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# Mitigating the sound of a flapping airfoil using optimal structural properties distributions

Michael Weidenfeld [a,*], Eran Arad [b]

[a] *Faculty of Aerospace Engineering, Technion - Israel Institute of Technology, Technion City, Haifa, 32000, Israel*
[b] *Senior Research Associate, RD&E Division, RAFAEL, POB 2250, Haifa, 3102102, Israel*

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ABSTRACT

We study the effects of structural properties distributions on the sound radiation of a thin elastic airfoil. Focusing on flapping-flight in a high-Reynolds and low-Mach regime, we seek optimal conditions to mitigate flapping-sound while maintaining aerodynamic efficiency. The airfoil is immersed in a two-dimensional potential flow field, and is subjected to leading-edge actuation in the form of a small-amplitude periodic heaving motion. The near-field dynamics is governed by Euler-Bernoulli's beam equation of motion and analyzed using thin airfoil theory in conjunction with a discrete-vortex wake model. The near-field results are introduced as an effective dipole-type source term to the right-hand-side of the Powell-Howe acoustic wave equation, and the associated far-field sound is calculated using Green's function formulation. Considering the elastic flapping configuration, we seek optimal material properties and a linear thickness distribution to reduce the sound of an otherwise rigid airfoil while retaining the lift amplitude of the rigid configuration. To this end, the aeroacoustic model is introduced into an optimization scheme, where minimal sound amplitude is sought in the lift direction, subjected to the aforementioned lift force constraint with a 33% assigned tolerance value. The relatively wide tolerance produces in turn an effective Pareto front, reflecting the trade-off between the competing objectives of lower sound levels and aerodynamic efficiency. Compared with the rigid heaving airfoil, over 10 [dB] sound reduction was obtained for the optimal flexible configuration producing the same lift amplitude. The Pareto front also displays a linear relation between sound reduction ratio and lift amplitude ratio, indicating a further substantial sound reduction of up to 30 [dB] for smaller lift ratio values. The effect of optimal structure thickness distribution on the equi-lift sound reduction mechanism is two-fold: The motion and wake dipoles are shifted to an antiphased mode thus reducing the total sound signal, and the motion dipole which represents the unsteady forces, exerted by the airfoil on the fluid while transversing, is fixed in magnitude, thus retaining the lift amplitude value. The system dynamics leading to the opposing sound dipoles is evoked by phase-locking the airfoil motion and circulation, and following Kelvin's theorem, antiphase-locking the airfoil motion and wake circulation. Implications on flapping flags and streamers is briefly discussed as well.


* Corresponding author.
*E-mail addresses:* smickeyw@gmail.com, wmichael@rafael.co.il (M. Weidenfeld).

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## 1. Introduction

The canonical fluid-structure interaction problem involving a flapping flexible sheet (flag, airfoil, sail, etc.) immersed in a uniform flow, is analyzed in the present work in an attempt to study novel means to mitigate the associated far-field noise. In general, the unsteady filament motion, and the interaction between the surface and wake vorticity, give rise to acoustic pressure-waves which then radiate as sound [1]. In line with the ongoing interest in controlling noise generated aerodynamically by airborne vehicles [2], for both civil and military applications, the study of far-field sound originating from unsteady surface motion, plays a key role.

The flapping sheet configuration was studied extensively throughout the literature [3], and serves as a model problem for several engineering applications, mainly in the context of flutter problems [4–7], bio-inspired flight [8,9], and energy harvesting techniques [10–12], including piezo-electric [13], and elctro-mechanical [14] based harvesting methods, where the latter underlines the significance of the mounting to the resulted system dynamics. These and other theoretical works [15–17] focused on the near-field dynamics and aerodynamic qualities, where other studies concentrated on stability analyses [18–20], to determine critical conditions for flutter onset.

The associated noise problem of a flapping configuration only recently received attention in the context of several bioacoustic phenomena and engineering applications, such as micro-air-vehicles design [21,22], blade-vortex interaction (BVI) noise-reduction systems [23,24], palatal snoring [25–27], "insect songs" - the sound produced by insects' flapping, significantly affecting their social behaviour [28,29], and "whistle" sounds meant as warning alarms, notifying a flock of birds about the presence of a nearby predator [30]. Theoretical works examined the sound radiation of rigid and flexible airfoils in unsteady motion and flow conditions [17,20,31–33], while other computational studies examined the noise of a rigid flapping setup [34] and a flexible wing setup [35,36]. Clearly, a significant effort is invested in underlying the noise generating mechanisms of flapping sound, and exploring means to control noise radiation.

Inspired by the nature of owls' "silent" flight, several studies [37–39] examined their different noise reduction mechanisms, first identified by Graham [37] as (1) leading edge stiff comb, (2) trailing edge flexible fringe, (3) and soft upper-wing coating. Whether in gliding or flapping flight, the combined effect of all three features is to eliminate turbulence related noise at frequencies higher than 2 [kHz], where the owl's prey is most sound sensitive. Though not directly associated with flapping *tonal*-noise, these features suggest incorporating non-uniform geometry and elastic properties as a methodology for noise reduction. Most studies regarding such non-uniformities focused on trailing-edge noise, and included sawtooth serrations [40–42], brush-type extensions [43], elasticity [44,45], surface roughness [46,47], and permeability [48,49].

In a recent effort to inspect and utilize the specified owls' "technology" for flapping flight, Weidenfeld and Manela [50] uncovered the role of airoil's permeability in reducing flapping noise. Their results indicate that the seeping-flow through the porous section of the airfoil produces a sound dipole opposite in phase with regards to the flapping-motion dipole, thus reducing the total noise radiation by negating the direct motion sound. To these authors knowledge, no other studies examined means by which owls noise reduction mechanisms may be incorporated in a flapping flight. Subsequently, in the present work we wish to determine whether and how variable geometry and structural features can be optimally exploited for flapping wing noise reduction.

Variable geometry, elasticity and mass distributions are often considered in the context of flapping (bio-inspored) flight [51], fan and rotor noise [52–54], where optimal designs are often sought. Shahzad et al. [55] studied the aerodynamic performance of rigid and flexible flapping wings, with different planform area distributions. Their results distinctly show exceeding performance for flexible wings with preference to an outboard planform area distribution. Gur et al. [56] performed a multidisciplinary optimization for maximizing flight endurance of a vehicle with a propeller based propulsion system, and for designing a quiet propeller [57], under several constraints. Using simplified models for aerodynamics, structure, and acoustic radiation, they obtained optimal configurations for ultralight aircrafts and electric mini UAVs. They specifically allowed the variation of geometrical and structural properties along the blade such that maximal stress constraints were met. The optimization process included a mixed-strategy approach which combined a genetic algorithm, a simplex scheme, and a gradient-based method, to obtain optimal results.

Other studies regarding optimal fluid-structure interactions focused on optimizing fixed- and flapping-wing flight efficiency. Hunsaker et al. [58] sought to reduce the induced drag of a morphing fixed-wing under structural loading constraints for various flight conditions. Nikbay et al. [59] presented a practical approach for multidisciplinary aeroelastic optimization combining several commercial codes. They obtained a Pareto-front reflecting the compromise between aerodynamic efficiency and aircraft total weight, under structural constraints. Tan et al. [60], applied genetic algorithms to find optimal localized stiffening to stabilize fluid loaded flexible panels. They managed to find a configuration satisfying the divergence-onset specifications. Ilário da Silva et al. [61] obtained a Pareto front reflecting the trade-off between the conflicting objectives of noise reduction and aerodynamic performance. Oyama et al. [62] employed an evolutionary search algorithm to find an optimal pitching and plunging motion-cycle to maximize the performance of a two-dimensional rigid airfoil. Stanford et al. [63] examined optimal flapping wings with active shape morphing and a rectangular planform to maximize propulsive efficiency using a gradient based algorithm. Stewart et al. [64] considered a plate-like flapping wing with a modified zimmerman planform, suitable for describing complex biomimetic wings. Using gradient based search, they sought for an optimal wing planform geometry and thickness distribution to maximize thrust and minimize input power over a cycle, a formulation leading to a Pareto front of best possible designs.