Influence of the Wavelength of Cut-In Sinusoidal Trailing Edge Shape to the Aerodynamics Characteristic of the Airfoil

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Abstract
The influence of the cut-in sinusoidal trailing edge shape with different wavelengths on the aerodynamics characteristic has been parametrically investigated by numerical unsteady RANS simulation, open-source code; Code_Saturne. The results were compared with the benchmark baseline and blunt profile trailing edge shape. The geometry of NACA0012, NACA4412 and NACA4415 airfoil with a small modification to obtain a zero thickness trailing edge are selected as a baseline profile. The blunt trailing edge is a cut-offs at the trailing edge for 10% of the chord. Three wavelengths of sinusoidal trailing edge shape at 0.25c, 0.50c and 0.75c with 0.05c amplitude are selected, where c is the airfoil chord length. The flow is studied at high Reynolds numbers (Re) 10^6 for the angle of attack 5 degrees. The results show the change in lift and drag characteristics with changing of NACA profiles and the modified trailing edges.

1. Introduction
There is evidence that the turbulent boundary layer (henceforth TBL) trailing edge noise is one of many causes of an airfoil self-noise [1-2]. It is now well established that a modification of the trailing edge geometry could reduce this noise [2-6]. The main challenge faced by many researchers is the NACA0012 with cut-in sinusoidal trailing edge shape at "Re" =5000 and the angle of attack 5 degrees provides 10% more of the lift force compare with the baseline trailing edge shape. However, it may cause the drag penalty of 2.5% [7].

The specific objective of this study was to extend the investigation of an airfoil with cut-in sinusoidal trailing edge shape in ref [7] at the high Re. Cross-sectional profiles were NACA0012, NACA4412 and NACA4415. The trailing edge shape was a cut-in sinusoidal shape. The first aim is to understand the aerodynamics characteristics due to the changes of wavelengths of the sinusoidal
shape. The second one is to investigate the influence of camber on the flow. Finally, this study set out to assess the effect of thickness of asymmetric airfoil’s profile to the flow.

2. Theoretical approach

2.1 Total drag prediction

Physically, the aerodynamic forces are calculated by the pressure \( (P) \) and wall shear \( (\tau_w) \). If the total lift force and the total drag force on the airfoil are predicted, the lift and drag coefficient can then be estimated by

\[
C_L = \frac{\text{Total lift}}{0.5 \rho V^2 sc}
\]

and

\[
C_D = \frac{\text{Total drag}}{0.5 \rho V^2 sc}
\]

where \( \rho \) is the fluid density, \( c \) is the aerofoil’s chord, \( s \) is the span.

The airspeed \( (V) \) is considered in term of Reynolds number,\n
\[
Re = \frac{\rho V L}{\mu}
\]

which based on airfoil characteristic length \( (L) \) and where \( \mu \) is the fluid viscosity.

To predict the accurate aerodynamic forces of the flow pass fully immersed body, Reynolds Averaged Navier Stokes (RANS) simulation has proved to provide a reasonably accurate result.

2.2 RANS

By assuming the flow is incompressible, the continuity equation and the momentum equation can be written as:

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0
\]

\[
\rho \left( \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} \right) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left\{ \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right\} - \rho \frac{\partial u'_i u'_j}{\partial x_j}
\]

where \( i \) is Cartesian coordinates in \( X, Y \) and \( Z \) and \( U_i \) are the Cartesian mean velocity components \( (U_x, U_y, U_z) \). The Reynolds stress tensor \( (\partial u'_i u'_j) \) is represented in the turbulence closure.

2.3 Code Saturne

The Code Saturne has been proposed which can solve the Navier-Stokes equations for various types of flow. This open-source software is based on a co-located Finite Volume approach and SIMPLEC type algorithm that accepts three-dimensional meshes. It can be built on any type of cell (tetrahedral, hexahedral, prismatic, etc.). The ready-to-used graphic user interface and capability for parallel code coupling make it simple for any user. The code is selected and validated by many references [8-10]. The unsteady solver is selected in this work and a RANS-Shear Stress Transport (SST) turbulence model with wall function, implemented in the Code_Saturne is employed. Second, the order linear upwind (SOLU) scheme is selected to discrete convection terms. The time step is 0.01 s with at least 20000 iterations. The selected criterion for convergence is RMS residual, which is less than \( 10^{-8} \). The run type used in this study is Intel CORE i7, 4 logical cores, with 2GB RAM.

3. Numerical modelling

3.1 Airfoil modelling

As shown in Figure 1, the profile of NACA0012, NACA4412, NACA4415 is modelled for 1 m chord length \( (c) \). To obtain a zero thickness trailing edge (TE), the geometry with small modification is chosen as a baseline profile, as shown in Figure 2 (a). As can be seen from Figure 2 (b), the blunt TE is selected by cutting the baseline profile at 0.9c from the leading edge. Figure 2 (c) provides the sinusoidal equation that is implemented into the trailing edge to build the cut-in sinusoidal TE.

\[
\bar{x}(z) = c - h - h \cos \left( \frac{2\pi}{L} z \right)
\]
As shown in the equation illustrated above, the symbolic variables can be defined as: \( c \) is the chord length, \( h \) is the waviness amplitude and \( \lambda \) is its wavelength, \( \bar{x}(z) \) is the physical coordinate in the chord direction (x-axis), and \( z \) is the spanwise coordinate in the computational domain. While \( s \) is the span-wise length of the computational domain. Table 1 provides a list of TE’s parameter used in this study.

![Figure 1. NACA0012, NACA4412 and NACA4415.](image)

![Figure 2. Airfoil with baseline, blunt and cut-in sinusoidal trailing edge shape.](image)

Table 1. Parameters of the sinusoidal trailing edge.

| Case | baseline | blunt | L25 | L50 | L75 |
|------|----------|-------|-----|-----|-----|
| \( s/c \) | 0.125 | 0.125 | 0.125 | 0.250 | 0.375 |
| \( \lambda/c \) | 0 | 0 | 0.25 | 0.50 | 0.75 |
| \( h/c \) | 0 | 0 | 0.05 | 0.05 | 0.5 |

3.2 Model domain and boundary condition

The fluid domain extends up to 20\( c \) and 20\( c \) in the upstream and downstream direction (x), respectively. And it can be extended up to \( s/c \) in the span-wise direction (z) (see Table 1). Symmetry conditions are imposed at both side boundaries. The flow inlet velocity (\( V \)) used in this experiment is 1 m/s with 1% turbulent intensity. A fluid density (\( \rho \)) is a 1 kg/m\(^3\), and dynamics viscosity (\( \mu \)) is \( 10^{-6} \) Pa.s. It consists of the chord \( Re = 10^6 \). An aerofoil surface is implemented with smooth wall condition.

An appropriate mesh strategy and mesh resolution are set to capture the effect of the boundary layer and wake flow. Consequently, the result obtained showed high fidelity. The sample of domain mesh is presented in Figure 3. As Figure 4 shows, there is an isometric view of the structure mesh of airfoil and side meshes. A structured mesh with local refinement is built around aerofoil and in the wake regions. The study included the refinement at the walls (\( y^+ \approx 30 \)) in accordance with the selected model so-called 2 scales (log law) wall function that is also implemented in the Code Saturne.

4. Result

4.1 Mesh convergence

To assess the accuracy of the numerical simulation, the mesh convergence was used. Figure 5 shows the result of mesh convergence. Due to the simplicity of structured mesh, the convergence of meshing from coarse (50k), medium (100k), medium-fine (150k) to the fine mesh (200k) can be obtained for
$C_L$ and $C_D$. Regarding the accuracy and time consumption prospect, the medium mesh was selected in this study.

Assessment of the results for the baseline TE was carried out using a comparison of Xfoil’s estimation and experimental data from the references [11] and [12].

4.2 Interpretation of forces results

The chord length ($c$) is an important parameter for estimating of $C_L$ and $C_D$. $C_L$ and $C_D$. It can be scaled in two ways. The first one is to scale by using the physical chord length $c = 1$ m, $0.95$ m and $0.9$ m for baseline, cut-in and blunt TE, respectively. Second, it can be carried out by using the baseline chord length $c = 1$ m.
These results were found to be different. This inconsistency may be different scaling. This result may be explained by the fact that the ratio of lift and drag coefficient ($C_L/C_D$) for both cases are the same (see Figure 6). For example, the NACA 4412 was found to be better performance than 4415 and 0012. The results obtained from $C_L/C_D$ show a similar trend for modified TE. The finding showed that the lowest and the highest of $C_L/C_D$ are NACA with blunt TE and baseline TE. It is possible; therefore, that the wavelength has no effect on $C_L/C_D$ of NACA with cut-in sinusoidal TE.

Table 2 presents the percentage differences of lift coefficient ($\%C_L$) and drag coefficient ($\%C_D$) of modified TE airfoils compared to baseline TE airfoil using both scalings. The equations are as follows:

$$\%C_L = \frac{C_L, \text{modified TE} - C_L, \text{baseline}}{C_L, \text{baseline}} \times 100\%,$$

$$\%C_D = \frac{C_D, \text{modified TE} - C_D, \text{baseline}}{C_D, \text{baseline}} \times 100\%.$$

|      | $\%C_L$ (using physical chord lengths) | $\%C_D$ (using physical chord lengths) | $\%C_L$ (using baseline chord length) | $\%C_D$ (using baseline chord length) |
|------|----------------------------------------|----------------------------------------|--------------------------------------|--------------------------------------|
|      | 0012 | 4412 | 4415 | 0012 | 4412 | 4415 | 0012 | 4412 | 4415 | 0012 | 4412 | 4415 |
| blunt| 7.8  | 0.6  | 8.1  | 58   | 33   | 40   | -3.0 | -9.5 | -2.7 | 42   | 20   | 26   |
| L25  | 4.5  | -0.4 | 5.3  | 24   | 13   | 16   | -0.7 | -5.4 | 0.0  | 18   | 7    | 11   |
| L50  | 4.4  | -0.1 | 4.1  | 23   | 10   | 11   | -0.8 | -5.1 | -1.1 | 17   | 5    | 6    |
| L75  | 4.6  | -0.1 | 4.4  | 24   | 10   | 12   | -0.6 | -5.1 | -0.8 | 18   | 4    | 6    |

Note: ‘Minus’ sign of $\%C_L$ means the decreasing of lift when compared with baseline TE.

4.3 Scaling with physical chord lengths

In this section, $C_L$ and $C_D$ of airfoils have been scaled by the physical chord lengths, $c = 1\, m$, 0.95 m and 0.9 m for baseline, cut-in and blunt TE, respectively (see Figure 7). Table 2 shows $\%C_L$ and $\%C_D$ for modified TE compared with baseline (see column 2-7 above).

4.3.1. Blunt and baseline TE

By comparing the blunt TE with baseline, the results of 0012 revealed that lift increases by 7.8% and drag penalty up to 58%. The effect of the trailing edge shows a significant difference between the symmetric airfoil (0012) and the airfoil with camber (4412). In contrast, it shows less drag penalty (25%) for 4412 than that of 0012.

The results of the baseline TE suggest that the airfoil 4412 provides more drag than 0012 (with the blunt TE). On the other hand, the airfoil 4412 provides less drag than 0012.

The 8.1% increasing of lift and 44% of drag penalty for 4415 shows that the airfoil with camber (44xx) and the thicker airfoil 4415 provide higher lift than that of 4412 except for higher drag penalty.
4.3.2. Influence of cut-in sinusoidal trailing edge shapes

To compare the cut-in sinusoidal TE with a baseline for 0012, all wavelengths were found to exhibit a similar trend of increasing lift about 4.4% to 4.6% with the drag penalty 23% to 24%. An implication of this is the possibility that the wavelength does not effect for 0012.

Regarding 4412, all wavelengths showed a similar trend of lift decreasing 0.1% to 0.4% with the drag penalty 10% to 13%. This result may be explained by the fact that the influence of cut-in sinusoidal TE can be observed from comparing 0012 and 4412. We can see that the effect of camber is almost vanished for drag. Both NACAs has similar drag.

For 4415, the results show the influence of wavelength. While there is 5.3% lift increment, and 16% drag penalty for L25. The data showed similar results for L50 and L75, increasing of lift by 4.1% to 4.4% and increasing of drag by 11% to 12%. To compare 4412 and 4415, the effect of the cut-in sinusoidal trailing edge is used for the thicker airfoil, with a small increase of drag penalty.

Figure 7. $C_L$ and $C_D$ scaled by $c = 1$, 0.95 and 0.9 m for baseline,

![Figure 7](image)

Figure 8. $C_L$ and $C_D$ scaled by baseline chord length $c = 1$ m.

4.4 Scaling with baseline chord length $c = 1$ m

As can be seen from Figure 8, it provides the results obtained from $C_L$ and $C_D$ of the airfoil which scaled by $c = 1$ m. The $\%C_L$ and $\%C_D$ is also represented in Table 3 (Columns 8-13).
As shown in Table 3, the lift coefficients of the modified TEs are higher than the baseline case when the physical length \((c = 1, 0.95\) and \(0.9\) m. for baseline, cut-in and blunt TE, respectively) is used (see columns 2-4). It can thus be suggested that it is lower when \(c = 1\) m is used (columns 8-10).

Regarding the comparison of the blunt TE and the baseline TE, the lift is reduced more than 2.7% for all profiles. While comparing cut-in sinusoidal TE with baseline, all wavelengths showed a similar trend of decreasing of lift and was less than 1.1% for 0012 and 4415 and it can decrease from 5.1% to 5.4% for 4412.

The results of the comparison of the influence of airfoil’s characteristics were camber, thickness, and the lift and drag. The results indicated the same trend as in the previous discussion (see Section 4.3).

5. Conclusion

This study set out to present the cut-in sinusoidal trailing edge shape with three wavelengths (0.25\(c\), 0.50\(c\) and 0.75\(c\)) with 0.05\(c\) amplitude is parametrically investigated by numerical unsteady RANS simulation, open-source code; Code_Saturne. The results obtained were used to compare with the benchmark baseline and blunt profile trailing edge shape. This study has identified the geometry of NACA0012, NACA4412 and NACA4415 airfoil with a small modification to obtain a zero thickness trailing edge, and to be used as a baseline profile. This study has found that generally the cut-off baseline TE at 10% of chord from the trailing is modelled as the blunt trailing profiles. The flow is simulated at high \(Re\) of \(10^6\) for the angle of attack 5 degrees.

The influence of wavelength on aerodynamics characteristic has been observed. One of the more significant findings to emerge from this study is that the wavelength does not have an effect on \(C_L/C_D\) of NACA with cut-in sinusoidal TE. It also suggests that modification of TE can increase the lift coefficient with a drag penalty (when aerodynamics coefficients are calculated using physical chords of the airfoils).

The research has also shown that the drag penalty of an airfoil with modified TE occurs from 20% and up to 50%, and it depended on the TE shape. The results of this research support the idea that the desired modified modelling recommended from this study is the magnitude of \(C_D \approx 0.1C_L\), the 8% increase of lift with 40% of drag penalty in case of blunt TE or the 5.3% of lift increment with 16% of drag penalty in case of cut-in sinusoidal TE of NACA 4415. These data suggest that the modified TE with the same airfoil thickness can be achieved through using a cambered profile rather than the symmetric profile.

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