CFD-CAA Simulation of Geometrically Resolved Porous Trailing Edge

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Introduction

Porous trailing edges (TE) are known to attenuate the overall sound emission of airfoils. The low frequency levels are reduced, whereas at high frequencies additional noise may be produced. We will present simulation results of both, solid and porous TE valid over the complete frequency range, showing the sound reduction as well as its increase at the respective frequencies.

The method applied is a cost efficient wall modeled incompressible LES together with the hydrodynamic/acoustic splitting approach to predict the sound. The porous material is geometrically resolved. Test case is a NACA profile with a porous TE of defined shape [1]. The published measurement data are used for validation of flow structures and sound emission.

The present work is an extension of previous work, which was modelling the porous material as an equivalent fluid and was not able to show the additional high frequency sound emission [2].

Produced and absorbed sound power are analyzed based on the acoustic energy balance and serve as a starting point to gain insight in the mechanisms responsible, especially for the high frequency effects which are not yet fully understood.

Test case

Measurement

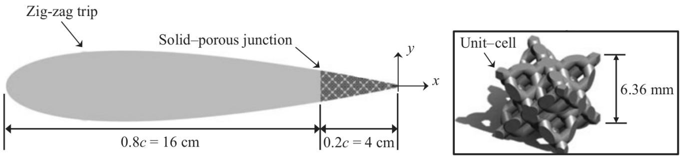

Figure 1: NACA 0018 airfoil with porous TE. Figure taken from [1]

Considered is a NACA0018 airfoil with a cord length $c = 0.2m$ and an airflow of $U_\infty = 20m/s$ at zero angle of attack ($Re = 2.7 \cdot 10^5$, $Ma = 0.065$). Measurements had been performed in the an-echoic vertical open-jet wind tunnel (AV-Tunnel) at TU Delft [3] with a spanwise width $b = 0.4m$. The radiated sound was measured by an array of 64 free-field microphones at $r = 1.43m$ distance from the airfoil TE. The spectra had been scaled to a span of $b_{\text{meas}} = 1m$ and a distance of $r_{\text{meas}} = 1m$. A turbulent boundary layer was tripped by a zig-zag trip at 20% of the cord. In the baseline case the complete airfoil was solid, in the porous case the last 4cm of the cord had been replaced by a 3D printed porous structure, which consisted of periodically repeated porous diamonds, see. Fig. 1. The measured data is published together with results of Lattice-Boltzmann-Method simulations [1]. These simulations predicted the low frequency noise reduction, but failed to predict the high frequency noise penalty due to numerical noise artefacts.

Simulation

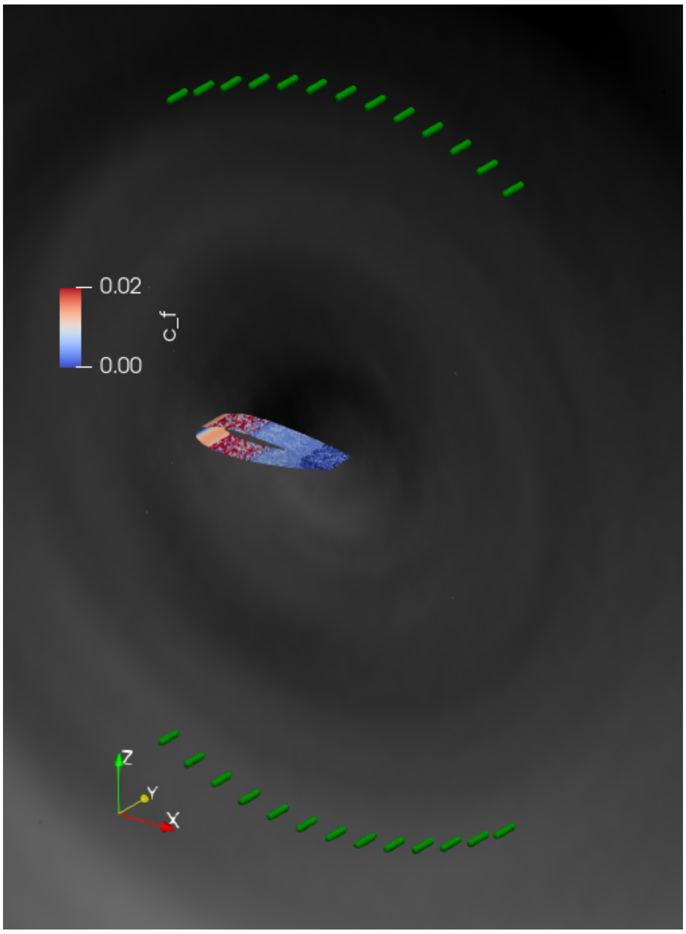

Figure 2: Simulation setup

To compute this case we used the CFD-CAA code MGLET based on a hydrodynamic acoustic split approach, where an incompressible wall modeled LES is coupled with acoustic perturbation equations by a source term in the momentum balance [4]. It is a finite volume method with skew symmetric convective operator on cubic Cartesian hierarchical grids. Arbitrary geometry is represented by a cut cell immersed boundary. Domain and grid had been chosen based on experience with previous airfoil simulations: The domain extends $2.44m \times 0.05m \times 2.44m$ in cord, spanwise and normal direction. The fine grid around the airfoil had a spacing of $\Delta x = 0.199mm$. The complete grid consists of 38 mio. cells. A physical time of 0.25s, sufficient for the computation of spectra, could be computed using only 5000 CPUh. Unresolved scales are modeled by the Smagorin-

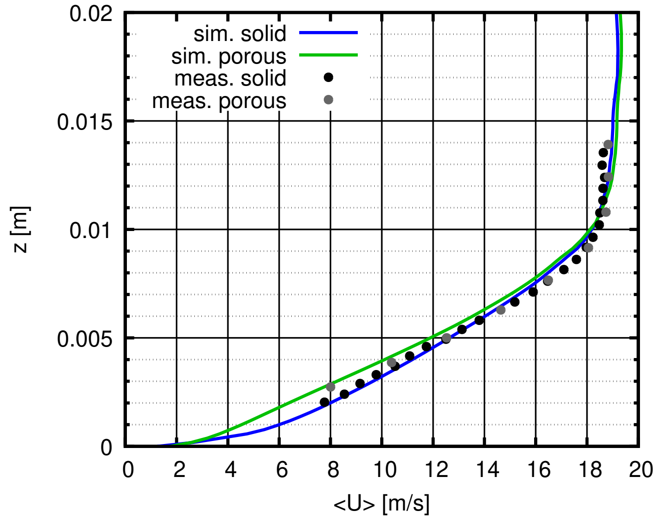

Figure 3: Boundary layer profiles 2mm upstream TE

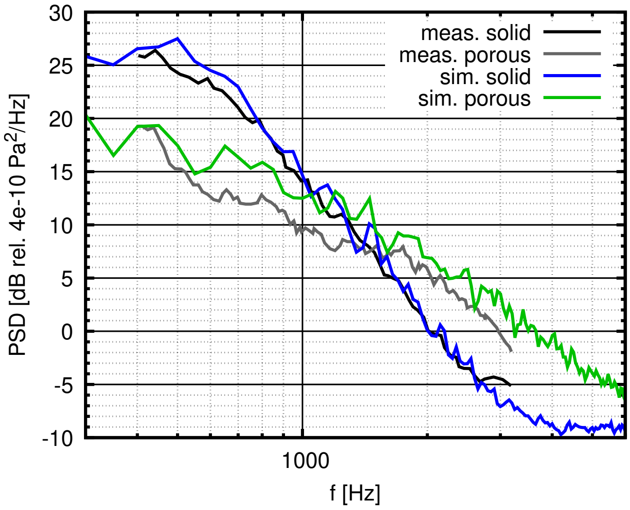

Figure 4: Spectra of radiated sound

sky model and the wall shear stress is computed using a wall model based on scalings for boundary layers exposed to pressure gradients [5].

The radiated sound was evaluated at microphones at $r_{\text{sim}} = 0.5m$ distance, see Fig.2. The pressure signal was span-wise averaged, the spectra had been averaged of the two 60° arcs. To compare the spectra with the measurements, they are scaled in the same way as in previous studies of TE noise [2]:

$$PSD = PSD_{\text{sim}} \frac{b_{\text{meas}}}{b_{\text{sim}}} \frac{b_{\text{sim}}^2 \cdot f}{r_{\text{sim}} \cdot c} \frac{r_{\text{sim}}^2}{r_{\text{meas}}^2} \frac{1}{\sqrt{2}} \quad (1)$$

This takes into account the span-wise extent, 2D versus 3D sound propagation, the microphone distance and an empirical factor.

Modeling porous material

Since the mean pore size of the porous diamond is $1.2mm$, a grid study has been performed to show whether the chosen grid spacing is sufficient. $2 \times 2 \times 1$ diamonds were discretized in a periodic domain. The flow was driven by a volume force corresponding to a pressure gradient with different values between $500Pa/m$ and $40000Pa/m$. Three different grid spacings of $\Delta x = 0.265mm$, $0.199mm$ and $0.132mm$ have been tested. Comparison with the measured linear and quadratic resistance showed for the two finer grids an maximal deviation of bulk velocity of 10% from the expected value, even though grid convergence is not jet reached. So the grid spacing of $\Delta x = 0.199mm$ chosen for the airfoil simulations is considered sufficient.

Comparison measurement / simulation

Before performing aeroacoustic computations, 9 LES with varied tripping had been performed to match the measured velocity profile for the solid case at the TE. This resulted in a tripping between 10% and 40% of cord with a sand roughness of $k_S = 2.4mm$. The match of velocity profiles can be seen in Fig.3. Also the profiles of velocity fluctuations match reasonably well between

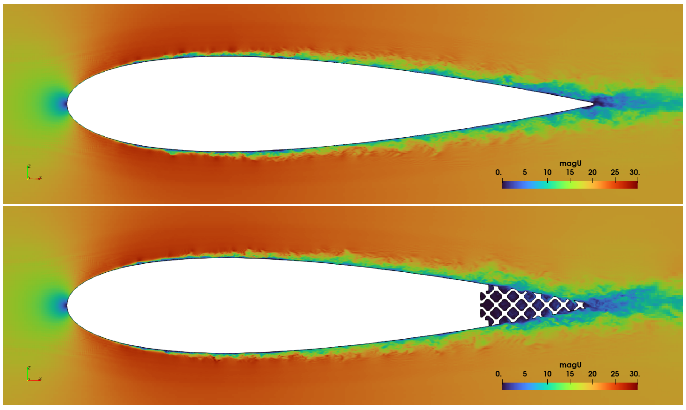

Figure 5: Cut-plane of instantaneous velocity. Top: solid case; Bottom: porous case.

measurement and simulation with a difference in the order of 20%. As the boundary layer at the TE is resolved by 55 cells, the resolution requirements for wall modeled LES are easily met.

Fig.4 shows the spectra of radiated sound, comparing measurement and simulation for both solid and porous case. The match is perfect for the solid case and good for the porous, with a slight over prediction. The simulation is able to reproduce both, the low frequency gain and the high frequency penalty. So this simulation setup can be used to investigate the high frequency behaviour of the porous material.

The instantaneous flow fields shown in Fig.5 show additional turbulence in the wake caused by the porous TE. The porous material is very open, velocities up to $\approx 0.2U_\infty$ show up inside pores.

Effect of roughness

The low frequency sound attenuation is known to be caused by short cutting of pressure fluctuations between upper and lower side of the airfoil. To investigate the effect of the roughness of the porous structure alone, a thin horizontal splitter plate was inserted in the porous trailing edge. To get different degrees of roughness, an

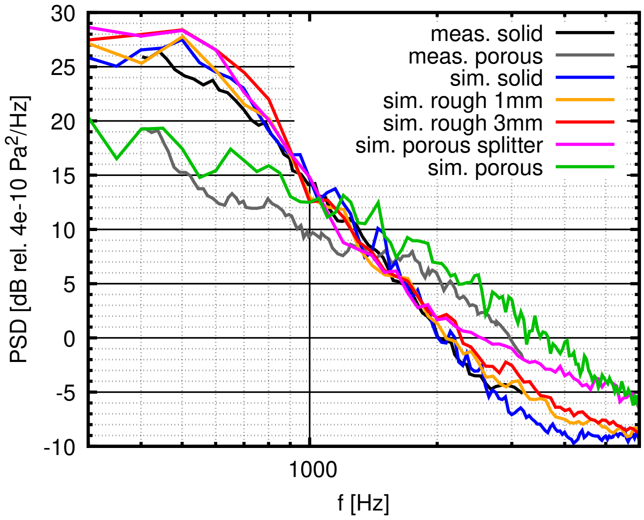

Figure 6: Spectra of radiated sound

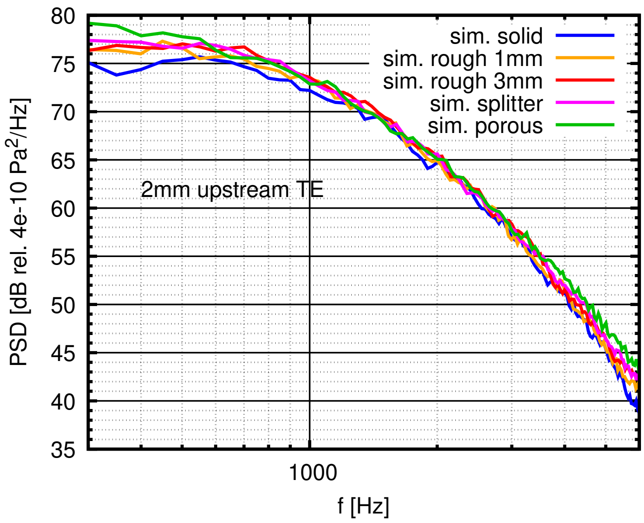

Figure 7: Surface pressure upstream TE

additional solid cone covered the inner part of the porous structure. Three cases have been investigated: mild roughness, with only an outer layer of 1mm thickness of the porous structures open, a medium case where a 3mm deep layer is open and the maximal variant with only the splitter plate.

Roughness increases the high frequency noise, but even the most rough case causes only a slight increase compared to the porous case, see Fig.6. All kinds of roughness result in the same amount of additional turbulence at the TE. The surface pressure spectra at the TE are influenced by roughness only at low frequencies (Fig.7). At the frequencies of the extra noise in the porous case, e.g. 2000Hz to 3000Hz, the surface pressure spectra are identical for all cases: solid, various roughnesses and porous case. This confirms the previous finding that additional turbulence due to roughness is not the cause for the high frequency noise.

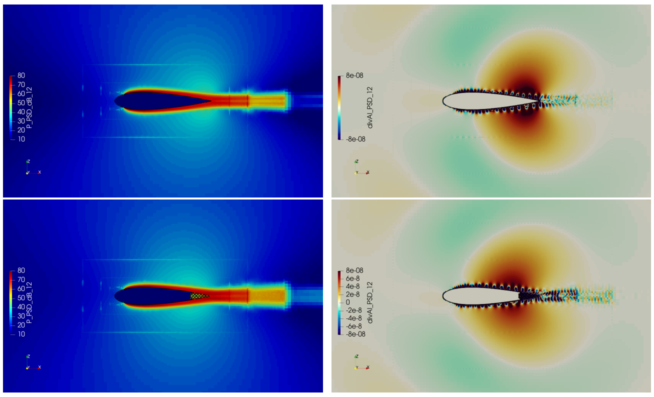

Figure 8: Incompressible pressure (left) and source strength (right) in the 1200Hz band. Top: Solid case; Bottom: Porous case

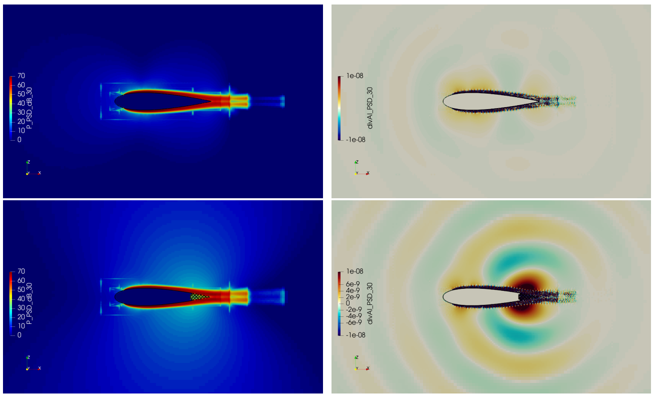

Figure 9: Incompressible pressure (left) and source strength (right) in the 3000Hz band. Top: Solid case; Bottom: Porous case

Acoustic energy production

Balance equation

The hydrodynamic-acoustic split approach [4] allows to define an acoustic energy [6] as

$$E^a = \frac{1}{2}\frac{p^a p^a}{\rho c^2} + \frac{1}{2}\rho \vec{u}^a \cdot \vec{u}^a \qquad (2)$$

and to evaluate its balance equations. Time averaged and neglecting convection terms it reads

$$\underbrace{\nabla \cdot \langle \vec{u}^a p^a \rangle}_{\text{Div. of acoustic intensity } \nabla \cdot \vec{I}^a} = \underbrace{-\frac{1}{\rho c^2}\left\langle p^a \frac{\partial p^{ic}}{\partial t}\right\rangle}_{\text{Production}} - \text{Dissipation} \qquad (3)$$

The divergence of acoustic intensity can be interpreted as net production or source strength with units $[\frac{W}{m^3}]$. Its volume integral with units $[W]$ equals the produced sound power.

Comparison solid — porous TE

The source strength $\nabla \cdot \vec{I}^a$ is evaluated for two selected frequency bands.

At 1200Hz the solid and porous case radiate sound equally (Fig.4). Also the fields of power spectral density of incompressible pressure p^{ic} and source strength $\nabla \cdot \vec{I}^a$

(Fig.8) are very similar. Only the main region of positive source strength is shifted from upstream the trailing edge in the solid case to upstream the interface between solid and porous part in the porous case. The alternating positive an negative structures inside the turbulent boundary layer and the wake are assumed to cancel each other.

At 3000Hz the porous TE causes an increase in noise by about 10 dB. In the solid case the source strength is weak, its main positive values are around the region of turbulence transition at the first sections of the airfoil. In the porous case there is additionally a high amplitude source region around the interface between solid and porous parts.

Conclusions

CFD-CAA with the finite volume code MGLET solving incompressible wall modeled LES coupled with acoustic perturbation equations is able to predict TE noise and the effects of a porous TE – the low frequency noise reduction as well at the high frequency penalty – accurately and at low computational cost. Trying different rough TEs, the previous finding that additional turbulence intensity is not causing the high frequency penalty is confirmed. Analysis of the acoustic source strength showed that in the solid case the main sound production is at the TE at low frequencies and at the transition region of the boundary layer at high frequencies. With porous TE, the main sound production is always located around the interface between the solid and the porous part of the airfoil. The latter finding is not to be generalized, since the present porous material has a very large pore size and may be not representative for all materials investigated for airfoil acoustic applications. An explanation of the mechanism for the observed additional high frequency noise with porous TE still is missing.

Acknowledgments

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