Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Numerical study on reduction of aerodynamic noise around an airfoil with biomimetic structures

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ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
10 November 2016
Accepted 14 November 2016
Handling Editor: P. Joseph

Keywords:
Aeroacoustics
Noise reduction
Biomimetic structures
Flow control

ABSTRACT

A biomimetic airfoil featuring leading edge waves, trailing edge serrations and surface ridges is proposed in this study, based on flow control with each section meeting the NACA 0012 airfoil profile. Numerical simulations have been conducted to compare aerodynamic and acoustic performances between the NACA 0012 and biomimetic airfoils. These simulations utilize the large eddy simulation (LES) method and aeroacoustic analogy at an angle of attack of 0° and a Reynolds number of 1.0×10^5, based on using the airfoil chord as the characteristic length. The simulation results reveal the overall sound pressure levels (OASPLs) for all frequencies and at the seven observer points around the biomimetic airfoil, and a decrease of 13.1–13.9 dB is observed, whereas the drag coefficient is almost unchanged. The biomimetic structures can transform the shedding vortices in laminar mode for the NACA 0012 airfoil to regular horseshoe-type vortices in the wake, and reduce the spanwise correlation of the large-scale vortices, thereby restrain the vortex shedding noise around the biomimetic airfoil.

1. Introduction

Flow control as a scientific discipline and a technological curiosity is perhaps more intensely pursued by scientists and engineers than any other area in fluid mechanics [1]. Fundamental principles are related to controlling structures of boundary layers or wakes to achieve transition delay, separation postponement, lift increase, skin-friction and pressure drag reduction, turbulence augmentation, heat transfer enhancement, or noise suppression. Flow control involves passive or active devices that exert a beneficial change on the flow field. Passive flow control may be easily applied to engineering as flow is modified without external energy expenditure. A considerable amount of related research has then been performed to modify the structures of the boundary layer and wake flow. Bionics promotes the development of flow control methods and techniques [2]. Biomimetic flow control has recently received increased focus as it imitates biological surfaces and special structures of living organisms to improve the effectiveness of flow control. Anders [3] and Choi [4] provided exhaustive reviews of early and recent biomimetic flow control research, respectively, presenting several examples of successful biomimetic flow controls.

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http://dx.doi.org/10.1016/j.jsv.2016.11.021
0022-460X/

Please cite this article as: J. Wang, et al., Numerical study on reduction of aerodynamic noise around an airfoil with biomimetic structures, *Journal of Sound and Vibration* (2017), http://dx.doi.org/10.1016/j.jsv.2016.11.021

Biomimetic flow control includes biomimetic boundary layer control and biomimetic wake flow control. Boundary layer control utilizing riblets with different cross-sections has received considerable attention after Walsh reported drag reduction benefits through the use of riblets [5–7]. Researchers were intrigued with the large variety of surface structures on the skin of fast sharks [8–10]. These are naturally optimised riblet geometries that achieve significant drag reduction performance improvements. The optimised riblets, which act passively, can reduce drag by up to 10% in turbulent flow [11,12]. Riblet surfaces also act to reduce the boundary layer noise [13,14]. An alternative approach of passive flow control, widely utilized to reduce form-drag [15] and self-noise, is wake control. Shapes and structures of living organisms have shown adaptability to the flow fields around them, inspiring novel structures of vortex generators. Tubercles on the leading edges of the humpback whale pectoral flippers, for example, inspired Fish and Battle [16] to propose a novel hydrodynamic design. The numerical study performed by Watts and Fish [17] confirmed that leading edge tubercles can reduce the lift of a wing by 4.8%, the drag by 10.9%, and increase the lift to drag ratio by 17.6%. Force measurements at a Reynolds number of 220,000, performed by Bolzon et al. [18], indicate that for angles of attack ranging from 1° to 8°, tubercles reduce lift and drag by 4–6% and by 7–9.5%, respectively, resulting in a 2–6% increase in the lift-to-drag ratio and a 3% increase in the maximum lift-to-drag ratio. Recent work [19–21] also confirms the morphological features of marine mammals for flow control may be utilized in the biomimetic design of engineered structures for increased power production and increased efficiency. A typical example of biomimetic passive wake control is trailing edge serrations inspired by feathered structures. Gruschka et al. [22] conducted a series of tests at the University of Tennessee Space Institute to determine the level and characteristics of noise produced by owls during flight, especially during gliding approaches. Bachmann et al. [23,24] compared barn owl feathers to pigeon feathers, deducing that the adaption of barn owl wings to silent flight is due to the wing geometry, where the wing feathers have a velvet-like upper surface and also have leading edge serrations and trailing edge fringes. Recent numerical and experimental investigations confirm that leading-edge waves [25–29], trailing edge serrations [30–34] and also the combination of the two [35] show performance related to drag or noise reduction. These previous work have confirmed the feasibility of noise reduction by flow control.

In this study, we proposed a biomimetic airfoil based on the biomimetic flow control concept with leading edge waves, trailing edge serrations, surface ridges and each section reflecting the conventional NACA 0012 airfoil profile. The main purpose was to find a new structure of flow control to reduce the airfoil noise without changing its aerodynamic performance. It is well known that airfoil self-noise is due to the interaction between an airfoil blade and the turbulence produced in its own boundary layer and near wake. For zero angle of attack, at low Reynolds number based on the chord length, largely laminar boundary layers develop, whose instabilities result in regular vortex shedding and associated noise from the trailing edge [36]. The vortex shedding noise includes a main tone and a set of regular spaced side peaks due to a ladder-type structure for the dependency on the free stream velocity [37], whose mechanism was focused on by many researchers, and summarized by Doolan [38]. A recent experimental study found an improved understanding that the effective tone noise generation requires the incoming T-S waves to be amplified by a separated boundary layer first [39]. Therefore, if the proposed biomimetic structures can control vortex shedding mode, it would be feasible to reduce the airfoil noise. In order to verify the validation of noise reduction by the proposed biomimetic structures, three-dimensional numerical simulations were conducted, utilizing the large eddy simulation (LES) and the aeroacoustic analogy of Ffowcs-Williams and Hawkings [40]. These were used for comparing aerodynamic and acoustic performances of the NACA 0012 and biomimetic airfoils at an angle of attack 0°. The difference of the wake flow structure between the two airfoils is addressed in order to explain the noise reduction properties of the biomimetic airfoil.

2. Computational details

2.1. Descriptions of the biomimetic model

The biomimetic airfoil was created utilizing a loft feature with detailed dimensions illustrated in Fig. 1. Two outlines are the NACA 0012 airfoil profile with a fixed chord, c, of 100.9 mm, a span of 100 mm and a guide curve, which has an arc with the radius of 7.1 mm. The overall length of the biomimetic airfoil in flow direction is 2.1 mm larger than the chord length of NACA 0012 airfoil. However, compared with NACA 0012 airfoil, the maximum thickness of biomimetic airfoil does not change. The biomimetic airfoil has three typical characteristics including leading edge waves, trailing edge serrations and surface ridges (Fig. 2).

2.2. Mathematical model and solving methods for flow simulations

Large Eddy Simulations (LES) were performed first to simulate aerodynamic characteristics, often applied to solve similar issues [41]. Sound pressure levels at the observer points were then calculated from the fluctuating surface pressure on the airfoils based on the Ffowcs Williams and Hawkings (FW-H) equation [40].

Governing equations employed for LES are obtained by filtering the time-dependent Navier-Stokes equations, details of which are given in ANSYS Fluent Theory Guide [42]. The large scale eddies may be resolved directly utilizing this approach, while small eddies are modeled. A filtering variable is defined as: