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AEROACOUSTIC DESIGN AND BROADBAND NOISE PREDICTIONS OF A TURBOFAN STAGE WITH SERRATED OUTLET GUIDE VANES

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This work, realized in the framework of the European project TurboNoiseBB, presents the aeroacoustic design of serrated OGVs (Outlet Guide Vanes), including details on their broadband noise and aerodynamic performance. The serrated OGV corresponds to a modified stator from a turbofan model tested at the AneCom facility (Germany) and shared by the Consortium. Leading edge sinusoidal patterns with varying amplitude and wavelength along the span are designed in collaboration with Safran Aircraft Engines. Serrations are adjusted to account for the turbulence characteristics provided by RANS calculations. Optimal parameters are found using simple design rules discussed in the paper. Down selection of serrated OGV designs (patent pending) was performed in accordance with industrial specifications. Broadband noise simulations are performed using a CAA code solving the linearized Euler equations with a synthetic turbulence model. Numerical predictions at approach conditions are compared to available experimental measurements and an analytical Amiet-based model. Predictions on the untreated case show a fairly good agreement by comparison to the PSD measured at the bypass casing, and a PWL reduction around 3-4 dB roughly estimated by the design process is numerically achieved by the present method.

Keywords: fan noise, isotropic turbulence, computational aeroacoustics, leading edge serrations

1. Introduction

Over the past few years, turbulence interaction noise reduction using leading edge serrations has been extensively studied [1-7]. Although promising results have been found in experimental [2-3], analytical [7] and numerical studies [1,4] using isolated airfoils, the use of leading edge serrations on realistic rotor/stator stages [5-6] remains challenging from an industrial perspective.

The present work, performed in the frame of the European project TurboNoiseBB, presents the aeroacoustic design of leading edge serrations applied to a realistic turbofan model, including details on broadband noise and aerodynamic performance. The investigated fan/OGV stage has been recently tested at AneCom Aerotest's facility [8] in Wildau (Germany) and shared by the Consortium. As no experimental data were available at the beginning of this work, the present design is fully based on turbulence characteristics from RANS calculations performed by ONERA [9] and DLR [10].

Broadband noise predictions are assessed using an in-house CAA code that solves the linearized Euler equations with a synthetic turbulence model. ONERA's hybrid methodology and first simulations on the baseline case have already been presented by Cader et al. [9]. Here, a similar method is used to evaluate the acoustic performance of one low-noise OGV concept. RANS calculations provide the turbulence characteristics of turbulent wakes interacting with the stator. Those characteristics information are necessary to calibrate the isotropic turbulence spectrum required by the CAA method. Fan/OGV simulations using a mixing plane approach are analyzed to assess the aerodynamic response of some selected serrated OGVs with respect to the baseline case (with straight leading edge). An "optimal" low-noise OGV concept has been identified from aerodynamic perspectives with the associated performance of 3D CAA simulations.

The paper is organized as follows:

- Section 2 discusses recent works in the field and practical guidelines to choose relevant leading edge serration parameters for noise reduction on isolated airfoils;
- Section 3 presents the ACAT1 model and describes AneCom's experimental set-up;
- Section 4 describes the design of serrated OGVs using RANS information;
- Section 5 and 6 are devoted respectively to the control of aerodynamic performances and to the CAA set-up with acoustic predictions, respectively. Firstly, numerical noise predictions from the baseline case are compared to available measurements. Secondly, a comparison of the low-noise OGV response is discussed in detail;
- Finally, first conclusions are presented in Section 7.

2. Background on acoustic performance of leading edge serrations

Many studies on leading edge serration effects have been performed by the Aeroacoustic community in the last decade. Some of the most relevant results in the field have been obtained from experimental investigations conducted by ISVR on isolated airfoils [2-3]. From ONERA and ISVR background and know-how, one can identify two major noise reduction mechanisms in the case of sinusoidal wavy patterns (see Fig. 1):

- A correlation loss in the spanwise direction directly linked to the transverse correlation length scale Λ_t, and therefore to the turbulent integral length scale, Λ;

- A modification of the aeroacoustic response giving rise to a loss of efficiency in the acoustic radiation from incoming gusts. Clair et al. [1] first proposed an explanation based on a simple reformulation of the dispersion relation in the presence of serrations (approximated by sawtooth), which shows a filtering of the incoming parallel gusts when the inclination angle of the serrations is close to 90°. This inclination angle is defined by $\theta = \tan\left(\frac{4h}{\lambda}\right)$, which highlights the role of the serration amplitude, h, in the noise reduction mechanism. This was confirmed by key insights [2-3] and recent advanced analytical solutions [7].

From these considerations, the best compromise for isotropic turbulence is to set the serration wavelength to $\lambda = 4\Lambda_t = 2\Lambda$. The second key parameter is the choice of a suited ratio h/λ. Although the acoustic benefit could be improved by increasing h, a practical limitation is required to avoid a noticeable loss of aerodynamic performance for industrial applications, as investigated in [5]. Hence, setting $h/\lambda = 1$ gives $\theta = 76°$, which can be considered as a reasonable value close to the optimum according to Refs. [2-3]. Another important result highlighted by Chaitanya et al. [3] is that the sound power attenuation, ΔPWL, achieved with serrated airfoils, is approximately proportional to the Strouhal number, $S_{th} = fh/U$at the optimum serration wavelength, where U is the upstream (convection flow) velocity. The following empirical law was proposed:

$$\Delta PWL(dB) = 10 + 10\log_{10}(S_{th}) \qquad (1)$$

In practice, a significant PWL reduction (> 3 dB) can be expected if $S_{th} \geq 0.2$ for isolated airfoils with leading edge serrations. Such a criterion is used in Section 4 for a preliminary design assessment of the basic design parameters.

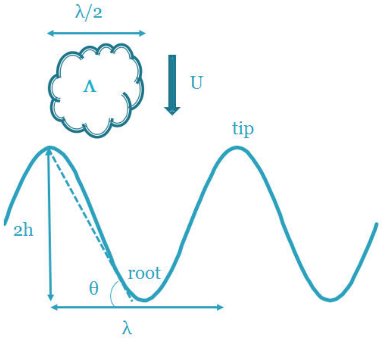

Figure 1: Sketch of sinusoidal serrations with main related parameters (courtesy from ISVR [3]).

3. ACAT1 model and AneCom tests

The AneCom AeroTest Rotor 1 (ACAT1) turbofan model considered in this study is a 85-cm diameter rotor with a fan-OGV stage equipped with 20 blades and 44 vanes (Fig. 2). The acoustic calculations are performed at approach (APP) Operating Point (OP) condition, while the aerodynamic performances are investigated at the aerodynamic design point (ADP).

The aerodynamic and noise database in the Universal Fan Facility for Acoustics (UFFA, Fig. 3) were obtained during a test campaign performed in 2018 [10]. The present investigation is limited to the baseline (short gap) configuration with a rotor-stator spacing close to 1.5 rotor axial chord.

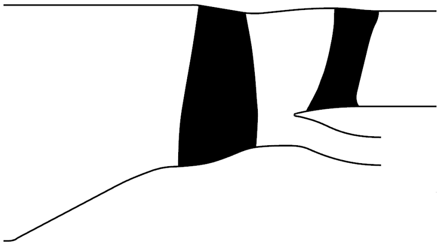

Figure 2: ACAT1 fan module geometry

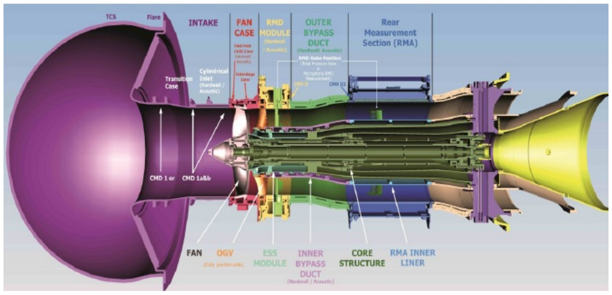

Figure 3: Sketch of the rig setup at AneCom's UFFA

4. Basic design using RANS information

In this study, RANS simulations are based on k-ℓ Smith and k-ω Menter SST turbulence models from ONERA [9] and DLR [10] using *elsA* and *TRACE* codes, respectively. RANS outputs are extracted from mixing-plane fan/OGV simulations right upstream of the mixing plane (Fig. 4, left), whereas outputs from fan alone RANS simulations (Fig. 4, right) are extracted close to the leading edge of the OGV. Relevant parameters for the rotor-stator interaction (RSI) noise generation are radial (circumferentially-averaged) profiles of the turbulence intensity (TI), the turbulence length scale (Λ or TLS), and the absolute (streamwise) flow velocity. These data are also used as inputs to an in-house acoustic code based on Amiet's theory extended to ducted annular cascade and used to estimate the SPL and PWL in-duct spectra. Two approaches are considered to estimate the TLS profiles. The first approach (referred to as "Pope") relates Λ to the RANS turbulence model variables, $\Lambda = \frac{C_{\mathrm{Re}}}{C_\mu}\frac{k^{1/2}}{\omega} \propto C_{\mathrm{Re}}\ell$ with $C_\mu = 0.09$ and C_{Re} set to 0.45, according to Pope's work [11]. The second approach (referred to as "Ganz") uses an empirical Gaussian wake approximation proposed by Ganz et al. [12] that relates Λ to the Gaussian wake width (L_w) as $\Lambda = 0.21\ L_w$. Both TLS profiles are plotted in Fig. 5 from RANS ONERA simulations. Results show different trends in the radial distribution, particularly in the casing region. DLR RANS post-processed data (TI and TLS profiles), obtained at three OP conditions including approach are plotted in Fig. 6. It shows dominant turbulence levels in the casing region and relatively similar TLS profiles for the three flow conditions.

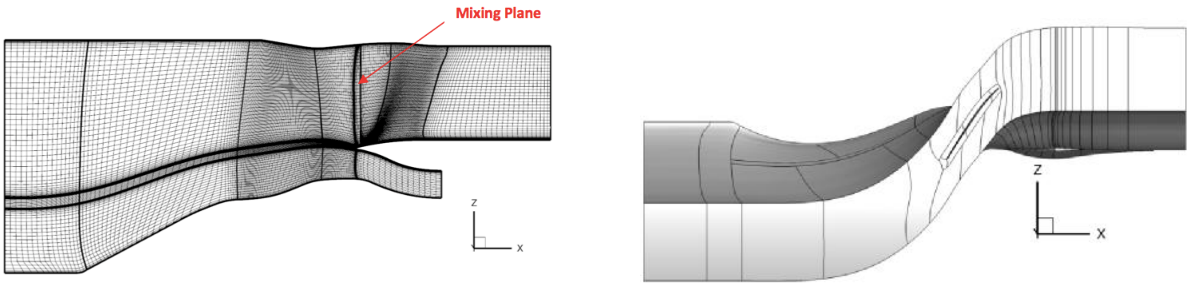

Figure 4: Section grid of mixing plane (left) and rotor alone domain (right) of ONERA RANS calculations

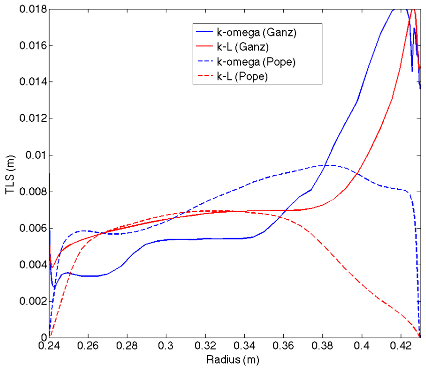

Figure 5: TLS profiles from ONERA RANS (k-ℓ) simulations at approach OP

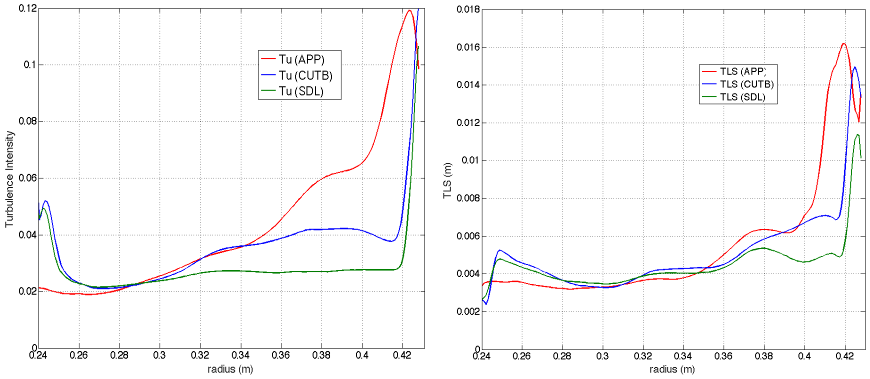

Figure 6: TI (left) and Ganz-based TLS (right) profiles from DLR RANS (k-ω) simulations at approach, cutback, and sideline OP

A first design has been conducted by considering radially constant Λ values (see Fig. 7). These are obtained from a full averaging of two TLS profiles given in Fig. 5 using k-ℓ Smith model. Design rules described in Section 2 led to 12-waves "GanzUniform" and 16-waves "PopeUniform" serrated OGVs designs, which are shown in Fig. 8. Table 1 shows an estimation of the potential noise reduction for the "GanzUniform" OGV design by using Eq. (1), where the Strouhal number is based on h and the peak frequency of the broadband noise spectra provided by ONERA Amiet-based code (not shown here). This preliminary assessment, which is considered to be valid for isolated airfoils in isotropic turbulence, indicates that a PWL reduction of at least 4 dB could be expected.

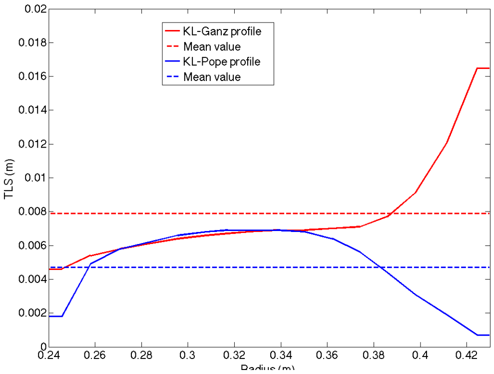

Figure 7: Radially constant TLS profiles

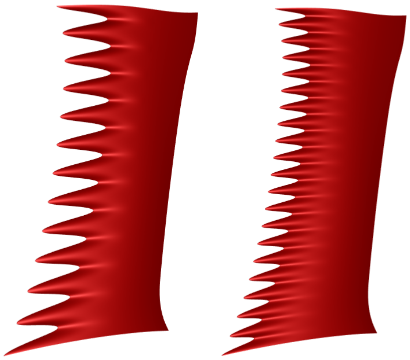

Figure 8: First design of serrated OGVs

Table 1. Strouhal number values (based on *h*) and expected PWL reduction for the 3 OP conditions

OP	U_{mean} (m/s)	f_{peak} (Hz)	h (mm)	$f_{peak}\,h/U_{mean}$	ΔPWL (dB)
APP	120	2000	16	0.27	4.3
CUTB	173.5	3500	16	0.32	5
SDL	193	4500	16	0.37	5.7

Nevertheless, results in Table 1 are probably over-estimated due to the variations of the turbulence characteristics along the span of the OGV, which highlights a limitation of the radially constant TLS assumption. Thus, a new design with a radial variation in h and λ has been studied. Local values of h and λ are set by using a strip approximation of continuous profiles. Furthermore, additional requirements have been set to improve various aerodynamic and structural aspects: (i) a local cancellation of the undulations ($h = 0$) near the hub, where TI levels are reasonably small, and (ii) a limitation of serration amplitude (using the criterion $h/c \leq 0.15$). Such requirements inspired the "GanzRadialOpt" and "PopeUniformOpt" designs of an OGV with leading edge serrations, as shown in Fig. 9, and have led to a joint patent application between Safran Aircraft Engines and ONERA. These designs were down selected after a control of aerodynamic performances assessed over a few serrated OGVs and briefly discussed in the next Section.

5. Control of aerodynamic performances

Aerodynamic behaviour of 5 selected designs (see Fig. 9) have been checked by performing RANS mixing plane calculations to be compared to the baseline OGV. The target is to ensure that the impact on the overall aerodynamic efficiency is reduced at the aerodynamic design point (ADP).

RANS simulations are performed with the k-ℓ Smith model at ADP. The mesh was designed by applying a 3D morphing technique near the undulations using an ONERA in-house modeller and ensuring at least 40 points per wavelength in the spanwise direction. The fan pressure ratio and isentropic efficiency is computed upstream and downstream of the fan/OGV. The FPR-mass flow characteristics of the different configurations are given in Fig. 10 (left). Fan alone performances are not affected by the presence of a serrated OGV. In contrast, the fan-OGV stage performance can vary due to aerodynamic loss through the different OGV concepts. Consequently, OGVs with leading edge serrations show a lower FPR than the reference case. However, a significant reduction of the aerodynamic loss is obtained with the modifications applied on "PopeUniformOpt" and "GanzRadialOpt". These 2 configurations show very similar stage FPR performances (maximal FPR value close to 1.42 instead of 1.43 for reference).

The radial distributions of the OGV loss coefficient are plotted in Fig. 10 (right) for a particular OP near the maximum efficiency and ADP mass flow rate. Radial locations where the "PopeUniformOpt" and "GanzRadialOpt" configurations mitigate the aerodynamic loss can be clearly identified. A conclusion of this analysis is that the loss reduction of the optimized configurations is obtained from the cancellation of the undulations below 20% of span (significant improvement in this region compared to "GanzRadial") and the limitation of the serration amplitude (almost the same level of loss as the reference configuration above 80% of height).

RANS calculations performed at approach OP confirmed this behaviour with a negligible impact on aerodynamic stability and limited impact on isentropic efficiency compared to ADP case. Indeed, the maximum penalty found equal to -0.7 pt at ADP is decreased to -0.58 pt at APP OP.

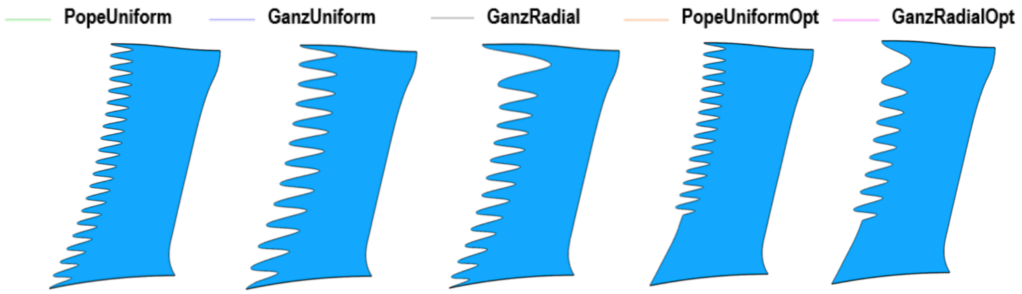

Figure 9: 5 serrated OGVs selected for aerodynamic performance check (at ADP) using RANS

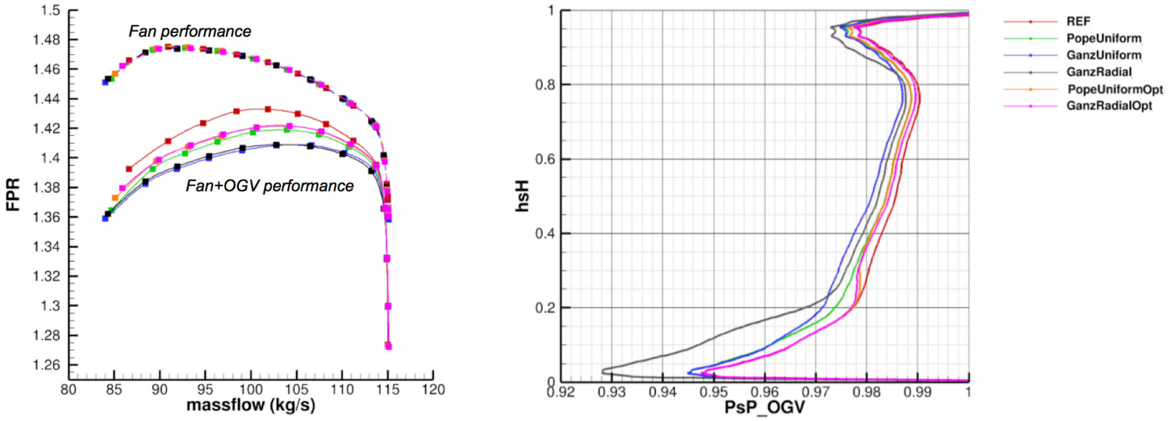

Figure 10: Comparisons of FPR-mass flow characteristics (left) and radial distribution of loss coefficient (right)

6. CAA predictions

This section presents acoustic results from CAA simulations of the baseline and the "GanzRadialOpt" OGV designs at approach OP. To this end, 3D numerical simulations were performed using ONERA CAA code *sAbrinA*. This code solves the linearized Euler equations in the time domain with a 6th-order space scheme and uses a synthetic turbulence method based on Fourier modes [9]. Unsteady wall pressure on the vane surface are injected into a Ffowcs-Williams and Hawkings (FWH) solver that uses Goldstein's formulation for in-duct propagation. In order to reduce the computational cost, the CAA domain is limited to a single vane passage, and inflow turbulence is fitted on to a 2-wavenumber (streamwise and spanwise components) Von-Karman spectrum using TI and Ganz-based TLS profiles from the RANS k-ℓ simulation (see Ref. [9] for further details). The mean flow is obtained from mixing plane RANS simulations and is interpolated onto the CAA grid, so that realistic velocity fields and convection effects can be modelled around the OGVs. A high mesh refinement (800 radial points along the span) is necessary to accurately discretize the serrations, so that each CAA domain restricted to 1-vane passage totalizes about 37 million points. Simulations were run with a frequency resolution of $\Delta f = 250$ Hz and $f_{max} = 10$ kHz, which required about 60 hours of CPU time (160000 iterations per period over 657 processors) to get a roughly converged solution. Although the same CAA set-up was initially adopted for comparisons, the first run on baseline case crashed before reaching the convergence. It was attributed to an incorrect CAA pre-processing of a recirculation zone created at the trailing edge (near the hub) captured by the actual fine grid and responsible for the divergence of local solution. For this reason, only available solution issued from Ref. [9] and previously obtained from a CAA simulation with a medium grid covering 4-vane channels and a frequency spacing $\Delta f = 100$ Hz could be considered in this paper.

As a preliminary validation, the capability of the CAA simulation using RANS-based inputs is shown in Fig. 11 for the baseline OGV case, where the SPL spectrum (at bypass casing) from the numerical prediction in Ref. [9] is compared to experimental measurements from AneCom's fan rig [10] and an analytical prediction based on Amiet's theory. A good agreement can be observed between numerical and experimental data, although numerical results are 3-4 dB below at mid and high frequencies, whereas Amiet-based solution over predicts the levels (partially due to cascade effects neglected in Amiet's theory).

RMS pressure levels on the vane skin for baseline and serrated OGVs are plotted in Fig. 12. As expected from previous studies [1,4-5], the source strength is found to be highly reduced at the peaks and hills of the serrations and mainly concentrated at the roots. However, spurious noise sources are generated at the trailing edge and propagates towards the leading edge in the hub region. These spurious sources are due to strong mean flow gradients along the trailing edge, which are not satisfying the non-viscous approximation (slip wall condition) of Euler equations, and which can lead to a crash when diverging (as explained above for the baseline case). Thus, the FWH integration surface is practically restricted to the most reliable zone (indicated by dotted lines) to predict the in-duct sound radiation from each OGV. The acoustic performance of the "GanzRadialOpt" OGV is assessed in terms of delta of PWL spectrum in the bypass duct as shown in Fig. 13. Preliminary results indicate a significant sound power reduction along a wide frequency range. Up to 6 dB OAPWL (overall power level) reduction can be observed. The maximum noise reduction is nearly 8 dB at 3000 Hz, where the experimental peak level occurs (see Fig. 11). Such raw estimations should be confirmed by ongoing simulations with an advanced CAA set-up, including improved mean flow corrections at trailing edge.

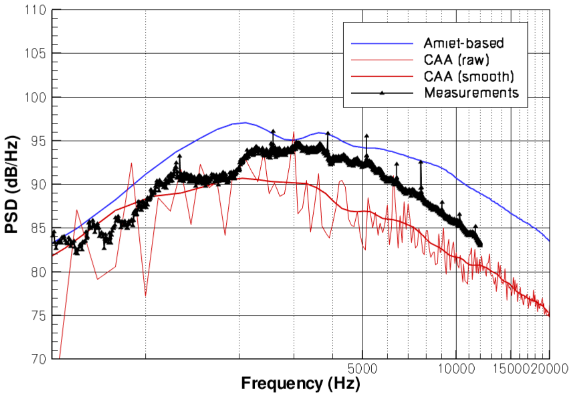

Figure 11: PSD spectra (at bypass casing) predicted by a CAA simulation compared to Amiet-based solution and measurements

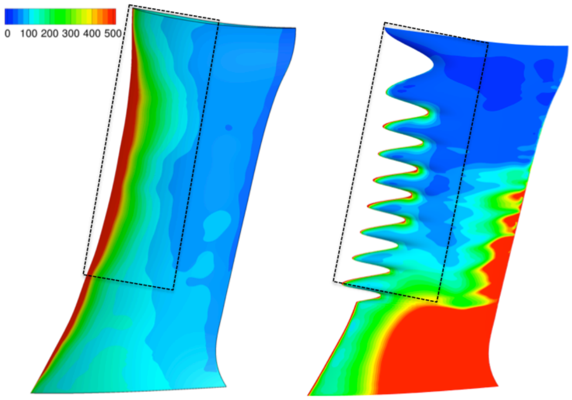

Figure 12: RMS pressure levels over the vane skin for baseline (left) and serrated OGV (right)

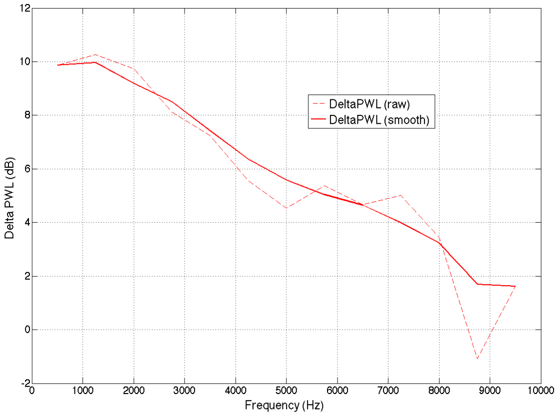

Figure 13: PWL reduction due to serrations assessed by 3D CAA

7. Conclusions

In this study, innovative concepts of serrated OGVs have been investigated from an aerodynamic and acoustic perspective. Sinusoidal undulations have been designed by using simple design rules for isolated airfoils and RANS turbulence characteristics along the OGV span. The design accounts for the spanwise variations of turbulence statistics and industrial aerodynamic requirements to tune the geometries. From RANS calculations, the impact of leading edge serrations on the aerodynamic efficiency and loss coefficient was found to be reduced at ADP for optimized designs with local suppression of the undulations in the hub region. A hybrid approach that combines 3D CAA simulations from a linearized Euler equation solver and a synthetic turbulence model has been recently used by ONERA [9]. CAA results have been compared to available experimental data from the baseline short gap OGV tests in AneCom's facility [10]. Then, the numerical methodology has been applied to the so-called "GanzRadialOpt" OGV to estimate the sound power level reduction. Preliminary results show a significant OAPWL reduction of 6 dB. However, spurious sources were found in the CAA simulation along the trailing edge due to the presence of strong sheared flows. These were artificially removed by restricting the extent of the wall-pressure surface used in the FWH solver. An ongoing simulation with an enhanced CAA set-up should be able to confirm these raw estimations.

Acknowledgments

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