Journal of Sound and Vibration 421 (2018) 348–376

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Numerical analysis of the impact of permeability on trailing-edge noise

Seong Ryong Koh [a,*], Matthias Meinke [a,b], Wolfgang Schröder [a,b]

[a] *Institute of Aerodynamics and Chair of Fluid Mechanics, RWTH Aachen University, Wüllnerstraße 5a, 52062 Aachen, Germany*
[b] *JARA – High-Performance Computing, Forschungszentrum Jülich, 52425 Jülich, Germany*

ARTICLE INFO

Article history:
Received 16 March 2017
Revised 7 February 2018
Accepted 9 February 2018
Available online XXX

Keywords:
Porous material
Trailing-edge noise
Permeability Reynolds number
Porous impedance
Volume-averaged Navier-Stokes equations

ABSTRACT

The impact of porous surfaces on the near-wall turbulent structures and the generated trailing-edge noise is analyzed for several trailing-edge shapes of finite thickness using a high resolution large-eddy simulation (LES)/computational aeroacoustics (CAA) method. The porous surface of the trailing edge is defined by the porosity and the viscous permeability determined by the solution of a turbulent flat plate boundary layer at a Reynolds number 1280 based on the displacement thickness in the inflow cross section. The volume-averaged approach for the homogeneous porous medium shows that the porous impedance scales linearly with the porosity and exponentially with the mean structure size of a porous medium. The drag induced by the porous surface changes the friction velocity and the permeability Reynolds number Re_K which determines the porous impedance R_s scaled by $\mathrm{Re}_K^{-2/3}$. The trailing-edge noise is analyzed for three solid and three porous trailing edges. The effect of a finite span is investigated by the spanwise correlation model based on the measured coherence distribution. The acoustic prediction shows a good agreement with measurements of the broadband spectrum and the strong tone generated by a finite trailing-edge thickness. The pressure gradient inside the porous media is redistributed by the Darcy drag defined by the viscous permeability and the porosity. The mean pressure increases in the upstream direction inside the porous medium such that the flow acceleration involved in the acoustic generation is reduced inside the porous medium. The noise reduction by a porous medium reaches 11 dB for the trailing-edge shape which possesses a sharp corner for the solid surface. The porous surface applied to a semi-circular trailing edge achieves a 4 dB noise reduction. The directivity pattern for individual components of the acoustic spectrum shows that the massive noise reduction is determined at the tone. Enhanced wave diffraction by the thick flat plate changes the directivity pattern in the high frequency range.

1. Introduction

Turbulent flows over porous media are often encountered in engineering applications due to their capability to absorb acoustic energy. The energy dissipation occurs via various mechanisms, e.g., viscous stresses convert fluid kinetic energy into heat or a substantial portion of the acoustic energy penetrates the porous surface and interacts with the internal rigid structures. The noise reduction varies with porosity, internal structure size, and the shape of the porous medium. That is, to use the proper porous media for acoustic absorption, multidisciplinary knowledge of acoustics and the science of porous materials is required.

* Corresponding author.
E-mail address: s.koh@aia.rwth-aachen.de (S.R. Koh).

https://doi.org/10.1016/j.jsv.2018.02.017
0022-460X/

Therefore, in this introduction, we first briefly discuss some fundamental studies that provide the foundational analysis of the porous material that is later used for the investigation of noise reduction. Then, the results from the literature with respect to the impact of porous surfaces on airframe noise are addressed. The discussion of the experimental and numerical findings will evidence the reason for this study.

The theory of general porous media has been developed by assuming a statistically isotropic medium. If the characteristic length of a porous medium is much larger than the size of the pore structures, i.e., the porous properties are both homogeneous and isotropic, then the fluid and the solid phase can be treated as being continuous when the control volume itself is also homogeneous [1]. The transport equations for porous media were derived to analyze a drying process which included a heat transfer problem with all three phases. Solid, liquid, and gas phases occupied an averaging volume and phase changes between gas and liquid state were considered [2]. In an investigation based on experimental data [3], the momentum equation of porous media was modified by tuning the coefficients correlated with the porosity and characteristic length of the porous media. The macroscopic Darcy law defining fluid permeability was first derived in an ensemble-averaged formulation for slow viscous flow through a porous medium in Ref. [4]. The rigorous upper and lower bounds of permeability were given in terms of various correlation functions which statistically characterize the micro-structure of the medium. In a fluid saturated porous material an external forcing by mechanical waves generates a pressure gradient in the fluid phase and slight oscillations of the solid frame of the material. The drag force induced by the mechanical waves was modeled for materials with variable pore width in Ref. [5]. In Ref. [6], Darcy's law with the Forchheimer correction for homogeneous porous media was derived. The relationship between the pore structure and the permeability was detailed in Ref. [7]. It was shown that the fluid network inside porous media causes unsteady transport processes including diffusion by the interaction of the fluid with the micro scales of the pore structures. The effective absorption of acoustic energy also depends on the interconnected paths for the fluid that interacts with the solid surface of the micro-structures inside the porous medium [8]. Considering the variation of the fluid-solid interaction due to a porous surface, it is clear that scientists considered porous material to reduce airframe noise.

In experimental studies, porous media were used to lower noise generation from flap-side edges by preventing sound transmission to the rigid surface underneath the porous media [9]. In Ref. [10] a porous medium was applied to the half-span flap to reduce the turbulence intensity near the flap-side edge. The PIV measurements showed that the porous material shifted the major vortex roll-up further off the flap surface such that the surface pressure fluctuations were significantly reduced in the high frequency band. In Ref. [11] the porous skin treatment reduced flap-side noise by 3–4 dB in the entire frequency range and the porous fairing was the most effective concept for reducing noise from a landing-gear system by 2–3 dB noise reduction over the mid- and high-frequency ranges of the farfield sound spectra. Partial porous surfaces on airfoils [12] were considered to reduce the trailing-edge noise without drastically impairing the aerodynamic performance. The flow over the airfoil with a porous surface at the trailing edge underwent a noticeable noise reduction. In Ref. [13] the acoustic properties were measured using various porous materials configured by the pore size and the flow resistivity. The results showed that the pore size was the dominant parameter to minimize the high-frequency self-noise contributions to trailing-edge noise.

In numerical analyses, a porous surface has been described either by a boundary condition, which mimics the behavior of a boundary layer over a Darcy-type porous wall, or by volume-averaged transport equations derived for a fluid-saturated homogeneous porous medium. In the former approach, the Reynolds-averaged Navier-Stokes (RANS) equations were solved to find the noise reduction mechanism due to porous media on high-lift devices [14,15]. The turbulent shear flows over a permeable wall were investigated using a transpiration boundary condition in incompressible [16] and compressible flows [17]. In compressible flows a linear impedance acoustic boundary condition was adopted which was tuned by a permeability and damping ratio to suppress the near-wall turbulent structures. Using spatial averaging formulations for a multiphase control volume [1], the volume-averaged transport equations, i.e., the latter approach, were used to resolve the effects of complex porous surfaces. To simulate the impact of permeable walls on turbulent flows a numerical approach based on a dispersed multiphase flow assumption was used in Refs. [18–20]. In the direct numerical simulations in Ref. [18], the turbulent boundary layer modified by the porous wall was analyzed in detail with respect to the turbulence generation and the flow parameters which dominate the porous drag force based on the volume-averaged approach. In the numerical studies in Refs. [19,20], the porous surface was assumed a homogeneous distribution based on the macroscopic description of multiphase systems. The surface pressure spectra showed drag related acoustics at the blunt trailing-edge base. The strong tone generated by vortex shedding at the solid trailing edge was massively reduced by the porous surface.

The discussion of the experimental and numerical analyses in the literature shows that the porous surface was defined more or less independently from the flow field and the model geometry. However, an optimal low-noise porous surface requires to analyze the solid and the porous surface for the same geometry and flow parameters. Furthermore, the relationship of the material parameters with the acoustic variables has to be known to define an optimal porous surface in terms of noise reduction. To find the correlation of the flow variables with the characteristic length scales of the porous material, it is necessary to quantify the porous surface effects on the flow field, e.g., the wall-shear stress, and the porous impedance which is determined by the ratio of the pressure fluctuation to the velocity fluctuation. Moreover, the studies in the literature focused on a comparison of acoustic fields generated by solid and porous surfaces of one single geometry, i.e., no variation of the configuration was considered. Therefore, this study possesses the following structure.

In the first part of the investigation, the impact of porosity on the porous impedance based on the numerical studies of a turbulent boundary layer on various porous materials is determined. The porous media are assumed to be composed of a homogeneous distribution of micro-scale rigid particles such that the permeability and the porosity are determined by the characteristic length of the porous structures. The acoustic properties will be quantified and the fundamental parameter directly associated