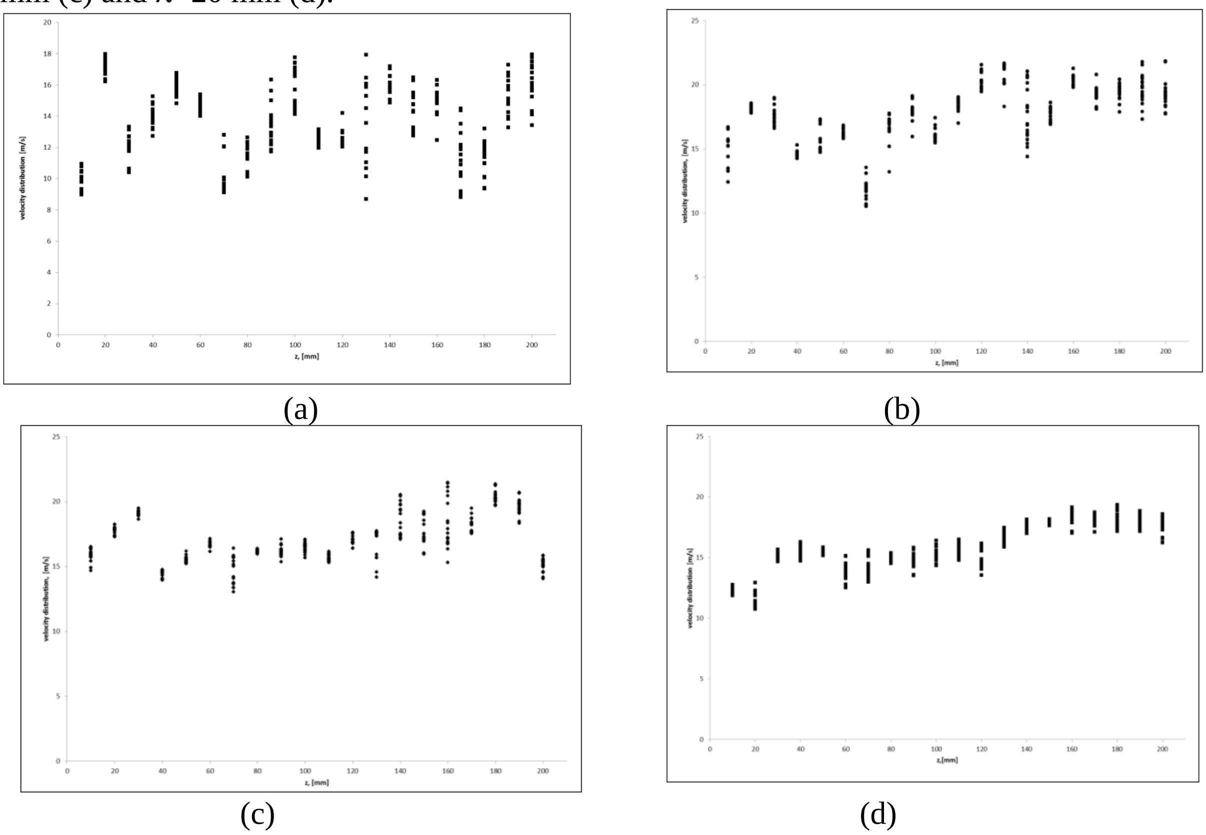

Fig. 17. The distribution of velocity at ν_2=20 m/s and at a distance 5 mm behind the flat plate: straight (a) and flat plate with λ=5 mm and modified trailing edge as isosceles teeth (b), elliptical arcs (c) and rectangular teeth (d).

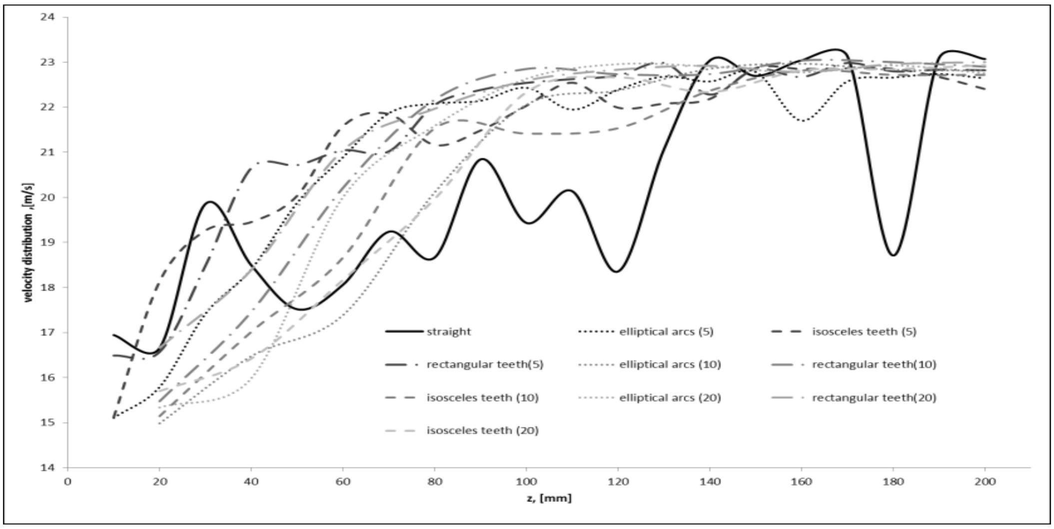

Fig. 18. The distribution of velocity at v_2=20 m/s at a distance of 100 mm behind the flat plate: straight and flat plate with modified trailing edge.

However, for plates with cutting trailing edges of the pressure distributions are more stable. There isn't such significant fluctuation pressure and velocity. The values measured at one point are comparable. For these plates alignment air-stream occurs faster. The energy dissipation is smaller, so that formed vortices are smaller, which translates also into a noise signal. The velocity distribution at distance of 100 mm for all test plates is shown in Fig 18. A curve plotted with the mean values for each test point along the z axis. Also see alignment the stream behind plates with cutouts. The higher speeds are obtained at the edge of the plates (between 10-80 mm) and almost perfect alignment of streams for all flat plates in region 80-200 mm (center of plates). Higher values of velocity in region between 10-80 mm were obtained for plates with λ=5 mm. This means that smaller distance between the cutting is more favorable in terms of flow.

Due to the number of studied objects and the information obtained from test results the trailing edge boundary layer thickness, displacement thickness, momentum thickness and shape factor will be considered in the next publication. Also a comparison of experimental acoustic parameters with known noise prediction models (for example; BPM- Brooks, 1989) will be discussed separately.

CONCLUSION

This paper has presented the result of an experimental investigation on flow over, and noise generated by cutting edged flat plates models at four (low) Reynolds number. The result include far-field acoustic spectra, FFT acoustic spectra behind the cutouts and information about unsteady pressure and velocity character near trailing edge. Different geometries of the flat plates with the cutting trailing edge have been studied. A significant effect on the radiated noise levels by this cutting has been shown. It is also important that similar acoustic effects were obtained for all types of cuts. However, at lower speeds, a better noise reduction effect was obtained for the plates with edges as elliptical arcs, but more research is demanded. Potential noise reduction at low and mid frequencies about 20 dB was observed at the measurement by microphone in the top of the trailing edge. Also a noise reduction of about 3-5 dB was observed in the measurement behind the trailing edge. Generally, a decrease in the sound pressure level was observed at lower frequencies but at higher frequencies followed an increase in the SPL. A strong oscillatory effect was observed in the FFT spectra for the different cutting. The best noise reduction effect was obtained for the flat plate with the elliptically cuts on the trailing edge. On the basis of the above tests it can be concluded that other types of notches on the trailing edge (not just a sawtooth) also reduce the aerodynamic noise of flat plate. But the mechanisms by which cutting trailing edges reduce the radiated noise demand more researche by using other techniques, for example the bearforming or multichannel analysis with investigations of the directional noise source.

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