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Benefits of curved serrations on broadband trailing-edge noise reduction

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ABSTRACT

Far-field noise and flow field over a novel curved trailing-edge serration (named as *iron-shaped* serration) are investigated. Spectra of the far-field broadband noise, directivity plots and the flow-field over the iron-shaped serration are obtained from numerical computations performed using a compressible Lattice-Boltzmann solver. The new design is compared to a conventional trailing-edge serration with a triangular geometry. Both serration geometries were retrofitted to a NACA 0018 airfoil at zero degree angle of attack. The iron-shaped geometry is found to reduce far-field broadband noise of approximately 2 dB more than the conventional sawtooth serration for chord-based Strouhal numbers $St_c < 15$. At higher frequencies, the far-field broadband noise for the two serration geometries has comparable intensity. Near-wall velocity distribution and surface pressure fluctuations show that their intensity and spectra are independent on the serration geometry, but a function of the streamwise location. It is found that the larger noise reduction achieved by the iron-shaped trailing-edge serration is due to the mitigation of the scattered noise at the root. This effect is obtained by mitigating the interaction between the two sides of the serration, by delaying toward the tip both the outward (i.e., the tendency of the flow to deviate from the centerline to the edge of the serration) and the downward (i.e., the tendency of the flow to merge between the upper and bottom side of the serration) flow motions present at the root of the sawtooth.

1. Introduction

Broadband trailing-edge noise generated by the scattering of a turbulent flow convecting over the trailing edge of an airfoil [1,2] is a relevant contributor to wind-turbine noise [3].

Many passive mitigation strategies have been proposed to reduce this source of noise. Acoustic measurements, carried out both in wind tunnels and in-field, reported that sawtooth trailing-edge serrations offer the most effective noise reduction per simplicity of design [4–11]. Far-field noise reductions with respect to the straight trailing-edge configuration, expressed as difference in Sound Pressure Level (SPL), of approximately 7 dB and 3 dB were measured in both wind tunnel [12] and in-field applications [4].

Many analytical approaches have been proposed [13–17] to predict trailing-edge noise in presence of sawtooth trailing-edge serrations. Howe [13,16] formulated the first analytical model to estimate broadband noise generated by a low Mach number

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turbulent flow over a flat plate at zero angle of attack with sawtooth trailing-edge serrations. The model predicts an asymptotic noise-reduction intensity, at relatively high frequencies, of $10\log_{10}[1+(4\,h/\lambda)^2]$ dB where λ and $2h$ are the serration wavelength and length, respectively. When compared to experimental results [4,7,10,11], the current triangular designs are not able to match the predicted noise reduction intensity. Moreover, the model cannot explain the characteristic *cross-over* frequency f_c, corresponding to a Strouhal number $St_\delta = f_c\delta/U_\infty \approx 1$ (based on the free-stream velocity U_∞ and boundary layer thickness δ estimated with XFOIL [18] in the study of Gruber et al. [19]), after which noise increases again. Recently, Lyu et al. [14,17] developed a new semi-analytical model applying Amiet's trailing-edge noise theory [20] to sawtooth trailing edges. Results showed that the predicted noise reduction are closer to the one experimentally measured. Lyu et al. [14,17] detected two non-dimensional parameters that substantially affect noise reduction: $k_1 \times 2h$ and $l_{zp}(f)/\lambda$, where k_1 is the wavenumber in the chordwise direction and $l_{zp}(f)$ is the spanwise correlation-length of the surface pressure fluctuations. The studies of Lyu et al. concluded that far-field noise can be reduced when both $k_1 \times 2h$ and $l_{zp}(f)/\lambda$ are much larger than unity. This implies that the serration should be long enough to ensure a considerable phase difference of the scattered pressure waves at the edge of the serration. In addition, if the spatial range of the phase difference, i.e. λ, is sufficiently small compared to the correlation length in the spanwise direction, radiated sound waves may destructively interfere with each other.

More recent investigations on the actual flow fields [7,10,21,22] have shown that the flow past serrated airfoils is strongly three dimensional, with vortical structures developing along the edges of the serrations. Because of the complex flow field and of the streamwise varying pressure gradient, both aerodynamic effects and acoustic scattering are mutually dependent [3,23,24]. Flow measurements [7,10,24] and computations [22,25] showed that, even at small angles of attack, the turbulent flow tends to seep into the empty space in between serrations. More in details, both an outward (i.e., from the centerline toward the edge) and an inward (i.e., from the edge toward the centerline of the serrations) flow motions characterize the flow field respectively at the root and the tip of the sawtooth trailing-edge serrations [10,24]. This flow distortion is found to reduce the effective angle seen by the turbulent flow convecting over the edge of the serrations thus reducing the effectiveness of the serrations in mitigating far-field noise [21].

Aiming at reducing the broadband far-field noise even further, several variations of the serration geometry were proposed and tested, e.g. brushed [26], sinusoidal [15], slitted [27,28] and even randomly-shaped trailing edges [29]. More recently, it was shown that broadband far-field noise can be reduced, with respect to conventional serrations, by filling the empty space in between serrations with combs or slits [3]. A first attempt to give a physical explanation behind the achieved noise reduction was reported by van der Velden and Oerlemans [30].

Based on previous experimental observations [7,10], curved trailing-edge serrations may reduce the far field noise by mitigating the negative effect due to the outward and downward flow motions at the root. In this manuscript, curved trailing-edge serrations are investigated with the commercial Lattice-Boltzmann Method (LBM) solver *Exa* PowerFLOW. The iron-shaped serrations are compared to more conventional sawtooth trailing-edge serrations with same length ($2h$) and wavelength (λ). A similar shape was patented by Vijgen et al. [31] with the purpose of improving lift and drag of lifting surfaces and by Oerlemans [32] for noise reduction. Aim of this paper is to investigate the physical reasons behind the larger noise reduction achieved by the iron-shaped serrations with respect to the conventional sawtooth serrations. In the following study, the serrations are retrofitted to a NACA 0018 airfoil placed at zero angle of attack, similarly as in the reference experiments [7,27].

2. Methodology and solver

The commercial software package *Exa* PowerFLOW 5.3b was used to solve the discrete Lattice-Boltzmann equations for a finite number of directions. For a detailed description of the equations used for the source field computations the reader can refer to Succi [33] or van der Velden et al. [34].

The discretization used for this particular application consisted of 19 discrete velocities in three dimensions (known as the D3Q19 model) involving a third-order truncation of the Chapman-Enskog expansion to retrieve the Navier Stokes equations. For three dimensional computations of low Mach number ideal gas flows, this was found to accurately reproduce the flow field [33]. The distribution of particles was solved using the kinetic equations on a Cartesian mesh, with the conventional Bhatnagar-Gross-Krook (BGK) collision term operator [35]. A Very Large Eddy Simulation (VLES) was implemented as viscosity model to locally adjust the numerical viscosity of the scheme [36]. A sub-grid scale model is essential to obtain solutions of transient high Reynolds flow problems within feasible turn-around times. The model consists of a two-equations k-ε Renormalization Group (RNG) modified to incorporate a swirl based correction that reduces the modeled turbulence in presence of large vortical structures, required for stability of the code.

Due to the limitations of the discretization model D3Q19, the cells, further denoted as voxels, are equally sized in each direction. This makes challenging to perform wall-resolved simulations. Hence, a turbulent wall-model was used to resolve the near-wall region [37]. The particular choice of the model allowed to obtain, for this particular configuration, a reliable estimate of the boundary layer till the viscous sub-layer.

Due to the fact that the LBM is inherently compressible and it provides a time-dependent solution, the sound pressure field was extracted directly from the computation domain. Sufficient accuracy is obtained when considering at least 16 cells per wavelength for the LBM [38]. The obtained far-field noise was further compared with noise estimated by using an acoustic analogy. For this purpose, the Ffowcs-Williams and Hawkings (FWH) [39] equation was employed. The time-domain FWH formulation developed by Farassat [40] was used to predict the far-field sound radiation of the serrated trailing-edge in a uniformly moving medium [41,42]. The input to the FWH solver is the time-dependent pressure field over the