Coupled Morphing of Leading and Trailing-Edge Aerofoil for Improved Aerodynamic and Aeroacoustic Performance

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Keywords: Morphing Aerofoil, Unsteady Aerodynamics, Aeroacoustics, Dynamic Morphing, Dynamic Mesh

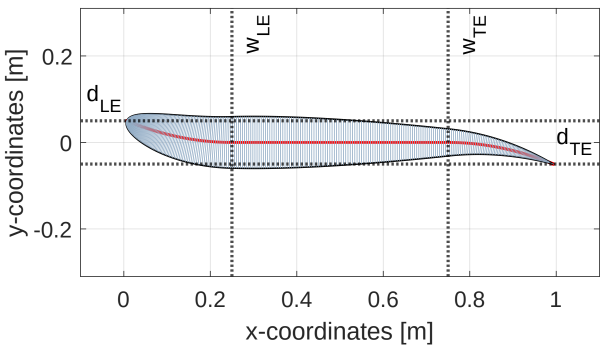

Figure 1: Example of a NACA-4 digit showing out-of-phase morphing. Where w_{LE} & d_{LE} is the start location of the leading edge morphing and deflection position respectively. w_{TE} & d_{TE} is the start location of the trailing edge morphing and deflection position respectively.

Extended Abstract

Inspired by nature, this study aims to investigate the impact of in-phase and out-of-phase dynamic morphing frequencies and amplitudes on the aerodynamic and aero-acoustic response of an aerofoil. The primary focus is to apply the coupled harmonic motions of both leading and trailing edges to further advance previous studies of Abdessemed et al. [1] and Zi et al. [2], who investigated the aerodynamic and aero-acoustic aspects of the dynamic morphing of wing aerofoil leading and trailing-edges separately. The present approach enables a comprehensive examination of dynamic flow interactions between the leading and trailing-edge deformations, and associated phase frequency and amplitude. Therefore we can improve and optimise designs for both aerodynamic performance enhancement and noise reduction. An experimental study previously by Jodin et al. [3] demonstrated considerable reductions of up to 5% pressure drag and 20dB of dominant frequency, together with a 2% increase in lift for a hybrid A320 morphing wing concept, using a high-frequency low-amplitude approach. The work presented here provides a systematic approach towards the design and evaluation of highly adaptable aerofoils that have the potential to significantly improve performance compared to traditional rigid aerofoils.

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Table 1: Results of baseline comparison

Averaged Coefficients	URANS (SBES)	URANS De Gennaro et al. [7]	Experiment Sheldahl and Klimas [8]
C_L	0.45	0.46	0.44
C_D	0.0073	0.0071	0.0083
C_L/C_D	63	64	53

The approach of Zi et al. [2] is adopted to enable the deforming of the leading and trailing-edge of an aerofoil. This is achieved by the introduction of grid node positions of the leading-edge, mean camber line and trailing-edge angle of deflection, as seen in Figure 1. In order to replicate this aerofoil profile, a slope integration method is used to determine the aerofoil coordinates for further numerical studies - completed in two steps. Firstly, a panel code XFOIL [4] version 6.99 is used, similar to that of Woods et al. [5], to provide fast performance evaluations over a wide range of angle of attack (AoA), followed by computational fluid dynamics (CFD) using ANSYS® Fluent 2022R1 software. Figure 2 presents a comparison of both XFOIL and steady RANS predictions alongside wind tunnel data of Rivero et al. [6] for Fish Bone Active Camber (FishBAC) aerofoil (instead of both leading and trailing-edge deformation). Morphing is initiated at 75% of the cord and a Reynolds number of 0.54×10^6 with a velocity of $30\,\mathrm{m\,s^{-1}}$. Several turbulence models are considered including the one-equation SA model and the two-equation SST model and its transition model TSST. A precursor mesh-independence study was also performed, before the main simulations. The CFD model implemented the trailing-edge deflection angles derived from the transverse displacement measurements by Rivero et al. [6]. The numerical analysis of lift behaviour broadly captures the expected trends from experimental results providing validation to our modelling assumptions.

This CFD study continues with unsteady RANS simulation over some deformation cycles until statistically converged results are achieved. Table 1 shows the CFD predicted aerodynamic performance in terms of lift and drag coefficients, in comparison with experimental data of Sheldahl and Klimas [8]. Here steady URANS adopts stress-blended eddy simulation (SBES) and URANS shows time-averaged mean results. It is worth noting that both SBES and URANS models, as seen

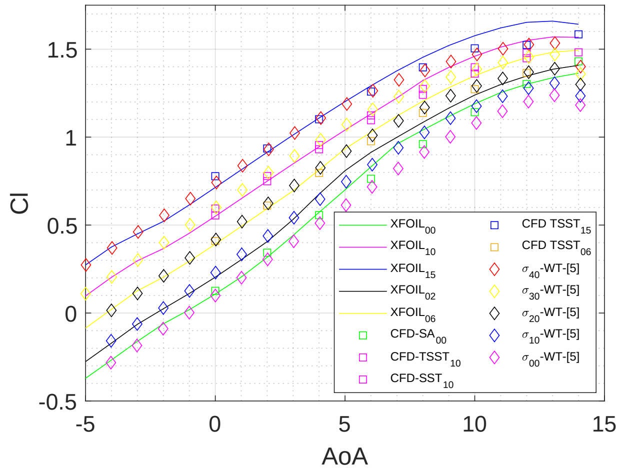

Figure 2: NACA23012 C_L vs AoA; XFOIL, Fluent and experimental (WT- [6]).

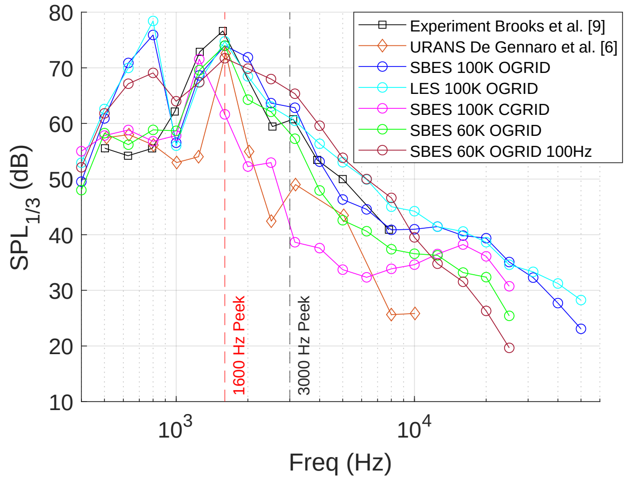

Figure 3: Sound Pressure Level (SPL) in one-third octave band of a NACA0012.

in Table 1, under-predicted C_D and over-predicted C_L. The inconsistency observed may stem from the limitations of the 2D model, as it inherently fails to capture the complexities of 3D flow behaviour. In essence, the aerofoils are subjected to a three-dimensional flow field in which vortices forming in the boundary layer can significantly influence the aerodynamic and aero-acoustic characteristics.

The Aero-acoustic study considers the same aerofoil configuration with Reynolds number of 0.62×10^6, Mach number of 0.115 and angle of attack (AoA) of 4°. The Ffowcs Williams-Hawkings (FW-H) [9] integral method was used to quantify the sound pressure level in 1/3 Octave at the pre-defined receiver location 1.2c. In addition, using User Defined Function (UDF) within ANSYS® Fluent 2022R1 is implemented, this allowed the study to investigate dynamic morphing cases where the amplitude and frequency's of morphing are predefined within the code. Figure 3 gives the CFD predictions, in comparison with wind tunnel measurement of Brooks et al. [10] and the CFD predictions of De Gennaro et al. [7]. The results from the SBES model demonstrate a correlation between the amplitude decay and the increase in frequency, aligning with the experimental findings. Additionally, the analysis successfully predicted the primary peak frequency at 3 kHz.

Our results demonstrate that the behaviour of a highly adaptive aerofoil (morphing both leading and trailing-edge) can be successfully analysed using the approach of Zi et al. [2] together with with slope integration method. Both the panel method and CFD predictions confirm the validity of the approach in comparison to experimental data for both the performance curve and time-averaged lift/drag coefficients. The Aero-acoustics predictions, applying the FW-H method, are generally in good alignment with published wind tunnel data and CFD results. Further studies will focus on the underlying flow physics, such as vortex shedding from trailing-edge, K-H vortex/boundary-later integration, and wake dynamics, capturing this will allow greater insight into the dominating aerodynamic and aero-acoustics characteristics of the aerofoil. The complete manuscript will include detailed data analysis, quantification and exploration of the aerofoil's behaviour. Studies exploring 3D aerofoil geometry are beyond the scope of the current work.

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