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On the attenuating effect of permeability on the low frequency sound of an airfoil

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A R T I C L E I N F O

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A B S T R A C T

The effect of structure permeability on the far-field radiation of a thin airfoil is studied. Assuming low-Mach and high-Reynolds number flow, the near- and far-field descriptions are investigated at flapping-flight and unsteady flow conditions. Analysis is carried out using thin-airfoil theory and compact-body-based calculations for the hydrodynamic and acoustic fields, respectively. Airfoil porosity is modeled via Darcy's law, governed by prescribed distribution of surface intrinsic permeability. Discrete vortex model is applied to describe airfoil wake evolution. To assess the impact of penetrability, results are compared to counterpart predictions for the sound of an impermeable airfoil. Considering the finite-chord airfoil as “acoustically transparent”, the leading-order contribution of surface porosity is obtained in terms of an acoustic dipole. It is shown that, at all flow conditions considered, porosity causes attenuation in outcome sound level. This is accompanied by a time-delay in the pressure signal, reflecting the mediating effect of permeability on the interaction of fluid flow with airfoil edge points. To the extent that thin-airfoil theory holds (requiring small normal-to-airfoil flow velocities), the results indicate on a decrease of ~ 10 percent and more in the total energy radiated by a permeable versus an impermeable airfoil. This amounts to a reduction in system sound pressure level of 3 dB and above at pitching flight conditions, where the sound-reducing effect of the seepage dipole pressure becomes dominant. The applicability of Darcy's law to model the effect of material porosity is discussed in light of existing literature.

1. Introduction

When an air vehicle passes through unsteady flow conditions, commonly formed as incoming gust or local turbulence, in either fixed-wing or flapping-flight setup, it experiences time variations in the aerodynamic forces acting on it. These variations are inevitably radiated as sound waves, propagating into the far field through flow pressure fluctuations. Airfoil aerodynamic noise contributes significantly to the sound radiation in this case, and to the noise generated by many other aero-machinery structures, including wind turbines and engine fans. With nowadays increasing interest in controlling sound generation for both civil (reduction of airport and wind farm noise pollution) and military (monitoring acoustic signature) applications, it is important to study novel means by which airfoil aerodynamic noise may be efficiently suppressed [1].

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In searching for an optimal method to minimize airfoil noise, owls are known to have the ability to maintain an almost "silent" flight [2,3]. Considering the growing interest in using biomimetics to improve on engineering applications, it therefore seems natural to study the methods by which owls control their flight acoustic radiation. It is now commonly accepted that owls fly silently owing to main three reasons [2]: a leading edge comb of stiff feathers; a fringe of flexible filaments at the feathers trailing edges; and a soft coating at the upper part of the wings. These features suggest that an appropriate combination of airfoil elasticity, structure porosity and material non-homogeneity may result in considerable decrease in flight aerodynamic noise. Focusing on ongoing efforts to analyze the impacts of the above on sound emission, the present work seeks to study the separate effect of airfoil permeability on its far-field sound at unsteady flow conditions.

The theoretical problem of sound radiation by perforated materials was first treated by Ffowcs-Williams [4], who examined the far-field radiation of turbulence interacting with a uniform array of circular orifices over an infinite plane. Both acoustically "opaque" and "transparent" surfaces were considered, yielding leading monopole and dipole radiations, respectively. Following works have focused on various planar geometries with different forms of structure perforations, and included both theoretical [5–10] and experimental [11,12] investigations. Other configurations, such as acoustic liners [13], sandwich panels [14] and circular cylinders [15,16], have also been considered. In common to all theoretical investigations, the total radiation by a perforated surface was calculated based on detailed analysis of the sound emitted by a single cavity interacting with the flow. In cases where an array of pores was considered, the results for the overall radiation were obtained based on a number density parameter, indicating the number of surface pores per unit area. In a single work where non – uniform perforation has been modeled [5], a comparison between uniform and non – uniform pore distributions is made.

In a recent effort to develop novel noise-control methodologies for reducing fluid-structure interaction sound, a sequence of studies have examined surface porosity as means for passive noise control in finite and semi-infinite transparent configurations. To this end, Geyer et al. [17,18] experimented on the effect of porosity on the sound of an airfoil trailing edge interacting with a turbulent boundary layer. Following works examined the impact of surface perforations in other natural [19] and engineering [20,21] applications. Significant pressure level reduction was measured in some of the cases, and the dependence of sound attenuation efficiency on specific details of surface treatment and perforation extent was tested. The above experimental studies were accompanied by numerical and theoretical investigations. Thus, Bae and Moon [22] demonstrated the dampening effect of a porous trailing edge in a flat plate setup using large-eddy simulations. Jaworski and Peake [23] considered the acoustic field of a turbulent eddy interacting with a semi-infinite poroelastic plate using a Wiener-Hopf asymptotic technique. Khorrami et al. [24] suggested porosity to control rotor tip-clearance-induced noise, and Liu et al. [25] examined the impact of perforated coating on the sound of a tandem-cylinder setup.

While the above works are of valuable practical significance, the numerical efforts involved in the course of analysis are rather demanding. It is therefore of interest to suggest a scheme that is significantly less expensive, yet physically meaningful, as an alternative for studying the problem. The present work suggests such an approach, through incorporation of a thin-airfoil-theory calculation for the near-field, and an acoustic-analogy-based scheme for the far-field. The near-field solution is considerably less demanding than the computational-fluid-dynamics calculations applied in Refs. [22,24,25]; the far-field calculation then uses the near-field description as a source term in a linearized acoustic-analogy formulation. In a sense, the suggested approach takes advantage of previous studies [4,7,8,10], without necessitating exact geometrical knowledge on structure perforations. This is realized through application of Darcy's law [26,27], according to which the microscopic description of body permeability is replaced by an intrinsic functional relation. This enables study of non-homogeneous porous media (where porosity is non-uniformly distributed along the surface), which was previously tackled only in spherical shell and semi-infinite plate geometries [5].

An outline of the paper follows. We consider a two-dimensional model problem of a thin permeable airfoil subject to leading-edge pitching actuation and incoming flow unsteadiness (incident vorticity). Low-Mach and high-Reynolds number flow conditions are assumed, supporting application of a compact-body description for the acoustic problem. The near- and far-field problems are formulated and analyzed in Section 2. The results, quantifying the effect of airfoil porosity on its acoustic signature, are presented in Section 3. Concluding comments are given in Section 4. An assessment of the applicability of Darcy's law formulation is made in the Appendix.

2. Problem formulation

Schematic of the problem is shown in Fig. 1. Consider a two-dimensional setup of a porous rigid airfoil of chord $2a$. The airfoil is immersed in uniform flow of speed U in the x_1-direction. At time $t=0$, sinusoidal leading-edge pitching actuation of the form

$$\left(\frac{\partial \xi}{\partial x_1}\right)_{x_1=-a} = \bar{\varepsilon}_p \sin(\omega_p t) \tag{1}$$

is commenced. Here, $\xi(x_1, t)$ marks airfoil displacement in the x_2-direction, $\bar{\varepsilon}_p \ll 1$ in accordance with a linearized formulation (hereafter, overbears mark non-dimensional quantities), and ω_p denotes the pitching frequency. Additionally, the airfoil is subject to aerodynamic loading in the form of an incident line vortex of strength Γ, introduced at $t = 0$ at a prescribed