The Effect of Corrugated Skins on Aerodynamic Performance

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Abstract

Corrugated skins provide a good solution to morphing wings due to their highly anisotropic behavior. If the low stiffness corrugation plane is aligned in the chordwise direction the airfoil shape change is possible. In contrast to the traditional smooth skin of an airfoil, a corrugated skin influences both the local and global aerodynamics of a wing. The aim of this study is to investigate the effect of a corrugated skin on the global aerodynamics of an airfoil, particularly lift and drag characteristics. First, the aerodynamic analysis of a NACA 0012 airfoil with a smooth profile is conducted, both in the wind tunnel and by CFD, at different Reynolds numbers, and compared to the data in the literature. The lift and drag coefficients at different angles of attack, between $-10^\circ$ and $10^\circ$, are considered. Next, two NACA 0012 airfoils with different sized corrugated profiles are investigated both experimentally and by numerical simulation. The effect of corrugation size and Reynolds number are analyzed, quantified relatively to the standard NACA0012 airfoil with a smooth skin. Preliminary numerical results are validated using the experimental data.

1. INTRODUCTION

The concept of morphing aircraft is attracting a lot of attention as it could yield higher aerodynamic performance than the conventional fixed wing aircraft. Although there is a significant progress in adaptive structures for morphing wings \cite{1}, research on morphing skins \cite{2} is relative behind. Corrugated laminates offer a solution due to their extremely anisotropic behavior. Compliance in the chordwise direction, which assumed to be the corrugation direction as well, allows shape change and increase in surface area. In contrast, stiffness in the spanwise direction (transverse to the corrugation) enables the aerodynamic and inertial loads to be carried. There are many papers on the estimation of the equivalent stiffness of corrugated panels \cite{3-12}, however the aerodynamic investigation for corrugated skins is rarely found in the literature, although the aerodynamic performance plays a key role in the application of corrugated skins.

It is generally believed that the non-smooth surface is not suitable for an aerodynamic profile operating in high Reynolds number as it has relatively poor aerodynamic performance, generating low lift and high drag. However in nature some insects, dragonflies, damselflies, and others have corrugated wing profiles \cite{13} which operate in relatively low Reynolds numbers. Rees \cite{14} indicated that at very low Reynolds

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number around $10^3$ to $10^4$, a well-designed corrugated wing profile could reach a similar level of aerodynamic performance compared to traditional streamlined airfoils.

Lissaman [15] reviewed different types of low Reynolds number airfoils and mentioned a critical Reynolds (Re) number of about 70,000. Below this number, because of relatively large viscous effects, the maximum lift-to-drag ratio of rough airfoils is higher than the conventional smooth profiles; however above this value the roughness of the profiles plays an important role and smooth airfoils have higher values of lift-to-drag ratio. Although there have been many experimental investigations [16-18] and computational fluid dynamics (CFD) [19] simulations for the corrugated profiles, the majority of previous studies were conducted at very low Reynolds numbers. Hu and Tamai [20] investigated the aerodynamic performance of bio-inspired corrugated airfoils by using the (particle image velocimetry) PIV technique at Re=34,000. Murphy and Hu [21] conducted further studies at Re number range of 58,000-125,000. Whitehead et al. [22] and Thill et al. [23] performed wind-tunnel tests and CFD analysis of airfoils with corrugated skins in the aft 1/3 of the chordwise section at Reynolds numbers between 250,000 and 1,000,000.

The aim of this study is to investigate the effect of a corrugated skin on the global aerodynamic response of an airfoil, particularly on lift and drag coefficients. First, the aerodynamic analysis of a NACA 0012 airfoil with a smooth profile is conducted, both in the wind tunnel and by CFD, at different Reynolds numbers, and compared to NACA0012 data in the literature. The lift and drag coefficients at different angles of attack, between -10° and 10°, are considered. Next, two NACA 0012 airfoils with different sized corrugated profiles are investigated both experimentally and by numerical simulation, at different Reynolds numbers. The effect of corrugation size and Reynolds number are analyzed and compared to the standard NACA0012 airfoil with a smooth surface.

2. RESEARCH PROCEDURE

2.1 Model

The NACA0012 airfoil is chosen as the base airfoil for this study. Two NACA 0012 airfoils with different sized corrugated profiles are chosen for further analysis of the effect of the corrugated skin, shown in Figure 1. The labels COR01 and COR02 are used to indicate the two corrugated profiles. These models have a chord length $c$ of 178 mm and round corrugation shapes with radius $R=0.5\%c$ for COR01 and 1$\%c$ for COR02.

![Figure 1. Analysis models of NACA0012 airfoil with round corrugations](Chord normalized airfoil dimensions)
2.2 Wind-tunnel Setup

The aerodynamic experiments were conducted in a low speed, open circuit, and closed test section wind tunnel with octagonal cross test section[24, 25]. At the inlet, an aluminum honeycomb flow-straightener and a fiberglass mesh is used to condition the flow. Flow velocity during the tests is observed using four static ports at the inlet of the test section. The test section was converted to a 610 mm by 152 mm rectangular cross section for two-dimensional experiments with the use of two removable splitter plates shown in Figure 2.

![Wind Tunnel Setup Diagram](image)

**Figure 2.** The wind tunnel experimental setup. Note that the upper and lower walls of the test-section and fairing around the sting are omitted.

All parameters are controlled and measured automatically with a National Instruments (NI) cDAQ data acquisition system and a personal computer. A total of 16 channels are monitored using four NI 9239 four channel, isolated, 24-bit voltage input cards. The output signals are generated using two NI 9263 16-bit, four channel voltage output cards. For each test point, a 20 second data is sampled at 100 Hz and then averaged to get the mean value.

Barlow et al.[26] suggests several corrections due to the existence of the walls around the airfoil. The solid blockage term $\epsilon_{sb}$ and the wake blockage terms $\epsilon_{wb}$ described by Rae et al.[26]. The wind tunnel wall effects and buoyancy corrections were applied as necessary using the standard techniques found in Barlow et al.[26]. The reported corrected lift and drag coefficients are calculated by:

$$C_l = C_{lu}(1 - \sigma - 2\epsilon_{sb} - 2\epsilon_{wb}) \quad (1)$$

$$C_d = C_{du}(1 - 3\epsilon_{sb} - 2\epsilon_{wb}) \quad (2)$$

The uncorrected lift and drag coefficients, $C_{lu}$ and $C_{du}$, are calculated by:

$$C_{lu} = F_{lift}/(0.5\rho c b r v_{q_c}^2) \quad (3)$$

$$C_{du} = F_{drag}/(0.5\rho c b r v_{q_c}^2) \quad (4)$$

The streamwise turbulence of the flow in the empty test section is measured by a standard Hot Wire Anemometry technique. The probe is placed at the centre of the test section (aligned approximately at the quarter chord location along the streamwise direction) for all turbulence tests. After proper conversion of the measured voltages to velocity ($V$), the turbulence intensity ($TI$) is calculated by:

$$TI = \frac{V_{rms}}{V_{mean}} \times 100, \text{ where } V_{rms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (V_i - V_{mean})^2} \quad (5)$$
where the index $i$ represents each sample. Turbulence intensity is measured at several velocities for different filter settings. Based on the test results, the turbulence intensity of the wind tunnel, for the 2D test section, is $T/I = 0.075\% \pm 0.01\%$, which is derived from 2.5 Hz-10 kHz band-pass filtered signal for the velocity range of 5-30 m/s.

The experimental analysis was conducted at chord Reynolds numbers of around 120,000, 240,000 and 360,000. Each of the three profiles was measured over the angle of attack range from $-10^\circ$ to $10^\circ$ with the angle step of $0.5^\circ$.

### 2.3 Computational Procedure

The ANSYS/Fluent 14.0 software was used for the CFD analysis, and ANSYS/Gambit 2.4.6 software was used for the mesh generation. A total of 553,990, 1,731,200 and 2,086,400 quadrilateral cells were generated for the NACA0012, COR01 and COR02 models respectively. Sufficient numbers of cells were used so that the mesh was fine enough to ensure convergence. The mesh in the near-wall area, which needs to meet the $y+$ constraint based on the turbulence model, is generated within the boundary layer of each model. Figure 3 shows the mesh for COR01.

As the Mach numbers in this study are low, incompressible flow is considered for the fluid model. Furthermore, steady flow is considered. Velocity inlet and pressure outlet boundary conditions are used in the far-field. The k-ε turbulence model with enhanced wall treatment was used to estimate the viscous effect. The SIMPLE scheme was used to solve the pressure-velocity coupling. For the spatial discretization, PRESTO! was used for pressure, and a second order upwind scheme is chosen for the momentum equation. Only the 2-D solver was used for the analyses.

The calculations were performed at Reynolds numbers of around 120,000, 240,000 and 360,000, for comparison with the experiment study. Each of the three profiles were simulated over the angle of attack range from $-10^\circ$ to $10^\circ$ with a step $1^\circ$ for each Reynolds number.

![Figure 3. Mesh of COR01 (1,731,200 cells)](image-url)
3. RESULTS AND DISCUSSION

3.1 Validation

The experimental and computational results of the NACA 0012 are compared to the experimental results published in the literature. As there is a limited amount of literature with aerodynamic data at the Reynolds numbers, we use the drag and lift factor data in Ref. [27] at the Reynolds number of $1.0 \times 10^6$ for comparison of the trend, which are higher than the test environment for the current study.

![Figure 4. 2D lift and drag coefficient comparison of NACA0012 at different Re](image)

![Figure 5. Drag characteristics of NACA0012 at different Re](image)

Figure 4 show the lift and drag characteristics of the NACA0012 from both wind tunnel tests and CFD analyses. The experimental lift coefficient results are well predicted by the CFD results. The slope of the lift coefficient curves ($\partial C_l/\partial \alpha$) are predicted correctly in the test range and the lift-to-drag ratio increases with increasing Re number. These trends matched with the literature [27].

3.2 The Effect of Corrugation Size

Figures 6(a)-8(a) present the lift coefficient response of the NACA0012, COR01, COR02 airfoils at different Reynolds numbers. For each positive angle of attack, from smooth airfoil (NACA0012) to the
small-corrugation airfoil (COR01), then to the large-corrugation airfoil (COR02), the lift coefficient is reduced. From these figures we conclude that the slope of the lift coefficients curve (\(\partial C_l/\partial \alpha\)) decreases with increasing the size of the corrugation for the range of corrugations that are examined. Figures 6(b)-8(b) present the lift-drag ratio response of the NACA0012, COR01, COR02 airfoils at different Reynolds numbers. For each positive angle of attack, the drag coefficient increases with the increased size of the corrugation.

Loftin and Smith [27] mentioned that the minimum drag coefficient of the airfoil with roughed leading edge is higher than the airfoil with smooth leading-edge. It is also reported in Ref. [27] that the lift-curve slope of an airfoil with smooth surface is larger than the airfoil with roughness. In our study, as expected, the corrugations reduced the lift-curve slope (\(\partial C_l/\partial \alpha\)) and lift-drag ratio (\(\partial C_l/\partial C_d\)).

Figure 6. 2D lift coefficient and lift-drag ratio comparison at Re=120,000

Figure 7. 2D lift coefficient and lift-drag ratio comparison at Re=240,000
3.3 The Effect of Reynolds Number

Figures 9-10 present the comparison of the lift coefficient and lift-drag ratio for the COR01 and COR02 airfoils at different Reynolds numbers. The results suggest that a slightly larger lift-curve slope ($\partial C_l/\partial \alpha$) is obtained by increasing the Reynolds number from 120,000 to 360,000. Unlike smooth airfoils, the aerodynamic performance of corrugated airfoils at low angles of attack, quantified in terms of lift-to-drag ratio, has tiny variation as the Reynolds number is increased.
3.4 Flow Behavior of Corrugated Airfoils

Figure 11 shows the static pressure coefficient distribution around the corrugated airfoil (COR01) at an angle of attack of 5° and at Re=240,000. Figure 12 illustrates the local streamlines around the corrugations. These figures show that the local flow sustains an attached flow (outside the corrugation troughs). The eddies fill the troughs of the corrugations and 'smooth' the shape of the corrugated structure so that the flow outside the corrugation is similar to that around streamlined airfoils.
3. CONCLUSION

This article investigated the two-dimensional aerodynamic effect of chordwise corrugations in a two-dimensional NACA 0012 airfoil in terms of lift and drag coefficients by using both experimental and computational methods. It was found that the lift-curve slope (\(\partial C_l/\partial \alpha\)) decreased and the minimum drag coefficient (\(C_d\)) increased with the increasing size of corrugation (i.e. the roughness of the skin). The results for the corrugated airfoils suggest that a slightly larger lift-curve slope (\(\partial C_l/\partial \alpha\)) is obtained by increasing the Reynolds number from 120,000 to 360,000. Unlike smooth airfoils, the aerodynamic performance of corrugated airfoils at low angles of attack, quantified in terms of lift-to-drag ratio, has tiny variation as the Reynolds number is increased. The CFD flow field plots show that the local flow sustains an attached flow (outside the corrugation troughs). The eddies fill the troughs of the corrugations and ‘smooth’ the shape of the corrugated structure so that the flow outside the corrugation is similar to that around streamlined airfoils.

Based on this study, in-depth simulations and wind-tunnel experiments will be conducted to further understand the effect of a) corrugation size and geometry; b) Reynolds number; c) turbulence intensity and the choice of turbulence model; d) aerodynamic performance at large angles of attack.

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References


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