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Study on relationship between the geometry of leading and trailing edges of airfoil and their aeroacoustics parameters at low Reynolds number

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ABSTRACT

In last few year's there has been considerable interest in the use of edge modifications for the reduction of airfoil noise. One of the most commonly used methods is sawtooth serration edge inspired by the owl's wing. The edge serration is known to be quite effective in reducing aerodynamic drag and self noise radiation. But the correlation between edges modifications of airfoil and noise reduction was studied also for other forms such as wavy or M-shape. Results of an experimental study on turbulent flow over the NACA 0012 airfoil, with a flat and serrated trailing and serrated, arc and wavy leading edge are presented in this paper. Detailed aeroacoustic measurements are presented of the noise radiated by study airfoils in a low to moderate speed flow under acoustical free field conditions. Parametric studies of the amplitude and wavelength characteristics are conducted to understand the effect of edges modifications on noise reduction. The influences of geometric parameter applied tooth, arc and waves, free-stream velocity on the noise reduction effect of are observed.

Keywords: noise, airfoil, NACA 0012, trailing edge, leading edge

1. INTRODUCTION

Airfoil self-noise is mainly associated with the laminar or turbulent boundary layer on the blade surfaces. This type of noise can have tonal or broadband characteristics, and is considered to be caused by several mechanics, such as trailing edge noise, laminar boundary layer vortex shedding noise, tip noise, separated or stalled flow noise, and blunt-trailing-edge noise. Trailing edge (TE) noise has been an comprehensive aeroacoustic research topic for more than fifty years, both experimentally and analytically. In literature reduction of trailing-edge noise is inspired by the silent flight of owls [1] and the capability of trailing-edge serrations in noise attenuation [2,3,4] in theoretical, experimental and numerical aspect [5,6]. To reduce trailing edge noise several passive methods such as serrated trailing edge [7], porous surface [8] and brushes [9] have been investigated. Experimental investigation [10] showed that the serrated trailing edge of airfoil may cause a self-noise reduction of up to 2 and 6 dB with significant reduction at high frequencies without the loss of aerodynamic performance. The last works showed that further noise reduction can be achieved by the use of more complex trailing edges such as: slitted edge, sawtooth with hole, slitted-sawtooth edge and randomly serrated trailing edges [11]. The character and level of trailing edge self-noise is highly sensitive to Reynolds number, angle of attack, airfoil geometry and trailing edge bluntness. Trailing edge noise radiated in high Reynolds number flow has got broadband in nature but in low Reynolds number trailing edge noise has a distinctive narrow band character comprising a broadband hump superimposed with a number of high amplitude "tones" [12]. In this situation the boundary layer on the airfoil surface is mainly laminar but potentially unstable.

The presented paper is a studies of the aeroacoustic and aerodynamic behavior of symmetrical airfoil NACA 0012 with trailing edge serrations with additional serrated, arched and wavy plates on the leading edge. Welocity distribution around the airfoil and 1/3 octave sound pressure level at low Reynolds number has been investigated and presented.

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2. EXPERIMENTAL METHOD

2.1 Test model

In current work NACA 0012 airfoil has been investigated. The airfoil were manufactured by 3D printing using PLA material. Airfoil with chord 0,15m and span 0,35m has got 4,0 mm (thickness) blunt trailing edge with a 25mm deep and 2.0 mm thick slot cut through the trailing-edge and leading edge along the span in order to allow flat plate serration inserts to be fitted to the airfoil, as shown in Figure 1. Chord of flat and serrated plate added to trailing edge were c = 75 mm, a span of s = 350 mm and a thickness of d =2,0 mm. Chord of serrated plate added to leading edge were c = 30 mm. The part of each plates (25mm) was insert into the notch in the airfoil. The airfoil with straight unserrated trailing edge and unserrated leading edge (baseline) was used as a reference model for airfoil with serrated plates. The serrated plate on the trailing edge has got height of teeth 50mm, with distance between the tip of teeth 5mm. The serrated plates on the leading edge have got teeth, arcs and wave with height 5mm and distance between the tip was 5mm (serrated and arc) or 10mm (waves). The flat plate and serrated plates were used in this experiment as a additional trailing and leading edges. The geometries serrated plates added to airfoil are presented on the Figure 2 and Table 1.

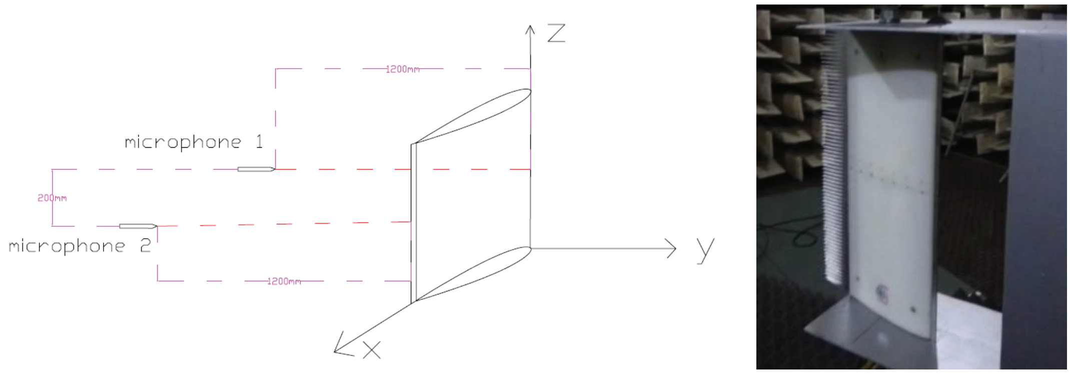

Figure 1. Studied airfoil and locations of microphones and thermo anemometer around the airfoil.

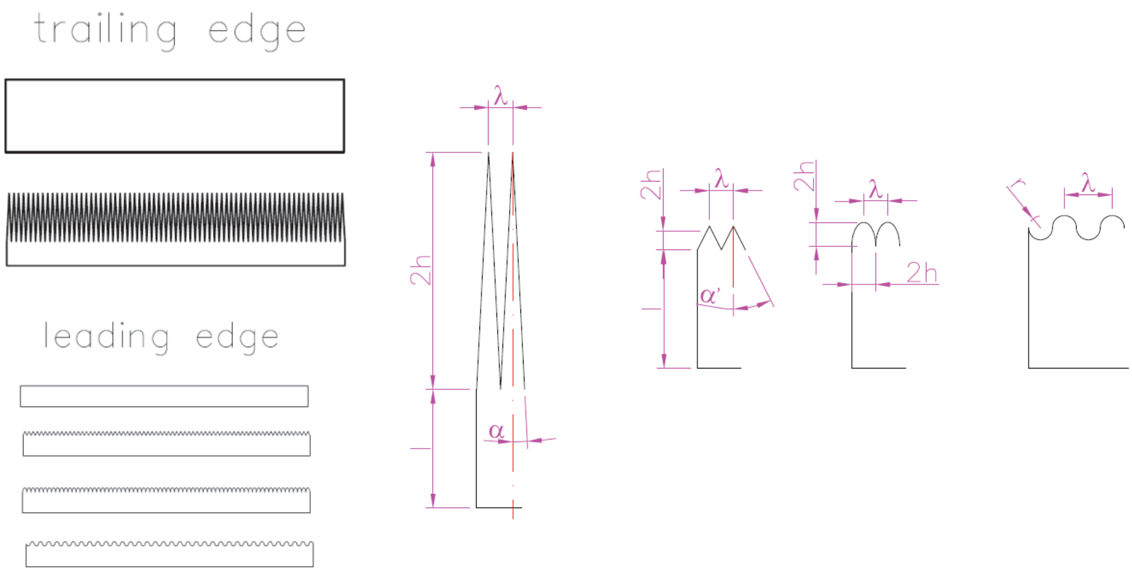

Figure 2. The geometries serrated plates added to airfoils.

Table 1. The parameters of serrated plates.

Term	Model of airfoil	Parameters of studied plates					
		l [mm]	2h [mm]	2h’ [mm]	λ [mm]	α [°]	r [mm]
Baseline	Flat plates on trailing and leading edge	25	-	-	-	-	-
Serrated	Flat plate on trailing edge and serrated plate on leading edge	25	50	-	-	26,6	-
Serrated - serrated	Serrated plate on trailing edge and serrated plate on leading edge	25	50	5	5	26,6	-
Serrated – arcs	Serrated plate on trailing edge and arc plate on leading edge	25	50	5	5	-	-
Serrated - wavy	Serrated plate on trailing edge and wavy plate on leading edge	25	50	5	10	-	2,5

2.2 Aeroacoustical measurement

The measurements were performed on the special constructed test stand with the outlet to the anechoic room. The outlet was square with parameters 150×350 mm. Airflow was induced by a fan mounted on the inlet of the stand and regulated by the power inverter. The outlet of test stand was in the anechoic room at the Institute of Power Energy in Lodz. The anechoic test chamber is cubic, approximately 350m3 in size and has walls that are acoustically treated with foam wedges providing a reflection free environment. The airfoil was held by side plates in outlet of test duct. To measure the far-field noise was made by SVAN 958. The two microphones was located on trailing and leading edge (perpendicular to the direction of the flow) positioned at a distance 1200mm from the edges (in middle of airfoil). To generate turbulence structures, and obtain an elevated level of turbulence intensity in the freestream, a rhombus grid (mesh of grid 10mm, angles of mesh 50° and 130°) was placed outside the outlet of test duct. The experimental setup for NACA 0012 is shown in Figure 3. The microphone was calibrated before commencing the acoustic test.

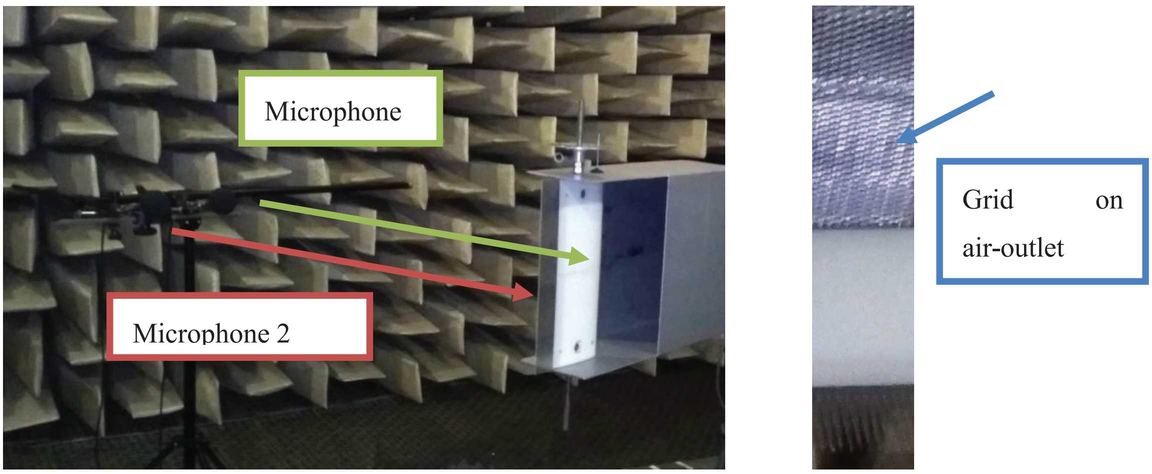

Figure 3. The photograph of NACA 0012 during the measurements

The aeroacoustical and aerodynamical parameters were studied at 0° angles of attack (zero angle was in level at x-axis). The measurements were taken at five flow velocities in outlet of duct: 6m/s;

9m/s; 12m/s; 15m/s. The velocities distribution in outlet of the stand test were measured by using a Pitote probe and calculated by using log-Chebyshev method. For these investigations a small single probe was used to this with a diameter of 2 mm by using data acquisition station - SAD-2, equipped with the ADAM modules 4000+, an integrated PC with the application GeniDAQ equipped with a Visual Basic language.

Additional, detailed flow measurements at several point along the chord line on upper surface have been performed using thermo anemometer measurement technique for NACA 0012 airfoil in order to better understand the effects of serration on the aerodynamic performance of the airfoil. The measurements were carried out at angle of attack, $\alpha = 0°$ for chord corresponding to Re=1,0×105. For thermo anemometer the point measurement were logged at locations y=10mm, 30mm 50mm relative to the lateral surface of airfoil. Each measurement plane was populated with 33 measurement points to accurately capture the flow behavior at that region.

3. EXPERIMENTAL RESULTS

3.1 Acoustical parameters

The knowledge about aerodynamic and acoustic parameters of airfoil in low Reynolds number is important for learning its physical nature. Most of the flight animals (insects, birds) fly at Reynolds number of 103-105 due to their low speed and small length scales. Current trend "inspiration on nature" to improved the aerodynamical of flight and reduce flight's noise parameters requires knowledge in this aspect. In this work the acoustic measurements of NACA 0012 airfoil as the baseline and serrated configurations were carried out for 0° angle of attack and velocities: 6m/s; 9m/s; 12m/s; 15m/s which correspond to chord-based Reynolds Re = 8×104 to 2,0×105. The main goals of this work was to determine the impact of plates steel, cut as flat, serrated, arc and wavy and added to trailing and leading edges of two studied airfoils, to emitted noise.

The spectra of the acoustic pressure level in the 1/3 octave bands were determined for tested airfoil with different configuration. As we seen from Fig. 4 and 5 there are differences in spectrum of SPL between baseline and serrated models and for the rest of studied models. Tonal character of SPL spectrum of studied models of airfoils is observed.

For baseline and serrated models three peaks are observed at lower Reynolds number: in 400Hz (observed also for the rest models), 1600Hz and 4000Hz (Fig. 4). For the rest of studied models - serrated-serrated, serrated-arc and serrated-wavy - between frequencies 1250 – 7000 Hz significantly lower SPL values are observed than for the baseline and serrated models. So, its suggest then airfoil with modified trailing and leading edge could reduce noise of airfoil. From Fig. 4 is seen that there are not so significantly differences between the spectrum from microphone 1 and 2 - probably the distance between the microphones was too small, what can influence on the spectrum. One difference is observed - the small peak around 1000Hz - for serrated-serrated, serrated-arc and serrated-wavy models. For serrated-serrated and serrated-arc models small inflexion point at 2500Hz is observed

The some differences in spectrum of SPL between baseline and serrated models and for the rest of studied models are observed in higher Reynolds number (Fig. 5) . Tonal character of SPL spectrum of studied models of airfoils is also observed. For baseline and serrated models peaks are observed in 400Hz, 1600Hz, 4000Hz and 6300Hz. For serrated model small inflexion point at 1000Hz is observed. For serrated-serrated, serrated-arc and serrated-wavy models, between frequencies 3500 - 10000Hz significantly lower SPL values are observed compared to baseline and serrated models. For serrated-serrated, serrated-arc and serrated-wavy models three peaks, at 400Hz, 800Hz, 2500Hz and 3150Hz are observed. The peak at 400Hz is not related to spectrum of studied airfoil models. This peak is observed also in spectrum of test duct, without of models. So, the test duct must be modified, if the studied will carried out in lower frequencies (below 500Hz). But in these studies, the comparison of 1/3 octave SPL spectrum between the model with flat plates added to leading and trailing edges to the models airfoil with serrated edges is important. So, it does not matter the SPL spectrum of background (test duct). Based on the results, it could be concluded that combination of modified edges of airfoil could reduce of its noise.

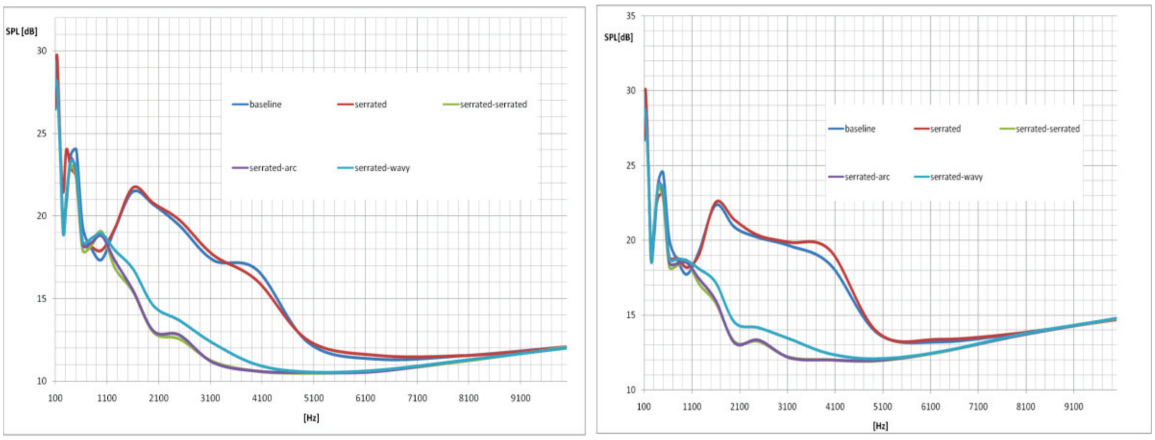

Figure 4. The 1/3 spectrum of SPL from microphone 1 (on the left from leading edge) and microphone 2 (on the right from trailing edge) for tested models of NACA 0012 with flat plate and serrated added to trailing and leading edge, at α=0° and Re = 8×10^{4}.

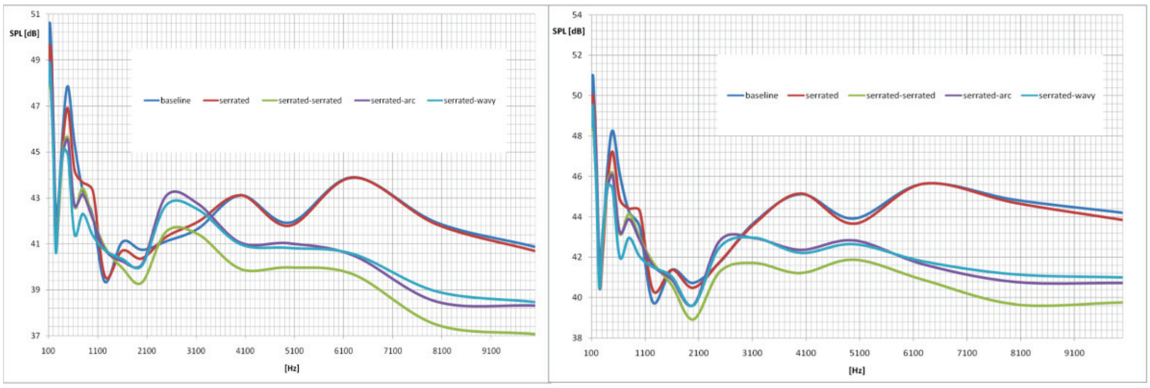

Figure 5. The 1/3 spectrum of SPL from microphone 1 (on the left from leading edge) and microphone 2 (on the right from trailing edge) for tested models of NACA 0012 with flat plate and serrated added to trailing and leading edge, at α=0° and Re = $2{,}0\times10^{5}$.

In this work, it was important to understanding, how different serrated added to leading edges of tested airfoils influence on the noise of these airfoils in regard with the airfoils with straight edges. The differences in the sound pressure level between airfoils with straight and serrated edges were determined ("differential SPL"). That allowed to define the bands in which the added plates reduce the noise. The difference of measured SPL between serrated and straight airfoils depending to velocities for NACA 0012 airfoil are presented in Figure 6 and Figure 7 as a colour-maps. As is seen from the Figure 6 and Figure 7 the maximum noise reduction value, depending on velocity and frequency, and it could exceed 6dB (red fields on the maps) for all studied models with serrated edges.

Impact of leading edge noise at low frequency becomes more prominent from 11m/s onwards (pictures b), c) and d)). In each case (Figure 6) noise reduction is observed, e.g. for serrated model at about 7m/s above 2000Hz and 9m/s in whole range of frequencies (approximately 2dB). After add the serrated plates to leading edge of airfoil the noise reduction increase, e.g. for serrated-serrated model above 11m/s in whole range of frequencies noise reduction is around 5-7dB.

The noise contributions associated with the leading edge and trailing edge are well separated in the frequency domain and velocity. In lower velocity there are not influence of modified (serrated) plates added to leading edge of airfoil, what suggest that in these range of Reynolds number and in these conditions will not reduction of noise.

Generally the noise reduction of studied airfoils have got a resonance character, what mean that the increase and decrease of differential SPL depended on frequencies is observed – especially around 10m/s, where are minus values of differences SPL what mean that in this region and by this velocity there are not noise reduction.

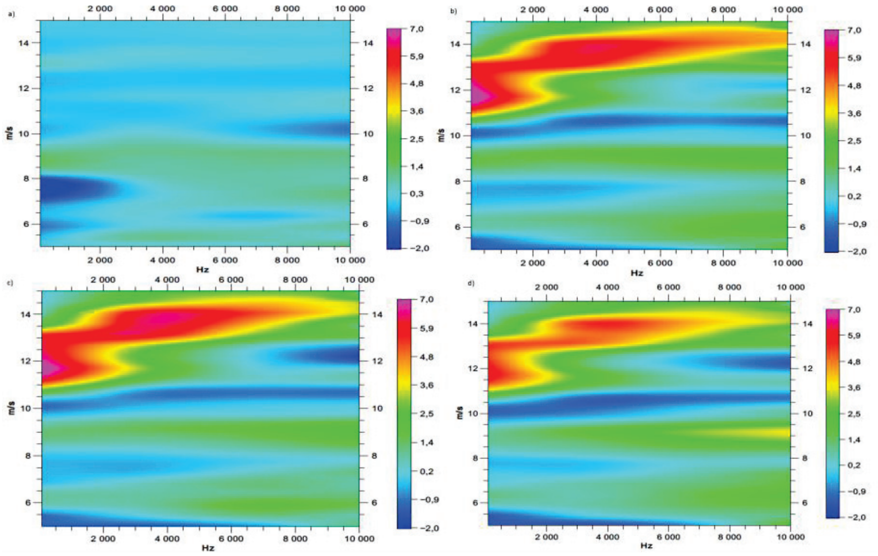

Figure 6. Colour-maps of relationship difference sound pressure level between baseline airfoil and serrated airfoils depending on velocities for microphone 1 (from leading edge), dB (ref 20 μPa), for NACA 0012 for the case of α= 0° (differences between baseline and serrated -a); differences between baseline and serrated-serrated b); differences between baseline and serrated-arc c); differences between baseline and serrated-wavy d)).

Colour-maps of differential SPL are very similar for signals obtained from microphone 2. As is seen from the Figure 7 the maximum noise reduction value also exceed 6dB (red fields on the maps) for all studied models with serrated edges. Impact of leading edge noise at low frequency becomes more prominent from 11m/s onwards (pictures b), c) and d)). In each case noise reduction is observed, as a red fields for serrated-serrated, serrated-arc and serrated-wavy models and as green fields for serrated model. No differences in differences SPL colour-map (from microphone 1 and 2) indicate any need of modification of test duct and its retesting.

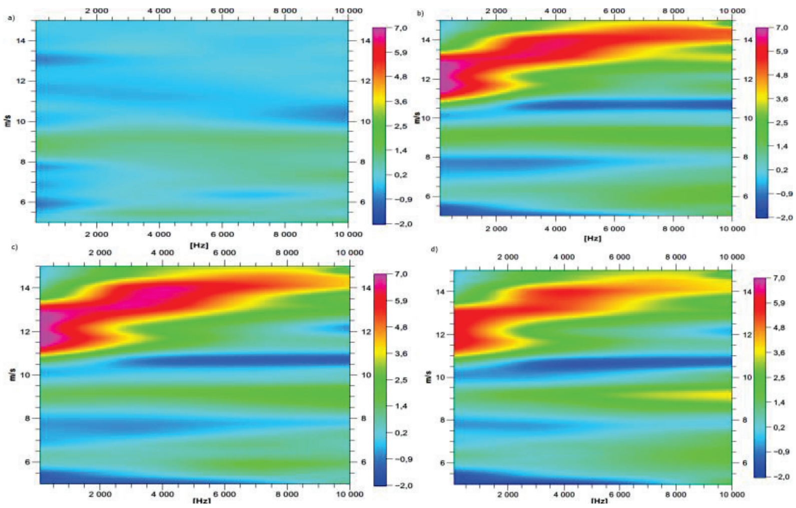

Figure 7. Colour-maps of relationship difference sound pressure level between baseline airfoil and serrated airfoils depending on velocities for microphone 2 (from trailing edge), dB (ref 20 μPa), for NACA 0012 for the case of α= 0° (differences between baseline and serrated -a); differences between baseline and serrated-serrated b); differences between baseline and serrated-arc c); differences between baseline and serrated-wavy d)).

3.2 Aerodynamical parameters

Flow measurements at several point along the chord line on upper surface have been performed using thermo anemometer measurement technique, to illustrate the laminar flow separations.

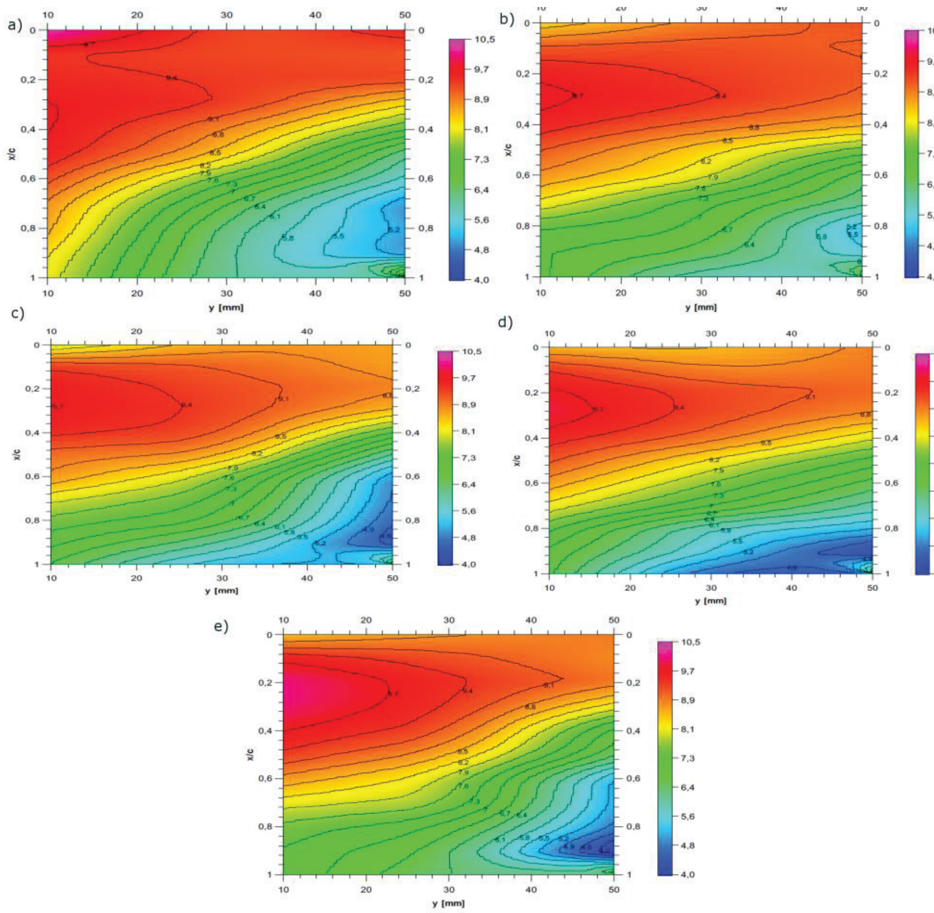

Figure 8. Colour-maps distribution of velocity along the chord on upper side of airfoil NACA 0012 for the case of α= 0° (baseline -a); serrated b); serrated-serrated c); serrated-arc d); serrated-wavy-e)).

The laminar separation bubble is formed when the previously attached laminar boundary layer encounters an adverse pressure gradient of sufficient magnitude to cause the flow to separate. In the first region of airfoil, near the leading edge, relatively slow flow is observed, which is responsible for forming the bubble. In the next region of flow consists of the free shear layer which undergoes transition due to disturbance amplification occurring in the unstable laminar layer. Momentum transfer due to turbulent mixing eventually eliminates the reverse flow near the wall and the flow reattaches to the surface of airfoil (in point "a"). For studied models point “a” slightly move to leading edge for three models: serrated-serrated, serrated-arc and serrated-wavy (this point is near x/c=0,7) in compared to baseline model, where point “a” is x/c=0,9-1,0. Process of separation, transition and reattachment results in a laminar separation bubble that has a predominate effect on the entire airfoil flow field and its decrease can improve of lift force of airfoil.

4. CONCLUSIONS

In this work the experimental results show that the serrated trailing and leading edges of airfoil can change the aerodynamic performances and have got influence on SPL spectrum, reduce the noise in some frequencies. The level of these change depends on the type of airfoil, and the geometrical characteristics of the serration. The colour-map results show that the serrations significantly affect on noise reduction compared to the baseline but its dependent on velocity and frequencies. The noise spectra usually comprise two or three peak dependent on geometries of added plates. Generally the noise reduction of studied airfoils with modified edges have got a resonance character, what mean that the increase and decrease of differential SPL depended on frequencies is observed. This is very important when considering noise generated from example by fan flow interaction with inlet turbulence plays a major role in airfoil self noise and further works in this aspect can allow for construction of "silence fan".

A physical phenomena of laminar flow separations and suppress the burst of the laminar separation bubbles for better aerodynamic performances of low-Reynolds-number airfoils is very important. This requires a detailed knowledge about transient behavior of the separated laminar boundary layers and the evolution of laminar separation bubbles. In low Reynolds number in which appearance of laminar separation (formation of a separation bubble on the airfoil) is observed, flows around the airfoil has got unsteady nature, it makes the flow field complicate and influence oh noise of airfoil. This is also major factor of deterioration of lift force of airfoil by due to boundary layer separation on the airfoil.

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