Notation

- $c$: chord length
- $o$: flap overhang
- $y$: main element-flap gap
- $\alpha$: flap deflection
- $x$: horizontal position
- $C_D$: total drag coefficient
- $C_L$: total lift coefficient
- $C_{Lf}$: flap lift coefficient
- $C_{Lm}$: main element lift coefficient

Subscript

- $D$: drag
- $L$: lift
- $Lf$: flap lift
- $Lm$: main element lift

1. INTRODUCTION

The generation of noise by airfoils is of interest over a vast number of disciplines. Wind turbine blades generate noise which influences people residing in the neighbourhood. Aircraft airframes as well as turbomachinery generate significant amounts of noise. Over the years there has been an effort to reduce the noise generated through these by changes in design as well as working conditions. With an increase in the stringency of norms regulating the generation of noise, it has become ever more important to understand and control the process.

Among the foremost industries where aeroacoustics finds relevance is the aerospace industry. Airframe noise emanating from high-lift devices of an aircraft when landing forms a major portion of the total noise generated [1]. In a comprehensive study on the self-noise created by airfoils, Brooks et al. [2] presented 3 main generation mechanisms based on the Reynolds number and angle of attack:

- Turbulent Boundary Layer – Trailing Edge (TBLTE) noise
- Laminar Boundary Layer – Vortex Shedding (LBL-VS) noise
- Separation – Stall (S-S) noise

TBL-TE takes place at high Reynolds numbers, due to the development of turbulent boundary layers over large regions of the airfoil. LBL-VS occurs at lower Reynolds numbers, due to vortex shedding caused by instabilities. SS occurs due to large scale separation created at large angles of attack. Attached or separated boundary layers generate broadband noise, whereas laminar boundary layers generate whistles, due to the development of vertical disturbances [3].

Over the years, Computational Fluid Dynamics (CFD) has proved an efficient tool to simulate fluid dynamics phenomena, including boundary layer and vortex shedding. This makes possible the simulation of aeroacoustic processes, which has been increasingly done using CFD and Computational Aeroacoustics (CAA). De Gennaro et al. [4] validated the use of CFD with the transitional k-ω [5] model for an isolated NACA 0012 airfoil, while Stepanov et al. [6] did the same for application in the aeroacoustic analysis of rotor blades with NACA 0012 airfoil section. Caicedo and Virk [7] conducted a multiphase numerical study of the aeroacoustic response of NACA 0012 airfoil, testing RANS, LES and DES approaches. Hosder et al. [8] created a CFD-based noise metric for the modelling of aerodynamic noise and conducted dimensional studies to validate the same.

Appendages such as flaps and slats are often included in airfoils in order to supplement the lift experienced by it. These appendages may also supplement the noise created by the airfoil. While flaps provide a large amount of lift, slats pre-
vent the separation of airflow over the main part of the airfoil. Dobrzynski et al. [9] showed that while slat noise dominated at lower frequencies, flap side-edge noise tended to at higher frequencies.

The deflection of flaps in airfoils is used to modulate the lift and drag generated by the airfoil across a range of applications, and lead to major changes in the same. Similarly, an increase in airfoil camber has also been shown to impact the lift and drag experienced by it. However, these changes in design are also bound to generate noise. Going through literature available, it is evident that computational research on the impact of flap deflection on the noise created by cambered airfoils is minimal. There is hence a need for a parametric investigation into the impact of flap deflect and camber on the noise created by airfoils. This study is an effort in the direction. The effect of flap deflection has been studied on non-cambered, moderately-cambered and highly-cambered airfoils in order to assess various parameters such as turbulence intensity, surface acoustic power level, self-noise and shear noise over the surface of the airfoil.

2. METHODOLOGY

A 2-dimensional (2D) CFD simulation was performed with the NACA 0012 (0% maximum camber), NACA 4412 (4% maximum camber) and Eppler 423 (9.5% maximum camber) airfoils as the main element of the airfoil and the high-lift Selig 1223 as the flap airfoil for all three configurations. Flap deflection was varied from 0° to 30°.

2.1. CAD Geometry

A 2D geometry for the analysis was created using SolidWorks 2018. It consisted of the main airfoil of chord length c and the flap of length 0.25c. The flap overhang o was of length 0.03c and the gap between the flap and the main airfoil at the trailing edge y was 0.02c. The deflection of the flap α was varied in each analysis. The geometry is shown in Fig. 1.

2.2. Computational Domain

In order that efficient visualisation of the wake region and pressure contours of the airfoil is possible, a large computational domain is opted for. The length from the inlet and vertical walls to the airfoil is 10c, and the length from the airfoil to the outlet is 15c [10]. The inlet is modelled as a semicircle in order that changes in angle of attack may be achieved without altering the geometry. The computational domain is shown in Fig. 2.

2.3. Meshing

The mesh was generated using ANSYS ICEM Mechanical. A high quality mesh was created with a base element size of 50 mm. A grid independence test was carried out in order to ascertain this length. Prismatic cells were used in order to model the boundary layer at the airfoil, allowing for cells of high aspect ratio, while reducing excessive stream-wise resolution. In order that flow close to the airfoil was predicted accurately, the first grid point y" was maintained close to 1.

Tab. 1 summarizes the number of elements and skewness characteristics for the 3 main airfoils studied. Fig. 3 shows the generated mesh.

<table>
<thead>
<tr>
<th>Main Airfoil</th>
<th>No. of Elements</th>
<th>Minimum Skewness</th>
<th>Maximum Skewness</th>
<th>Average Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA 0012</td>
<td>1,78,432</td>
<td>1.3x10^-10</td>
<td>0.119</td>
<td>7.6x10^-3</td>
</tr>
<tr>
<td>NACA 4412</td>
<td>1,79,943</td>
<td>1.3x10^-10</td>
<td>0.125</td>
<td>7.7x10^-3</td>
</tr>
<tr>
<td>Eppler 423</td>
<td>1,79,990</td>
<td>1.3x10^-10</td>
<td>0.128</td>
<td>7.7x10^-3</td>
</tr>
</tbody>
</table>

Fig. 3: Mesh generated for analysis
2.4. CFD Model

A 2D CFD analysis of the airfoils was conducted on ANSYS Fluent 18.2 [11]. The numerical model used for the analysis was the two-equation shear stress transport (SST) k-ω turbulence model, where k is the turbulent kinetic energy while ω is the specific turbulence dissipation rate [12]. The SST model considers values of shear stress, thus increasing the near-wall accuracy of the calculation. The transport equations of k and ω are given as follows.

\[
\frac{\partial (p k)}{\partial t} + \frac{\partial (p k u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \Gamma_k \frac{\partial k}{\partial x_i} \right] + \bar{G}_k - Y_k + S_k
\]  

(1)

\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{\partial (\rho \omega u_i)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \Gamma_\omega \frac{\partial \omega}{\partial x_i} \right] + \bar{G}_\omega - Y_\omega + D_\omega + S_\omega
\]  

(2)

Where

- \(\bar{G}_k\) represents the generation of \(k\) due to mean velocity gradients,
- \(\bar{G}_\omega\) represents the generation of \(\omega\),
- \(\Gamma_k\) and \(\Gamma_\omega\) represent the effective diffusivity of \(k\) and \(\omega\) respectively, which are calculated as described below.
- \(Y_k\) and \(Y_\omega\) represent the dissipation of \(k\) and \(\omega\) respectively,
- \(D_\omega\) represents the cross-diffusion term,
- \(S_k\) and \(S_\omega\) are user-defined source terms.

The broadband noise-based acoustic model solver was used in conjunction, with a far field sound speed of 340 m/s and a far-field density of 1.225 kg/m³, while the reference acoustic power was 10⁻¹² W. Linearized Euler Equations (LEE) extend Lighthill’s Analogy [13], dealing with only small perturbations. Linearized around a stationary mean flow, they may be written as follows [14].

\[
\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + H = S
\]

(3)

Here,

\[
U = \begin{pmatrix} \rho' \\ \rho' u' \\ \rho' v' \\ \rho' w' \end{pmatrix}
\]

\[
E = \begin{pmatrix} \rho' u_0 + \rho' u' \\ u_0 \rho' u' + p' \\ u_0 \rho' v' + \gamma p' \\ u_0 \rho' w' \end{pmatrix}
\]

\[
F = \begin{pmatrix} \rho' v_0 + \rho' v' \\ v_0 \rho' v' + p' \\ v_0 \rho' w' + \gamma p' \\ v_0 \rho' w' \end{pmatrix}
\]

\[
H = \begin{pmatrix} 0 & 0 & 0 & 0 \\ (\rho' u_0 + \rho' u') \frac{\partial u_0}{\partial x} + (\rho' v_0 + \rho' v') \frac{\partial u_0}{\partial y} \\ (\rho' u_0 + \rho' u') \frac{\partial v_0}{\partial x} + (\rho' v_0 + \rho' v') \frac{\partial v_0}{\partial y} \\ (\gamma - 1)(\rho' v_0 + \rho' v') \frac{\partial p_0}{\partial x} - \gamma v_0 \frac{\partial p_0}{\partial y} \end{pmatrix}
\]

Where \(\rho', p', u', v', w', \) are the density, pressure and velocity respectively of the mean flow and \(\rho, P, \) and \(u\) are small perturbations superimposed on it.

The total drag and lift of the airfoil, as well as the individual lifts of the main element and the flap element were taken as output parameters. Analyses were carried out between flap deflection angles of 0° to 30°, at a gap of 15° between consecutive analyses. After all deflections had been analyses for one main airfoil, it was replaced by the next in the geometry. Each analysis was terminated when residuals of continuity, x-velocity, y-velocity, k and \(\omega\) all reached 10⁻⁷, ensuring high precision of results reported.

2.5. Grid Independence Test

In order to determine a base size for the mesh elements, a grid independence test was performed. The SST k-ω turbulence model was utilized for the analysis of an isolated NACA 0012 airfoil with an inlet velocity of 30 m/s. Grids with base element sizes 150 mm, 100 mm, 50 mm and 25 mm were studied. The values of pressure coefficient (\(C_p\)) over the surface of the airfoil were plotted against the relative horizontal chord position (\(x/c\)). The results of the analysis are presented in Fig. 4.

![Grid Independence Test](grid_independence_test.png)

As is evident from the figure, the values of pressure coefficient for element sizes 150 mm and 100 mm deviate highly from others, while the values for sizes 500 mm and 25 mm are nearly concordant. Giving due consideration to the time of computation, which is higher for small elements, the element size 50 mm was chosen for further analysis.

2.6. Validation

The numerical model used in the study was validated by comparing values of pressure coefficient over the surface of an isolated NACA 0012 airfoil with those obtained by Marsden et al. [15] using CFD code and Lee and Kang [16] through
an experimental study. The values of pressure coefficient are plotted against x/c. The results are shown in Fig. 5. The values obtained through the current numerical methods are seen to be in close agreement with the reported values.

![Validation Study](image)

**Fig. 5:** Results of present study validated against CFD results of Marsden et al. and measurements of Lee and Kang

3. RESULTS AND DISCUSSION

Analysis was carried out in order to predict characteristics such as lift coefficient and drag coefficient as well as graphs of turbulence intensity, surface acoustic power level and self and shear noise from x-directional sources and y-directional sources at flap deflections 0°, 15° and 30°. Three different airfoils with main elements NACA 0012, NACA 4412 and Eppler 423 were studied. The results are discussed in subsequent sections.

3.1. Analysis with Main Element NACA 0012

The total drag coefficient \( C_D \) and total lift coefficient \( C_L \) as well as the components contributed by the main element \( C_{L_{m}} \) and flap \( C_{L_{f}} \) at various flap deflections are summarised in Tab. 2.

![Table](image)

**Tab. 2:** Aerodynamic characteristics of airfoil with main element NACA 0012

Both lift coefficient and drag coefficient are seen to exhibit a considerable increase between flap deflections 0° and 30°. The increase in drag coefficient may be attributed to the increase in frontal area with increase in flap deflection. The presence of a flap increases the curvature of the airfoil, which causes the air to flow with a slower velocity under the airfoil. This in turn increases the pressure under the airfoil, producing lift. With increasing flap deflection, the curvature also increases, increasing lift. It is also observed that the lift coefficient of the flap is a substantial part of the total lift coefficient of the airfoil.

![Fig. 6](image)

**Fig. 6:** Contours of turbulence intensity for \( \alpha = 0°, 15° \) and 30° with main element NACA 0012

Fig. 6 presents the contours of turbulence intensity over the airfoil, while Fig. 7 contains graphs of turbulence intensity over the surface of the airfoil. An increase in flap deflection is found to produce an increasingly large region of flow separation, leading to an increasingly turbulent wake. The surface turbulence intensity on the suction side of both the main element and flap of the airfoil is found to increase with an increase in flap deflection, with a substantial increase being observed on the flap surface. This is due to adverse pressure gradients steepening with increase in angle of attack.
Fig. 7: Graph of turbulence intensity across airfoil profile for \( \alpha = 0^\circ, 15^\circ \) and \( 30^\circ \) with main element NACA 0012

Fig. 8 presents graphs of surface acoustic power level over the surface of the airfoil. It is evident from the figure that the noise produced by the airfoil at a point has a direct correlation with the turbulence intensity observed at the point. The surface acoustic power level is observed to increase particularly on the flap, with increase in flap deflection. A sudden increase in this quantity is observed around \( x/c = 0.97 \), where the flap is located. The presence of the flap introduces a constrain in the flow, producing an acceleration that increases velocity and produces a region of increasingly low pressure. The turbulence caused by this phenomenon produces the peak in noise observed. A similar peak in surface acoustic power level is observed at the trailing edge of the flap. Due to the turbulent boundary layer passing the sharp trailing edge of the flap, the hydrodynamic turbulent energy is scattered, producing the noise. This trailing edge noise is observed to increase with angle of attack. This is in concordance with similar experimental results reported by Hutcheson and Brooks [17].

Fig. 8: Graph of surface acoustic power level across airfoil profile for \( \alpha = 0^\circ, 15^\circ \) and \( 30^\circ \) with main element NACA 0012

Figs. 9 and 10 contain the graphs of self and shear noise respectively due to X and Y-directional sources. It is observed that both self and shear noise follow trends similar to those of turbulence intensity and surface acoustic power level. The leading edge of the main airfoil, and the leading edge of the flap are observed to be regions of particularly high noise generation. When the leading edge of an airfoil interacts with turbulence structures in the free stream, large-scale pressure fluctuations are produced. This leads to turbulence, and the amplified unsteady lift generates broadband noise [18].
Significant peaks in noise are also observed at the trailing edges of the main element and the flap. This is the trailing edge noise caused due to interaction of the sharp trailing edge with the turbulent boundary layer, as mentioned previously. It is also noted that Y-directional sources (perpendicular to the direction of flow) are dominant at greater flap deflections. Tollmien-Schlichting waves are initiated due to the interaction of sound with the leading edge of the airfoil, and grow in amplitude (a y-directional source) along the airfoil.

![Graph of LEE self-noise across airfoil profile for α = 0°, 15° and 30° with main element NACA 0012](image)

**Fig. 9: Graph of LEE self-noise across airfoil profile for α = 0°, 15° and 30° with main element NACA 0012**

3.2. Analysis with Main Element NACA 4412

Tab. 3 summarises the total drag coefficient $C_D$ and total lift coefficient $C_L$ as well as the components contributed by the main element $C_{Lm}$ and flap $C_{Lf}$ at various flap deflections on an airfoil with main element NACA 4412.

<table>
<thead>
<tr>
<th>α</th>
<th>$C_L$</th>
<th>$C_{Lm}$</th>
<th>$C_{Lf}$</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.726</td>
<td>0.712</td>
<td>0.014</td>
<td>0.024</td>
</tr>
<tr>
<td>15°</td>
<td>1.829</td>
<td>1.538</td>
<td>0.291</td>
<td>0.0220</td>
</tr>
<tr>
<td>30°</td>
<td>2.471</td>
<td>2.063</td>
<td>0.407</td>
<td>0.0354</td>
</tr>
</tbody>
</table>

**Tab. 3: Aerodynamic characteristics of airfoil with main element NACA 4412**

Both lift coefficient and drag coefficient show increasing trends with increase in angle of attack. The values for both...
quantities are considerably greater than those observed for the airfoil with main element NACA 4412 for all cases. This effect can be attributed to the increased camber. The increase in curvature causes air to flow at a greater velocity above the airfoil, producing a low pressure region which in turn contributes to greater lift.

Fig. 11 contains the contours of turbulence intensity over the airfoil, while Fig. 12 contains graphs of turbulence intensity over the surface of the airfoil. It is observed that the intensity of turbulence increases gradually with increase in flap deflection angle, as does the difference among the turbulence intensities of the upper and lower surfaces of the airfoil. The turbulence at the suction side is observed to increase over the airfoil with main element NACA 0012.

The graph of surface acoustic power level over the airfoil is shown in Figure 13. A similar trend to that observed for turbulence intensity is observed. The surface acoustic power is seen to increase over the airfoil with main element NACA 0012 on the suction side, and decrease on the pressure side. Similar results were obtained computationally by Lee [19], who observed that an increase in camber also produces low frequency noise of the suction side.
Fig. 13: Graph of surface acoustic power level across airfoil profile for $\alpha = 0^\circ$, $15^\circ$ and $30^\circ$ with main element NACA 4412

Fig. 14 and 15 contain graphs of the X and Y-directional LEE Self Noise and Shear Noise respectively. While the trend of the graph is similar to the graph for the quantities observed for the airfoil with main element NACA 0012, the noise levels are observed to be higher on the suction side. The increase in camber leads to increased adverse pressure gradient and boundary layer thickness on the suction side, which leads to an increase in the level of noise produced. When the leading edge of an airfoil interacts with turbulence structures in the free stream, large-scale pressure fluctuations are produced. This leads to turbulence, and the amplified unsteady lift generated broadband noise [18].
buted to the high camber of the Eppler 423 airfoil. However, the value of flap lift coefficient at 0° flap deflection is observed to be lower than for the other two airfoils. This is due to the region of low pressure and high turbulence generated below the airfoil due to its highly cambered shape, which causes flow separation very close to the leading edge. This also increases the drag on the airfoil.

Fig. 6 presents the contours of turbulence intensity over the airfoil, while Fig. 7 contains graphs of turbulence intensity over the surface of the airfoil. It is observed that at 0° flap deflection, a region of high turbulence is created close to the leading edge of the airfoil on the pressure side. Also, the trend of the graphs is seen to be similar to the graphs of turbulence intensity in the other airfoils. However, an increase in turbulence is observed on the suction side of the airfoil while a decrease is observed on the pressure side. A relatively lower turbulence intensity is observed at the leading edge of the flap. Due to the highly cambered shape of the main airfoil, the highly constricted region between the main element and the flap is relatively shorter, which ensures a reduction in turbulence.

3.3. Analysis with Main Element Eppler 423

Tab. 4 summarises the total drag coefficient $C_D$ and total lift coefficient $C_L$ as well as the components contributed by the main element $C_{Lm}$ and flap $C_{Lf}$ at various flap deflections on an airfoil with main element Eppler 423.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$C_L$</th>
<th>$C_{Lm}$</th>
<th>$C_{Lf}$</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.420</td>
<td>1.410</td>
<td>0.010</td>
<td>0.034</td>
</tr>
<tr>
<td>15°</td>
<td>1.617</td>
<td>1.286</td>
<td>0.331</td>
<td>0.021</td>
</tr>
<tr>
<td>30°</td>
<td>2.961</td>
<td>2.654</td>
<td>0.307</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Tab. 4: Aerodynamic characteristics of airfoil with main element Eppler 423

The values of lift and drag coefficients are observed to be the greatest among the three airfoils studied. This may be attri-

Fig. 15: Graph of LEE shear noise across airfoil profile for $\alpha = 0°$, 15° and 30° with main element NACA 4412

Fig. 16: Contours of turbulence intensity for $\alpha = 0°$, 15° and 30° with main element Eppler 423
Fig. 17: Graph of turbulence intensity across airfoil profile for $\alpha = 0^\circ$, $15^\circ$ and $30^\circ$ with main element Eppler 423

Fig. 18: Graph of surface acoustic power level across airfoil profile for $\alpha = 0^\circ$, $15^\circ$ and $30^\circ$ with main element Eppler 423

Fig. 18 shows the graphs for surface acoustic power level along the surface of the airfoil. This is observed to follow a similar trend to turbulence intensity, with the acoustic power increasing on the suction side and decreasing on the pressure side. The difference between the power observed on the suction and pressure side increases with flap deflection. A marginally lower surface acoustic power level is observed on the surface of the flap, and a trough close to $x/c = 1$ indicates a region of considerably low turbulence on the pressure side of the flap at the location. This can also be observed in Fig. 16.

Fig. 19 and 20 show the graphs for the X and Y-direction self-noise and shear noise respectively. A considerable increase in the high-noise region is observed over the previous two airfoils. This region is seen to increase with increase in the deflection of the flap. Similarly, a region of high noise is also observed on the suction surface of the flap, which increases with increase in flap deflection. The high camber of the main airfoil creates a considerably larger amount of disruption in the free stream, causing pressure fluctuations when turbulence structures interact with it. This in turn leads to broadband noise being created. The flap creates increasingly higher noise with increase in flap deflection, due to increase in the flow separation region.
Fig. 19: Graph of LEE self-noise across airfoil profile for $\alpha = 0^\circ$, $15^\circ$ and $30^\circ$ with main element Eppler 423

Fig. 20: Graph of LEE shear noise across airfoil profile for $\alpha = 0^\circ$, $15^\circ$ and $30^\circ$ with main element Eppler 423

4. CONCLUSION

2D CFD simulations were conducted using ANSYS Fluent in order to assess the impact of flap deflection and camber on the aerodynamic and aeroacoustic characteristics of airfoils. Analyses were conducted on airfoils with main elements NACA 0012 (maximum camber 0%), NACA 4412 (maximum camber 4%) and Eppler 423 (maximum camber 9.5%), with flap deflections $0^\circ$, $15^\circ$ and $30^\circ$. The following inferences can be drawn from the results:

1. The lift coefficient of an airfoil increases with increase in main element camber. It also increases with increase in flap deflection. The drag coefficient also increases with increase in these quantities.
2. The flap lift coefficient decreases with an increase in main element camber.
3. The turbulence intensity observed on the suction side of the airfoil marginally increases with increase in main element camber, and that on the pressure side marginally decreases. A similar trend is observed in surface acoustic power level.

4. The difference between the turbulence intensities observed at the suction and pressure side of the airfoil increases with flap deflection, as does the surface acoustic power level.

5. A direct correlation can hence be drawn between the turbulence intensity and surface acoustic power level.

6. The X and Y-directional self and shear stresses increase on the suction side with increase in main element camber. They also increase with an increase in flap deflection. Y-directional sources dominate at higher flap deflections.

REFERENCES


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