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Airfoil Turbulence-Impingement Noise Reduction by Porosity or Wavy Leading-Edge Cut: Experimental Investigations

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ABSTRACT

The present work is aimed at assessing the effectiveness of two possible techniques to reduce the noise produced by turbulence impinging on the leading edge of an airfoil. The first technique consists in replacing the straight leading edge by a wavy leading edge. The second one consists in manufacturing part of the airfoil with a porous material. Both are tested on modified versions of the same baseline rigid-airfoil NACA-0012 airfoil, by placing the mockups in grid-generated turbulence in the flow delivered by an open-jet anechoic wind tunnel. Additional tests are made with thin plates instead of the airfoil or with a circular cylinder instead of a turbulence grid. A step-by-step procedure is described to subtract background noise and trailing-edge noise sources in order to unambiguously quantify the benefit of the reduction techniques. Both are found to reduce the noise by amounts between 4 to 8 dB in substantial frequency ranges.

Keywords: Aeroacoustics, Turbulence, Airfoil noise

1. INTRODUCTION

Broadband aerodynamic noise is a major contribution to the total noise from many rotating blade technologies, typically for the low-speed fans used in various air-conditioning or cooling systems. Because of their installation most fans operate in highly disturbed flows. The fan blades ingest turbulence that produces noise by impingement on the leading edges. The turbulence in itself is not an intrinsic feature of the fan and must be often considered as an unavoidable consequence of the installation. Therefore acting directly on the blades to make them less sensitive to it in terms of acoustic response can be a promising strategy. The present paper assesses such a strategy, by analyzing sets of data collected from basic experiments conducted at Ecole Centrale de Lyon during student projects in the past years. This explains its didactic character and also justifies that the experimental means remain simple. In particular only relative variations in the far-field acoustic measurements are inspected. The study is dealing with the effect of leading-edge sinusoidal serrations, on the one hand, and with the effect of porosity, on the other hand, finally comparing both. The focus is on ranges of Mach-and-Reynolds numbers characteristic of low-speed fan noise problems. The work is a continuation of a previous study by Roger *et al.* (1); it is aimed at showing evidence of the turbulence-impingement noise reduction that can be achieved by various modifications of a baseline airfoil, either geometrical or structural. The technological options must also ensure that the aerodynamic performances of the modified airfoil do not deviate significantly from those of the baseline. For air-conditioning industry a small deterioration of the performances is not an issue if it is the price to pay for a significantly lower emitted noise. Furthermore most low-speed fans are not designed for a special application and can be mounted on any environment, already operating off their design point. The situation would be different for aircraft propulsion systems in which a small loss of efficiency is not acceptable.

Ideas for structural or geometrical modifications arise from some basic knowledge of the mechanisms of sound generation according to the acoustic analogy as formulated by Ffowcs Williams & Hawkings (2). In essence the analogy states that vortex dynamics in a compressible fluid generates sound, especially as vortical patterns interact with a solid surface because of the blockage effect of the surface. Another theoretical basis is also found in Chu & Kovasnay's analysis (3). The vortical and

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acoustic modes of oscillation in a gas are coupled by their velocity field at any solid boundary: the sum of the acoustic and vortical velocities has to go to zero at a solid wall. This is why sound reduction can be expected from porosity, for instance, because part of the incident velocity on the surface penetrates the porous material and can be slowed down progressively, reducing the time variations of inertia and taking benefit of increased viscous effects. In the case of the serrations, additional three-dimensional effects could help to reduce the coherence of the impingement and of the associated distributed sources of sound. Both techniques are addressed separately in the following sections.

Many parameters have *a priori* an effect on turbulence-impingement noise on the leading-edge of an airfoil. They are essentially of aerodynamic and geometrical nature for a serrated airfoil, and also structural for a porous airfoil. The main geometrical parameters are typically the blade chord and span c and L, the maximum thickness e, the leading-edge curvature radius, and the serration-shape parameters (pitch d and depth h) for a serrated airfoil, or the cell dimensions and cell-wall positioning for a porous cell-type structure. Structural parameters are essentially related to the properties and layered structure of the material used to manufacture a porous airfoil. Finally the involved flow parameters are the mean-flow speed, the turbulence rate and the associated integral length-scale, the homogeneous-isotropic or more general statistical properties. Facing this variety, the present effort is only a partial investigation in a multidimensional space that still deserves much deeper attention, in the continuation of a previous work also attempting at predicting the reduction (1) with an analytical approach. It expectedly complements the numerous works already reported by previous investigators. The emphasis is also on the significant sensitivity of the results to some of the aforementioned parameters, as well as on the similarity properties of the broadband noise reduction in terms of a characteristic Strouhal number.

2. EXPERIMENTAL APPROACH

2.1 Experimental Setup

All measurements have been made in the low-speed open-jet anechoic wind tunnel of ECL using the same protocol. In this installation the rectangular nozzle is blowing in a large room with walls covered by fiberglass. In view of the relatively low mass-flow rate, the flow is simply evacuated by an open lateral door. The residual recirculation has no significant effect on the acoustic measurements. The airfoil is held vertically between horizontal end-plates fixed on the nozzle and the span fits the nozzle height of 30 cm. The flow width is 15 cm, by only 20% to 50 % larger than the airfoil chords. This is not prejudicial to the reliability of the results as long as the angle of attack is set to zero. The measurements are performed in the mid-span plane, 1.5 m away from the airfoil leading-edge normal to the flow direction and to the airfoil span. The far-field conditions are fulfilled for the whole frequency range of interest. It is worth noting that frequencies below a typical threshold of 100 Hz are not interpreted; they could be due to a contamination of the airfoil by the near-field pressure fluctuations originating from the nozzle-jet shear layers.

The data acquisitions have been made with a bandwidth of 1 Hz over a time interval of 30 seconds in order to produce converged results. Yet the differences of spectra needed in the analysis exhibit a large scatter with this resolution at high frequencies, therefore they have been averaged to reduced resolutions of 16 Hz or 64 Hz, without significant loss of information. Depending on the data set, the same measurements on the same configurations have been repeated for 3 or 4 velocities ranging from 18 m/s to 35 m/s. This makes the maximum Mach number around 0.1. Varying the velocity allows to track scaling laws for the sound-reduction spectra.

2.2 Extraction of Turbulence-Impingement Noise Data

Experimentally investigating the effect of airfoil modifications on turbulence-impingement noise first requires that this noise is measured unambiguously. Attention must be paid to other noise sources, especially related to installation effects. It must be first noted that the investigated sources are homogeneously distributed along the span. Therefore, even for far-field measurements, the closest sources experience reflection on the end walls that contribute to the measured sound. This could require a span-length correction were the measurements to be compared to predictions, but is not an issue here because the study focuses on spectral differences. Apart from that, spurious noise contributions arise from various unsteady flows having nothing to deal with turbulence-airfoil interaction. They are expectedly included in the background noise, defined as the noise radiated when the airfoil is removed and the wind tunnel turned on, and are listed below.

- The grid inserted in the nozzle to generate turbulence produces self-noise associated with the formation of vortices in its wakes.
- The grid turbulence and the natural boundary layers inside the nozzle generate trailing-edge noise when blown past the nozzle lips.
- The turbulent boundary layers forming along the end-plates also produce trailing-edge noise at the

terminations of the plates. This noise radiates dominantly normal to the plates and therefore has a minor contribution in the measuring plane. In comparison, nozzle-lip trailing-edge noise radiates preferentially in the same direction as the investigated airfoil noise.

- The mixing noise from the wind-tunnel jet, less efficient because of its quadrupole nature, dominates however in the low-frequency range. In that range airfoil noise is not accessible with a single far-field microphone but usually the information of interest is at substantially higher frequencies. Moreover large-scale oscillations in the free-jet shear layers possibly induce additional hydrodynamic pressure fluctuations on the airfoil because the chord-to-width ratio is quite large. As pointed out by Moreau *et al.* (4) such conditions correspond to a typical aerodynamic cascade behavior of the airfoil instead of the expected isolated-airfoil behavior. The associated acoustic effect of the chord-to-width ratio is hard to quantify in the experiment. It could explain the changes in the measured spectral shape at lower frequencies; this is why only the frequencies beyond 100 Hz are taken into account.

All aforementioned background noise sources are considered as not correlated with the turbulence-impingement noise of interest, so that they are measured separately and can be eliminated from the measurements made with the airfoil installed by simple spectral subtraction. This is justified if the background noise sources are not modified by the presence of the airfoil, which would not be the case anymore when testing a loaded airfoil. Indeed, because the equivalent lateral momentum injection deviates the jet flow from its targeted direction, the associated spurious sources are also modified. Moreover horseshoe vortices develop around the airfoil at the junctions with the end-plates; this flow feature is possibly associated with localized sound sources that must be also considered as spurious but that are missed when measuring the background noise. Such sources are expectedly minimized for unloaded airfoils, especially with the present aspect ratios of about 3, but they are often assessed by localization techniques based on the use of microphone arrays in similar studies.

Even after subtracting the background-noise contribution, airfoil noise is not only turbulence-impingement noise. It is also made of trailing-edge noise, due to the scattering of boundary-layer turbulence as sound at the trailing edge. Complementary wall-pressure measurements with various turbulence rates in the oncoming flow, not reported here, indicated that the developing boundary layers somewhat protect the wall from external turbulence in the aft part of the airfoil. No significant change was observed in the trailing-edge area. Finally the turbulence impingement at leading edge and the trailing-edge scattering always contribute together as uncorrelated sources. This fact is confirmed by the numerical simulations of the tandem rod-airfoil test case performed by Eltaweel & Wang (5). The study involved the NACA-0012 airfoil in an arrangement similar to the one described in the section 3.4. The results stressed that beyond the third multiple of the vortex-shedding frequency the broadband radiated sound was originating dominantly from the trailing-edge area. It is also recognized that airfoils with thick and rounded leading edges have a reduced response to incident turbulence at high frequencies when compared to thin airfoils. For these reasons, trailing-edge noise must be estimated and also subtracted in the post-processing procedure in order to isolate the turbulence-impingement noise. Yet this correction remains ambiguous because the boundary-layer turbulence possibly differs for the baseline and the modified airfoils. The method used in the present work to subtract trailing-edge noise is detailed anyway in section 2.4.

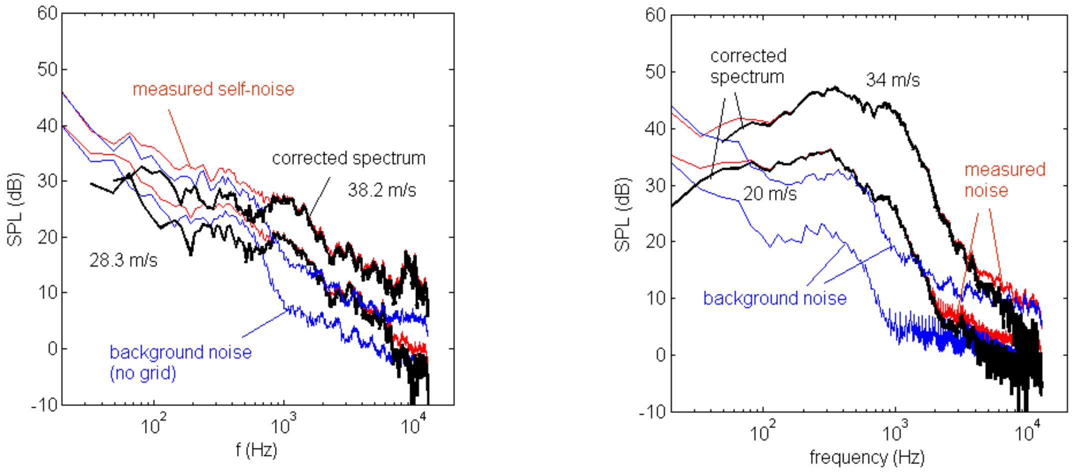
2.3 Tested Configurations

Various mock-ups have been tested, keeping in mind that the Mach and Reynolds numbers are low to moderate and that the conclusions could be questioned for larger ranges of parameters. The flow speed ranges up to 30-35 m/s (Mach number up to 0.1) for airfoils with chords of 10-12 cm (chord-based Reynolds numbers between 1.3 10^5 and 2.8 10^5). The NACA-0012 airfoil is selected because it is well documented and often referred to in the literature about airfoil noise. Furthermore its thickness is large enough to enable a porous design. Two baseline mock-ups of 10 cm (reference (1)) and 12 cm (present new results) chord lengths and of 30-cm span with the standard airfoil cross-section are taken as references. The results are also complemented with rigid thin plates having straight and wavy leading edges.

The incident turbulence is generated by a grid installed inside the nozzle just upstream of the contraction from a section of 30 cm by 30 cm to the exit cross-section of 30 cm by 15 cm. The turbulence has been measured at the leading-edge location but without airfoil with a hot-wire probe and interpolated by a model homogeneous and isotropic von Kármán spectrum. The turbulence rate is of 4.5% and the integral length scale is of 9 mm.

2.4 Trailing-Edge Noise Estimates

Subtracting the trailing-edge noise produced by the airfoil is only possible if that noise can be characterized separately by removing the turbulence grid from the nozzle. Now trailing-edge noise highly depends on the developing boundary layers and the latter in turn depend on the general flow conditions. Typically, for the zero angle of attack and the transitional Reynolds numbers addressed in this study the baseline NACA-0012 airfoil in clean flow is known to generate high-amplitude tonal trailing-edge noise because of the selective amplification of laminar boundary-layer instability waves. Therefore both sides of the airfoil were tripped in the present experiment around the chordwise position of maximum thickness with a strip of rough tape. The tripping forces the transition to turbulence in the boundary layers and ensures low-amplitude broadband trailing-edge noise emission. Again the background noise must be subtracted in order to extract airfoil self-noise, the former being now measured when removing both the airfoil and the turbulence grid. Even once this subtraction is achieved it cannot be guaranteed that the extracted noise is exactly the trailing-edge noise that the airfoil produces in the presence of the grid-generated turbulence. The only clue that they could be nearly identical is that at zero angle of attack the pressure-coefficient distribution was not found to significantly differ in the measurements. Moreover a clear change of spectral shape is observed at high frequencies, as shown in Fig.1-b. This change cannot be explained by the frequency content of the impinging turbulence nor by the expected response of the airfoil to a monotonically decreasing turbulence spectrum. Its strong similarity with the complementary trailing-edge noise measurement in Fig.1-a suggests that the high-frequency range is actually trailing-edge noise, typically beyond a chord-based Strouhal number of 10. This makes the present correcting procedure reliable. For a thinner airfoil in a highly turbulent stream the correction could be ignored. It is required for the NACA-0012 because its leading-edge thickness makes the response lower at high frequencies, for which precisely trailing-edge noise takes over.



(a) (b)

Figure 1 - Sample reference results for the baseline NACA-0012 airfoil. (a): trailing-edge noise characterization. (b): turbulence-impingement noise measurements. Raw data in red and background-noise decontaminated data in black.

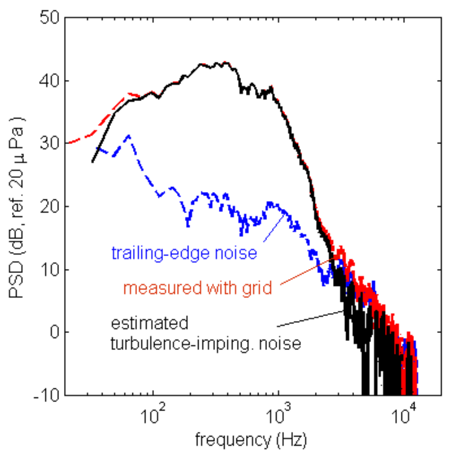


Figure 2 - Extraction of turbulence-impingement noise for theNACA-0012 airfoil. 28.3 m/s.

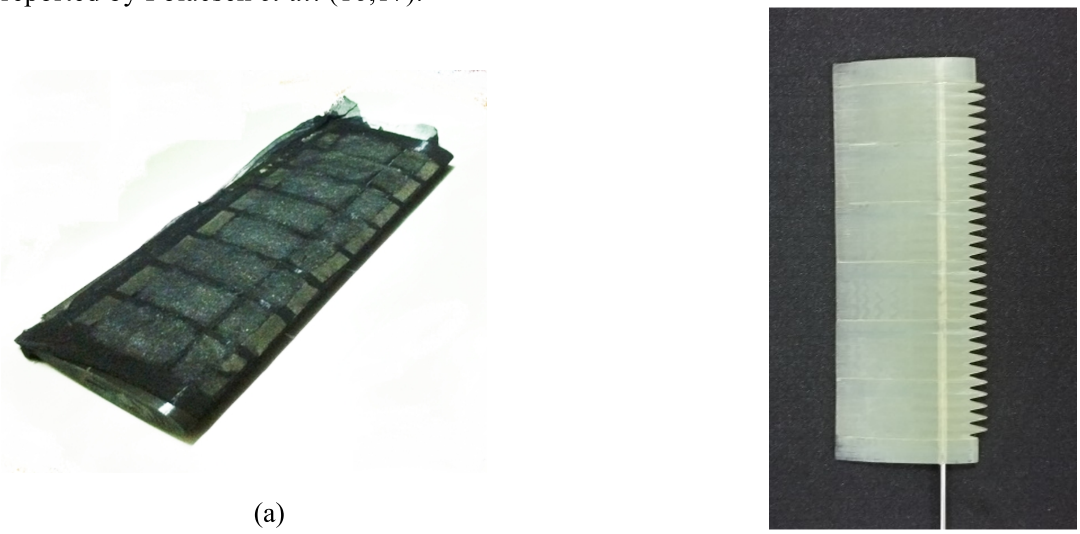
The extraction of reliable turbulence-impingement noise data for the baseline NACA-0012 in the high-frequency range is illustrated in Figs.1 and 2. Trailing-edge noise spectra decontaminated from their background noise are first shown in Fig.1-a. The maximum emergence is only of about 10 dB; yet this is enough to provide a clear estimate of the trailing-edge noise. When comparing to the decontaminated turbulence-impingement noise spectra in Fig.1-b it is clear that the high-frequency part actually combines both mechanisms. After the second subtraction procedure in Fig.2, the pure turbulence-impingement noise plotted in black is found down to 6 dB lower than what corresponds to the total airfoil noise. The correction seems to be essential for the NACA-0012 airfoil. Yet it has not been always applied. It is also worth noting that the local flow around a wavy leading edge possibly triggers different boundary layers with respect to the baseline, leading to different trailing-edge noise sources. Amongst others Hansen *et al*. (6) reported about the beneficial effect of serrations on the tonal noise. This open question justifies that the results obtained at higher frequencies are taken with care.

3. MOCKUP MANUFACTURING AND MAIN RESULTS

3.1 Serrated NACA-0012 Airfoils

Leading-edge serrations or wavy leading edges have been thoroughly investigated in the literature, both for their effect on the aerodynamic operation of airfoils and for their effect on sound generation in disturbed flows. Only an indicative list of references is given here, Chaitanya *et al*. (7), Clair *et al*. (8), Gruber *et al.* (9), Haeri *et al*. (10), Hersch *et al*. (11), Kim *et al.* (12), Lau *et al*. (13), Liu *et al*. (14), Narayanan *et al*. (15), Polacsek *et al*. (16,17). The effect of the serrations on the response to incident turbulence is *a priori* a function of the geometrical parameters of the sinusoidal cut, of the thickness of the airfoil in the leading-edge part and of the characteristic size of turbulent eddies, represented by the integral length scale Λ. Only one set of serration and incident-turbulence parameters has been tested in the present study, on two mock-ups of 10 cm and 12 cm chord lengths. The projected wavy leading-edge profile in the chord plane has a pitch d (spanwise wavelength) of 10 mm and a depth h (tip-to-root distance of the serrations) of 12 mm. This means that in this investigation the airfoil thickness e and the parameters d, h have the same orders of magnitude. Furthermore the integral length scale of the grid turbulence is of 9 mm, as deduced from hot-wire measurements. As a result the impingement of oncoming disturbances has probably very strong three-dimensional effects that are expectedly determinant for the general vortex dynamics around the serrations and the associated sound generation.

Two modified versions have been manufactured to address the effect of a wavy leading edge, with a three-dimensional printer. The leading-edge area has been extended and retracted following a sinusoidal line around the straight leading-edge line of the baseline, in such a way that the serrations merge smoothly with the baseline shape. For the smallest airfoil of 10 cm chord length, the maximum thickness has been kept unchanged. For the larger airfoil of 12 cm chord length, the maximum thickness also slightly varies in the spanwise direction (see picture in Fig.3-b). In any case the purpose was to keep some averaged features of the airfoil constant, which presumably fits better with the requirement of comparable aerodynamic performances. Yet the design of the serrations was empirical in both cases. The design is in fact similar to that of the FLOCON project for a different airfoil, as reported by Polacsek *et al*. (16,17).



(a) (b)

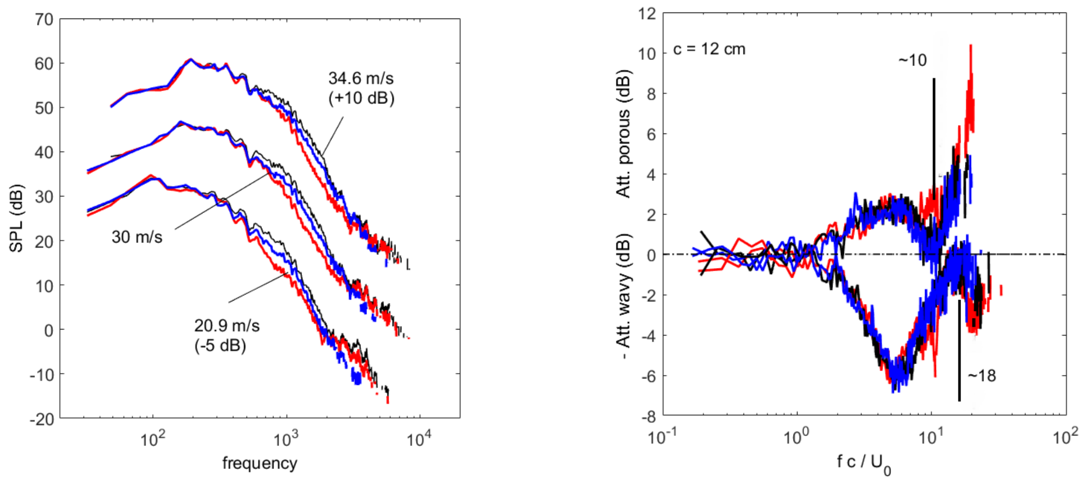
Figure 3 - Picture of the modified NACA-0012 airfoils of baseline chord length 12 cm. (a): porous airfoil, showing the cells filled with metal wool and foam patches, prior to covering with the external wire-mesh. (b): serrated airfoil. 3D-printer manufacturing.

3.2 Porous NACA-0012 airfoils

Various aspects related to the aerodynamic noise of porous airfoils have been investigated for instance by Sarradj & Geyer (18) and Geyer *et al*. (19,20). The effect on rotor-stator interaction noise has also been addressed by Tinetti (21). Porosity is identified here as a way of reducing the conversion of kinetic energy of the vortical motion into acoustic energy. This requires that the fluid can penetrate the porous material and that dissipation by viscosity inside it is efficient. The same conditions are required for acoustic-absorbing materials, though the problem is different here: it is of unsteady aerodynamic nature. In particular the aerodynamic length scales at low Mach numbers are much smaller than the acoustic wavelengths. Moreover the airfoil is designed initially to provide a given lift for a minimum drag. Preserving its performances when using porous materials imposes at least to prevent averaged flow transpiration between the pressure side and the suction side. In other words the required penetration must operate on the zero-average unsteady flow only and keep the mean flow around the airfoil unchanged. This led to an empirical design of cell-type structure including a thin rigid plate featuring the chord of the airfoil. Two airfoils have been manufactured following this principle. The first airfoil, of 10 cm chord, had two spanwise rigid stiffeners of thickness 2 mm located 1 cm apart from each other around the chordwise location of maximum thickness (Roger *et al.* 2013). The stiffeners were fixed to another 2-mm thickness plate covering the whole airfoil span and sharpened at the trailing edge. Metal wool was used to fill the remaining volumes and a sheet of metal foam used to shape the leading-edge area. Afterwards the whole arrangement was covered by a fine wire-mesh ensuring a smooth external surface and enabling air transpiration. The second airfoil, of 12 cm chord, is shown in Fig.3-a. It has been made similarly but by assembling identical plastic sections produced with a three-dimensional printer. Eight sections were made, featuring a single spanwise and eight streamwise separation walls of 5 mm thickness. Again the spanwise separator was located at the maximum thickness point. The same materials were used to fill the cells. Finally the wire-mesh skin of this airfoil has been closed at the trailing-edge and fixed with a metallic tape that makes the sides of that edge impermeable over a length of 1 cm. Both choices expectedly tend to force the mean flow to follow the external skin, partially because of the skin resistivity, and allow for unsteady penetration. However the precise flow structure around the airfoil has not been checked. The minimum roughness achieved with the wire-mesh as well as the deviations from the true NACA-0012 airfoil geometry have not been accurately assessed either. They would probably be an issue for trailing-edge noise emission because of modifications in the developing boundary layers. But turbulence-impingement noise is obviously insensitive to minor changes as long as the overall airfoil shape (thickness and chord, especially) are preserved. Moreover the tests with the porous materials were first aimed at demonstrating the effectiveness of this technology to reduce turbulence-impingement noise, prior to a more controlled investigation.

3.3 Noise Reduction Spectra

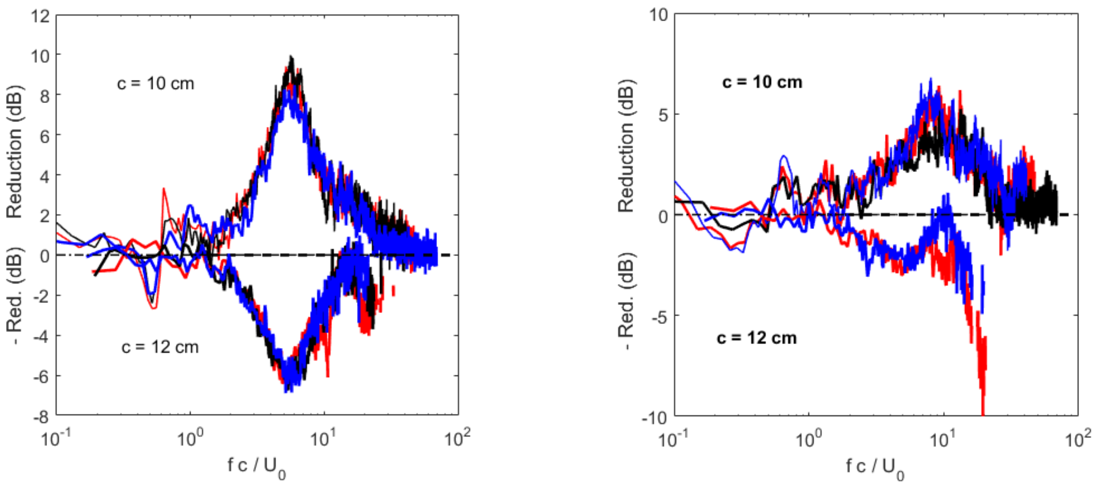
Compared noise reductions for the modified NACA-0012 airfoils of 12 cm chord length are reported in Fig.4 in order to assess the benefit of the wavy leading-edge shape and of the porosity. Far-field sound spectra (Fig.4-a) show evidence of the reduction in a wide range of frequencies. In the middle frequency range the serrations perform better, whereas in the high-frequency end the lowest noise levels are obtained with the porous airfoil. When difference spectra are calculated the summary plot of Fig.4-b is produced. For an easier comparison the reduction achieved with the serrated airfoil is plotted as negative whereas that of the porous airfoil is plotted as positive.



(a) (b)

Figure 4 - Overview of present results. (a): far-field sound spectra at various flow speeds measured with the baseline (black), serrated (red) and porous (blue) NACA-0012 airfoils. (b): difference spectra in a dimensionless frequency scale.
The reduction with the serrated airfoil is plotted as negative for an easier comparison.

Two frequency ranges are obviously pointed out. Typically, chord-based Strouhal numbers below 10 and roughly corresponding to the frequencies below the crossing of spectra in Fig.4-a are associated with a clear reduction of the turbulence-impingement noise. This Strouhal number of 10 for the NACA-0012 in the present investigation is estimated as the threshold beyond which trailing-edge noise takes over. At higher frequencies the lower sound level obtained with the porosity is attributed to a reduction of the trailing-edge noise. Indeed the porosity is distributed over more than 90% of the airfoil surface and as such it acts on both sources of broadband noise; in contrast the serrations mainly act in the leading-edge area. This interpretation is comforted by the results of Figs.1 and 2 for the baseline NACA-0012 airfoil. The secondary increasing amount of reduction beyond St=20 for the serrated airfoil is hard to explain (Fig.4-b). It could be an artifact of the double subtraction procedure, again caused by the trailing-edge contribution.



(a) (b)

Figure 5 - Summary of compared reductions on the two modified NACA-0012 mockups. (a): serrations, (b): porous treatments. Dimensionless frequency range, various flow speeds.

Previously measured reductions of turbulence-impingement noise as reported by Roger *et al.* (1) with the serrated airfoil of 10 cm chord are compared with the new results in Fig.5-a. No procedure was applied in the previous results to remove the contribution of the trailing-edge noise (the smaller chord length and thickness probably make trailing-edge noise relatively less important). A larger scatter is found at higher frequencies, making the interpretation questionable beyond a chord-based Strouhal number of 10. Yet the amount of reduction is clearly larger with the smaller mock-up though the main parameters of the serrations are the same, typically with a maximum close to 10 dB against only 7 dB for the larger airfoil. Furthermore the maximum of the reduction is reached for the same Strouhal number, thus a higher frequency with the smaller chord length. This suggests that the effect of the serrations depends on the chord length or on the corresponding leading-edge thickness of the airfoil shape.

The same comparison for the two versions of the porous airfoil is reported in Fig.5-b. The treatment of the previous airfoil of 10-cm chord seems to be more efficient than the present one, and its reduction spectrum shifted to higher frequencies. In fact both treatments perform differently. In the 10-cm configuration the reduction spectrum is a broad hump similar to that observed with the serrations, with a maximum around 6 dB. In the 12-cm configuration a first hump at lower frequencies is found, with a maximum of only 2.5 dB, followed by a high-frequency increase up to 8 dB that has been already attributed to a reduction of the trailing-edge noise. The difference is probably due to the different design of the porous cells, especially at the leading edge. In the previous study (10-cm chord) a layer of metal foam was bent around the leading edge to reproduce the NACA-0012 shape, which made the very leading-edge area already porous. In contrast the 12-cm chord configuration involves a small rigid part at the very leading-edge; the latter could be a necessary manufacturing feature for ensuring the aerodynamic performances.

3.4 Rod-Airfoil Tandem Configurations

The effect of the leading-edge serrations has also been tested in rod-airfoil tandem configurations in a previous work (1). In this case the airfoil is placed at zero angle of attack in the center wake of a circular cylinder in such a way that the impinging turbulence is that of the vortex shedding of a cylinder, instead of grid-generated turbulence. The background noise is defined as the noise measured with the rod only. This requires slight corrections because the presence of the airfoil in the wake of the cylinder causes a slight decrease of the flow speed and of the vortex-shedding frequency, which makes the direct spectrum difference questionable. Therefore the frequency scales were slightly tuned to make the spectral peaks coincide before the subtraction procedure.

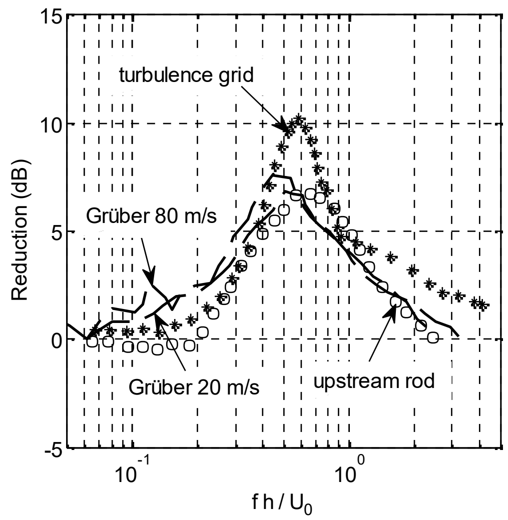


Figure 6 - Compared reduction spectra obtained with a serrated leading-edge in the present study and by previous investigators, from Roger *et al.* (1). Averaged dimensionless data based on a serration-depth based Strouhal number.

Various rod diameters compatible with the overall set-up dimensions were tested in order to select various frequency ranges for the excitation. Yet the excitation remains random in essence. Similar results were obtained in terms of frequency range of achieved reduction irrespective of the rod diameter (8 mm, 10 mm and 15 mm for a 12 mm thickness), despite the fact that the vortex street is far from the conditions of homogeneous and isotropic turbulence. The peak value of the reduction was reduced by a couple of decibels. The results are reproduced in Fig.6. They confirm that the achieved reduction remains significant in configurations representative of turbomachinery stages involving wake-interaction noise. The same was also concluded by Gruber *et al.* (9) in the FLOCON Project from an experimental setup involving tandem airfoils; the corresponding results are plotted in Fig.6 as well, for comparison. Though further investigations should be made to confirm that point, the comparison suggests that the rod-airfoil and the tandem airfoil arrangements provide similar reductions, whereas the serrations perform better with the grid-generated turbulence.

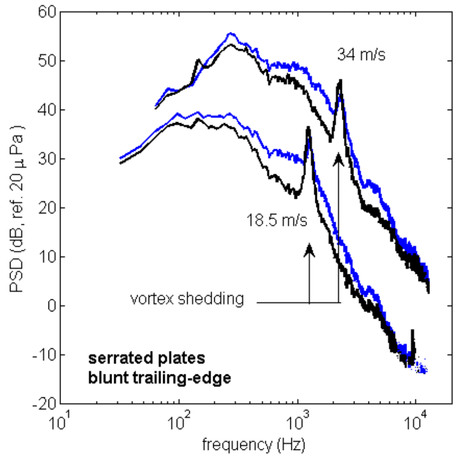
3.5 Thin-Plate Results

The high-frequency reductions obtained with the NACA-0012 airfoil in the present experiment are questionable because of the difficulty to subtract the contribution of trailing-edge noise, of same order of magnitude as the high-frequency turbulence-impingement noise. This is why testing the effect of the serrations on thinner bodies makes sense. Thin plates of 10 cm chord length and of two different sinusoidal cuts at leading edge have been also tested to get rid of a strong thickness effect. The plates are shown in Fig.7-a. They have a thickness of 3 mm and the cuts have a depth of 12 mm and a pitch of 10 mm for the so-called small serrations and 20 mm for the so-called large serrations. The small-serration parameters are therefore the same as for the NACA-0012. The serration corners have been arbitrarily rounded to avoid artificial flow separation at leading edge. Sample sound spectra are shown in Fig.7-b and the dimensionless reduction spectra are reported in Figs.7-c and d for the small and large serrations, respectively.

Because the thin plate radiates more sound than the NACA-0012 airfoil at high frequencies no correction for trailing-edge noise subtraction is needed. The counterpart is that vortex-shedding sound is emitted in a narrow-frequency range around the Strouhal frequency 0.2 U_0 /e, if e now stands for the plate thickness. Within that range the effect of the serrations on leading-edge noise cannot be assessed but it can be deduced by simple continuation of the trends observed on each side of the peak (note that the latter does not coincide with the maximum attenuation). Plotting the reduction as a function of the Strouhal number confirms the self-similarity of the results. Furthermore the small serrations ensure a better maximum reduction than the large ones, typically 2 dB more around the maximum. They perform almost equivalently when compared to the serrations of the NACA-0012 airfoil at Strouhal numbers around the maximum reduction and below. In contrast the fat-plate serrations seem to ensure a larger reduction in the high-Strouhal number range. This range precisely corresponds to frequencies at which the response of the NACA-0012 drops because of the thickness effect.

It is worth noting that the vortex-shedding peak level is higher with the serrated leading-edge than with the baseline flat plate. This indicates that the sinusoidal cut also has an effect on the boundary layers close to the trailing edge.

(a)



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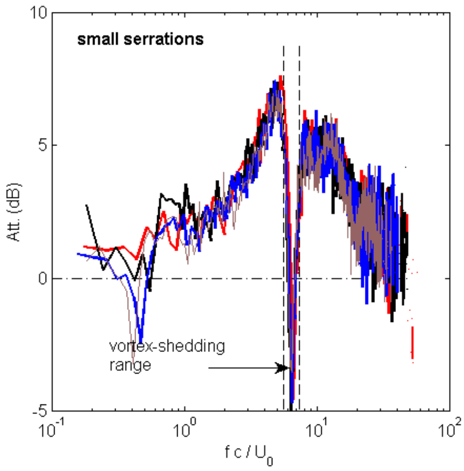
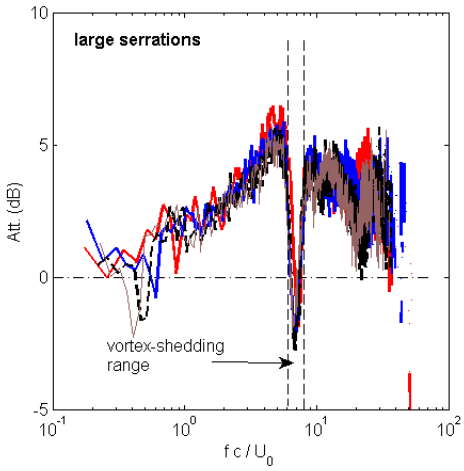


(c)



(d)

Figure 7 - Reduction of turbulence impingement noise on flat plates of 3 mm thickness and 10 cm chord length. (a): wavy leading edges. (b): sample spectra for the baseline and serrated (small serrations) plates. Reduction spectra achieved with the small (l = 1 cm, (c)) and large (l = 2cm, (d)) serrations of same depth 12 mm. 4 tested flow speeds ranging from 18.5 m/s to 35 m/s.

4. CONCLUSIONS

Various simple tests have been reported in this paper to quantify the effects of leading-edge serrations and of cell-type porosity on the acoustic response of a NACA-0012 airfoil to oncoming turbulence. Complementary tests performed with flat plates of 3% relative thickness in the same grid-generated turbulence, on the one hand, and on the serrated NACA-0012 in the wake of circular cylinders, on the other hand, help to point out the sensitivity of the reduction to the design parameters. The main outcomes are summarized below.

- In the investigated ranges of low Mach numbers and Reynolds numbers the noise-reduction spectra are found self-similar when the flow speed is varied: for a given configuration, the amount of reduction in dB is a function of the chord-based Strouhal number. This behavior, observed for both techniques, is expected from the self-similar property of the incident turbulent flow, produced either by a turbulence grid or by the vortex shedding of a cylinder.

- For the serrations, the reduction spectra are hump-like, extending over a wide range of frequencies. They reach a maximum of 5 to 10 dB depending on the configuration, at a chord-based Strouhal number of about 5-6. The reduction drops at high frequencies, but the precise trend there is hard to extract because of the contamination by the trailing-edge noise.

- For the porous treatments, lower performances are reached. The maximum of the hump is found between 2.5 and 6 dB, around a Strouhal number that is significantly dependent of the cell-type structure. Further investigations are still needed to identify the clear effects of design parameters. Furthermore if the porosity extends far enough in the aft part of the airfoil, the trailing-edge noise is also significantly reduced at higher frequencies.

Globally the present results confirm observations made by previous investigators, even though the finest underlying mechanisms still remain to be elucidated, for instance by the accurate unsteady flow simulations performed elsewhere in the aeroacoustic community.

REFERENCES

1. Roger M, Schram C & de Santana L, Reduction of Airfoil Turbulence-Impingement Noise by Means of Leading-Edge Serrations and/or Porous Materials, 19th AIAA/CEAS Aeroacoustics Conference, Paper 2013-2108, Berlin, 2013.
2. Ffowcs Williams JE & Hawkings DL, Sound generation by turbulence and surfaces in arbitrary motion, Phil. Trans. Roy. Soc. A 264, 1969.
3. Chu BT & Kovásznay LSG, Interactions in a viscous heat-conducting compressible gas, J. Fluid Mech. Vol. 3(5), 1958.
4. Moreau S, Henner M, Iaccarino G, Wang M & Roger M, Analysis of Flow Conditions in Freejet Experiments for Studying Airfoil Self-Noise, AIAA J. vol 41(10), pp. 1895-1905, 2003.
5. Eltaweel A & Wang M - Numerical Simulation of Broadband Noise from Airfoil-Wake Interaction, 17th AIAA/CEAS Aeroacoustics Conference, Portland, paper 2011-2802, 2011.
6. Hansen K, Kelso R & Doolan C, Reduction of flow induced airfoil tonal noise using leading edge sinusoidal modifications, Acoustics Australia, vol. 40, pp.172-177, 2012
7. Chaitanya P, Narayanan S, Joseph PF, Vanderwelt C, Turner J, Kim JW & Ganapathisubramani B, Broadband noise reduction through leading edge serrations on realistic aerofoils, 21st AIAA/CEAS Aeroacoustics Conference, 2015.
8. Clair V, Polacsek C, Le Garrec T, Reboul G, Gruber M & Joseph PF, Experimental and numerical investigation of turbulence-airfoil noise reduction using wavy edges, AIAA journal, vol. 51, pp. 2695-2713, 2013
9. Grüber M, Jospeh PF, Polacsek C. & Chong TP - Noise reduction using combined trailing edge and leading edge serrations in a tandem airfoil experiment, 18th AIAA/CEAS Aeroacoustics Conference, AIAA paper 2012-2134, Colorado Springs, CO, 2012.
10. Haeri S, Kim JW & Joseph PF, On the mechanisms of noise reduction in aerofoil-turbulence interaction by using wavy leading edges, 21st AIAA/CEAS Aeroacoustics Conference, 2015
11. Hersh AS, Sodermant PT & Hayden RE, Investigation of acoustic effects of leading-edge serrations on airfoils, Journal of Aircraft, vol. 11, pp. 197-202,1974
12. Kim JW, Haeri S & Joseph PF, On the reduction of aerofoil-turbulence interaction noise associated with wavy leading edges, J. Fluid Mech. Vol. 792, pp. 526-552, 2016
13. Lau AS, Haeri S & Kim JW, The effect of wavy leading edges on aerofoil-gust interaction noise, J. Sound and Vib. vol. 332, 2013
14. Liu X, Azarpeyvand M & Theunissen R, Aerodynamic and Aeroacoustic Performance of Serrated Airfoils, 21st AIAA/CEAS Aeroacoustics Conference, 2015
15. Narayanan S, Chaitanya P, Haeri S, Joseph PF, Kim JW & Polacsek C, Airfoil noise reductions through leading edge serrations, Physics of Fluids, vol. 27, 2016
16. Polacsek C, Reboul G, Clair V, Le Garrec T & Deniau H, Turbulence-airfoil interaction noise reduction using wavy leading edge: An experimental and numerical study, InterNoise 2011, Osaka.
17. Polacsek C, Clair V, Le Garrec T & Reboul G, Numerical simulation of turbulence interaction noise applied to a serrated airfoil, InterNoise 2012, New-York.
18. Sarradj E & Geyer T, Noise Generation by Porous Airfoils, 13th AIAA/CEAS Aeroacoustics Conference, paper 2007-3719, Rome 2007.
19. Geyer T, Sarradj E & Fritzsche C, Porous Airfoils: Noise Reduction and Boundary Layer Effects 15th AIAA/CEAS Aeroacoustics Conference, paper 2009-3392, Miami 2009.
20. Geyer T. & Sarradj E, Trailing edge noise of partially porous airfoils, 20th AIAA/CEAS Aeroacoustics Conference, paper 2014-3039 Atlanta, 2014
21. Tinetti AF, On the Use of Surface Porosity to Reduce Wake-Stator Interaction Noise, Virginia Tech. PhD dissertation, 2001