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# Experimental and numerical investigation of aerodynamic performance for airfoils with morphed trailing edges

Hasan Kamliya Jawahar [a, b], Qing Ai [a, c, *], Mahdi Azarpeyvand [a]

[a] University of Bristol, Bristol, BS8 1TR, United Kingdom
[b] Department of Aerospace Engineering, University of Bristol, Bristol, BS8 1TR, United Kingdom
[c] Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, United Kingdom

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## ABSTRACT

The aerodynamic performance of a NACA 0012 airfoil with morphing flaps were studied experimentally and numerically. Comprehensive aerodynamic measurements including pressure distribution, lift and drag forces and wake flow for airfoils with different morphing flap camber profiles were carried out over a wide range of angles of attack and chord-based Reynolds numbers. The results show that the morphing flap camber profiles significantly affect the aerodynamic performance and the downstream wake development. It was found that the highly cambered flap profiles provide higher lift coefficients compared to the moderately cambered flap profiles, with an insignificant reduction in the overall lift-to-drag ratio. Furthermore, the *Q*-criterion iso-surface results show that the separation near the trailing-edge is further delayed at high angles of attack for airfoils with high flap camber. This study shows that the effective design space of the morphing flaps can be expanded by taking into account the optimal aerodynamic performance requirements. The study also suggests that in order to achieve optimum aerodynamic performance, an independent surface morphing of the suction and pressure surface camber will be required to delay the onset of flow separation.

## 1. Introduction

Sustainable and green energy including wind, solar and tidal energies have received significant growing attention in past decades due to public concerns over air pollution. As the main source of renewable energy, wind energy industries have been facing disruptive technological revolutions including new materials, increased turbine size and novel control methods for improved efficiency and reduced cost [1]. In the past decade, the turbine size, both in terms of the tower height and turbine length, has been continuously increasing. As such, traditional control methods for wind turbine blades, the pitch and yaw, is losing their virtues considering the efficiency under control tasks like tower load control, gust load mitigation, turbine load management and fatigue load reduction. In order to address such issues, various new passive and active control methods have been considered [2–4].

Featuring active and prompt responses to dynamic operation conditions, shape-adaptive structures are enabling wind turbine blades and aeroplane wings for improved performance with reduced weight and complexity penalty. Containing smooth geometric changes and continuous structural surfaces, these compliant light-weight control surfaces, which are increasingly known as morphing structures, remain conformal to the flow. As such, significant aerodynamic performance improvement and noise reduction are envisaged through morphing structures. The research motivation of this paper is to investigate the flow behaviours and performance enhancement mechanisms of morphing trailing-edges for airofoils, which is of fundamental importance in development and application of these novel high-lift devices for the next generation of wind turbine blades.

Morphing structures have received significant interest from engineering community including wind energy, aviation and automobile industries, owing to their potential of high performance, low-mechanism complexity and light-weight [5]. Current high-lift systems mainly consist of discrete rigid structured components, which are articulated around hinges and linkages to achieve wing shape change for flow control purposes. As such, the overall system complexity and structure weight are considerably

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[*] Corresponding author. Advanced Composites Centre for Science and Innovation (ACCIS), United Kingdom.

*E-mail addresses:* hasan.kj@bristol.ac.uk (H. Kamliya Jawahar), qingai.aero@outlook.com (Q. Ai), m.azarpeyvand@bristol.ac.uk (M. Azarpeyvand).

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**Nomenclature**

| | |
|---|---|
| $b$ | trailing-edge flap length, m |
| $c$ | airfoil chord length, m |
| $C_L$ | lift coefficient |
| $C_{L,max}$ | maximum lift coefficient |
| $C_D$ | drag coefficient |
| $C_p$ | pressure coefficient |
| $k$ | turbulent kinetic energy, $m^2/s^2$ |
| $l$ | airfoil span length, m |
| $L_x \times L_y \times L_z$ | cell dimensions of computational grid |
| $p_{ref}$ | reference pressure ($=2 \times 10^{-5}$), Pa |
| $Q$ | second invariant of the velocity-gradient tensor, $1/s^2$ |
| $Re_c$ | chord-based Reynolds number |
| $S$ | wing area, $m^2$ |
| $U$, $U_\infty$ | mean velocity, freestream velocity, m/s |
| $\overline{u'u'}$ | streamwise Reynolds normal stress component |
| $\overline{v'v'}$ | crosswise Reynolds normal stress component |
| $x$, $y$, $z$ | streamwise, crosswise and spanwise coordinates, m |
| $y^+$ | dimensionless wall distance |
| $\alpha$ | angle of attack, ° |
| $\beta$ | morphing flap tip deflection angle, ° |

increased. Unlike the conventional high-lift wing control surfaces, morphing structures usually use the conformal structural deformation to adaptively change wing shape, leading to simplified systems and reduced weight. Furthermore, the continuous deformation shape and smooth surface in morphing structures are expected to significantly reduce the associated aerodynamic noise, particularly the cavity type noise present in the hinged-flap configurations.

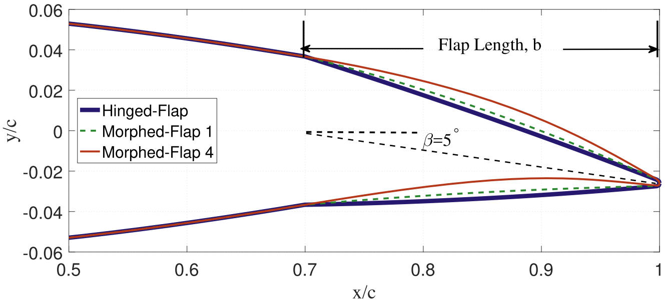
Studies have shown that the deformation shape and curvature of the morphing structure significantly affects the aerodynamic performance of the airfoils. Daynes et al. [4] showed that a morphing flap can provide the same change in the lift coefficient with a 30% less tip deflection compared to a hinged flap of equal flap length. This enhanced control effectiveness is believed to originate from the differing mean camber profiles between the airfoils. Wolff et al. [6] conducted a two-dimensional numerical investigation of a wind turbine airfoil fitted with morphing trailing-edges and found that the deformed morphing trailing-edge significantly affects the lift coefficient and stall behaviour of the airfoil. Results showed that the changes to the lift coefficient are dependent on the size, curvature and deflection angle of the deformed trailing-edge and strongly curved deformed trailing-edge can produce lower maximum lift-to-drag ratio and also increased the root bending moment coefficient compared to a gently curved deformed trailing-edge. Yokozeki et al. [7] developed a morphing airfoil concept using corrugated structures and wind tunnel tests of the demonstrator showed that the morphing wing presented superior properties in lift coefficient compared to a reference wing using the conventional flap, which was believed to result from the seamless morphing deformation. Ai et al. [8] proposed a novel morphing trailing-edge design using honeycomb core of axial variable stiffness and proved that introducing variable stiffness materials into the morphing structures could change the actuation energy of the system. Preliminary modelling has also shown that tailoring of the flap morphing profiles, significantly affects the aerodynamic and aeroacoustic performance of the airfoil. While the aerodynamic and aeroacoustic performance of other passive methods, such as serrations [9–11], surface conditioning [12] and porous treatments [13] etc, have been the subject of much research, which the morphing trailing-edges have not received.

Even though continuous progress has been made on the structural aspects (*e.g.*, compliant mechanisms, smart actuators drivers, piezoelectric actuators *etc.*) of morphing devices over the last decade, detailed understanding and documentation of the aerodynamic performances of morphing structures are lacking. In this paper, detailed experimental and numerical studies have been performed to investigate the aerodynamic performance of morphing flaps on airfoils. A NACA 0012 airfoil is chosen for the tests and fitted with a series of flaps having different flap camber profiles but with the same flap tip deflection and surface area. Wind tunnel tests including aerodynamic forces measurements and wake development analysis were carried out. High-quality CFD studies were also carried out to further investigate the flow structures, boundary layers and shear stresses influencing the aerodynamic performance.

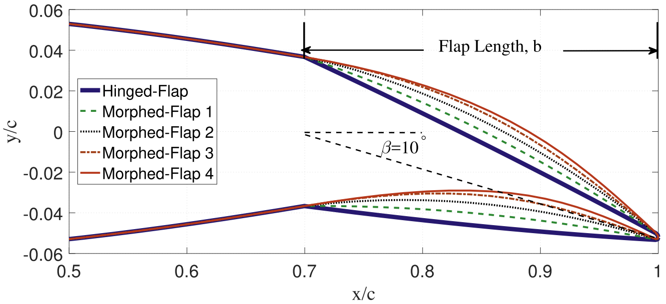
## 2. Experimental and computational setup

### 2.1. Airfoil model setup

A NACA 0012 airfoil model with a chord length of $c = 0.2$ m and a span length of $l = 0.45$ m was manufactured using RAKU-TOOL® WB-1222 polyurethane board. The airfoil was designed with an interchangeable trailing-edge section with a chord-wise length of $b = 0.06$ m ($0.3c$), see Fig. 1. Several trailing-edge flap profiles with different flap angles were manufactured and tested. The flap deflection angle ($\beta$) is defined as the ratio of the morphing flap



(a) $\beta = 5°$



(b) $\beta = 10°$

**Fig. 1.** Geometric details of NACA 0012 airfoil with different flap profiles employed in the current study for deflection angle $\beta = 5°$ (top) and $\beta = 10°$ (bottom).