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Effects of Localised Application of Porous Material on Trailing-Edge Noise of a Circulation-Controlled Wing

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Abstract

This manuscript reports on the effects of localised application of porous material on trailing-edge noise of a circulation-controlled wing. This circulation-controlled configuration consists of a main wing with a droop-nose and a highly deflected flap, where the flow on the flap is attached due to the Coanda effect. The rear 10% of the flap consists of porous material. The numerical investigation was mainly carried out with a High fidelity Zonal Overset-LES method. Due to the strong pressure difference between the pressure and suction side, the flap's porous inset experiences an enhanced flow through the porous medium as compared to the reference configuration with a non-porous flap. As a result, the boundary layer on the flap's suction side was considerably thickened. Upon analysing the turbulent sound sources, it became evident that the application of porous material resulted in higher levels of the power spectral density of surface pressure fluctuations across the complete spectrum, related to the aforementioned strong flow through the porous material. However, the turbulent eddies traversing on the porous material were slowed down (observation based on stream-wise correlations), which was a noise reduction mechanism observed

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in the current study. The far-field sound characteristics revealed that a noise reduction could be seen for certain radiation directions when considering only the flap's trailing-edge noise as a sound source. Even when the full flap noise is considered, the noise reduction effect of the porous material is evident for frequencies f between 500 Hz and 10 kHz in the forward-downward radiation direction (as defined by the polar angle $\theta \in [180°, 270°]$). To conclude, this study provides novel insights regarding the importance of the flow-through aspect of porous material and the subsequent boundary layer thickening and argues that this phenomenon needs to be kept moderate in order to achieve noise reduction. Furthermore, the study emphasises on the importance of curvature noise which needs to be the focal point of noise reduction in such circulation-controlled wings.

Keywords: Airframe noise reduction, High-lift flap, Porous material, Coanda jet, Large-Eddy Simulation.

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1. Introduction

Turbulent boundary layer-trailing edge noise has been a subject of intense research for the last 50 years (see, e.g., [18]). Trailing-edge noise arrises when a boundary layer passes the trailing edge. Attempts to reduce turbulent boundary layer-trailing edge noise can be dated to 1976 (see, e.g., Bohn [15]). The reduction of turbulent boundary layer-trailing edge noise can be broadly categorised into active methods and passive methods. These latter passive noise reduction methods have gained considerable attention in the recent years. Examples of such passive methods include retrofitted serrations (see Jones and Sandberg [38], Moreau and Doolan [47]), finlets (see Bodling and Sharma [13] or Ananthan and Akkermans [4]), and porous materials (see , e.g., Geyer et al. [34], Herr et al. [35], or Ananthan et al [7]).

With retrofitted serrations, the larger incoming coherent structures are broken down into finer scales due to enhanced turbulent mixing, thereby reducing the edge scattering phenomenon [38]. Serrations have also been successful in inducing a destructive interference of the sound radiated from the trailing edge. For detailed discussions on serrations, the readers are directed to Moreau et al. [47], Jones and Sandberg [38], and Oerlemans et al. [52]. Another promising passive noise reduction method is the application of stream-wise finlets. Such finlets have proven to be effective in pushing the highly energetic eddies away from the wall, subsequently resulting in a weaker edge scattering phenomenon. For details on the noise reduction potential of finlets, reference is made to the experimental study of Clark et al. [21] and to the numerical investigations of Bodling and Sharma [13] or Ananthan and Akkermans [4].

In the last decade, a significant number of research articles regarding the effect of porous materials on hydrodynamics and far-field acoustics have become available. These mainly concerned flat plates or ”clean” airfoils/wings with moderate camber. For instance, Herr et al. [35] experimentally invesigated the application of porous material to the trailing edge of a lifting DLR-F16 airfoil. Although these authors reported a promising 8 to 10 dB reduction in sound pressure levels (SPLs), the benefits were limited only to relatively small angles of attack. As opposed to this, the noise reduction benefit diminished for higher angles of attack. Furthermore, the friction between porous material and the fluid resulted in higher levels of SPLs for a higher frequency range. Similar trends were already reported in the experimental studies by Geyer et al. [34]. For a broader overview on noise reduction mechanisms of porous materials, reference is made to the experimental work by Geyer et al. [34], Carpio et al. [20] and high-fidelity numerical studies by Bae and Moon [9], Koh et al. [41], Bernicke et al. [10], and Ananthan et al. [7]. The widely established noise reduction mechanisms include the breakdown of span-wise coherence in combination with a reduction in the convective velocity of the turbulent eddies. Recently, porous material is being further explored to reduce the turbulence-leading edge interaction noise via the Rapid Distortion Theory (see Zamponi et al. [61]).

By utilising the Coanda effect, the flow's tendency to separate on the aft part of a wing can be postponed or prevented. The aerodynamics of such circulation-controlled airfoils/wings have been reviewed by Englar [25]. The

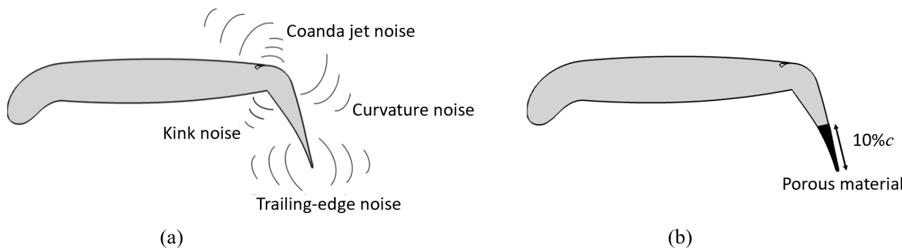

Figure 1: (a) Schematic representation of noise sources from a Coanda-jet equipped flap as identified by Howe [36]. (b) Schematic of the Coanda-jet equipped flap with a porous trailing-edge, as used in the current study.

design of such a high-lift device was discussed by Burnazzi and Radespiel [19]. Reger et al. [54] experimentally studied the scaling of the Coanda jet noise for a circulation control wing. An LES of such a circulation controlled wing equipped with Coanda jet (for rounded trailing edges) was performed by Nishino et al.[50] where they focussed on jet mixing phenomena affecting the jet spread rate and the point of flow separation. Francois et al. [32] performed Delayed Detached Eddy Simulations, focusing on the aerodynamic benefits of a circulation-controlled wing with actuated dynamic blowing Unfortunately, no discussion on the sound sources in this latter study was performed.

For a Coanda-jet equipped flap configuration during landing phase conditions, noise sources have been identified as [also schematically represented in Fig. 1(a)]:

1. Curvature noise: resulting from the significant fluid acceleration around the strongly curved part of the flap.
2. Flap trailing-edge noise: originating from the turbulence scattering at the flap trailing-edge (similar to the classical trailing-edge noise).
3. Flap kink noise: originating from the sudden change in the geometry at the intersection of the pressure side of the main wing and the flap.
4. Coanda jet mixing noise: resulting from the turbulence mixing at the exit of the jet blowing slot (analogous to the classical jet noise).

5. Flap deceleration noise: noise stemming from the highly decelerating flow on the flap's suction side (between the strong curvature and the trailing-edge of the flap).

These sources have been confirmed by the numerical simulations of Howe [36], Rossian et al. [55] (based on a 2D CAA study), and Ananthan et al. [6]. A detailed LES analysis of the importance of the different sound sources can be found in the latter reference.

From the above it becomes clear that noise reduction by porous material application to flat plates and/or wings received quite some attention in the literature. Moreover, recent studies have been published that specifically investigate the aerodynamics and noise sources associated with circulation-controlled wings (see, e.g., [19, 6]). However, the feasibility of applying porous materials to mitigate the noise from a circulation-controlled wing is seldom discussed in the literature. For example, the effect of flow-through the porous material (deemed considerable for a circulation controlled wings which generates a high lift-coefficient) and the subsequent boundary layer thickening have not been understood and that there is no consensus on the importance of curvature nose when applying porous material to a circulation-controlled wing.

The goal in this study is to provide a physical understanding of the complex noise generation and propagation in a high-lift configuration, which is originated by the interaction between a turbulent flow field and the wing. We aim to analyze this interaction by simulating the complex flow regime using a high-fidelity 3D Overset-LES approach. Two configurations are considered: i) the reference configuration with a solid flap and ii) the flap with a porous trailing edge. Both cases have a chord-based Reynolds number Re_c of 10^6. The presence of the porous medium is numerically accounted for with a volume-averaged approach which results in additional terms in the governing equations (e.g., linear Darcy and non-linear Forchheimer term in the momentum equations). In this work, a densely packed porous material is applied to the rear 10% of the flap's trailing-edge as shown in Fig. 1(b). Using the results of these detailed simulations, we analyze the noise propagation using a CAA approach in the far-field. Here we demonstrate how the flow-through aspect of a porous material and the boundary layer affects the noise reduction. Moreover, we provide detailed evidence that the fluid acceleration around the strongly curved part of the flap plays a major role in the noise generation for circulation-controlled wings with porous insert.

The here studied high-lift configuration was considered in the framework of the Collaborative Research Consortium (CRC880) [53]. This configuration significantly differs from the more classical 3-element high-lift wing with a slat, main-wing, and flap (e.g., as studied in Terracol and Manoha [59]). In the present study, a gap-less configuration of a Coanda-jet equipped flap [22] with a droop nose at the leading edge is considered [as depicted, e.g, in Fig. 1(b)]. Such gap-less configurations remedy the reduced stall angles that typically tend to occur for the classical 3-element configurations. An overview of aerodynamic benefits of such circulation-controlled wings which utilise the Coanda effect can be found in Refs. [25, 19].

The remainder of the manuscript is organized as follows: Section 2 deals with the governing equations for the Overset-LES and a short description of the porous modeling. The discretization method is given in subsection 2.3. In section 3, the computational set-up for the Overset-LES is described. Results are presented in section 4, with a focus on averaged flow statistics in subsection 4.1, instantaneous flow fields in subsection 4.2, mechanisms of noise generation in subsection 4.3, and far-field sound pressure levels in subsection 4.4. Finally, conclusions are given in section 5.

2. Methodology

2.1. Overset-LES equations

The perturbation form of the compressible Navier-Stokes Equations (NSEs) supplemented with a classical Smagorinsky sub-filter scale model is used for the Overset-LES in the current work. The formulation is obtained by extending the