Aerodynamic and Wake Development of Aerofoils with Trailing-Edge Serrations

By

XIAO LIU

Department of Mechanical Engineering
UNIVERSITY OF BRISTOL

A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of DOCTOR OF PHILOSOPHY in the Faculty of Engineering.

NOVEMBER 2018

Word count: fifty three thousand
路途漫漫，灯塔是否依旧在彼方……
A comprehensive study of the aerodynamic performance and wake development of aerofoils fitted with different types of trailing-edge serrations is provided. A symmetric NACA 0012 and a cambered NACA 65(12)-10 aerofoils have been studied experimentally. Tests have been carried out over a wide range of angles of attack and Reynolds numbers. The aerodynamic force measurements have shown that the use of trailing-edge serrations can lead to significant reduction of the lift coefficient at low angles of attack for cambered aerofoils, while remaining negligible for symmetric counterparts aerofoils. The force measurements have also shown that the stall characteristics of the aerofoils do not change greatly as a result of the implementation of the trailing-edge serrations.

The wake flow characteristics have been investigated using Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and hot-wire anemometer in an attempt to improve the understanding of the wake development and the energy-frequency content of the wake turbulent structures associated with serrated trailing-edge. At relatively high angles of attack, where maximum lift-to-drag can be obtained, the turbulent kinetic energy and Reynolds stress results for the cambered aerofoils have shown that the wake flow turbulence can be greatly reduced in the aerofoil near wake region by using trailing-edge serrations, while that for the symmetric aerofoil were found to be less effective. The reduction of the wake turbulence for serrated cambered aerofoils is
believed to be due to a complex interaction between the flow field over the tip and root planes and three dimensional horseshoe and streamwise turbulent structures in the near-wake. The wake turbulence frequency-energy content results have also shown that the implementation of serrations can lead to significant reduction of the wake flow energy over a wide range of frequencies. The reduction of turbulence within the near wake offers a new possibility in reducing noise generated by wake-aerofoil interaction. This will have significant implications for industrial applications involving multiple rows of aerofoils such as contra-rotating propellers, rotor-stator configuration, canard-wing body configuration, etc.

As such, to investigate the effectiveness of trailing-edge serrations for reducing wake-aerofoil interaction, two cambered NACA 65-710 aerofoils were used to form a tandem aerofoil configuration, resembling contra-rotating propellers or rotor-stator configurations. The front aerofoil is fitted with different trailing-edge serrations to control the turbulence level of the gap flow and thus turbulence interaction with the rear aerofoil. To reveal the effects of serration on the tandem aerofoil configuration, the rear aerofoil was equipped with several pressure taps and surface pressure transducers. Flow experiments were performed using different serrations, for a number of tandem aerofoil configurations. The results show that the use of serrations at the high angle of attack (\( \alpha = 10^\circ \)), can lead to a significant reduction in turbulent kinetic energy of the wake flow field and over the rear aerofoil, and moreover a clear reduction in surface pressure fluctuations can be achieved over the leading-edge area of the rear aerofoil. The wake and surface pressure results have confirmed that the use of serrated trailing-edges can lead to notable reduction of wake turbulence and aerofoil interaction.
DEDICATION AND ACKNOWLEDGEMENTS

First, I would like to thank my supervisor, Dr Mahdi Azarpeyvand, who gave me the chance to join this project and advised and supported me throughout the project, and my second supervisor, Dr Raf Theunissen, for guidance and help during this project work.

Special acknowledgements go to my A2RG colleagues, who are always available to help and discuss problems. I feel blessed to have such friends by my side during the last four years. My sincere thanks to my dear friend, Syamir, for all the help during the corroboration of the project and spending countless hours in the office or laboratories with me. To Hasan and Yannick, for the excellent company during the project.

Also, special thanks go to all technicians who have been involved in building my test modes, particularly, Mr Neil Pearce and Mr Lee Winter.

Finally, to my parents, I would like to acknowledge your support. Without your understanding and encouragement, I would not have the chance to go this far to explore and learn. Thank you!

Xiao Liu

Queens Building, Bristol, United Kingdom.

June 2018
AUTHOR’S DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate’s own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .......................... DATE: ..........................
NOMENCLATURE

Roman Symbols

\( C_L \)  
Lift coefficient

\( C_D \)  
Drag coefficient

\( C_p \)  
Pressure coefficient

\( C'_p \)  
Pressure coefficient fluctuation

\( H_a \)  
Thickness of the aerofoil [mm]

\( H \)  
Slot depth of the slotted-sawtooth serration [mm]

\( L \)  
Aerofoil span [mm]

\( L_b \)  
Separation bubble length [mm]

\( R1, R2 \)  
First and second flow re-attachment location [mm]

\( Re \)  
Reynolds number

\( Re_c \)  
Chord-based Reynolds number

\( R_{p'p'} \)  
Signal autocorrelation

\( S \)  
Flow separation location [mm]

\( S_a \)  
Aerofoil cross-section area [m^2]

\( U_{\text{mean}} \)  
Total mean velocity [m/s]

\( U_0 \)  
Freestream velocity [m/s]

\( W \)  
Tandem aerofoil separation distance [mm]
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<th>Description</th>
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<tr>
<td>$c$</td>
<td>Aerofoil chord [mm]</td>
</tr>
<tr>
<td>$d$</td>
<td>Slot width of the slotted-sawtooth serration [mm]</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>$h$</td>
<td>Serration amplitude [mm]</td>
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<tr>
<td>$p$</td>
<td>Surface pressure [Pa]</td>
</tr>
<tr>
<td>$p'$</td>
<td>Surface pressure fluctuation [Pa]</td>
</tr>
<tr>
<td>$u,v$</td>
<td>Streamwise and normal velocity [m/s]</td>
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<thead>
<tr>
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<tr>
<td>$\alpha$</td>
<td>Angle of attack of the aerofoil [deg]</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>Serration angle [deg]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Serration periodicity wavelength [mm]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity [kg/ms]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity [m²/s]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Air density [kg/m³]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time delay [s]</td>
</tr>
<tr>
<td>$\phi_{pp}$</td>
<td>Surface pressure PSD [dB/Hz]</td>
</tr>
<tr>
<td>$\phi_{uu}$</td>
<td>Velocity PSD [dB/Hz]</td>
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<tr>
<td>AoA</td>
<td>Angle of Attack</td>
</tr>
<tr>
<td>CROR</td>
<td>Contra-Rotating Open Rotor</td>
</tr>
<tr>
<td>DNS</td>
<td>Direct Numerical Simulation</td>
</tr>
<tr>
<td>FoV</td>
<td>Field of View of the camera</td>
</tr>
<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
</tr>
<tr>
<td>LES</td>
<td>Large Eddy Simulation</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>RMP</td>
<td>Remote Microphone Probe</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound Pressure Level</td>
</tr>
<tr>
<td>TE</td>
<td>Trailing-edge</td>
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<tr>
<td>TKE</td>
<td>Turbulence Kinetic Energy</td>
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Journal papers:


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1.1 Motivation

The increasing popularity of air travel and rapid growth in the number of airports close to the cities have increased noise pollution, leading to negative physiological and psychological effects on people living in the vicinity of large airports and under busy flight paths. Stringent standards have, therefore, been set by the international and local authorities to reduce such impacts and noise at source by developing new technologies. Noise generated by jet transport aircraft can be broadly classified as airframe noise and engine noise. The engine noise can be divided into fan noise, combustion noise, turbine noise, and jet noise. The jet noise has been reduced considerably over the last half century by the introduction of high bypass ratio turbofan engines and the implementation of chevrons for improving turbulence mixing in the jet flow. However, the reduction of broadband noise from the compressor and turbine, due to the interaction of laminar and turbulent flows with blades, has remained a challenging task. Also, the noise from
rotating blades dominates the noise from large propeller-driven aircraft. Due to the complex nature of flow interaction with high-speed rotating blades and rapid changes to the effective angle of attack of the blades, characterisation and accurate prediction of the broadband noise from high-speed propellers is a difficult task. The noise from rotating blades in a uniform flow can, however, be generally categorised as trailing-edge noise, early separation and stall noise [12].

The aerodynamic noise produced by the rotating blades has been studied over the past decades. The noise from rotating blades, as a component of compressors and turbines, caused as a result of the interaction of turbulent flow from the front-blade with the rear-blade, has remained a challenging task. The noise generation mechanism of contra-rotating open rotor (CROR) propulsion systems has also attracted much research interest in recent years [18]. It has been shown that the interaction of the tip and wake flow caused by the front propeller with the rear blades is a significant source of noise; therefore, reduction of the front-blade wake turbulence intensity can significantly reduce the overall noise signature of the CROR system.

The reduction of blade trailing-edge noise has been investigated extensively over the past decade, and several methods have been proven analytically and experimentally with excellent noise reduction. However, the relationship between aerodynamic performance and aeroacoustic performance is still unclear. In this thesis, to expand the existing knowledge and better understand the aerodynamic performance of treated aerofoils with good acoustic performance (i.e. serrated trailing-edge), lift and drag measurements will be carried over a wide range of Reynolds number and angle of attack. To better understand the underlying physics of noise reduction using trailing-edge serration, Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and hot-wire measurements will be performed to understand the aerofoil wake development and tur-
bulence energy within the wake region.

Following from the result of the first part of the thesis, the possibility of reducing the turbulence level using serrations shows an option for a new technique for reducing noise generated due to wake-aerofoil interaction. This will have industrial implications for applications involving multiple rows of aerofoils, such as contra-rotating propellers, rotor-stator configuration, canard-wing body configuration, etc. Since the noise from rotating blades, as a component of the compressor and turbine, caused as a result of the interaction of turbulent flow from the front-blade with the rear-blade [18–22], the reduction of turbulence interaction noise has remained a challenging task and has been investigated extensively over the past decade.

As part of this project, the aerodynamic performance and the flow development of aerofoils in tandem configuration are investigated in this thesis. Detailed studies of the wake development and surface pressure fluctuations have also been carried out using the two-dimensional Particle Image Velocimetry (PIV) technique and pressure scanner. Thorough measurements have also been performed for pressure coefficient distributions on the rear aerofoil. The effect of serrations on the noise generation for the tandem NACA 65-710 configuration has also been studied by studying the surface pressure fluctuations on the rear aerofoil using the remote sensing probe method.


## 1.2 Literature review

### 1.2.1 Aerofoil self-noise mechanisms

Aerofoil self-noise and turbulence interaction noise are significant components of the overall noise from engines and airframe [23]. The aerofoil self-noise is also a dominant noise source of the modern wind turbines [24]. Aerofoil self-noise is produced when the flow field generated around the aerofoil, such as the boundary layer flow or the tip flow, interacts with the body of the aerofoil. In the study carried out by Brooks and Schlinker [12], under the subsonic flow conditions, the aerofoil self-noise is categorised into five groups. These five self-noise sources are: (a) *Trailing-edge noise* (Fig. 1.1a): Trailing-edge noise is the noise produced when the turbulent boundary layer over the surface of the aerofoil interacts with the trailing-edge, radiating as a dipolar noise source. (b) *Laminar boundary layer instability noise* (Fig. 1.1b): Boundary layer instability noise occurs at low Reynolds numbers, often for aerofoil at low angles of attack, and is due to the non-linear coupling between sound waves of the trailing-edge and the laminar boundary layer Tollmien-Schlichting waves, causing strong tones. (c and d) *Separation and stall noise* (Fig. 1.1c, d): At high angles of attack, the noise generated from the aerofoil will have a different characteristics to that of trailing-edge noise. The flow will contain large coherent structure with long spanwise coherence. At stall and deep stall, vortex shedding can also occur due to early or leading-edge separation, resulting in tonal behaviour at vortex shedding frequencies. (e) *Trailing-edge bluntness noise* (Fig. 1.1e): Trailing-edge bluntness can cause vortex shedding from the trailing-edge and emergence of tonal noise. (f) *Tip vortex formation noise* (Fig. 1.1f): Tip vortex formation noise results from the interaction of the highly turbulent vortex flow with the tip edge and the trailing-edge of the wing.
Figure 1.1: Aerofoil self-noise sources [12]: a) Turbulent boundary layer, b) Laminar boundary layer, c) Separation (Boundary-layer separation), d) Separation (deep stall), e) Trailing-edge bluntness, f) Tip vortex formation noise.
• Trailing-edge noise

The topic of trailing-edge noise, its underlying generation mechanism and methods to suppress the noise has been subject of much studies. Roger and Moreau [25, 26] reported that the trailing-edge noise is referred to the scattering of the boundary layer turbulence structures converted into acoustic energy by the geometrical discontinuity of the trailing-edge. A smaller vertical eddy, when convecting in a flow, is associated with pressure gradients that tend to balance the induced centrifugal forces. According to the law of thermodynamics, density variation is induced as a result of the pressure fluctuation from any inertia variation. Sound is then generated from such density variation. The rate of change in inertia is small when the vortical disturbances are parallel to a surface. Therefore, no noticeable sound is generated. However, far more efficient variations are expected at any geometrical singularity of the surface, such as in the vicinity region where a deep reorganization of the vortical structure takes place (i.e. at the trailing-edge of an aerofoil). This is why sound is mainly generated and radiated at the trailing-edge of the aerofoil as the vorticity in the boundary layer convects past. Broadband noise is generated from turbulent boundary layers attached or separated at the trailing-edge. Thus, the boundary layer characteristics, such as the boundary layer thickness, separation location, spanwise coherence of the turbulent structures, etc, play an important role in the level of noise generated [12]. The resulting trailing-edge noise is of dipolar or cardioid nature, and its acoustic power depends on the velocity raised to between the fourth and fifth power [27]. At low Mach number, the trailing-edge noise is in particular, strong at the trailing-edge due to the efficient scattering of the turbulent fluctuations over the solid trailing-edge [28]. In the next section, a review of the different flow and noise control methods used for the control of noise at sources will be provided.
1.2.2 Trailing-edge noise reduction method: passive flow and active flow

Various methods have been introduced and tried for controlling the trailing-edge noise at source. In this context, the noise and flow control techniques can be generally categorised as the active and passive methods. In the following, a literature review of the currently employed active and passive methods and their pros and cons is provided.

- **Active flow control methods**: Active flow control methods generally refer to the methods requiring external power, which can be switched on and off, depending on the flow condition and operation envelope, such as flow injection, suction, micro-jets, sweeping jets, etc [29]. Studies have been carried out on the effect of boundary layer injection and suction [30–42]: Early experimental and numerical studies by Antonia et al. [30], Park et al. [33] and Oyewola et al. [34] investigated the effects of applying uniform blowing (suction) into a turbulent boundary layer flow. For rotor-stator noise, using trailing-edge blowing was investigated extensively. Leitch [31, 32] experimentally studied the effects of adding mass flow at the trailing-edges of four stators upstream of an aircraft engine simulator. Results show that a noise reduction of 2.6 to 8.9 dB can be achieved by using trailing-edge blowing. Borgoltz [38] found large noise reductions of up to 6 dB by applying trailing-edge blowing on GE-Rotor-B blades. An average reduction of 2 to 3 dB in the broadband SPL was found by Sutliff [37] for a low-speed fan. Later, Winkler et al. [43] showed the use of trailing-edge blowing can lead to a successful reduction of noise by 2.9 dB to 4.1 dB for frequencies below 2 kHz. To reduce the trailing-edge noise, Koh [39, 40] investigated the use of a high-density gas (CO₂) injection into the boundary layer of a NACA 0012 aerofoil and it was shown that noise reductions (up to 4 dB) could be achieved in the frequency range of 0.6 and 3 kHz. Later, Wolf et al. [41] experimentally investigated the aerodynamics and aeroacoustics of wall-normal boundary layer
suction. The effect of boundary layer suction on the trailing-edge noise was studied by applying five individual suction chambers on a NACA 64\textsubscript{3}-418 aerofoil section. The results showed a reduction up to 3.5 dB. More recently, Szoke et al. [42], performed a comprehensive study of different active flow control methods on a flat plate with a sharp trailing-edge. Three flow control scenarios were investigated in this study, namely flow suction, injection and micro-jets. Results have shown that both flow injection and suction can deliver up to 10 dB/Hz reduction in surface pressure spectra over a wide range of frequencies.

**Passive flow control methods:** Passive flow control methods for aerodynamic noise mitigation normally involves geometrical modifications, such as applying porous materials, 3D riblets, chevrons or different types of serrations on the trailing-edge of aerofoils. Unlike the active flow control device, passive control devices are always in operation, and no additional energy is required, which leads to a lower cost [29]. In what follows, a brief review of some of the most used passive techniques for reducing aerofoil self-noise is provided, namely, porous materials, brushes, morphing, etc.

Howe [44] addressed a new mechanism to reduce trailing-edge noise by modifying the impedance properties of the trailing-edge. Based on his analytical model, a reduction of 10 dB or more is achievable using porous trailing-edges. Then porous treatment have been introduced into the serious of studies [8, 45–51]. Fink et al. [52] showed that introducing porous materials at the trailing-edge of a slat and at the trailing-edge of a flap can lead to a noise reduction of up to 2 to 3 dB. Bae et al. [53] later also investigated the effects of a porous surface on the turbulence noise generated by a blunt trailing-edge of a flat plate. Using incompressible LES, they computed the three-dimensional turbulent flow over the flat plate. Their results showed a 3–10 dB noise reduction over a wide range of frequency. More recently, Geyer [45, 46, 48] measured broadband trailing-edge
noise from a semi-symmetrical SD7003 profile aerofoils made with porous material with a chord length of 0.235 m and a span of 0.4 m. In his study, sixteen porous materials with different flow resistivity were used. Noise measurements were obtained and compared against the non-porous solid aerofoil. The results showed a reduction of about 10 to 20 dB of broadband trailing-edge noise. However, due to the flow resistivity decrease, for the porous aerofoil, the aerodynamic lift and drag of the aerofoil were observed to, respectively, decrease and increase significantly. Furthermore, an increase of the noise also occurred at high frequencies due to surface roughness. The use of brushes as a permeable surface for the reduction of trailing-edge noise has also been reported in the literature [54, 55]. A parametric study on brush-type trailing-edge provided by Herr and Dobrzynski [54] showed that a reduction of up to 10 dB can be achieved by this passive flow control method. In the study provided by Finez et al. [55], brushes made of a single row of flexible polypropylene fibres were integrated in the trailing-edge of a cambered aerofoil. The result showed noise reduction potential reaching 3 dB over a wide frequency range. In this study, space-time correlation measurements of the velocity in the wake were performed behind the brushes and showed a decrease of up to 25% of the spanwise correlation length in the trailing-edge region. More recently, morphing structure [56–59] and 3D surface treatments [60–62] have also been introduced into the subject of trailing edge noise control. While several passive methods have been tried in the past few decades, the use of serrations have been the most popular choice and has attracted much research interest [3–5, 63–70].

1.2.3 Trailing-edge serration treatment for noise reduction

**Biometrics design:** The study of the evolution of animals often provides us with new ideas to overcome complex engineering problems. In the context of aerodynamic noise, studies on owl’s wing structure and flight noise [71–73] showed that owl’s wing gen-
erates a low level of noise (under 2 kHz), which is lower than the minimum hearing threshold of their prey animals. The owl’s wing structures therefore became an interesting topic of research for its implications in terms of design of low noise lifting devices.

Different from other birds, the leading-edge of an owl’s wing has a comb-like streamed serrations, and the trailing-edge of the wing is fringe type and permeable [71]. These special adaptations were considered to result in their quieter flight. Feathers of owls’ wing were first studied by Garham [71] to determine the mechanisms for quieter flight. The following studies have been carried out since Graham’s work. A detailed comparison of the structural differences of the feather of the owl and other birds was made by Sick [74], and Hertel [75], which provided detailed microscopy pictures of the barbules of special feather structures of owl’s wing. Thorpe et al. [76] published the first results on acoustical measurements of owls during flapping flights. Following that, flight noise measurement of owls was done by Kroeger et al. [77], Gruschka et al. [78], and Neuhaus et al. [79] providing the first experimental evidence by comparing owls’ flight noise with other such as Mallard Ducks.

Bachmann et al. [13] conducted the morphometric characterisation of the barn owl wing feathers on a macroscopic level and compared the results with a bird that cannot deliver silent flight. Geyer et al. [80] carried out measurements of the noise generated by a Sparrowhawk and a Tawny Owl, as shown in Fig. 1.2. Later, Bachmann et al. [81, 82] provided noise measurements at natural flying conditions, i.e. flight path, flight speed etc., of different species of birds, including owls and nonquiet flying birds by using new measurement techniques. More recently, Geyer et al. [83, 84] presented and discussed the superior noise characteristics of owls. Flyover measurements of a barn owl, a harris hawk, and a common kestrel were carried out. The results, in agreement with previous studies, showed that owl’s silent flight can be observed mainly in the
mid-to-high frequency range (0.5 kHz to 6 kHz).

![Leading-edge ↔ | → Trailing-edge](image1.png) ![Leading-edge ↔ | → Trailing-edge](image2.png)

(a) owl (b) pigeon

Figure 1.2: Morphometric characterisation of the wing feathers (a) barn owl, (b) pigeon.

[13]

All these studies on the special structure of the owl’s feathers show a noticeable reduction of the noise generated during the flight. Based on this phenomenon, the possibility of transferring utilisable mechanics of the silent flight from owl to a technical application for designing a quieter aircraft was then introduced by Kroeger et al. [77] into the design of a quieter air-vehicle. Until now, some of these mechanisms, for example, serrations, have been studied and tested as a source of inspiration for designing a quieter air-vehicle.

**Trailing-edge serration treatment:** Early studies on the effects of trailing-edge serrations on aerofoil self-noise were performed in the 1970s by Kroeger et al. [77]. The study by Arndt et al. [85] for the use of trailing-edge serrations on a 60.96 cm diameter fan blades for a rotor speed of 840 and 1440 rpm showed a reduction of 4 – 8 dB. Herch et al. [86] also measured the far-field noise using sawtooth serrations with different amplitudes and ranges of angle of attack. Their results also confirm significant reduction of trailing-edge noise. Despite the clear experimental evidence for the efficacy of trailing-edge serrations for reducing aerofoil self-noise, the underlying physics of the noise reduction mechanism remained unknown for a long time. Understanding the noise reduction mechanisms can also be important for the development of alternative and effective noise reduction techniques based on the same principles. The first
attempt at assessing the effectiveness of serrations for trailing-edge noise was perhaps that of Howe’s [87–90]. Howe’s analytical investigations have shown that simple modifications, such as sawtooth and sinusoidal serrations to the trailing-edge, can reduce the efficiency of the aerofoil’s trailing-edge noise generation by introducing destructive sound interference. It is also believed this sound interference breaks the spanwise correlation length of the turbulence near the edge aiding in noise reduction. It was shown that the magnitude of the noise reduction depended upon the frequency, length, and the spanwise spacing of the serration teeth. Howe’s mathematical model also showed that optimal attenuation could be achieved with trailing-edge elements having sharpness larger than 45°. It was, however, noticed that Howe’s model overestimates the absolute noise reduction levels when compared to experimental data. A more recent analytical model developed by Lyu et al. [91–93] has shown better agreement with experimental data. The new model has shown that, in addition to the destructive interferences predicted by Howe, there also exists some constructive sound interferences. The comparison provided between the analytical model and finite element results have shown that such destructive and constructive interferences lead to a more realistic noise reduction, as observed in experimental works.

Dassen et al. [14] performed an experimental study on the effects of trailing-edge serrations for the reduction of aerofoil trailing-edge noise in 1996. In their study, wind tunnel measurements were carried out using eight aerofoils and six flat plates of 250 mm chord length, with different geometries (see Fig. 1.3). The results show the serrated flat plates lead to noise reductions of up to 10 dB from 1 to 6 kHz, while serrated aerofoils showed reductions of up to 8 dB. Various implementations of the serrations at the trailing-edge of a flat plate were tested. However, there is no significant effect greater than 2 dB found in the results. The noise results for the sawtooth serration with the flow at a sweep angle of 15° showed an increase at high frequencies. Furthermore, an
extensive detailed study of noise reduction capability of trailing edge serrations for 3D wind turbine blades were carried out. By applying the serrations to a full-scale wind turbine blade trailing-edge, the effects of length, position, and orientation of the teeth on the noise reductions were determined. This study included small-scale experiments, and the results showed that serrations can give an overall reduction of 2 dB at low frequencies and an increase of the noise at high frequencies at high incidence angles of attack. A number of studies were later carried out by Hagg et al. [94], Parchen et al. [95] and Schepers et al. [96]. Results were obtained by applying serrations on full-scale or mid-scale rotors. The issue of noise increase in the higher frequencies was also addressed by Parchen et al.[95] and Schepers et al. [96].

Figure 1.3: Survey of serrated flat plates in Dassen et al. [14] study

Parchen et al. in 1999 [97] carried out an experimental study using serrated trailing-
edges to verify Howe's theory [87–89]. Serrations were applied to both wind tunnel scale and full-scale wind turbines models (30.5 m diameter Lagerwey LW45 750 kW prototype wind turbine and 50.5 m diameter Nedwind 30 250 kW test wind turbine). The experiment results showed that around 6 dB of noise reductions could be achieved. This value confirmed that, compared to experimental measurement results, Howe's theoretical model predicted much larger noise reduction values. Furthermore, noise increases were found in the case of misaligned serrations. However, in the study by Gruber et al. [16, 98–100], this noise increase occurred at all angles of attack. Later, in 2005, another experimental study of serrated trailing-edges on an aerofoil was conducted by Herr [54], who introduced various configurations of brushes at the aerofoil trailing-edge. This trailing-edge treatment design is similar to the fringes attached to the owl’s trailing-edge wing. This can provide a smooth mix between the boundary layer pressure from both the pressure and suction sides of the wing. In Herr’s studies, various fibre diameters, fibres separation distance between and lengths of brush-serrations, were tested in a wind tunnel. The results show a noise reduction of 2 to 14 dB over a large frequency range. The longer trailing-edge brushes resulted in the more effective noise reduction. Herr suggests that this reduction may be caused by viscous damping of the unsteady turbulent velocities in the brush region. Herr [101] also provided further experimental results later by using a single row of fibres and slit type trailing-edges. In this study, the use of Comb-type and slit trailing-edges show a significant noise reduction (2-10 dB). The length of the fibres and fibre diameter and the separation distance between fibres were found to be the critical parameters for achieving noise reduction. The length of the fibres was required to be at least the boundary thickness or larger. The fibre diameter and the separation distance between fibres were found to be as close as possible to the inner scales in the turbulent boundary layer, typically an almost zero spacing of the comb fibers (< 0.1 mm).
Experimental investigations on full-scale wind turbine blades were carried out by Oerlemans et al. in 2009 [15]. The experiments were conducted on a 94 m diameter, three-bladed wind turbines, and scaled model in an open-jet wind tunnel. A NACA-64418 aerofoil model, as commonly used in modern wind turbines, was selected as the reference blade. Serrations were applied on one of the blades, with aerodynamically optimised design applied to the second blade, and the last one was used as an untreated reference (see Fig. 1.4a). The results of the optimised blade showed an overall 3.2 dB of trailing-edge noise reduction and a maximum noise reduction of 5 dB up to a frequency of 1 kHz (see Fig. 1.4b). Further reductions of about 2–3 dB were shown in the serrated blade results. However, apart from the noise reduction at low frequencies, a significant high-frequency noise increase was also reported in this study.

Gruber et al. [16, 98–100, 102] carried out a detailed near-field and far-field study using different type of complex serrations, such as slotted edge, sawtooth with hole, slotted-sawtooth edge, and serrations with random edges. The results in Fig. 1.5 from these tests showed that the serration geometry plays a vital role in the intensity and
frequency of noise reduction. Amongst all the tested serrations, sawtooth and slotted-sawtooth serrations performed best with noise reduction of $1 - 5$ dB at low to mid frequency ranges. An increase in noise of up 1 dB was observed at higher frequency range for the tested serrations. A speculated reason for this increase in high-frequency noise is the misalignment of the serrations with the mean camber-line. Gruber also observed only a minimal increase in the high-frequency noise by the use of slotted-sawtooth serrations compared to the other geometries [16].

![Figure 1.5: Sound power level PWL as a function of frequency at $U_0 = 40$ m/s [16] a) At $5^\circ$ from 300 Hz to 7 kHz, b) At $5^\circ$ from 7 kHz to 20 kHz, c) At $15^\circ$ from 300 Hz to 7 kHz, d) At $15^\circ$ from 7 kHz to 20 kHz.](image)

Moreau et al. [66, 103–107] conducted several tests with a trailing-edge serrated tapered flat plate. The results show that, at moderate Reynolds numbers, a broadband reduction of 3 dB can achieved. A better noise reduction was achieved in the case of serrations with larger angles, contrary to Howe’s predictions. Additionally, for straight trailing-edge reference configuration, vortex shedding noise were observed at higher
frequencies range ($f > 7$ kHz), whereas the serrated case provided up to 13 dB noise reduction for blunt vortex shedding noise at high frequencies. Also, for both the straight and serrated trailing-edge cases, the noise spectra results were found to scale well with displacement thickness of the boundary layer of trailing-edge. Studies have also been carried out by adding serrations with different wavelength ($\lambda$), amplitude ($2h$) on the trailing-edge of the aerofoil. Results show that the use of wide trailing-edge serrations ($\lambda/2h = 0.6$) significantly reduces the trailing-edge vortex shedding, which lead to an overall sound pressure level reduction of up to 11 dB. For narrower trailing-edge serrations ($\lambda/2h = 0.2$), high amplitude tonal noise and an increase in the overall sound pressure level (up to 4 dB) can be obtained.

Chong et al. produced a series of wind tunnel experiments on flat plate serrations and non-flat plate serrations [47, 67, 108]. In 2013, Chong et al. [47, 108] reported some tests using serrations that were not made by flat plate and were directly cut into the trailing-edge section of a NACA 0012 aerofoil. The results showed that the noise performance of a non-flat plate serrated trailing-edge by reducing the far-field noise by up to 7 – 8 dB; however, vortex shedding noise was also generated due to the bluntness near the serration root in which case another noise became visible. To eliminate this noise source, a woven wire mesh was then applied to cover the valleys of the serrations. This introduction of the woven wire mesh eliminated the vortex shedding noise, but a high-frequency noise increase was then noticed, which is believed to be due to the surface roughness induced by the mesh.

In a more recent study, Vathylakis et al. in 2015 [49] tested modified sawtooth serrated trailing-edges fitted in a NACA 0012 aerofoil to reduce the high-frequency noise observed in the previous tests. The space between the serrations, i.e. the serration valleys, were filled with materials like porous nickel chromium foams, Melamine foams,
brushes, etc. Acoustic measurements from these sawtooth serrations showed noise reduction of up to 7 dB. The modified poro-serrated trailing-edges reduced the tonal noise component from the vortex shedding and kept the overall high-frequency noise increase minimal. Later, Chong et al. [109] provided a further study to confirm that an optimum selection of the porous material can offer further reduction of the broadband noise level. The results showed that the metal foams used in the poro-serrated trailing-edge not only eliminated the vortex shedding tonal noise, but also further enhanced the broadband noise reduction compared to the non poro-serration case.

The increase in high-frequency noise was further investigated by León et al. [110, 111] using sawtooth serrations and varying the serration flap angle. Measurement for the serrations relative to the straight edge was done under a freestream velocity of 35 m/s. The far-field noise results showed that, at serration flap angle $\varphi = 0^\circ$, the serrations can offer a reduction of up to 7 dB in the frequency range between 1 kHz and 3 kHz. Beyond this upper limit, the reduction vanishes when approaching 5 kHz. When the serrations are placed at $\varphi = 6^\circ$, the noise reduction is less pronounced. In a very recent study [112], semi-permeable trailing-edge serrations had been tested to overcome the high frequency noise increase previously observed in the case of standard sawtooth serrations. Two variations of the slit serrations with different slit length cut designs (mixed solid/slit configuration and full slit) and two solid serrations were considered in this study. The results indicated that the mixed solid/slit configuration can provide a certain benefit in noise reduction, however, a fully slitted configuration does not show positive improvement in noise reduction performance of the serrations.

An aeroacoustic wind tunnel test was performed by Fischer et al. [113] for a DTU-CQU LN 118 aerofoil, fitted with two different serration geometries, sinusoidal serration and sawtooth serrations. The far-field sound measurements were performed using
a microphone array. The results showed that the far field noise was reduced effectively, by up to 8 dB, using both types of serrations at low angles of attack and in the high frequency range. For higher angles of attack, reductions of 3–5 dB could be found. The results also showed that the sinusoidal serrations gave better results than sawtooth serrations. The experimental results were then compared with a new CFD RANS based method introduced by Fischer et al. [114]. An acceptable match of sound pressure levels and correct tendencies between experiment and CFD confirmed that the model can be used for the optimisation of the serration geometry.

### 1.2.4 Aerodynamics of aerofoils with serrated trailing-edge

Prior research has shown that the implementation of add-on trailing-edge serrations along the outboard blade section can significantly reduce the aerofoil trailing-edge noise. Despite a great deal of research directed towards the noise reduction capabilities of serrations, the flow behaviour around the serration structures has remained largely unexplored.

Gruber et al. in 2010 [98] presented boundary layer measurements using hot-wire anemometry on a single sawtooth of the serrated aerofoil. The results showed that the tip of the trailing-edge has a boundary layer 15% larger than the baseline and the root of the trailing-edge. They also observed that the sharpness of the sawtooth affected the turbulent length scale and the turbulent intensity compared to the baseline case in the boundary layer region. Later, in 2013 and 2014, Moreau et al. [105–107] provided unsteady flow data near the serrated trailing-edge using hot-wire measurement, at low-to-moderate Reynolds number \((1.6\times10^5 < Re_c < 4.2\times10^5)\), for a variety of aerofoil aspect ratios (length to chord ratio), and different wavelength \((\lambda)\) to amplitude \((2h)\). The unsteady flow data near the trailing-edge wake showed that the serrations clearly affect the flow structure at the trailing-edge area of the aerofoil. For serrations with wide
serrated teeth (high wavelength ($\lambda$) to amplitude ($2h$) ratio), weak vortex shedding occurred at the position of the tip. For the narrow serrations, the formation of intense vortices could be observed across the span. The velocity spectra were also found to be related to the far-field noise results, which provided further insight into the serration noise reduction mechanism.

The relationship between the noise and near-field flow quantities was studied by Chong and Vathylakis [115] in 2015, using a highly equipped flat plate fitted with trailing-edge serrations. It was found that coherent structures in the form of horseshoe vortices are convected along the edges of the serration and it was suggested that the noise reduction was driven by the interaction between these horseshoe flow structures and the pressure driven oblique vortices. An illustration of the horseshoe vortices is given in Fig. 1.6. They also found that the dominant fluctuating components were present close to the sawtooth tip with higher frequencies present on the sides of the sawtooth edges. This concurred with the other observations made by Gruber [99] and Vathylakis et al. [49] where the results show that jet flow through the serration valley corresponds to high-frequency noise.

![Image of horseshoe vortices](image.png)  

**Figure 1.6:** The illustration of the horseshoe vortices form RANS results of NACA 65(12)-10 aerofoil for $\alpha = 10^\circ$ for chord based Reynolds number of $Re_c = 3 \times 10^5$. [5]
León et al. performed a series of studies on the flow field and boundary layer characteristics of a NACA 0018 aerofoil, with and without different trailing-edge serrations [110, 111, 116–118]. In 2015, León et al. [116] studied the flow close to the surface and in the wake of sawtooth trailing-edge serrations using Particle Image Velocimetry (PIV). Three different measurement locations, two over the surface of the serrations (pressure side and suction side) and one perpendicular to the flow in the wake, were chosen. The results showed that on the pressure side of the serrations, the flow close to the serration surface gets deflected outwards and straightened out again after having passed the trailing-edge. On the suction side, the flow remains mostly straight throughout the surface of the serration. After passing the trailing-edge, the flow then deflects inwards. Later, León et al. [110, 111] studied the flow field around a sawtooth serration fitted on the trailing-edge of a NACA 0018 aerofoil. The results showed that the serration flap angle could have a considerable effect on the flow behaviour, and the misalignment of the serration, i.e. the angle relative to the mean camber-line, is thought to be a critical factor in the increase of high-frequency noise. An analysis of the Stereoscopic PIV results indicated that while there is no upstream effect, the mean flow results showed significant changes to the flow field as it convects over the serrations. Also, compared to the baseline case, the shear stress for the serrated cases were found to be lower. The changes observed in the turbulence spectra of the flow structures within the boundary layer flow for the serrated cases was found to cause changes in the unsteady surface pressure, which would result in a reduction of trailing-edge noise [118]. The boundary layer flow properties obtained from the PIV measurements again showed a sharp increase in wall-normal component fluctuations ($u_{rms}$) on the pressure side of the serrations, with a significant rise in the spanwise velocity [119]. An increase in the energy content of the boundary layer structures was also found in the turbulence frequency spectrum results for the serrated cases, especially on the pressure
side of the aerofoil. This increase is believed to be due to the rise in $v_{rms}$. The PIV measurement [117] showed highly three-dimensional flow-field over the trailing-edge area. Furthermore, the results confirmed the development of streamwise horseshoe vortices emanating from the serrations even at low angles of attack. The magnitude of these streamwise vortices appeared to increase as the angle of attack is increased.

The aerodynamic measurement of the sawtooth serrated trailing-edges fitted on a NACA 0012 aerofoil provided by Vathylakis et al. [49] showed a reduction of 4% in the lift coefficient of the aerofoil below the stall angle for serrated trailing-edge compared to the baseline. As mentioned before, this study also confirmed that the jet flow through the serration valley is one of the critical factors in the generation of high-frequency noise for serrated trailing-edges.

Various computational studies have also been carried out to study the highly three-dimensional flow over the trailing-edge serrations. Jones and Sandberg [63, 120] performed a high fidelity direct numerical simulation (DNS) for a NACA 0012 aerofoil, with and without serrations. Simulations had been carried out for the aerofoil with a straight trailing-edge and two serrations with different amplitudes at the Reynolds number $Re_c = 50,000$. The results showed a reduction of 6 to 10 dB in broadband noise. Results had shown that the serrations can reduce the aerofoil self-noise by 6 to 10 dB and that the noise reduction is solely due to the scattering process. More importantly, results had revealed that the hydrodynamic field over the trailing-edge area is entirely changed by the introduction of the trailing-edge serrations. The large spanwise turbulent structures were found to be broken up by the serrations at the trailing-edge, giving rise to new horseshoe vortices.

Another noteworthy DNS study for a control diffusion aerofoil with and without
serration was carried out by Sanjose et al. in 2014 [121]. The results showed a slight reduction in the lift for the aerofoil with trailing-edge serration, in agreement with the experimental observations [49]. The near-wake region had found to have larger coherent horseshoe vortices, which were formed from the merging of other smaller vortices leaving the aerofoil surface. At the wake, the maximum velocity deficit and deflection angle were reduced for aerofoil with serration compared to the baseline case (untreated trailing-edge). Enhanced flow mixing in the wake region was also observed for the aerofoil with serrated trailing-edge. Arina et al. [122] studied the noise reduction mechanisms of trailing-edge serrations for a NACA 65(12)-10 aerofoil using a compressible Large Eddy Simulation (LES) at Reynolds number of $6 \times 10^5$. The LES results showed that the use of the sawtooth serrations on the trailing-edge of the aerofoil strongly affects the structure of the flow field near the trailing-edge. Compared to the baseline case, the serrated aerofoil showed high vorticity region near the serrations and smaller integral scale length of the flow structures. It is argued that to be due to the induced recirculation bubbles over the sawtooth serrations.

More recently, Avallone et al. [123] and Ragni et al. [124] investigated a novel curved trailing-edge serration. The far-field noise and flow field of novel curved trailing-edge serration (iron-shaped) were obtained numerically. A compressible Lattice-Boltzmann solver was used to obtain the flow-field over the serration and the far-field noise. The difference between the new design and conventional trailing-edge serration had been investigated. The analysis of the time-averaged near-wall velocity components showed that the new design results in a milder interaction between the pressure and suction sides of the aerofoil at the root location of the serration. At the serration tip locations, stronger outward and downward flow motions can also be obtained. The far-field noise results had also shown that for the chord-based Strouhal numbers $St_c < 15$, the iron-shaped geometry reduces the noise by 2 dB more than the conventional sawtooth serr-
1.2.5 Literature review summary

Even though trailing-edge serrations have proven to be a viable and effective means of aerofoil trailing-edge noise reduction, the mechanism through which the noise is reduced and, more importantly, the aerodynamic effects of serrations have not been completely studied or understood. The studies available on the flow field characterisation of serrated trailing-edges are limited and mainly focused on the flow field over the serration area. Only a few studies have reported the flow characterisation of the near- and far-wake regions of serrated aerofoils and their potential industrial applications, such as rotor-stator or contra-rotating configurations. Therefore, considering the large body of literature on the aeroacoustics of serrated aerofoils, a comprehensive aerodynamic study of the symmetric and cambered aerofoil fitted with trailing-edge serration is very timely. The study proposed in this work will include a detailed study of the aerodynamic loading, surface flow, wake development, and surface pressure fluctuations for selected symmetric and asymmetric isolated aerofoils with different types of trailing-edge serrations. The results for the isolated aerofoils can then be used for studying the implications of wake control using trailing-edge serration for controlling the unsteady aerodynamic loading and noise generation in configurations involving a series of aerofoils. As part of this project, both the aerodynamic performance and wake development of isolated aerofoils and tandem aerofoil configurations will be studied.

1.3 Aim and Objective

Among the passive flow control methods for reducing aerofoil noise, trailing-edge serration treatment has received the most attention. Although the aeroacoustic performance of trailing-edges has been studied extensively in recent years, few studies have been car-
ried out focusing on the aerodynamic performance of such passive edge treatments. The aim of this study is to expand the existing knowledge and better understand the mechanism through which serration change the flow field around the serration and within the wake. More importantly, in order to optimize the aerodynamic performance of aerofoils with trailing-edge serration treatment, it is imperative to better understand the flow behaviour of the aerofoils with and without trailing-edge serrations. This can be achieved by carrying out an extensive and yet systematic set of experimental investigations. The experiments carried out as part of this study includes:

- To study the aerodynamic load of the aerofoils with and without different types of trailing-edges serrations over a wide range of angles of attack and Reynolds numbers.

- To characterise the flow-field behaviour for different aerofoils with and without trailing-edges serrations, involving visualization of the surface flow patterns and the measurement of the near- and far-wake development.

- To study the effect of trailing-edge serrations on the noise generation for the aerofoils in tandem configuration, by studying the wake development, as well as the steady and unsteady surface pressure on the rear aerofoil.

1.4 Outline of the dissertation

The layout of the thesis is as follows:

Chapter 2 presents a detailed description of the wind tunnels used in this project. A full description of the experimental setup and the details of the measurement techniques, such as the pressure distribution aerodynamics force, wake development, flow
visualization, used for understanding of the aerodynamic performance of different aerofoils used in this project are provided in this chapter.

Chapter 3 presents the surface flow visualisation and aerodynamic performance of a symmetric NACA 0012 and a cambered NACA 65(12)-10 aerofoil fitted with differed trailing-edge serrations for a wide range of angles of attack and Reynolds numbers.

Chapter 4 presents the results of the wake flow measurements for the NACA 0012 aerofoil and the NACA 65(12)-10 aerofoil with and without different types of trailing-edge serrations. Results are obtained using LDV, PIV and hot-wire measurement techniques. The wake measurements were carried out at the geometric angles of attack of $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$ at the flow velocity of $U_0 = 20$ m/s and $U_0 = 30$ m/s, corresponding to the chord-based Reynolds number of $Re_c = 2 \times 10^5, Re_c = 3 \times 10^5$.

Chapter 5 presents the aerodynamic and acoustic performance of the aerofoils in a tandem configuration. A detailed study of the wake development and surface pressure fluctuations has been carried out for the tandem aerofoil configuration at different angles of attack, gap distances, etc. A pair of cambered NACA 65-710 aerofoils has been selected for this study. The gap flow field has been studied using the PIV technique. A thorough study has been carried out to understand the effects of the use of trailing-edge serrations on the front aerofoil on the steady and unsteady pressure distribution of the rear aerofoil.

Chapter 6 summarizes the work carried out in this project and provides some ideas and suggestions for future work.
This chapter describes the experimental facility and the aerodynamic measurement techniques used in this thesis to investigate the aerodynamic performance of NACA 0012, NACA 65-710 and NACA 65(12)-10 aerofoils. All the measurements have been carried out at the wind tunnel laboratory of the University of Bristol. This chapter also includes a full characterization of all three wind tunnels used and a full description of the detailed setup for different measurement techniques, such as aerodynamic forces, wake development, flow visualization and surface pressure used for the understanding of the aerodynamic performance of the aerofoils with or without trailing-edge serrations.

2.1 Methodology

To expand the existing knowledge and better understand the effect of using trailing-edge serrations on the aerodynamic and acoustic performance of aerofoils, a systematic set of experimental investigations was carried out. The aerodynamic performance of a
NACA 0012 and a NACA 65(12)-10 aerofoil with and without different types of serrations on the trailing-edge of the aerofoil was investigated in the first part of this study. Chapter 3 concerns the following two items:

- To study the effect of using the trailing-edge serrations on modifying the surface pattern and the flow separation/re-attachment locations of the trailing-edge serrated aerofoils, the surface flow patterns of the serrated and unserrated aerofoils (i.e. reference) were studied. The oil flow visualization technique was used to obtain surface flow patterns and to help interpret the flow separation/re-attachment locations of the aerofoils for a wide range of angles of attack.

- The aerodynamic performance of the serrated and unserrated aerofoils, lift and drag forces, were also carried out using a 6-DoF force balance in the wind tunnel facility.

To further understand the effect of using trailing-edge serrations on the wake development of aerofoils, detailed measurements of the near- and far-wake flow field of a NACA 0012 and a NACA 65(12)-10 aerofoil with and without different types of trailing-edge serrations were performed and discussed in Chapter 4. The following issues were investigated:

- To study the wake development, flow measurements for serrated and unserrated aerofoils at several downstream locations (near- to far-wake) were performed using two-dimensional Laser Doppler Velocimetry (LDV) measurement techniques. Furthermore, to gather a better picture of the effects of different types of trailing-edge serrations on the wake development, two-dimensional Particle Image Ve-
locimetry (PIV) measurement technique was also carried out to quantify the flow patterns in the near-wake region for different angles of attack.

- In addition to the general velocity and turbulent kinetic energy information obtained using the PIV and LDV techniques, the frequency-energy content of the wake turbulence also provides valuable information. The mean velocity and velocity fluctuation within the wake domain were obtained using a cross hot-wire probe.

Results in the first part of the study have shown that the implementation of trailing-edge serrations, such as sawtooth and slotted-sawtooth serrations, which have superior noise reduction efficiency [99], can also significantly reduce the wake turbulence intensity, particularly at high angles of attack, where maximum aerodynamic performance is obtained [3–5]. This ability of reducing the turbulence level using serrations present a possible new technique for reducing noise generated by wake-aerofoil interaction. This will have positive implications for industrial applications involving multiple rows of aerofoils such as the contra-rotating propellers, rotor-stator configuration, etc. In the second part of the study (Chapter 5), aerofoils arranged in different tandem configurations have been examined to validate such hypothesis, and to better understand the effects on the aerodynamic and aeroacoustic performance of serrated trailing-edge.

- A comprehensive aerodynamic study using a cambered NACA 65-710 aerofoil with and without trailing-edge serrations has been carried out using the two-dimensional Particle Image Velocimetry (PIV) technique for different angles of attack.

- The effect of trailing-edge serrations on the noise generation for the tandem NACA 65-710 configuration has also been studied by looking carefully into the surface
Pressure coefficient, surface pressure fluctuations on the rear aerofoil. Thorough measurements have been carried out using a pressure scanner for pressure coefficient distributions on the rear aerofoil. Surface pressure fluctuation measurements have been performed on the rear aerofoil using the remote sensing probe method. Measurements were carried out for different angles of attack and tandem configurations.

### 2.2 Aerofoil models

Three different aerofoils have been designed and manufactured as part of this project, namely, NACA 0012, NACA 65(12)-10 and NACA 65-710. The NACA 0012 aerofoil was manufactured from RAKU-TOOL® WB-1222 polyurethane board and the NACA 65(12)-10 and NACA65-710 aerofoils were manufactured from steel and aluminium. All three aerofoils were manufactured using a computer numerical control (CNC) machine. The trailing-edge part of the aerofoils was designed with a 1.8 mm blunt trailing-edge on a 15 mm deep and 1 mm (NACA 0012 aerofoil) or 0.75 mm (NACA 65(12)-10 and NACA 65-710 aerofoil) thick slot along the span, as shown in Fig. 2.1. The slots at the trailing-edge of the aerofoils are used for fitting the flat plate serrations at the trailing-edge of the aerofoil. There is no general consensus in the literature as to how to define the trailing-edge serrations. There are two methods that have been previously used by researchers: (i) to use the serration as a simple flap to the existing aerofoil, which increases the aerofoil surface area and (ii) to keep the aerofoil surface area constant, as suggested by Gruber [16, 98–100]. In order to understand the effects of both treatments two different benchmark cases have been considered in this study, namely Baseline and blunt aerofoil, as shown in Fig. 2.1. The blunt aerofoil uses the serrations as an additional flap configuration (thus increasing the aerofoil surface area), whereas the Baseline aerofoil is designed to have the same surface area as that of the serrated aerofoil, as shown in
The aerofoil geometries shown in Fig. 2.1 have a span length of \( L = 450 \) mm, but with varying chord-lengths. The blunt aerofoil has a chord-length of \( c = 140 \) mm with no trailing-edge flat plate inserts. The Baseline aerofoil has a slightly different chord-length that was achieved by adding a flat plate insert (without serrations) at the trailing-edge of the blunt aerofoil. This increases the effective chord-length of the aerofoil to \( c = 155 \) mm and thus increases the surface area of the aerofoil.
Figure 2.1: Aerofoil configurations employed in the current study (a) NACA 0012 aerofoil, (b) NACA 65(12)-10 aerofoil, (c) NACA 65-710 aerofoil.
2.2.1 NACA 0012 aerofoil

The symmetric NACA 0012 aerofoil was designed based on the aerofoil geometry data points listed in Table 2.1. The aerofoil was built in two pieces, with a span length of $L = 450$ mm. Figures 2.2(a) and 2.2(b) show the top view and the side view of the model. At the trailing-edge of the aerofoil, a 0.5 mm depth and 15 mm long step has been cut to build a 1 mm thick and 15 mm deep slot at the trailing-edge of the aerofoil in order to let the flat plate trailing-edge serrations to be fitted into the trailing-edge of the aerofoil, see Fig. 2.2(c). Two 5 mm diameter thick carbon tubes were added in the model to increase its structural strength, particularly when placed in the wind tunnel at high angles of attack at high speeds. The connecting parts of the aerofoil and the arm were manufactured from aluminium and are used to hold the two aerofoil parts together. The results for the NACA65(12)-10 will be presented and discussed in Chapters 3 and 4.

Figure 2.2: NACA0012 aerofoil with trailing-edge insert model (a) top view of the model, (b) side view of the model, (c) exploded view of the trailing-edge serrated model.
CHAPTER 2. EXPERIMENT SETUP

Table 2.1: NACA0012 aerofoil coordinate [9].

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2.2. AEROFOIL MODELS

2.2.2 NACA 65(12)-10 aerofoil

A NACA65 (12)-10 aerofoil was manufactured using the aerofoil geometry data points provided in Table 2.2. As shown in Fig. 2.3, the aerofoil is composed of a main steel body with a span length of $L = 450$ mm and chord length of 120 mm with two detachable trailing-edge parts. The first trailing-edge part is a 20 mm blunt trailing-edge part with 15 mm deep and 0.75 mm thick slot cut along the trailing-edge of the aerofoil, which can be used to fit different trailing-edge serrations (see Fig. 2.3(b)). The second part is an original trailing-edge part (see Fig. 2.3(c)). The main body and trailing-edge parts of the aerofoil can be assembled together using two 3 mm thick side plates. In this thesis, the configuration referred to as the Baseline aerofoil has a straight flat plate trailing-edge insert. The NACA65(12)-10 aerofoil is used to measure the aerodynamic forces, perform surface flow visualisation and investigate wake development. The results for the NACA65(12)-10 will be presented and discussed in Chapters 3 and 4.
Figure 2.3: NACA 65(12)-10 aerofoil with trailing-edge insert model (a) top view of the model, (b) side view of the serrated trailing-edge model, (c) side view of the original model, (d) exploded view of the trailing-edge serrated model.
Table 2.2: NACA 65(12)-10 aerofoil coordinate [10].

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2.2.3 NACA 65-710 aerofoil

A NACA65-710 aerofoil was designed using the data points presented in Table 2.3. The aerofoil consists of a main aluminium body and a detachable trailing-edge part, see Fig. 2.4. These two components were assembled together using 6 pin bolts. A 15 mm deep and 0.75 mm thick slot have been made at the trailing-edge of the aerofoil for holding different serrations. Different flat plate trailing-edge serrations have been designed and studied. In this thesis, the NACA 65-710 aerofoil is used to investigate the aerodynamic performance of serrated aerofoils and the wake development performance in tandem aerofoils configurations. The results for the NACA65-710 will be presented and discussed in Chapter 5.

Figure 2.4: NACA 65-710 aerofoil with trailing-edge insert model (a) top view of the model, (b) side view of the model, (c) exploded view of the trailing-edge serrated model.
### Table 2.3: NACA 65-710 aerofoil coordinate [10].

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<td>0.063865</td>
<td>-0.038591</td>
</tr>
<tr>
<td>0.091194</td>
<td>0.01167</td>
<td>0.083806</td>
<td>-0.044779</td>
</tr>
<tr>
<td>0.141099</td>
<td>0.012757</td>
<td>0.133901</td>
<td>-0.057443</td>
</tr>
<tr>
<td>0.220561</td>
<td>0.013541</td>
<td>0.214439</td>
<td>-0.072006</td>
</tr>
<tr>
<td>0.299785</td>
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<td>0.295215</td>
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</tr>
<tr>
<td>0.378898</td>
<td>0.012781</td>
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<td>-0.086813</td>
</tr>
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<td>0.457978</td>
<td>0.010815</td>
<td>0.457022</td>
<td>-0.087853</td>
</tr>
<tr>
<td>0.537126</td>
<td>0.007067</td>
<td>0.537874</td>
<td>-0.084223</td>
</tr>
<tr>
<td>0.616461</td>
<td>0.001969</td>
<td>0.618539</td>
<td>-0.076359</td>
</tr>
<tr>
<td>0.696066</td>
<td>-0.003408</td>
<td>0.698934</td>
<td>-0.065176</td>
</tr>
<tr>
<td>0.775992</td>
<td>-0.008026</td>
<td>0.779008</td>
<td>-0.051336</td>
</tr>
<tr>
<td>0.856279</td>
<td>-0.010756</td>
<td>0.858721</td>
<td>-0.035179</td>
</tr>
<tr>
<td>0.936989</td>
<td>-0.009793</td>
<td>0.938011</td>
<td>-0.016551</td>
</tr>
<tr>
<td>1.000000</td>
<td>-0.002</td>
<td>1.000000</td>
<td>-0.0002</td>
</tr>
</tbody>
</table>

---

39
The second NACA 65-710 aerofoil model, used as the rear aerofoil in the tandem aerofoil configuration studies in Chapter 5, is equipped with pressure taps on both the pressure and suction sides. A total number of 34 pressure taps have been used to study the static and dynamic pressure changes over the aerofoil. Details regarding the location of the pressure taps are provided in Table 2.4. The pressure taps are made of brass tubes with an outer diameter of 1.6 mm and inner diameter of 0.8 mm. To install the brass tube, 2 mm × 2 mm grooves were cut on the surface of the aerofoil. The grooves ran in the spanwise direction from the root extending slightly beyond mid-span. The brass tubes were then placed into the grooves and the gaps were filled with a resin. The aerofoil surfaces were then sanded and 0.4 mm holes were drilled in each of the brass tubes at the mid-span location.

Figure 2.5: NACA 65-710 aerofoil with pressure taps.
Table 2.4: NACA 65-710 aerofoil pressure tap locations.

<table>
<thead>
<tr>
<th>pressure tap number</th>
<th>pressure tap location (x/c)</th>
<th>pressure tap number</th>
<th>pressure tap location (x/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>18</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>0.03</td>
<td>19</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
<td>20</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>21</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
<td>0.11</td>
<td>22</td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>0.15</td>
<td>23</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>0.19</td>
<td>24</td>
<td>0.19</td>
</tr>
<tr>
<td>8</td>
<td>0.23</td>
<td>25</td>
<td>0.23</td>
</tr>
<tr>
<td>9</td>
<td>0.29</td>
<td>26</td>
<td>0.29</td>
</tr>
<tr>
<td>10</td>
<td>0.35</td>
<td>27</td>
<td>0.35</td>
</tr>
<tr>
<td>11</td>
<td>0.41</td>
<td>28</td>
<td>0.41</td>
</tr>
<tr>
<td>12</td>
<td>0.47</td>
<td>29</td>
<td>0.47</td>
</tr>
<tr>
<td>13</td>
<td>0.53</td>
<td>30</td>
<td>0.53</td>
</tr>
<tr>
<td>14</td>
<td>0.59</td>
<td>31</td>
<td>0.59</td>
</tr>
<tr>
<td>15</td>
<td>0.65</td>
<td>32</td>
<td>0.65</td>
</tr>
<tr>
<td>16</td>
<td>0.71</td>
<td>33</td>
<td>0.71</td>
</tr>
<tr>
<td>17</td>
<td>0.77</td>
<td>34</td>
<td>0.77</td>
</tr>
</tbody>
</table>
2.2.4 Aerofoil end-plates

To reduce the flow three-dimensionality effects associated with the aerofoil tip-flow separation, circular Perspex end-plates with a diameter 0.34 m (2.27 times the aerofoil chord) were used on the aerofoil, see Fig. 2.6. The end-plates were manufactured from 6 mm perspex sheets using laser cutting. The edges of these circular end-plates were chamfered to reduce flow distortion. The end-plates are large enough to leave $8.5H_a$ above and below the aerofoil and $4.28H_a$ downstream of the aerofoil, as suggested by Boutilier [125], with $H_a$ being the thickness of the aerofoil. A 3 mm thick slot has also been cut out at the trailing-edge side of the end plate to allow positioning of a digital angle meter (Bevel box) to measure the angle of attack of the aerofoil.

Figure 2.6: Aerofoil with end-plate (a) side view of aerofoil with end-plates, (b) top view of aerofoil with end-plates, (c) 3D configuration.
2.3 Trailing-edge serrations

Three types of serrations are selected for this study based on their good noise reduction performance, as demonstrated in previous experiments and analytical studies [16, 98–100, 126]. These three types of serrations tested and presented here are the sawtooth serration, sinusoidal serration and slotted-sawtooth serration (see Fig. 2.7). The sawtooth serrations can be defined in terms of the sawtooth amplitude \(2h\) and periodicity wavelength \(\lambda\), or the serration edge angle \(\alpha_s\), as shown in Fig. 2.7. The slotted-sawtooth are defined in a similar way to the sawtooth serrations, plus the slots, which are defined using their depth \(H\), width \(d\) and number of slots on each edge of the serration. Finally, the sinusoidal serrations are defined in terms of the amplitude \(2h\) and wavelength \(\lambda\). The list of the serrations used in the current study and the values of the geometrical parameters are summarized in Table. 2.5.

![Serrated trailing-edge treatments tested in the current study (a) sawtooth serration, (b) sinusoidal serration, (c) slotted-sawtooth serration.](image)

Figure 2.7: Serrated trailing-edge treatments tested in the current study (a) sawtooth serration, (b) sinusoidal serration, (c) slotted-sawtooth serration.
Table 2.5: Geometrical parameters of the trailing-edge serrations used in the current study.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Serration Types</th>
<th>$2h$ (mm)</th>
<th>$\lambda$ (mm)</th>
<th>$\lambda/h$</th>
<th>$\alpha_s$ (deg.)</th>
<th>$d$ (mm)</th>
<th>$H$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>blunt</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>Baseline</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 3</td>
<td>sawtooth</td>
<td>30</td>
<td>3</td>
<td>0.2</td>
<td>2.86</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 4</td>
<td>sawtooth</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 5</td>
<td>sawtooth</td>
<td>30</td>
<td>24.8</td>
<td>1.5</td>
<td>22.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 6</td>
<td>sinusoidal</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 7</td>
<td>sinusoidal</td>
<td>30</td>
<td>24.8</td>
<td>1.5</td>
<td>22.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 8</td>
<td>slotted-sawtooth</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td>Case 9</td>
<td>slotted-sawtooth</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>
2.4 Wind tunnel facility

Three different wind tunnels have been used in this project for the measurement of different aerodynamic quantities. Below, each wind tunnel and relevant equipment used are described:

(i) **The large 7′ × 5′ wind tunnel:** The 7′ × 5′ large wind tunnel is a low speed closed-circuit wind tunnel. The octagonal working section of the tunnel has a dimension of 2.1 m × 1.5 m × 2.7 m (see Fig. 2.8), with a contraction ratio of 3:1 and a stable velocity range of 10 m/s to 60 m/s. The wind tunnel velocity can be controlled using a computer with an in-build software. A six degree of freedom high frequency force balance system (AMTI OR6-7-2000) is placed under the working section, enabling accurate aerodynamics force measurements.

![Figure 2.8: 7′ × 5′ wind tunnel working section layout.](image-url)
(ii) **Low turbulence tunnel**: The low turbulence wind tunnel is a closed-circuit wind tunnel with an octagonal working section of $0.8 \, \text{m} \times 0.6 \, \text{m} \times 1 \, \text{m}$ (see Fig. 2.9), a contraction ratio of 12:1, maximum velocity of 100 m/s and with a turbulence level as low as 0.05%. The wind tunnel velocity and the force balance system can be controlled together using an operating software. The wind tunnel is optically accessible enabling flow velocity and turbulence measurements over the aerofoil surface and in the wake region to be performed using PIV and LDV methods.

![Figure 2.9: Low turbulence tunnel wind tunnel working section layout.](image-url)
(iii) **Open-jet wind tunnel**: The Open-jet wind tunnel has an exit nozzle diameter of 1.2 m with a 1.5 m long working space (see Fig. 2.9). The maximum reliable speed of this tunnel is 30 m/s with a turbulence level of 0.5%. The open space provided in this wind tunnel enables a wide range of flow measurement activities, such as hot-wire, china clay and oil visualisation, force measurement, *etc.* The general layout of the wind tunnel, the location of the fan, turning vanes, honeycomb and mesh treatments, *etc.* are provided in Fig. 2.10.

![Open-jet tunnel wind tunnel working section layout](image)

**Figure 2.10**: Open-jet tunnel wind tunnel working section layout.
2.5 Measurement methods

2.5.1 Force measurement

The aerodynamic lift and drag forces for all three different aerofoils were tested in the closed-circuit large 7' × 5' low-speed wind tunnel. The force measurements were taken using an AMTI OR6-7-2000 force balance. The 6-DoF force balance is fixed under the working section of the wind tunnel. The force balance measures the aerodynamic forces by passing a voltage induced by the force balance through the AMTI MSA-6 strain gauge amplifier, which is then converted into force (N) using an in-built control system, provided in the LabVIEW system design software. This yields to a resolution of $8.9 \times 10^{-13}$ N. A thorough data independency test using different sampling frequencies was carried out using bootstrapping [127]. A sampling frequency of 37 Hz, which provided the best data independency with uncertainty levels (at 95% confidence level) less than 3.5% for the lift and drag before stall and approximately 5% and below 10% for the lift and drag after stall. The final data sets were collected for a time period of 30 seconds and the post-processed results are presented in Chapter 3.

Figure 2.11: AMTI OR6-7-2000 force balance layout (a) AMTI OP6-7-2000 force balance, (b) footprint drawing of the force balance. [11]
### 2.5. MEASUREMENT METHODS

#### Table 2.6: Capacity and sensitivity of the AMTI OR6-7-2000 force balance. [11]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Units</th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>4448</td>
<td>4448</td>
<td>8896</td>
<td>N</td>
<td>2258</td>
<td>2258</td>
<td>1129</td>
<td>N-m</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.337</td>
<td>0.337</td>
<td>0.0843</td>
<td>µV/[V/N]</td>
<td>0.797</td>
<td>0.797</td>
<td>1.68</td>
<td>µV/[V/Nm]</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>360</td>
<td>360</td>
<td>500</td>
<td>Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Hz</td>
</tr>
</tbody>
</table>

#### 2.5.2 Laser Doppler Velocimetry (LDV)

Laser Doppler Velocimetry measurements were carried out using a two-component LDV system with 6-Watt argon-ion laser. The LDV system was set-up at the low turbulence wind tunnel. The system is mounted on a fully automated traverse system and operated in backscatter mode with a focal length of 600 mm. The velocity components were measured at the orthogonal intersection of the dual-green 514.5 nm and dual-blue 488.0 nm laser beams. The measurement volume at the beam intersection was a prolonged spheroid shape with a diameter of 0.16 mm and length 2.9 mm. A mixture of Polyethylene glycol 80 with a mean diameter of 1 µm was used to seed the air inside the low turbulence wind tunnel. The system is controlled using an in-built software package by Dantec (Burst Wave). The LDV system was used mainly for studying the wake formation behind the aerofoils. Data were collected for a total sample number of 8000 for each spatial location.

With the LDA data of longitudinal velocity (\(u\)) and traversal velocity (\(v\)), the wake mean velocity of numbers of data (\(N\)) is calculated using Eq. 2.1 and 2.2

#### 3D flow:

\[
U_{mean} = \frac{1}{N} \sum_{i=1}^{N} ((u_i^2 + v_i^2 + w_i^2)^{1/2}).
\]  

(2.1)

#### 2D flow:

\[
U_{mean} = \frac{1}{N} \sum_{i=1}^{N} ((u_i^2 + v_i^2)^{1/2}).
\]  

(2.2)
The \textit{rms} velocity terms can be calculated using Eqs. 2.3:

\begin{align*}
    u_{rms} &= \left( \frac{1}{N} \sum_{i=1}^{N} (u_i - u_{mean})^2 \right)^{1/2}, \\
    v_{rms} &= \left( \frac{1}{N} \sum_{i=1}^{N} (v_i - v_{mean})^2 \right)^{1/2}, \\
    w_{rms} &= \left( \frac{1}{N} \sum_{i=1}^{N} (w_i - w_{mean})^2 \right)^{1/2}.
\end{align*} \tag{2.3}

where \(N\) is the number of signal samples. The turbulent kinetic energy (TKE) can then be found from Eq. 2.4 and 2.5:

\begin{align*}
    \text{3D flow:} & \quad TKE = \frac{1}{2} (u_{rms}^2 + v_{rms}^2 + w_{rms}^2). \\
    \text{2D flow:} & \quad TKE = \frac{1}{2} (u_{rms}^2 + v_{rms}^2). \tag{2.4}
\end{align*}

The Reynolds stresses in \(u\) and \(v\) can also be calculated as:

\begin{align*}
    \overline{u'v'} &= \frac{1}{N} \sum_{i=1}^{N} ((u_i - u_{mean})(v_i - v_{mean})), \\
    \overline{v'v'} &= \frac{1}{N} \sum_{i=1}^{N} ((v_i - v_{mean})(v_i - v_{mean})), \\
    \overline{u'u'} &= \frac{1}{N} \sum_{i=1}^{N} ((u_i - u_{mean})(u_i - u_{mean})). \tag{2.6}
\end{align*}

The post-processed results are presented in Chapter 4.

\subsection{2.5.3 Hot-wire anemometry}

The steady and unsteady flow field measurements were performed using the Dantec 55P51 gold-plated cross-wire probe with two 3 mm long platinum-plated tungsten wire. The cross-wire probe is made of two 5 \(\mu\)m diameter wires, placed 90\(^\circ\) to each other.
and can be used for simultaneous measurement of the normal and streamwise velocity components. The hot-wire probes were driven by the Dantec StreamlinePro CTA 91C10 module and controlled through a National Instrument NI9215 four channel module (±10 V, 100 k/S/s/ch, 16-Bit). The hot-wire probes were calibrated using the Dantec 54H10 two-point mode hot-wire calibrator.

A yaw calibration for the cross-wire was performed between the angle of 45° and −45°, see Fig. 2.14a). The conversion of the voltage signal to velocity data has been carried out using a forth order polynomial fitting using Eq. 2.7 for both two sensors \(U_1\) and \(U_2\), shown in Fig. 2.13. Results for the yaw calibration between the angle and calculated velocity \(U_{cal1}\) and \(U_{cal2}\) have then been replotted in Fig. 2.14b).

![Cross-wire probe and wire coordinate.](image)

**Figure 2.12:** (a) Cross-wire probe [17], (b) Cross-wire probe and wire coordinate.

![Yaw calibration data and curve fits for each wire](image)

**Figure 2.13:** Yaw calibration data and curve fits for each wire (a) sensor 1, (b) sensor 2.
CHAPTER 2. EXPERIMENT SETUP

\[ U_1 = c_0 + c_1E_1 + c_2E_1^2 + c_3E_1^3 + c_4E_1^4, \]
\[ U_2 = c_0 + c_1E_2 + c_2E_2^2 + c_3E_2^3 + c_4E_2^4, \]

(2.7)

where \( E_1 \) and \( E_2 \) are the voltage signal for sensor 1 and 2.

\[ U_{e1} = U_1[\cos^2(90 - \alpha) + k_1^2\sin^2(90 - \alpha)]^{1/2}, \]
\[ U_{e2} = U_2[\cos^2(90 - \alpha) + k_2^2\sin^2(90 - \alpha)]^{1/2}, \]

(2.8)

Figure 2.14: Yaw calibration data (a) voltage result, (b) converged to velocity.

At each angle (\( \alpha \)), the yaw factor \( k_1 \) and \( k_2 \) have than calculated using 2.8 where \( U_e \) is the effective cooling velocity sensed by the wire and deducted from the calibration expression, and \( U \) is the velocity component normal to the wire [128–130].

\[ k_1^2U_1^2 + U_2^2 = \frac{1}{2}(1 + k_1^2)U_{cal1}^2, \]
\[ U_1^2 + k_2^2U_2^2 = \frac{1}{2}(1 + k_2^2)U_{cal2}^2, \]

(2.9)
which gives:

\[
U_1 = \frac{\sqrt{2}}{2} \sqrt{(1 + k_2^2)U_{cal2}^2 - k_2^2 U_{cal1}^2},
\]

\[
U_2 = \frac{\sqrt{2}}{2} \sqrt{(1 + k_1^2)U_{cal1}^2 - k_1^2 U_{cal2}^2},
\]

the velocity terms \( U \) and \( V \) in the probe coordinate system (see Fig. 2.12(b)) then can be calculated using:

\[
U = \frac{\sqrt{2}}{2} U_1 + \frac{\sqrt{2}}{2} U_2,
\]

\[
V = \frac{\sqrt{2}}{2} U_1 - \frac{\sqrt{2}}{2} U_2,
\]

with the total velocity magnitude \( U_{total} \) calculated from

\[
U_{total} = (U^2 + V^2)^{1/2}.
\]

The uncertainty of the flow velocity measured using the Dantec StreamlinePro is less than 0.45% (See Fig. 2.15). The flow field measurements were logged at a frequency of 20 kHz. The hot-wire probe was placed on an 1 m long steel rod connected to a two-axis (x – y) ThorLabs LTS300M traverse system covering a 300 mm by 300 mm domain with a typical minimum positioning accuracy of ±5 \( \mu \)m. The traverse was placed out-
side the flow field and was controlled using an in-built Matlab code. The post-processed results are presented in Chapter 4.

2.5.4 Particle Image Velocimetry (PIV)

The wake development and the energy content of the turbulence structure within the wake of the aerofoils were studied using two-component Particle Image Velocimetry (PIV) in the low turbulence closed-circuit wind tunnel. A Dantec DualPower 200 mJ Nd:YAG laser with a wavelength of 532 nm was used to produce 1 mm thick laser sheet with the time interval between each snapshots of 15 µs and a repetition rate of 15 Hz. The laser was placed below the working section of the wind tunnel. A mixture of Polyethylene glycol 80 with a mean diameter of 1 µm were used to seed the air inside the low turbulence wind tunnel. A total number of 1600 images for each measurement case were captured using a FlowSense 4 MP CCD camera with a resolution of 2048 × 2048 pixels and 14 bit, corresponding to Field of View ranging from 11.3 cm × 11.3 cm to 14.5 cm × 14.5 cm. The images were analysed with the DynamicStudio software from Dantec. The iterative process yielded a final grid correlation window of 16 × 16 pixels with an overlap of 50%, resulting in a final vector spacing of around 1.11 mm. Data were subsequently exported and post-processed using Tecplot and Matlab. The PIV results are presented and discussed in Chapters 4 and 5.

2.5.5 Oil flow visualization

The oil flow visualization technique was used for capturing the surface flow patterns over the surfaces of both the NACA 0012 and NACA 65(12)-10 aerofoils with and without the selected serrations. The oil mixture used in this study was made from Kerosene, Titanium Dioxide and a very small amount of oleic acid, with the kerosene to Oleic acid ratio of roughly 20:1 [131, 132]. The test models were covered with a thin black vinyl
2.5. MEASUREMENT METHODS

sheet for the flow visualization tests. The pigmented oil mixture was painted onto the aerofoil surface. The tests were performed in the Open-jet wind tunnel at the flow velocity of \( U_0 = 20 \text{ m/s} \), which corresponds to a chord-based Reynolds number of \( Re_c = 2 \times 10^5 \). The aerofoil was left in the wind tunnel until the kerosene evaporated completely, leaving the pigment showing the flow pattern on the surface of the aerofoil. The surface patterns were photographed alongside a ruler as the datum. The surface flow pattern results will be presented and discussed in Chapter 3.

2.5.6 Pressure distribution measurement

The static pressure measurement was carried out using two Chell Instruments 32 channels MicroDaq pressure scanners for the NACA 65-710 aerofoils (17 channels for each side), see Fig. 2.5. The instrument has system accuracy specified as \( \pm 0.25\% \text{ FS} \) [133] where \% FS is a percentage of full scale. The pressure taps used for the pressure coefficient distribution measurements were made from 1.6 mm diameter brass tubes with 0.4 mm pinholes perpendicular to the surface of the aerofoil to avoid any flow disturbance. One meter long plastic tubes with 1.6 mm outer diameter and 0.8 mm inner diameter were used to connect the brass tube and pressure scanner. The surface pressure data have been collected using the supplied MicroDaq software. The surface pressure measurements were logged at a frequency of 500 Hz for 60 seconds. Results are presented in Chapter 5

2.5.7 Unsteady surface pressure

The surface pressure fluctuation measurements were performed using remote microphone probes. On both sides of NACA 65-710 aerofoil, a total number of 34 pressure taps (See Fig. 2.5) were made from 1.6 mm diameter brass tube with 0.4 mm pinholes with the angle perpendicular to the surface of the aerofoil. 34 Panasonic WM-61A mi-
microphones fit into the remote microphone holders (see Fig. 2.17) are connected to the pressure tap brass tube using a plastic tubing with the inner and outer diameter of 0.8 mm and 4 mm. The sensitivity data for the Panasonic microphone are shown in Fig. 2.20. A sketch of the remote microphone probes setup is shown in Fig. 2.18. The calibration of the RMP is performed based on the calibration procedure prescribed by Schewe and Marsan [134–136]. The method employed in the calibration is sketched in Fig. 2.16.

![Diagram](image)

**Figure 2.16:** Method employed in the calibration of the Panasonic WM-61A microphones. Speaker response measurement using (a) G.R.A.S microphone transducer, (b) Panasonic microphone transducer frequency response

The calibration setup consists of a speaker connected to an extension cone filled with porous material and a steel extension pipe. The angle of the cone was made as small as possible to ensure a plane wave propagation through the whole path. A microphone holder was connected to the end of the extension pipe in order to align the reference microphone to the pinhole of the remote sensor to be calibrated. The design of the calibrator is shown in Fig. 2.5.7. The calibration consists of taking measurements of a G.R.A.S. 40 PL microphone and Panasonic WM-61A microphones transducers. In measurement a (top row in Fig. 2.16), since the calibration of the G.R.A.S., $S_{ref}$, is known (see Fig. 2.20), the output signal from the speaker $P_{sp}(f)$, in the frequency domain, can be calculated from Eq. 2.13.
\[ P_{Sp}(f) = \frac{V^a_2(f)}{S_{ref}}. \] (2.13)

With the output from the speaker \((P_{Sp}(f))\) and the input to the speaker, the white noise source \((V^a_1(t))\) and output for G.R.A.S. \((V^a_2)\), the speaker response \((S_p(f))\) can be calculated using Eq. 2.14

\[ S_p(f) = \frac{E[P_{Sp}(f) \cdot V^a_1(f) \leq V^a_1(f)]}{E[V^a_1(f) \cdot V^a_1(f)]} = \frac{G_{V^a_2V^a_1}}{G_{V^a_1V^a_1}} \cdot \frac{1}{S_{ref}}, \] (2.14)

where \(E\) is the expected value operator and \(G\) is the cross-spectrum defined in Eq. 2.15.

\[ G_{x,y}(f) = \sum_{m=-\infty}^{\infty} R_{x,y}(m)e^{-jf^m}, \] (2.15)

\[ R_{x,y}(m) = E[x_{n+m} \cdot y_n] = E[x_n \cdot y_{n-m}]. \]

where \(x_n\) and \(y_n\) are jointly stationary random processes.

In the measurement \(b\) (bottom row in Fig. 2.16), with the output from the noise source \((V^b_1(t))\) and the output from the Panasonic WM-61A microphone transducer \((V^b_2(t))\), the frequency response of the system produced by the speaker \((S_p(f))\) and microphone transducer \((PS(f))\) can be calculated from Eq. 2.16

\[ S_p(f) \cdot PS(f) = \frac{E[V^b_2(f) \cdot V^b_1(f)]}{E[V^b_1(f) \cdot V^b_1(f)]} = \frac{G_{V^b_2V^b_1}}{G_{V^b_1V^b_1}}, \] (2.16)

The Panasonic WM-61A microphone transducer frequency response \(PS(f)\) then can be evaluated using the Eq. 2.17.
\[
PS(f) = \frac{E[V_2^b(f) \cdot V_1^b(f)]}{E[V_1^b(f) \cdot V_1^b(f)]} \cdot \frac{1}{S_p(f)} = \frac{G_{V_2^bV_1^b}}{G_{V_1^bV_1^b}} \cdot \frac{G_{V_1^bV_1^s}}{G_{V_2^bV_1^s}} \cdot S_{ref}.
\] (2.17)

Figure 2.21 shows the coherence result between the reference microphone signals and the calibrated Panasonic microphone signals obtained using Eq. 2.18. It can be seen that in the frequency range of 30 Hz to 5.5 kHz, the coherence between the two signals (reference microphone and Panasonic microphone) is larger than 0.99.

\[
C_{x,y}(f) = \frac{|G_{x,y}(f)|^2}{G_{x,x}(f)G_{y,y}(f)}.
\] (2.18)

Here, \(G_{x,x}(f)\) and \(G_{y,y}(f)\) are power spectral densities, and \(G_{x,y}(f)\) is the cross power spectral density of input signals \(x_n\) and \(y_n\).

The microphone data was acquired with a sampling frequency of 65536 Hz and a total of 2097152 samples were recorded. In order to reduce the statistical convergence error, the spectra have been calculated by dividing the pressure time series into a sequence of records. The uncertainty was found using \(\frac{1}{\sqrt{N_r}}\cdot100\%\), resulting in a certainty level of about 0.98\%, where \(N_r\) is the window length of power spectral density (PSD). The unsteady surface pressure measurement results will be presented and discussed in Chapter 5.
2.5. MEASUREMENT METHODS

Figure 2.17: Remote microphone sensor holder (a) photo of the remote microphone sensor holder, (b) CAD drawing of the remote microphone sensor holder.

Figure 2.18: Remote microphone sensor set-up.

Figure 2.19: Remote microphone sensor calibration set-up.
Figure 2.20: Panasonic microphone sensitivity.

Figure 2.21: Coherence between calibrated microphone signal and reference microphone signal.
CHAPTER 3

FLOW VISUALISATION AND AERODYNAMIC PERFORMANCE

This chapter describes the aerofoil surface flow visualisation and aerodynamic performance of a NACA 0012 and a NACA 65(12)-10 aerofoil fitted with different types of serrations on the trailing-edge of the aerofoil. The Open-jet wind tunnel facility has been used to perform surface flow visualisation. The oil flow visualisation technique, described in Chapter 2, has been used to investigate the surface flow patterns of the serrated and unserrated aerofoils for a wide range of angles of attack. The aerodynamic performance of the serrated and unserrated aerofoils were also carried out using force balance in the 7’ × 5’ closed-circuit wind tunnel for a wide range of angles of attack and Reynolds numbers.
CHAPTER 3. FLOW VISUALISATION AND AERODYNAMIC PERFORMANCE

3.1 Surface flow visualisation

In order to visualise the flow patterns over the surface of the NACA 0012 and NACA 65(12)-10 aerofoils with and without trailing-edge serrations, oil flow visualisation technique has been used. The surface flow pattern visualisation on the upper and bottom surfaces of the serrated and unserrated aerofoils have been carried out for angles of attack ranging from $\alpha = 0^\circ$ to $20^\circ$ for the NACA 0012 aerofoil and $\alpha = -5^\circ$ to $20^\circ$ for the NACA 65(12)-10 aerofoil. Measurements were carried out under a flow velocity of $U_0 = 20\ m/s$, corresponding to the chord-based Reynolds number of $Re_c = 2 \times 10^5$. The flow visualisation results i.e., separation location (S), re-attachment location (R) and separation bubbles length ($L_b$) for the NACA 0012 aerofoil are presented in Figs. 3.1 to 3.3 and Table 3.1. The results for the NACA 65(12)-10 aerofoil with and without trailing-edge serrations are presented in Figs. 3.5 to 3.8 and Table 3.2.

3.1.1 Surface flow pattern for NACA 0012 aerofoil

As shown in Fig. 3.1 and Table. 3.1, the results for the NACA 0012 aerofoil illustrate that at low angle of attack, $\alpha = 0^\circ$ in Fig. 3.1(a), the flow remains attached to the surface, as seen the Fig. 3.4(a). The flow separation location occurs at about 77.4% of the aerofoil chord-length. As the angle of attack is increased to $\alpha = 7^\circ$, the separation location moves upstream towards the leading-edge of the aerofoil to around 16.12%. At higher pre-stall angles of attack, $\alpha = 8^\circ$ to $13^\circ$, the separation location is observed to occur near the leading-edge at 6.45% to 1.29% and a re-attachment at early leading-edge region, around 12.9% of the aerofoil. The separation bubble length ($L_b$) has been captured based on the location of separation and re-attachment presented in Table 3.1. This is believed to be due to the small vortex generated at the leading-edge of the aerofoil, see Fig. 3.4(b). As shown in the results in Fig. 3.3, in the post-stall range, $13^\circ < \alpha < 20^\circ$, the flow is fully separated and the leading-edge re-attachment occurs at 9.68% to 3.23% of the aerofoil
3.1. SURFACE FLOW VISUALISATION

A second re-attachment due to the vortex generated by the flow from the bottom surface can be captured at around the middle of the aerofoil, see Fig. 3.4(c). Also, at high angles of attack region, from $\alpha = 16^\circ$ to $\alpha = 20^\circ$, the separation bubbles length ($L_b$) was calculated based on the separation location and the second re-attachment location. Results show that with increasing of the angle of attack, the separation bubble length ($L_b$) increases. A similar relationship between the separation locations for angles of attack ranging from $\alpha = 6^\circ$ to $13^\circ$ was also observed by Chen et al. in their study on a NACA 0012 aerofoil at a similar Reynolds number [137]. At deep stall angles of attack, $\alpha = 15^\circ$ to $20^\circ$, a flow re-attachment can be observed at about 33% of the aerofoil chord, which slowly moves towards the trailing-edge of the aerofoil as the angle of attack increases.

<table>
<thead>
<tr>
<th>$\alpha = 0^\circ$</th>
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<td><img src="c" alt="Image" /></td>
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</tr>
</tbody>
</table>

Figure 3.1: Surface flow pattern images for top surface of a NACA 0012 aerofoil at low angles of attack range of $\alpha = 0^\circ$, 2°, 4° and 6°.

<table>
<thead>
<tr>
<th>$\alpha = 8^\circ$</th>
<th>$\alpha = 10^\circ$</th>
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</tr>
</tbody>
</table>

Figure 3.2: Surface flow pattern images top surface of a NACA 0012 aerofoil at pre-stall range of $\alpha = 8^\circ$, 10°, 12° and 14°.
CHAPTER 3. FLOW VISUALISATION AND AERODYNAMIC PERFORMANCE

$\alpha = 16^\circ$  $\alpha = 18^\circ$  $\alpha = 20^\circ$

(a)  (b)  (c)

Figure 3.3: Surface flow pattern images top surface of a NACA 0012 aerofoil at deep-stall range of $\alpha = 16^\circ$, $18^\circ$ and $20^\circ$.

Table 3.1: The separation location (S), re-attachment location (R) and separation bubble length ($L_b$) for NACA 0012 aerofoil at $R_e_c = 2 \times 10^5$ over $\alpha = 0^\circ$ to $20^\circ$, based on flow visualisation tests.

<table>
<thead>
<tr>
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<td>6</td>
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<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
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</tbody>
</table>

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3.1. SURFACE FLOW VISUALISATION

Figure 3.4: The separation location (S), reattachment location (R) and separation bubble length ($L_b$) for NACA 0012 aerofoil at (a) low angle of attack, (b) pre-stall angle of attack and (c) post-stall angle of attack.
3.1.2 Surface flow pattern for NACA 65(12)-10 aerofoil

The results for a NACA 65(12)-10 aerofoil with and without different serrations (sawtooth serration with $\lambda = 9$ mm, $2h = 30$ mm and $\lambda = 24.8$ mm, $2h = 30$ mm) all show a similar behaviour of the separation location moving towards the aerofoil leading-edge while increasing the angle of attack in the pre-stall region. As shown in the surface flow pattern images in Figs. 3.5 and 3.8 and the flow separation and re-attachment location results in Table 3.2, at $\alpha = -5^\circ$ the separation location occurs at about $64.52\%$ of the aerofoil chord for the Baseline case. This separation location gradually moves upstream to $52.9\%$ of the chord as the angle of attack $\alpha$ increases to $10^\circ$, with the first re-attachment location ($R_1$) moving from the chord location of about $93.55\%$ to $70.97\%$ in this $\alpha$ range. Similar observations on the separation locations have also been made in Gruber’s study for angles of attack between $\alpha = 0^\circ$ and $10^\circ$ [16, 98–100].

For the results of the aerofoil with sawtooth serration with $\lambda = 24.8$ mm and $2h = 30$ mm, in the same angle of attack range ($\alpha = -5^\circ$ to $10^\circ$), the separation location can be found at about $72.26\%$, moving upstream to $54.84\%$ of the aerofoil chord, with the first re-attachment location moving from around $93.55\%$ to $70.97\%$. For the result of the aerofoil with a sharp sawtooth serration ($\lambda = 9$ mm, $2h = 30$ mm), the separation location ($S$) occurs at about $69.68\%$ to $54.84\%$ of the aerofoil chord and the first re-attachment location ($R_1$) is found to move around $87.10\%$ to $70.97\%$, as the angles of attack changes from $\alpha = -5^\circ$ to $10^\circ$.

In comparison with the Baseline case, the separation location for the aerofoil fitted with sawtooth serration with $\lambda = 24.8$ mm shows that the use of serration leads to the separation locations moving around $5\%$ to $8\%$ of the chord downstream towards the trailing-edge of the aerofoil at the low angles of attack ($\alpha = -5^\circ$ to $\alpha = -3^\circ$). Similar to the results for the large serration, the separation locations for sharp sawtooth serration
case ($\lambda = 9$ mm) moved around 5% downstream at low angles of attack. The results for the first re-attachment location (R1) for the large sawtooth serration case ($\lambda = 24.8$ mm) are very similar to that of the Baseline aerofoil. However, for the sharp sawtooth serration case ($\lambda = 9$ mm), the first re-attachment location moves around 6% forward when compared to the Baseline case.

In the critical angle of attack range, $\alpha = 11^\circ$ to $18^\circ$ (see Figs. 3.7 and 3.8), for the Baseline case, results show that the flow is fully separated from the surface of the aerofoil. The first re-attachment location occurs when the aerofoil is set at the angle of attack $\alpha > 12^\circ$. The first re-attachment location (R1) moves upstream closer to the aerofoil leading-edge to about 4% of the aerofoil chord and the second re-attachment location (R2) moves from 83.87% to 61.29% of the aerofoil chord. Leading-edge flow separation can be observed at deep stall angles of attack, $\alpha = 18^\circ$ to $20^\circ$. In the case of aerofoils with trailing-edge serrations, the flow separates fully when the angle of attack $\alpha > 11^\circ$. Unlike the Baseline case, the serrated cases show that the first re-attachment location occurs at around 3.5% of the chord when $\alpha > 15^\circ$ and the second re-attachment location moves from 87.10% to 77.42% when the angle of attack changes from $\alpha = 16^\circ$ to $20^\circ$. 
Figure 3.5: Surface flow pattern images top surface of a NACA 65(12)-10 aerofoil at low angles of attack range of $\alpha = -4^\circ$, $-2^\circ$, $0^\circ$ and $2^\circ$. 
### 3.1. SURFACE FLOW VISUALISATION

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</tr>
<tr>
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<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
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Figure 3.6: Surface flow pattern images top surface of a NACA 65(12)-10 aerofoil at pre-stall angles of attack range of $\alpha = 4^\circ$, $6^\circ$ and $8^\circ$. 
Figure 3.7: Surface flow pattern images top surface of a NACA 65(12)-10 aerofoil at stall angles of attack range of $\alpha = 10^\circ$, $12^\circ$, $14^\circ$ and $16^\circ$. 
### 3.1. SURFACE FLOW VISUALISATION

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<tr>
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<td>(d)</td>
</tr>
<tr>
<td><strong>Sawtooth Serration ($\lambda = 24.8 \text{mm}$)</strong></td>
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Figure 3.8: Surface flow pattern images top surface of a NACA 65(12)-10 aerofoil at post-stall angles of attack range of $\alpha = 18^\circ$ and $20^\circ$. 
Table 3.2: The separation (S), transition (T) and re-attachment (R) locations for NACA 0012 and NACA 65(12)-10 aerofoil at $U_0 = 20$ m/s over $\alpha = -5^\circ$ to $20^\circ$, based on flow visualisation tests.

<table>
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### 3.1. SURFACE FLOW VISUALISATION

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<td>(b)</td>
<td>(c)</td>
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<td>(i)</td>
<td>(j)</td>
<td>(k)</td>
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</table>

Figure 3.9: Surface flow pattern images for bottom surface of the NACA 65(12)-10 with and without sawtooth serrations at selected angles of attack ($\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$).
Figure 3.10: Zoomed-in images of the surface flow pattern images for bottom surface of a NACA 65(12)-10 with sawtooth serration ($\lambda = 24.8\,mm$) at selected angles of attack ($\alpha = -5^\circ, 0^\circ, 5^\circ, 10^\circ, 15^\circ$ and $20^\circ$).
As presented in Fig. 3.9, the surface flow pattern results for the bottom surface of the NACA 65(12)-10 aerofoil with and without the two types of serrations (sawtooth serration with $\lambda = 9$ mm and $\lambda = 24.8$ mm) show similar behaviour over the whole surface at the angles of attack considered here. In Fig. 3.10, the zoomed-in images are provided for the surface flow pattern over the sawtooth area. At low angles of attack, ($\alpha = -5^\circ$ and $0^\circ$) the flow is found to remain nearly attached. When increasing the angle of attack, $\alpha = 5^\circ$ and $10^\circ$, clear signs of valley flow can be found at the near valley region, as well as edge vortex pattern along the edge of the sawtooth serrations. At high angles of attack, $\alpha = 15^\circ$ and $20^\circ$, when the flow is fully separated, the edge vortex pattern still can be found at the edge of the serration. This pattern for high angles of attack is not as clear as the results observed in the case of pre-stall angles of attack.
3.2 Aerodynamic loading of aerofoils with serrated trailing-edge

The aerodynamic lift and drag measurements of the NACA 0012 and NACA 65(12)-10 aerofoils with the Baseline, blunt and serrated configurations were carried out over a wide range of angles of attack and flow velocities of $U_0 = 20 \text{ m/s}$ to $60 \text{ m/s}$, corresponding to the chord-based Reynolds number range of $Re_c = 2 \times 10^5$ to $6 \times 10^5$. However, for the purpose of brevity the results for the flow velocities $U_0 = 30 \text{ m/s}$ and $50 \text{ m/s}$, corresponding to chord based Reynolds number $Re_c = 3 \times 10^5$ and $5 \times 10^5$ are presented and discussed in this section. The tests were carried out for the angles of attack ($\alpha$) ranging from $0^\circ$ to $20^\circ$ and $-5^\circ$ to $20^\circ$ for the NACA 0012 and NACA 65(12)-10 aerofoils, respectively. The following serrations are considered: three saw tooth serrations with different wavelengths $\lambda = 3 \text{ mm}$, $\lambda = 9 \text{ mm}$ and $\lambda = 24.8 \text{ mm}$, and amplitude of $2h = 30 \text{ mm}$; two sinusoidal serrations with different wavelengths $\lambda = 9 \text{ mm}$ and $\lambda = 24.8 \text{ mm}$, and amplitude of $2h = 30 \text{ mm}$; and two slotted-sawtooth serrations, with the wavelength and amplitude of $\lambda = 9 \text{ mm}$ and $2h = 30 \text{ mm}$, slot width of $d = 0.5 \text{ mm}$ and different slot depths of $H = 5 \text{ mm}$ and $H = 15 \text{ mm}$. The geometric details of the serrations used in this study can be found in Section 2.3

3.2.1 Aerodynamics force measurement setup

The study of the aerodynamic performance of a symmetrical NACA 0012 and a cambered asymmetric NACA 65(12)-10 aerofoil with and without trailing-edge serrations was performed in the $7' \times 5'$ large low-speed closed-circuit wind tunnel, as discussed in Section 2.4, see Fig. 3.11(a). As mentioned above, two aerofoils with different types of serrations (see Fig. 3.11(b)) have been investigated in this study. To reduce the probable flow three-dimensionality effects associated with tip-flow separation, circular end-
plates with a diameter of 0.34 m were used on the aerofoil. The edges of these circular end-plates were chamfered to reduce flow distortion. The aerofoils with the end-plates were fixed on steel support arms, connected to a force balance system installed under the tunnel’s working section (see Fig. 3.12). A slot has been cut out at the trailing-edge side of the end plate in order to fix an "L" shaped metal part to enable angle measurement using a "Bevel box", see Fig. 3.11. The aerodynamic lift and drag forces for both two aerofoils were measured using a strain-gauge based AMTI OR6-7-2000 force balance system, equipped with an AMTI MSA-6 amplifier and 16-bit A/D card. A thorough data independency test using different sampling frequencies was carried out before choosing a sampling frequency of 37 Hz. This frequency provided the best data independency with an uncertainty level (at 95% confidence level) less than 3.5% for the lift and drag force results before stall and approximately 5% to 10% for the lift and drag force results after stall angles of attack. The final data sets were collected for a time period of 30 seconds, resulting in 1000 independent samples for statistical post-processing. The aerodynamic lift and drag values were calculated following the bootstrap procedure proposed by Theunissen et al. [127]. The lift and drag force coefficients were then calculated using Eqs. 3.1

\[
C_L = \frac{L}{\frac{1}{2} \rho U_0^2 S_a}, \\
C_D = \frac{D}{\frac{1}{2} \rho U_0^2 S_a},
\]

where \(L\) and \(D\) are the lift and drag forces, respectively, \(S_a\) is the cross-section area, \(\rho\) is the air density and \(U_0\) is the freestream flow speed.
Figure 3.11: (a) Aerodynamic force measurement setup. (b) Trailing-edge serration.

Figure 3.12: Aerodynamic force measurement layout in the large wind tunnel facility of the University of Bristol.
3.2.2 NACA0012 aerofoil lift and drag coefficients

![Graphs showing lift and drag coefficients for NACA0012 aerofoil with serrations at different flow velocities.]

Figure 3.13: Lift and drag coefficient results for NACA 0012 aerofoil fitted with different serrations at $U_0 = 30$ m/s and $U_0 = 50$ m/s. Black solid line with circles: Baseline; Black dash line with circles: blunt aerofoil; (a) and (b) sawtooth serrations. Blue triangles: $\lambda = 9$ mm; Red squares: $\lambda = 24.8$ mm; (c) and (d) slotted-sawtooth serrations ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm); Blue triangle: $H = 5$ mm; Red square: $H = 15$ mm.

The NACA 0012 aerofoil force measurements for all different sawtooth and slotted-sawtooth serration configurations are presented in Fig. 3.13. The lift and drag force coefficients are presented for the flow velocities of 30 m/s and 50 m/s, corresponding to $Re_c = 3 \times 10^5$ and $5 \times 10^5$. The results for the sawtooth cases are presented in Fig. 3.13(a) and (b), and those for slotted-sawtooth serrations are presented in Fig. 3.13(c) and (d), respectively. The results for the NACA 0012 aerofoil fitted with serrations show almost no reduction in the lift coefficient for small angles of attack, ranging from $0^\circ$ to $9^\circ$, indicating that the effect of serrations on the lift coefficient is minor for NACA 0012 aerofoil. The serrations, however, significantly affect the maximum lift coefficient over the crit-
ical angle of attack ranges from 9° to 15°. The maximum lift coefficient for sawtooth serrations were around 3% to 5% lower than that of the Baseline case but higher than the blunt case. For the slotted-sawtooth serration cases, the lift coefficient is similar to that of the blunt case but around 10% lower than the Baseline cases. The lift coefficient results also appear to show improvement in the lift performance at deep stall angles from 17° to 20° for both the sawtooth and slotted-sawtooth serration cases at $U_0 = 50$ m/s. Furthermore, the use of serrations has been observed to cause a slight increase in the stall angle (from 13° to 14°) at high flow speeds.

The drag coefficient results for both the sawtooth and slotted-sawtooth cases show similar results when compared to the blunt and Baseline cases in the angle of attack range of 0° to 9°. In the pre-stall region, $\alpha = 13°$ to 15°, the drag coefficient for the serrated cases are similar to that of the blunt case and up to 48% lower than that of the Baseline case. When the angle of attack increases, in the deep-stall region ($\alpha > 16°$), the drag coefficient for the serrated cases is found to be slightly higher than that of the Baseline case, especially at high flow speeds.

Figure 3.14 presents the lift-to-drag ratio (L/D) for the NACA 0012 aerofoil with and without sawtooth and slotted-sawtooth serrations at $U_0 = 30$ m/s and $U_0 = 50$ m/s. The lift-to-drag ratio results at $U_0 = 30$ m/s, Figs. 3.14 (a) and (c), show that the serrated cases are roughly 8% to 11% different in value compared to the Baseline and blunt cases. Compared to the results presented for higher speeds, the lift-to-drag ratio curves at lower speeds are not very smooth, which is believed to be due to the small value of drag at low speed. As shown in the results for higher speeds in Figs. 3.14 (b) and (d), the lift-to-drag ratio for the serrated cases are close to that of the Baseline and blunt cases at most angles of attack. At higher angle of attack, $\alpha = 14°$, a noticeable improvement (up to 50%) in the lift-to-drag ratio can be observed for serrated cases compared with the
3.2. AERODYNAMIC LOADING OF AEROFOILS WITH SERRATED TRAILING-EDGE

Figure 3.14: Lift-drag ratio results for NACA 0012 fitted with different serrations at \( U_0 = 30 \text{ m/s} \) and \( U_0 = 50 \text{ m/s} \). Black solid line with circles: Baseline; Black dash line with circles: blunt aerofoil; (a) and (b) sawtooth serrations. Blue triangles: \( \lambda = 9 \text{ mm} \); Red squares: \( \lambda = 24.8 \text{ mm} \); (c) and (d) slotted-sawtooth serrations (\( \lambda = 9 \text{ mm}, 2h = 30 \text{ mm}, d = 0.5 \text{ mm} \)); Blue triangle: \( H = 5 \text{ mm} \); Red square: \( H = 15 \text{ mm} \).

Baseline results. On the other hand, when compared with the blunt case, the result for serrated cases is similar to each other. As shown in the previous Figs. 3.13 (b) and (d), the results for the serrated cases show a clear increase in lift coefficient and decrease in drag coefficient and the maximum lift coefficient appeared at 14°. In addition, the use of serrations allowed the aerofoil to stall at a higher angle of attach at higher Reynolds numbers.

3.2.3 NACA65(12)-10 aerofoil lift and drag coefficients

The measured lift and drag coefficients for all the three configurations of the NACA 65(12)-10 aerofoil are presented in Fig. 3.15. The aerodynamic force results are pre-
Figure 3.15: Lift and drag coefficient results for NACA 65(12)-10 fitted with different serrations at $U_0 = 30$ m/s and $U_0 = 50$ m/s. (a) and (b) sinusoidal serrations. Triangles: Blue: $\lambda = 9$ mm; Squares: Red: $\lambda = 24.8$ mm; (c) and (d) sawtooth serrations. Circle: Green: $\lambda = 3$ mm; Triangles: Blue: $\lambda = 9$ mm; Squares: Red: $\lambda = 24.8$ mm; (e) and (f) slotted-sawtooth serrations ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm); Triangle: Blue: $H = 5$ mm; square: Red: $H = 15$ mm.

Presented for sinusoidal trailing-edges, Fig. 3.15(a) and (b), sawtooth serrations, Fig. 3.15(c) and (d), and slotted-sawtooth, Fig. 3.15(e) and (f) at flow speeds of 30 m/s and 50 m/s. The geometrical details of the serrations used in this study can be found in Section 2.3.
The lift coefficient results show a noticeable difference in the overall behaviour of cambered NACA 65(12)-10 aerofoil to that of the symmetric NACA 0012 aerofoil. The force measurement results for NACA 65(12)-10 aerofoil with sawtooth serrations for the presented flow conditions show a reduction in the lift coefficient of up to 15% for small angles of attack, ranging from $-5^\circ$ to $10^\circ$ compared to the Baseline aerofoil. The results for the NACA 65(12)-10 aerofoil with slotted-sawtooth serrations show an even greater reduction in the lift coefficient of up to 30% for the entire range of angles of attack, with the maximum reduction observed at lower angles of attack. Aerofoils with trailing-edge serrations show increased lift coefficient in the pre-stall region but do not particularly change the stall behaviour of the aerofoil. The results also show a prominent loss in the lift coefficient for the blunt aerofoil compared to the Baseline aerofoil, which can be attributed to the decrease in the aerofoil trailing-edge area. As for the NACA 65(12)-10 aerofoil, the trailing-edge side of the aerofoil plays an important role in its aerodynamic performance (See aerofoil geometry in Chapter 2). The lift coefficient of the serrated aerofoils shows a significant increase in lift over the whole range of angles of attack in comparison to the blunt aerofoil. For the drag coefficient, the use of serration does not show a large effect at low angle region ($\alpha < 10^\circ$). For angles of attack larger than $10^\circ$, the drag coefficient for the sinusoidal and sawtooth serrated aerofoils are higher than that of the Baseline and Blunt aerofoils, while for the slotted-sawtooth aerofoils, the drag coefficient is found to be higher than that of the blunt aerofoil but smaller than the Baseline aerofoil.

The lift-to-drag ratio results obtained at $U_0 = 30$ m/s and 50 m/s for the NACA 65(12)-10 aerofoil fitted with different serrations are presented in Fig. 3.16. The results for the sinusoidal serrations are presented in Figs. 3.16(a) and (b), sawtooth serrations in Figs. 3.16(c) and (d), and slotted-sawtooth serrations in Figs. 3.16(e) and (f). It can be seen that at low flow speeds, the lift-to-drag ratio for the NACA 65(12)-10 aerofoil fitted
Figure 3.16: Lift-drag ratio results for NACA 65(12)-10 fitted with different serrations at $U_0 = 30 \text{ m/s}$ and $U_0 = 50 \text{ m/s}$. (a) and (b) sinusoidal serrations. Triangles: Blue: $\lambda = 9 \text{ mm}$; Squares: Red: $\lambda = 24.8 \text{ mm}$; (c) and (d) sawtooth serrations. Circle: Green: $\lambda = 3 \text{ mm}$; Triangles: Blue: $\lambda = 9 \text{ mm}$; Squares: Red: $\lambda = 24.8 \text{ mm}$; (e) and (f) slotted-sawtooth serrations ($\lambda = 9 \text{ mm}$, $2h = 30 \text{ mm}$, $d = 0.5 \text{ mm}$); Triangle: Blue: $H = 5 \text{ mm}$; square: Red: $H = 15 \text{ mm}$.

with sinusoidal serration are very similar to the Baseline case in the angle of attack range of $-5^\circ$ to $-1^\circ$, while the sawtooth serrations and slotted-sawtooth serration cases are observed to produce less $L/D$. A noticeable reduction of up to 42% can be observed for
the results for all three types of serrations in the angle of attack range between $-1^\circ$ to $6^\circ$. In the higher angle of attack region ($\alpha > 7^\circ$), the lift-to-drag ratio for the serrated cases resulted in similar values to that of the Baseline aerofoil. However, when compared to the results of the blunt case, a significant improvement for serrated cases can be found for $\alpha < 10^\circ$. At higher angles of attack ($\alpha > 11^\circ$), the serrations were found to only reduce the lift-to-drag ratio slightly. At higher flow speeds, in Figs. 3.16(b), (d) and (f), the use of serrations show similar behaviour to the results at low speeds. For the sinusoidal serrations and sawtooth serrations, the results are closer to the Baseline cases than the slotted-sawtooth serration. In summary, it can be found from these results that the use of slotted-serration leads to higher aerodynamic loss. Based on the previous analytical and experimental results discussed in the study by Guber et al [16, 126], sharp sawtooth (small $\alpha_s$) and slotted-sawtooth serrations provide large and robust noise reduction over a wide frequency range. The aerodynamic force measurements presented here, however, have revealed that such effective trailing-edge treatments (with respect to noise) are prone to a certain level of aerodynamic loss and that they are also highly sensitive to aerofoil shape and flow conditions.
Detailed flow measurements at several downstream wake locations have been performed using LDV, PIV and hot-wire measurement techniques for NACA 0012 and NACA 65(12)-10 aerofoils to better understand the effects of different types of trailing-edge serrations on the aerodynamic performance of the aerofoils. In what follows, however, the focus will lie on the cambered aerofoil (NACA 65(12)-10) due to its relevance to various engineering applications, such as wind turbine blades, engine blades, etc. The wake measurements were carried out at the geometric angles of attack, $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ at the flow velocity of $U_0 = 20$ m/s and $U_0 = 30$ m/s, corresponding to the chord-based Reynolds number of $Re_c = 2 \times 10^5$ and $Re_c = 3 \times 10^5$.

### 4.1 LDV wake results

The NACA 0012 and NACA 65(12)-10 aerofoils were mounted using tear-shaped support arms to minimise the support’s aerodynamic influence (Fig. 4.1). Measurements were performed in the Low Turbulence Wind Tunnel (see Chapter 2). The LDV wake
measurements were logged at the downstream locations $x/c = 0.2, 0.3, 0.5, 1.0, 1.5$ and 2.0 relative to the trailing-edge of the Baseline aerofoil (see Figs. 4.2(a) and (b)). As shown in Fig. 4.2(c), for the serrated aerofoil case, the results of the tip and root position have also been logged. At each of the downstream locations, 60 sampling points were aligned vertically with a spacing varying between $\Delta y/c = 0.02$ to 0.05 to accurately capture the flow behaviour within the wake region for freestream velocity of $U_0 = 30 \text{ m/s}$ (chord-based Reynolds number of $Re_c = 3 \times 10^5$).

In the following, variations in the wake velocity, turbulence kinetic energy (TKE) and Reynolds stresses for the NACA 0012 and NACA 65(12)-10 aerofoil with and without different types of serrations (see Table 4.1) will be discussed in detail.
4.1. LDV WAKE RESULTS

Figure 4.2: Chord- and span-wise locations used in the LDV measurements. View of the downstream profile extraction locations for the (a) Baseline and (b) serrated aerofoils. (c) Top view of the spanwise location of the measurement locations in the case of the serrated trailing-edges.

Table 4.1: Geometrical parameters of the trailing-edge serrations used in the current study.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Serration Types</th>
<th>$2h$ (mm)</th>
<th>$\lambda$ (mm)</th>
<th>$\lambda/h$</th>
<th>$a_s$ (deg.)</th>
<th>$d$ (mm)</th>
<th>$H$ (mm)</th>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>0.6</td>
<td>8.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 3</td>
<td>slotted-sawtooth</td>
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<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>0.5</td>
<td>15</td>
</tr>
</tbody>
</table>
4.1.1 NACA 0012 wake velocity and TKE profiles

Figures 4.3 to 4.10 demonstrate the wake velocity and wake TKE results of a NACA 0012 aerofoil at the angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$. Three trailing-edge configurations were considered: the Baseline, sawtooth serrations ($\lambda = 9$ mm) and slotted-sawtooth serrations ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm and $H = 15$ mm). The velocity and TKE profiles were extracted at both the tip and root locations of the serrations. The Reynolds stress and the individual components will be addressed latter in Section 4.1.3.

- Wake velocity and TKE profiles at $\alpha = 0^\circ$

At $\alpha = 0^\circ$ (in Figs. 4.3 and 4.4) for the serrated NACA 0012 aerofoil, the wake velocity profiles generally match with the Baseline aerofoil with a predominant two dimensional wake flow structure. Considering the TKE wake profile, however, the Baseline case shows a clear double peak feature in the near trailing-edge region, $x/c \leq 0.3$. Here, the turbulence intensity increases due to the interaction between the wake and freestream. These double peaks do not appear in the results of either the sawtooth or slotted-sawtooth cases, which is thought to be due to the difference in the effective chord length at the tip- and root-location, thus introducing higher flow mixing between the pressure and suction sides of the aerofoil. The results also show a minor increase in the TKE levels for the serrated NACA 0012 aerofoil in the wake region up to $x/c = 1.0$ and an increase in the width of the wake profiles when compared to the Baseline case in this wake region. For the slotted-sawtooth case, the relative increase in TKE within the near trailing-edge range ($x/c = 0.2$ and $x/c = 0.3$) is higher than that of the sawtooth serrated case, especially near the centreline line of the TKE wake profile.

- Wake velocity and TKE profiles at $\alpha = 5^\circ$
The streamwise wake velocity components and the TKE for the NACA 0012 aerofoil are presented for an angle of attack of $\alpha = 5^\circ$ in Figs. 4.5 and 4.6. The results show that both serrated aerofoils produce wake profiles similar to that of the Baseline but with a slightly increased velocity deficit along the tip location. In addition, the locations of the local minimum in the observed flow velocity deficit profiles (dip locations) along the y-axis for tip-flow show a downward shift relative to that of the Baseline flow. This is believed to be caused by the increase in the effective chord length at the tip position of the serrated cases. In the near-wake region of the NACA 0012 aerofoil ($0.2 \leq x/c \leq 0.3$), the two serrated aerofoil cases again show a notably larger TKE value than that of the Baseline case especially along the tip location. Contrary to the $\alpha = 0^\circ$ case, the TKE profiles for the serrated cases at $\alpha = 5^\circ$ follow the Baseline case with its double peak behaviour quite well. The peak locations along the y-axis for the tip position show a clear downward shift at the root location when compared with the Baseline results.

- Wake velocity and TKE profiles at $\alpha = 10^\circ$

For an angle of attack of $\alpha = 10^\circ$ in Figs. 4.7 and 4.8, the streamwise velocity results show that the two serrated aerofoils produce wake profiles similar to the Baseline case but with a slightly reduced velocity deficit at the root-position. For the sawtooth serrated case, the deficit dip location measured in the root-plane shows a minor upward shift in the y-direction compared to that of the Baseline case at the near trailing-edge wake region ($x/c \leq 0.3$) and a noticeable upward shift for both the tip and root positions when compared with the Baseline case. For the slotted-sawtooth cases, the results indicate a clear upward shift with respect to that of the Baseline results over the whole wake range. The wake TKE profiles for two serrated aerofoils show wake trends similar to that of the Baseline but with a slightly increased TKE level for the tip-flow result near the trailing-edge location $x/c = 0.2$. Also, in the far wake region for the sawtooth serrated
case \((x/c = 1.0 \text{ to } x/c = 2.0)\) and the entire wake range for the slotted-sawtooth case, a clear upward shift is observed in the TKE profiles (see Fig. 4.8).

- Wake velocity and TKE profiles at \(\alpha = 15^\circ\)

At a higher angle of attack of \(\alpha = 15^\circ\) (Figs. 4.9 and 4.10), the wake velocity profiles for both serrated aerofoils resemble that of the Baseline aerofoil with a lesser velocity deficit in the near trailing-edge wake region from the wake locations \(x/c = 0.2 \text{ to } x/c = 0.3\). For the TKE profiles, unlike the results at smaller angles of attack, the wake TKE profiles for serrated cases retain the characteristic double-peak behaviour but decrease significantly in magnitude (up to around 48\%) within the wake region between \(x/c = 0.3\) to \(x/c = 1.5\). However, the TKE values for the serrated aerofoils become comparable to that of the Baseline case beyond \(x/c = 2.0\).

In summary, as shown in the results, for a symmetric NACA 0012 aerofoil, the use of two different trailing-edge serrations does not show a remarkable change in the velocity wake profile for low angles of attack, \(\alpha = 0^\circ\) and \(\alpha = 5^\circ\). This also concurs with the lift and drag measurements presented in Chapter 3; serrations do not particularly change the aerodynamic performance of the aerofoil at low angles of attack. At higher angles of attack \(\alpha = 10^\circ\) and \(\alpha = 15^\circ\), the use of serrations generally results in a behaviour similar to that of the Baseline case with slightly reduced velocity deficit and a shift of deficit dip location. The wake TKE profiles for a serrated symmetric NACA 0012 aerofoil tend to resemble those of the Baseline for all the wake locations showing only slight increases in the energy content of the flow structures in the wake at low angle of attack region \(\alpha = 0^\circ\) and \(\alpha = 5^\circ\). However, at high angle of attack \(\alpha = 15^\circ\), the use of trailing-edge serrations leads to a significant reduction in TKE at the wake region \(x/c = 0.3\) to \(x/c = 1.0\). This shows that the effect of using trailing-edge serrations highly depends on the aerofoil
angle of attack.
Figure 4.3: Wake mean velocity for NACA 0012 aerofoil at $\alpha = 0^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.4: Wake turbulent kinetic energy for NACA 0012 aerofoil at $\alpha = 0^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
4.1. LDV WAKE RESULTS

Figure 4.5: Wake mean velocity for NACA 0012 aerofoil at $\alpha = 5^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.6: Wake turbulent kinetic energy for NACA 0012 aerofoil at $\alpha = 5^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
Figure 4.7: Wake mean velocity for NACA 0012 aerofoil at $\alpha = 10^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.8: Wake turbulent kinetic energy for NACA 0012 aerofoil at $\alpha = 10^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
4.1. LDV WAKE RESULTS

Figure 4.9: Wake mean velocity for NACA 0012 aerofoil at $\alpha = 15^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.10: Wake turbulent kinetic energy for NACA 0012 aerofoil at $\alpha = 15^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
4.1.2 NACA 65(12)-10 wake velocity and TKE profiles

The results presented in Figs. 4.11 to 4.18 compare the effects of trailing-edge serration on the wake velocity and wake TKE for a cambered NACA 65(12)-10 aerofoil. Results will be presented for the Baseline straight trailing-edge as well as those at the tip and root locations. Two different serrations have been considered, namely, sawtooth serration ($\lambda = 9$ mm) and slotted-sawtooth serration ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm and $H = 15$ mm). Results will be provided for the angles of attack of $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$. The Reynolds stress and the individual components will be addressed latter in Section 4.1.4.

- Wake velocity and TKE profiles at $\alpha = 0^\circ$

The wake velocity profiles for the Baseline and serrated NACA 65(12)-10 aerofoils at $\alpha = 0^\circ$ are presented in Fig. 4.15. In the near-wake region, $x/c = 0.2$ to 0.5, the tip-flow position of the sawtooth follows a similar wake profile to that of the Baseline but with a slightly higher velocity deficit. The higher velocity deficit of the tip-flow is once again attributed to the larger effective chord-length of the tip-flow. For the tip-wake, the deficit peak location along the y-axis is the same as that of the Baseline flow. Unlike the tip-flow, the root-flow exhibits a very different behaviour. The root-flow has a smaller velocity deficit, with the deficit peak location moved upward along the y-axis due the jet flow through the serration valleys. This upward jet through the serrations was also evidenced in the surface flow pattern visualisation results in Chapter 3. The differences between the wake velocity deficit and the deficit peak location at far-wake locations, $x/c = 1.0, 1.5$ and $2.0$, gradually disappears between the sawtooth and Baseline cases. Overall, it is clear that the root-flow can significantly change the nature of the wake development, even at small angles of attack. In the case of the NACA 65(12)-10 aerofoil fitted with a slotted-sawtooth trailing-edge, the tip velocity deficit is notably larger than
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that of the Baseline and the standard sawtooth serration. The flow at the root position was also moved slightly upward compared to the sawtooth and Baseline. Results also show that the use of serrations in the case of a NACA 65(12)-10 at small angles of attack, leads to slightly lower velocity deflection angles. As shown in Fig. 4.11, the flow behaviour for the Baseline aerofoil with a straight trailing-edge is predominantly two dimensional. However, in the case of serrated aerofoils, the presence of inclined edges (serrations) leads to significant changes to the flow, as shown in the flow visualisation results in Chapter 3, resulting in a highly three-dimensional wake flow.

The turbulent kinetic energy (TKE) results for the NACA 65(12)-10 aerofoil with treated and untreated trailing-edges for $\alpha = 0^\circ$ are presented in Fig. 4.12. In the vicinity of the trailing-edge, $x/c = 0.2$ to 0.5, the TKE magnitude of the sawtooth is similar to that of the Baseline. In the near-wake region, the TKE of the Baseline aerofoil shows a weak double-peak behaviour due to the upper and lower boundary layers of the aerofoil. The double-peak behaviour is even more evident for the tip-flow, due to the increase in the effective chord-length of the aerofoil. The TKE of the root-flow, however, peaks only in an area in the suction side of the aerofoil, indicating the presence of an upward flow through the serration valleys, as observed in flow visualisation results in Chapter 3. In the case of slotted-sawtooth, the peak due to the aerofoil pressure-side boundary layer is much larger than that of the sawtooth serration. This is believed to be due to the slots on the sawtooth, which increase the flow mixing at the trailing-edge of the aerofoil. Results have also shown that in the far-wake region, $x/c = 1.0, 1.5$ and 2.0, the high TKE domain for the aerofoil fitted with sawtooth and slotted-sawtooth serrations is slightly wider, but generally match with the Baseline aerofoil results.

- Wake velocity and TKE profiles at $\alpha = 5^\circ$
Figure 4.13 presents the results for the wake velocity profiles for the Baseline and serrated NACA 65(12)-10 aerofoils at $\alpha = 5^\circ$. The wake velocity results have shown that in the near-wake locations, $x/c = 0.2, 0.3$ and 0.5, unlike the results in Fig. 4.11 for $\alpha = 0^\circ$, both the tip- and root-flows have much smaller velocity deficit, i.e. weaker wake compared to the Baseline case, which is believed to be due to the flow through the serration valleys. In the case of the slotted-sawtooth, the root-flow has an even smaller velocity deficit than the normal sawtooth. As for $\alpha = 0^\circ$, the root-flow peak location lies in a region above the aerofoil mean camber-line, signifying the presence of a relatively strong upward flow within the serration valleys. As seen in Figs. 4.11 and 4.13, the interaction of the strong upward root-flow and the tip-flow leads to an overall upward deflection of the flow in the far-wake region compared to the Baseline aerofoil. This effect is more evident in the case of slotted-sawtooth aerofoil.

The wake TKE profiles for the NACA 65(12)-10 aerofoil at $\alpha = 5^\circ$ are presented in Fig. 4.14. The wake profiles of the Baseline aerofoil show a clear double-peak behavior, which is due to the interaction of the boundary layers on the pressure and suction sides of the aerofoil. The near-wake results show that the use of serrations can lead to significant changes to the TKE of the flow especially in the near-wake region. As observed before in Fig. 4.14, the root-flow has caused a region of high TKE above the mean camber-line, resulting in enlarged high TKE region along the y-axis. Results also show that the interaction of the tip- and root-flow results in increased mixing and a reduction in turbulence in the far-wake region.

- Wake velocity and TKE profiles at $\alpha = 10^\circ$

The wake velocity profiles and TKE results for the NACA 65(12)-10 aerofoil at $\alpha = 10^\circ$ with and without serrations are presented in Figs. 4.15 and 4.16, respectively. The
near-wake velocity profiles in Fig. 4.15 ($x/c = 0.2, 0.3$ and $0.5$) show that at high angles of attack, the velocity deficit difference between the tip- and root-flows increases and unlike the results at lower angles of attack, the resultant flow after mixing has an overall downward deflection compared to the Baseline flow. It can also be seen that in the near-wake region, the flow from slotted-sawtooth serrations has a smaller velocity deficit than that of the sawtooth serration, leading to a significant reduction of the TKE within, $x/c = 0$ to $0.5$. Therefore, it can be concluded from the velocity results that the use of serrations at high angles of attack (before stall), can significantly change the wake structure by reducing the velocity deficit, especially in the near-wake region. This is believed to be mainly due to the root-flow and the planar interaction occurring between the tip- and root-flows in the vicinity of the trailing-edge. As seen in Fig. 4.16, the TKE drops significantly to a very small value within a short distance from the trailing-edge. The wake TKE at $\alpha = 10^\circ$ for the slotted-sawtooth case has the largest reduction compared to all the other angles of attack. These results are particularly interesting as the OGVs, compressor blades, contra-rotating blade configurations, etc., are often operated at high angles of attack and the wake-turbulence interaction is considered as a major component of noise from such systems. Moreover, in the case of contra-rotating propeller, minimizing the energy content of the flow from the front row blades can significantly reduce the noise from the interaction of the wake flow with the rear row of blades.

- Wake velocity and TKE profiles at $\alpha = 15^\circ$

Figure 4.17 presents the results for the wake flow velocity for a NACA 65(12)-10 aerofoil at $\alpha = 15^\circ$. The results at $x/c = 0.2$ show the appearance of a large wake-width, indicating the presence of an early separation on the suction side of the aerofoil. Unlike the results at smaller angles of attack, the tip and root velocity profiles are very similar, but show much smaller deficit compared to the Baseline case in the near-wake
region. The velocity profiles, however, converge to that of the Baseline after $x/c = 1.0$. The wake deficit peak location for both serrations is located above the peak location of the Baseline case, which lies on the mean camber-line. The wake TKE results in Fig. 4.18 also show that the use of serrations can lead to a significant reduction of the energy content within the wake region ($x/c = 0.3$ to $1.0$). At the wake location $x/c = 0.2$, for both the serration cases, only a mild reduction in energy content can be observed compared to the Baseline with even lesser reduction above the mean camber-line due to the aerofoil’s early separation. This is believed to be due to the emergence of a new vortex, formed as a result of the interaction of the flow emerging through the serration valley from the aerofoil pressure-side with a highly angled serrated surface. However, the energy content for both the serration cases at locations $x/c = 0.3$, $0.5$ and $0.5$ has experienced significant reduction (around $56\%$ at location $x/c = 0.3$ and upto $51\%$ at locations $x/c = 0.5$ and $1.0$) in TKE compared to the Baseline case. Results also show that for the case of high angles of attack, very little difference can be observed between the normal and slotted-sawtooth serrations.

To summarize, the flow field results in this section have shown that for asymmetric NACA 65(12)-10 aerofoil, the serrations significantly affect the velocity deficit peak angle and deficit magnitude compared to the Baseline even at low angles of attack ($\alpha = 5^\circ$). The velocity profiles vary notably between the tip and root profiles that would cause significant shear stress between the tip and root planes. The velocity deficit peak location shows an upward shift in the wake profiles at the root positions relative to the Baseline and the tip positions. This indicates that the flow originating from the pressure surface passes through the serration root plane through the serration valleys moving upwards. The wake turning angle for the root positions are significantly lesser than that of the Baseline and tip positions. This shows that the flow field over the serration is predominantly three dimensional with strong vortices present in the spanwise and streamwise
direction. This three-dimensional flow and vortices influences the turbulent energy decay at the wake region and brings down the turbulence level significantly compared to the Baseline at about $x = 0.5c$. This is very important when considering noise generated from fan flow interaction with OGV since the inlet turbulence plays a major role in aerofoil self noise. Moreover, since the fan blades are operated at high angles of attack the reduction in inlet turbulence will aid delay the flow separation. The effect of serrations on the aerodynamic characteristics of a tandem aerofoil configuration will be discussed in Chapter 5.
Figure 4.11: Wake mean velocity for NACA 65(12)-10 aerofoil at $\alpha = 0^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.12: Wake turbulent kinetic energy for NACA 65(12)-10 aerofoil at $\alpha = 0^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
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Figure 4.13: Wake mean velocity for NACA 65(12)-10 aerofoil at $\alpha = 5^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.14: Wake turbulent kinetic energy for NACA 65(12)-10 aerofoil at $\alpha = 5^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
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Figure 4.15: Wake mean velocity for NACA 65(12)-10 aerofoil at $\alpha = 10^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.16: Wake turbulent kinetic energy for NACA 65(12)-10 aerofoil at $\alpha = 10^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
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Figure 4.17: Wake mean velocity for NACA 65(12)-10 aerofoil at $\alpha = 15^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).

Figure 4.18: Wake turbulent kinetic energy for NACA 65(12)-10 aerofoil at $\alpha = 15^\circ$ with varying trailing-edge serrations: sawtooth serration (Top) and slotted-sawtooth serration (Bottom).
4.1.3 Reynolds stresses for NACA 0012 aerofoil

To better understand the characteristics of the flow field in the wake region of serrated aerofoil, as a flow property which can reflect the effects of the momentum fluxes induced by the turbulence, the Reynolds stress can represent the degree of the momentum exchange at a given point in the flow and also be perceived as a conduit for transferring energy from the mean flow to the turbulence. Reynolds stress tensor components $u'u'$, $v'v'$ and $u'v'$ have been measured and discussed in this study. The Reynolds stress profiles for the NACA 0012 aerofoil with and without a sawtooth serration ($\lambda = 9$ mm) and a slotted-sawtooth serration ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm and $H = 15$ mm) at angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ were measured using the LDV method. The results of the steamwise direction Reynolds stress term $u' u' / U_0^2$, traversal direction $v' v' / U_0^2$, and shear stress term $u' v' / U_0^2$ for the Baseline case, serration tip and serration root positions at selected near- and far-wake locations $x/c = 0.2, 0.3, 0.5$ and $1.0$ are presented in Figs. 4.19 to 4.26.

- Reynolds stress profiles at $\alpha = 0^\circ$

As shown in Fig. 4.19, for a NACA 0012 aerofoil with sawtooth serration at angle of attack $\alpha = 0^\circ$, the longitudinal Reynolds stress term $u' u' / U_0^2$ for both serrated tip- and root- flow behaves similar to that of the Baseline case with a clear double peak structure at all four wake locations. For $v' v' / U_0^2$, the use of serrations yields an increase in $v$ fluctuations for both the serrated tip- and root- positions. The wake width for serrated cases also shows a smaller increase when compared to the Baseline case. The Reynolds shear stress term $u' v' / U_0^2$ for the sawtooth serrated case attains a similar magnitude to that of the Baseline case with a minor increase in the wake width along the root position for near trailing-edge location $x/c = 0.3$. As discussed in the previous section (Fig. 4.4), the increase in the TKE level at the near trailing-edge wake location for
sawtooth serrated case is due to the increase of flow mixing between the pressure and suction sides when using trailing-edge serrations.

Figure 4.20 shows the Reynolds stress results for a NACA 0012 aerofoil with and without a slotted-sawtooth serration at an angle of attack $\alpha = 0^\circ$. The results for both Reynolds stress in the longitudinal ($u'u'$) or transversal ($v'v'$) directions for the serrated cases show a clear increase in magnitude when compared with the Baseline case especially at locations close to the trailing-edge. The wake width of the serrated case is wider than that of the Baseline case at all wake locations considered. When compared with a sawtooth serrated aerofoil, the increase in stress for slotted-sawtooth serration is higher than that of sawtooth serrated case. This is believed to be due to the slots on the sawtooth causing an increased flow mixing in the wake especially near the trailing-edge region.

- Reynolds stress profiles at $\alpha = 5^\circ$

The Reynolds stress results for the NACA 0012 aerofoil with and without a sawtooth serration at the angle of attack $\alpha = 5^\circ$ are presented in Fig. 4.21. For both serrated tip- and root-flow, $\overline{u'u'}/U_0^2$ shows similar trends to that of the Baseline case with the root flow result slightly shifted upwards. For stress term $\overline{v'v'}/U_0^2$, the result for the tip-flow shows a clear increase to that of the Baseline case, especially in the peak regions at near trailing-edge locations $x/c = 0.2$ and 0.3. A double-peak structure can also be found in the root-flow result in this near tailing-edge wake region. The shear stress results presented here show that unlike the result for $\alpha = 0^\circ$, where positive and negative peak values extend almost symmetrically on either side of the wake centre-line, the magnitude for the negative peak increases when the angle of attack is increased. The results pertaining shear stress for serrated cases show similar profiles for the positive peak
values but negative peaks are located lower when compare with Baseline case.

In case of the slotted-sawtooth serrated aerofoil at the angle of attack $\alpha = 5^\circ$ in Fig. 4.22, the stress term $\overline{u'w'}/U_0^2$ follows the Baseline results generally quite well with the tip-flow results slightly shifted downward and the root-flow results slightly shifted upward. The result for $\overline{v'v'}/U_0^2$ and $\overline{u'v'}/U_0^2$ for the slotted-sawtooth serrated case shows a very similar behaviour to that of the sawtooth serrated case in Fig. 4.21 with higher tip-flow magnitude values.

- Reynolds stress profiles at $\alpha = 10^\circ$

At a higher angle of attack $\alpha = 10^\circ$, in Figs. 4.23 and 4.24, the magnitude of Reynolds stresses for both the sawtooth and slotted-sawtooth serrated cases are very close to that of the Baseline case with small increases of $\overline{v'v'}/U_0^2$ only at the wake location $x/c = 0.3$ or $x/c = 0.5$. A clear upward shift can be found in the results for both serrations in all three stress terms. As discussed above in Section 4.1.1, the changes in the wake TKE profiles for the serration case was very minimal and the overall results also showed that the serrations do not substantially affect the wake development of low cambered or symmetrical aerofoils such as NACA 0012, especially at pre-stall angles of attack.

- Reynolds stress profiles at $\alpha = 15^\circ$

Form the wake TKE profile results in previous Section 4.1.1, the use of serrations leads to a significant TKE level reduction in the wake region at observed locations $x/c = 0.3$ or $x/c = 1.0$ (see Figs. 4.25 and 4.26). From the $\overline{u'u'}/U_0^2$ and $\overline{v'v'}/U_0^2$ stress terms, at very near trailing-edge location ($x/c = 0.2$), no significant difference can be found between the serrated and unserrated cases. At further downstream locations, a clear reduction in magnitude can be found in the results for both the sawtooth and slotted-
sawtooth cases at wake location $x/c = 0.3, 0.5$ and 1.0. The reduction in magnitude of the stress term $\overline{v'v'}/U_0^2$ for the serrated case is higher than that of the stress term $\overline{u'u'}/U_0^2$. The shear stress ($\overline{u'v'}/U_0^2$) results for two serrated cases show that at the near trailing-edge location ($x/c = 0.2$) and far-wake location ($x/c = 1.0$), the use of serrations will lead to notable differences in the shear stress. However, from the shear stress ($\overline{u'v'}/U_0^2$) results for the wake locations $x/c = 0.3$ to $x/c = 0.5$, a clear reduction can be detected at both the positive and negative shear stress peaks.

In summary, the Reynolds stress profiles for the symmetric NACA 0012 aerofoil with and without a sawtooth and a slotted-sawtooth serration at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ at wake locations $x/c = 0.2, 0.3, 0.5$ and 1.0 were presented here. The results show that for low angles of attack ($\alpha = 0^\circ$ and $5^\circ$), at near trailing-edge location $x/c = 0.2, 0.3$ and 0.5, the result for serrated cases show similar trends compared to the Baseline case. The Reynolds stress magnitude for the slotted-sawtooth case was found to be higher than the sawtooth serration at near-wake location, which also corresponds to the higher TKE for slotted-sawtooth as discussed earlier. At further downstream locations, an upward shift can be observed for the serrated cases. At high angle of attack, $\alpha = 15^\circ$, the reduction in shear stress magnitude was substantial, especially at wake locations, $x/c = 0.3, 0.5$ and 1.0 compared to the Baseline case. This also agrees with other similar observations made in the near wake TKE in Fig. 4.10.
Figure 4.19: Reynolds stress profiles for NACA0012 aerofoil with sawtooth at $\alpha = 0^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'^2}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'^2}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.20: Reynolds stress profiles for NACA0012 aerofoil with slotted-sawtooth at \( \alpha = 0^\circ \), \( U_0 = 30 \) m/s. Reynolds stress term \( \overline{u'v'/U_0^2} \) (top row); Reynolds stress term \( \overline{v'v'/U_0^2} \) (middle row) and Reynolds shear stress \( \overline{u'v'/U_0^2} \) (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.21: Reynolds stress profiles for NACA0012 aerofoil with sawtooth at $\alpha = 5^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\frac{\overline{u'u'}}{U_0^2}$ (top row); Reynolds stress term $\frac{\overline{v'v'}}{U_0^2}$ (middle row) and Reynolds shear stress $\frac{\overline{u'v'}}{U_0^2}$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
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Figure 4.22: Reynolds stress profiles for NACA00120 aerofoil with slotted-sawtooth at \( \alpha = 5^\circ \), \( U_0 = 30 \text{ m/s} \). Reynolds stress term \( \overline{u'v'^2}/U_0^2 \) (top row); Reynolds stress term \( \overline{v'v'^2}/U_0^2 \) (middle row) and Reynolds shear stress \( \overline{u'v'}/U_0^2 \) (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.23: Reynolds stress profiles for NACA0012 aerofoil with sawtooth at $\alpha = 10^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\frac{\overline{u'v'}}{U_0^2}$ (top row); Reynolds stress term $\frac{\overline{v'v'}}{U_0^2}$ (middle row) and Reynolds shear stress $\frac{\overline{u'v'}}{U_0^2}$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.24: Reynolds stress profiles for NACA0012 aerofoil with slotted-sawtooth at \( \alpha = 10^\circ \), \( U_0 = 30 \) m/s. Reynolds stress term \( \overline{u' u'} / U_0^2 \) (top row); Reynolds stress term \( \overline{v' v'} / U_0^2 \) (middle row) and Reynolds shear stress \( \overline{u' v'} / U_0^2 \) (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
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Figure 4.25: Reynolds stress profiles for NACA0012 aerofoil with sawtooth at $\alpha = 15^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
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Figure 4.26: Reynolds stress profiles for NACA0012 aerofoil with slotted-sawtooth at $\alpha = 15^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\frac{u'u'}{U_0^2}$ (top row); Reynolds stress term $\frac{v'v'}{U_0^2}$ (middle row) and Reynolds shear stress $\frac{u'v'}{U_0^2}$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
4.1.4 Reynolds stresses for NACA 65(12)-10 aerofoil

The Reynolds stress profiles for the NACA 65(12)-10 aerofoil at $\alpha = 0^\circ$, 5°, 10° and 15° at the wake locations $x/c = 0.2, 0.3, 0.5, 1.0, 1.5$ and 2.0 are presented in Figs. 4.27 to 4.34.

- Reynolds stress profiles at $\alpha = 0^\circ$

Figure 4.27 shows the Reynolds stress results for NACA65(12)-10 aerofoil with and without a sawtooth serration at the angle of attack of $\alpha = 0^\circ$. A clear double-peak structure can be found in the longitudinal stress ($u'u'/U_0^2$) at $\alpha = 0^\circ$ for the Baseline case at all wake locations. When introducing serrations, similar profiles are obtained with a slight decrease in magnitude. Along the root results, an upward shift of the double-peak can be seen when dealing with serrations ($x/c = 0.2$ and 0.3). At $x/c = 1.0$, the results for both tip- and root-flow show a clear upward shift. For $v'v'/U_0^2$, at locations $x/c = 0.2, 0.3$ and 1.0, both the serrated tip and root positions show a similar behaviour as the Baseline case with a clear upward shift, especially for the root-flow results. High magnitudes of the Reynolds shear stress ($u'v'/U_0^2$) were observed in the near-wake regions at the position of maximum velocity deficit and its magnitude gradually reduced downstream. Unlike the Reynolds shear stress results for the symmetric NACA 0012 aerofoil in Section 4.1.3 in Fig. 4.19, for a cambered NACA 65(12)-10 aerofoil, the maximum magnitudes of the positive peak (suction side) and the negative peak (pressure side) are similar to each other. In the shear stress results for the asymmetric NACA 65(12)-10, the positive peak (suction side) show higher magnitude values than the negative peaks (pressure side). The magnitude of the positive peak is larger than that of the negative peak especially at near trailing-edge wake locations ($x/c$ upto 0.3). The shear stress results for the serration tip positions follow the Baseline case, although a clear upward shift is noticed. In general, by adding a sawtooth serration, at $\alpha = 0^\circ$, the stress results
do not change significantly in magnitude but an upward shift in the wake location can be found. However, from the Reynolds stress results for the slotted-sawtooth serration in Fig. 4.28, the peak magnitude values of $u'w'/U_0^2$ and $v'w'/U_0^2$ for the serrated tip position show a clear increase when compared with the Baseline case at the near trailing-edge locations $x/c = 0.2$ and 0.3. This originates from the increased mixing in the near trailing-edge wake flow as a result of the sawtooth serration slot. Further downstream ($x/c = 0.5$ and 1.0), the peak magnitude value for both the tip- and root-positions are similar or even slightly reduced for the serrated case. A clear upward shift for the serrated case can also be found in the results for the aerofoil with slotted-sawtooth serration in this figure.

- Reynolds stress profiles at $\alpha = 5^\circ$

When increasing the angle of attack, the streamwise stress term $u'u'/U_0^2$ for serrated cases shows similar profiles as the Baseline case with a slight decrease in the peak magnitude at the serrated tip-position in Fig. 4.29. An upward shift can again be seen in the result for the serrated case especially for the results at the serration root-position. The results for the stress term in $v$ direction, $v'w'/U_0^2$, show that at the near trailing-edge region ($x/c = 0.2$ and 0.3), the peak magnitude value along the serration root is higher than that of the Baseline case. However, the peak magnitude value for the serration tip shows only a small reduction. At downstream wake locations, $x/c = 0.5$ and 1.0, both the serration tip and root show the peak magnitude has decreased when compared to the Baseline case. The shear stress magnitude ($u'v'/U_0^2$) for $\alpha = 5^\circ$ at the near-wake location $x/c = 0.2$ was observed to be higher for the serration root case than that of the Baseline, which is believed to be due to the interaction between the tip- and root-flow, introducing higher shear stresses at the interference location between the different planes at the serrated trailing-edge. The shear stress for both the tip- and root-
flow then shows a clear reduction at further downstream wake locations. In Fig. 4.30, the use of a slotted-sawtooth serration generally shows a similar behaviour to that of a sawtooth serration with an increase in the width of stress profiles in both the $u$ and $v$ directions at the near trailing-edge locations. This is believed to be because of the slots on the sawtooth have increased the flexibility of the serration especially near the serration tip.

- Reynolds stress profiles at $a = 10^\circ$

At a higher angle of attack, $a = 10^\circ$ (Figs. 4.31 and 4.32), unlike the results for the NACA 0012 aerofoil in which the use of serrations does not show a big change in the stress results, the reduction in the stress magnitude for the sawtooth serrated cases is substantial, especially at the wake locations $x/c = 0.3$ to 1.0 compared to other low angles of attack and the Baseline case. The magnitude of the stress in the streamwise direction show around 32% to 82% reduction at the tip and root positions of the serrated cases. The results for the slotted-sawtooth serrated cases in Fig. 4.32 also show a similar level of reduction. The level of reduction in the stress magnitude for the slotted-sawtooth case is even higher than that for simple sawtooth serrations and this significant stress drop appears for all wake locations. These also agree with other similar turbulence reduction observations made for the TKE results in Fig. 4.16.

- Reynolds stress profiles at $a = 15^\circ$

Figure 4.33 presents the Reynolds stress results for the NACA 65(12)-10 aerofoil with a sawtooth serration at the angle of attack of $a = 15^\circ$. A clear double peaked flow feature can be observed in the streamwise stress term $\overline{u' u'}/U_0^2$ for the Baseline case at the wake location $x/c = 0.2$ to 0.5 and for $\overline{v' v'}/U_0^2$, at the near trailing-edge location $x/c = 0.2$ to 0.3. Results for the serrated case at $x/c = 0.2$ show no significant changes
in stress terms $u'\bar{u}'/U_0^2$ and $v'\bar{v}'/U_0^2$ between the sawtooth serrated and the Baseline cases. From the results presented at further downstream locations, a significant reduction of the stress magnitude value can be observed when serrations are in place. The results for the shear stress $u'\bar{v}'/U_0^2$ show that at the near-wake location ($x/c = 0.2$), unlike the Baseline case, a double peak behaviour can be observed in the negative part of results for the serrated tip case. The positive peaks of the shear stress for the serrated cases follow the Baseline case quite well at the wake location $x/c = 0.3$ to $0.5$ but a clear reduction of the shear stress for the serrated case can also be seen in this figure. Further downstream, $x/c = 1.0$, no clear difference of the shear stress magnitude was observed between the Baseline and the serration cases. The Reynolds stress for the aerofoil with a slotted-sawtooth shows similar profiles to that of the sawtooth serrated case.

To summarize, the Reynolds stress profiles for the asymmetric NACA 65(12)-10 aerofoil with and without a sawtooth and a slotted-sawtooth serration at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ at the wake locations $x/c = 0.2$, $0.3$, $0.5$, $1.0$ have been presented and discussed. The results show that for an asymmetric cambered aerofoil, the use of serrations significantly affect the Reynolds stress even at low angles of attack, $\alpha = 0^\circ$, $5^\circ$. An upward shift can be observed for both the sawtooth and slotted-sawtooth serrated cases. At high angles of attack, $\alpha = 10^\circ$ and $15^\circ$ the reduction in the Reynolds stress magnitude was substantial compared to the Baseline case. This also agrees with other similar observations made in the wake TKE profiles in Fig. 4.18.
Figure 4.27: Reynolds stress profiles for NACA 65(12)-10 aerofoil with sawtooth at $\alpha = 0^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.28: Reynolds stress profiles for NACA 65(12)-10 aerofoil with slotted-sawtooth at $\alpha = 0^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'/U_0^2}$ (top row); Reynolds stress term $\overline{v'^2}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'/U_0^2}$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.29: Reynolds stress profiles for NACA 65(12)-10 aerofoil with sawtooth at $\alpha = 5^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.30: Reynolds stress profiles for NACA 65(12)-10 aerofoil with slotted-sawtooth at $\alpha = 5^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.31: Reynolds stress profiles for NACA 65(12)-10 aerfoil with sawtooth at $\alpha = 10^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.32: Reynolds stress profiles for NACA 65(12)-10 aerofoil with slotted-sawtooth at $\alpha = 10^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.33: Reynolds stress profiles for NACA 65(12)-10 aerofoil with sawtooth at $\alpha = 15^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\frac{u'v'}{U_0^2}$ (top row); Reynolds stress term $\frac{v'v'}{U_0^2}$ (middle row) and Reynolds shear stress $\frac{u'v'}{U_0^2}$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
Figure 4.34: Reynolds stress profiles for NACA 65(12)-10 aerofoil with slotted-sawtooth at $\alpha = 15^\circ$, $U_0 = 30$ m/s. Reynolds stress term $\overline{u'u'}/U_0^2$ (top row); Reynolds stress term $\overline{v'v'}/U_0^2$ (middle row) and Reynolds shear stress $\overline{u'v'}/U_0^2$ (bottom row). Black solid line: Baseline, Red dash line: Serrated root position, Blue dash dot line: Serration tip position.
4.2 Wake topology

The inherent complexity of the flow-field and the emergence of new streamwise and spanwise structures around the trailing-edge serrations have been the subject of some recent studies [110, 115, 120]. The emergence of these new structures can significantly affect the hydrodynamic field around the trailing-edge and the formation and development of the wake flow. A numerical study by Jones and Sandberg [120] for a NACA 0012 at $\alpha = 5^\circ$ showed that, firstly, the use of serrations will enforce a limit on the spanwise correlation length of the coherent structures in the vicinity of the serrations and, secondly, the introduction of serrations promotes the development of horseshoe-type structures in the wake. Some more recent experimental observations have also confirmed the presence of contra-rotating streamwise vortices on the serrations and within the wake region [110, 115].

In order to improve our understanding of the flow characteristics and wake development in the vicinity of the serrated trailing-edges, in this section, the velocity flow field and streamline flow pattern in the aerofoil near-wake region $x/c = 0$ to 0.6 are obtained and discussed. The PIV measurements are provided for the Baseline, blunt and two different sawtooth serrations and one slotted-sawtooth serration (see Table 4.2) for the NACA 0012 and NACA 65(12)-10 aerofoils at $U_0 = 30$ m/s ($Re_c = 3 \times 10^5$) for angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$. During the measurement, the aerofoil was mounted in the Low Turbulence Wind Tunnel working section by a support arm and the PIV laser was placed under the working section with the bottom surface of the wind tunnel working section replaced with a clear window (see Fig. 4.35). A total of 1600 image pairs for each measurement case were captured using a FlowSense 4 MP CCD camera with a resolution of $2078 \times 2078$ pixels and 14 bit, corresponding to a field of view ranging from $11.3 \text{ cm} \times 11.3 \text{ cm}$ to $14.5 \text{ cm} \times 14.5 \text{ cm}$ (see Fig. 5.18). The images were analysed with
the DynamicStudio software from Dantec. The iterative process yielded grid correlation windows of $16 \times 16$ pixels with an overlap of 50%, resulting in a final vector spacing around 0.43 mm.

![Figure 4.35: PIV set-up in the Low Tubulence Wind Tunnel.](image)

Table 4.2: Geometrical parameters of the trailing-edge serrations used in the current study.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Serration Types</th>
<th>$2h$ (mm)</th>
<th>$\lambda$ (mm)</th>
<th>$\lambda/h$</th>
<th>$\alpha_s$ (deg.)</th>
<th>$d$ (mm)</th>
<th>$H$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>blunt</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>Baseline</td>
<td>15</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 3</td>
<td>sawtooth</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 4</td>
<td>sawtooth</td>
<td>30</td>
<td>24.8</td>
<td>1.65</td>
<td>22.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 5</td>
<td>slotted-sawtooth</td>
<td>30</td>
<td>9</td>
<td>0.6</td>
<td>8.53</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 4.36: PIV laser sheet direction and camera field of view.
4.2.1 Velocity field for the NACA 0012 aerofoil

Figures 4.37 to 4.40 show the PIV results for the Baseline, blunt and serrated NACA 0012 aerofoil at $U_0 = 30$ m/s for angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$. As seen earlier for the wake profile and wake TKE results in Section 4.1.1, the flow around the NACA 0012 aerofoil at pre-stall angles of attack remains similar. As mentioned previously in the LDV wake velocity profiles, at angles of attack $\alpha = 0^\circ$, using the serrations on a NACA 0012 aerofoil does not particularly change the velocity wake profile or reduce the TKE in the wake. In Fig. 4.37, the velocity flow field results for a serrated and unserrated NACA 0012 aerofoil at the angle of attack of $\alpha = 0^\circ$ shows that the use of serrations does not cause noticeable differences in the velocity field and streamline pattern results. This is because the NACA 0012 aerofoil is a symmetric aerofoil and the change in geometry at the trailing-edge of the aerofoil at such a low angle of attack does not show a clear effect. At moderately high angles of attack, $\alpha = 5^\circ$ and $10^\circ$ (in Figs. 4.38 and 4.39), the flow over the pressure and suction sides of the Baseline and blunt NACA 0012 aerofoils follow similar trends as the results for $\alpha = 0^\circ$ with a slight shift at the trailing-edge. The results for the sawtooth serration cases with $\lambda = 24.8$ mm (large serration) in the tip- and root-planes of the serrated NACA 0012 (Figs. 4.38(c), 4.39(c), 4.38(d) and 4.39(d)) show that the tip-flow has a thicker boundary layer and wake thickness due to the increased effective chord-length, whereas the root-flow shows a strong upward deflection through the serration valley. These observations based on the PIV data correspond well with the LDV results shown in Figs. 4.5 and 4.7. The wakes of the aerofoil with sawtooth serrations with $\lambda = 9$ mm (sharp serration) are shown in plots (e) and (f) in Figs. 4.38 and 4.39. The general flow characteristics for the sharp serration remain relatively unchanged when altering the serration wavelength to $\lambda = 24.8$ mm (plots (c) and (d) in Figs. 4.38 and 4.39). Similar flow trends were observed for the slotted-sawtooth serration results in plots (e) and (f) for the Baseline case for
NACA 0012 aerofoil at angles of attack, $\alpha = 5^\circ$ and $10^\circ$ but with an increased boundary layer thickness at the tip-flow and reduced boundary layer thickness and upward shift in the root plane.

Figure 4.40 presents the velocity field and the corresponding streamline pattern for the NACA 0012 aerofoil with and without trailing-edge serration at a high angle of attack, $\alpha = 15^\circ$. From the aerodynamic forces presented in Chapter 3, the stall angle for the NACA 0012 aerofoil is $\alpha = 13^\circ$. In the case of deep stall angles of attack ($\alpha = 15^\circ$) where an early separation can be observed (see surface flow pattern result in Chapter 3), there exists a large vortex above the trailing-edge, originating from the early separation on the suction side of the aerofoil. The flow field over the Baseline and blunt aerofoil are principally the same. As shown in Figs. 4.40(a) and 4.40(b), the flow is completely separated on the suction side of the aerofoil with a fixed vortex present above the aerofoil. The use of serrations, however, appears to have completely changed the wake flow field in the region of $x/c = 0$ to 0.2. In the case of the serrated NACA 0012 aerofoil, as seen in Fig. 4.40, the root-flow moves upward within the valley, causing a three-dimensional flow before $x/c = 0.2$. As observed in the PIV results, the flow from the aerofoil’s lower surface passes through the serration valley and causes a secondary small and highly three-dimensional vortex (valley vortex), spinning in the opposite direction of the early separation vortex. For the larger serration with the wavelength of $\lambda = 24.8$ mm, (see Figs. 4.40(c) and 4.40(d)), the valley vortex is present but is positioned aft of the serration at about $x/c = 0.2$ and the shape of vortices at tip- and root-location differ in size and structure, exhibiting the three dimensionality of the valley vortices. Results for the sharper and slotted-sawtooth serration show that the differences in flow structure between the two serrations are minimal, as the flow completely separates on the suction surface and the valley vortices have positioned themselves aft of the aerofoil. In the case of the symmetric NACA 0012 aerofoil, the valley vortex does not significantly affect the
location of the large early separation vortices.

Figures 4.41 and 4.42 show a slice view of the velocity contours over the wide serrations ($\lambda = 24.8$ mm) at angles of attack $\alpha = 10^\circ$ and $15^\circ$. In the case of the serrated aerofoils at angle of attack $\alpha = 10^\circ$, the streamline pattern along the tip to root of the sawtooth serration show similar trends, while the root-flow moves slightly upward within the valley, causing a three-dimensional flow before $x/c = 0.2$, as also observed in Fig. 4.7. At a higher angle of attack $\alpha = 15^\circ$, the results show the development of span-wise vortices. Results obtained using sharp serrations ($\lambda = 9$ mm) show that the vortex valley will remain mainly over the valley region and within $x/c = 0$ to 0.2, while in the case of wide serrations ($\lambda = 24.8$ mm) the valley vortex occurs at $x/c = 0.2$, making the valley much less effective for moving the separation vortex and reducing the TKE in the near-wake. The shape and location of the valley vortex changes along the span over the serrations, as illustrated in Fig. 4.42, forming a highly three-dimensional and periodic structure. The valley vortex is particularly large in the middle of the serration valley, with its centre near the root, and becoming smaller towards the tip location while moving further downstream.
Figure 4.37: Velocity contours from PIV for NACA 0012 aerofoil at $\alpha = 0^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.38: Velocity contours from PIV for NACA 0012 aerofoil at $\alpha = 5^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
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Figure 4.39: Velocity contours from PIV for NACA 0012 aerofoil at $\alpha = 10^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.40: Velocity contours from PIV for NACA 0012 aerofoil at $\alpha = 15^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.41: Slice view of velocity contours over the sawtooth serration ($\lambda = 24.8$ mm) for NACA 0012 at angle of attack $\alpha = 10^\circ$, $U_0 = 30$ m/s.
Figure 4.42: Slice view of velocity contours over the sawtooth serration ($\lambda = 24.8 \text{ mm}$) for NACA 0012 at angle of attack $\alpha = 15^\circ$, $U_0 = 30 \text{ m/s}$.
4.2.2 Velocity field for the NACA 65(12)-10 aerofoil

As seen from the wake velocity and TKE surveys for the NACA 65(12)-10 aerofoil presented in Section 4.1.2, at small angles of attack ($\alpha = 0^\circ$ and $5^\circ$), by using the serrations, a narrow wake with a shift in the location of the wake deficit peak was observed due to the aerofoil geometry and the flow moving upward through the serration valleys but with no particular changes in the wake TKE profiles. However, for higher angles of attack ($\alpha = 10^\circ$ and $15^\circ$), where maximum lift reduction were obtained, the wake width becomes larger and the effect of the serrations becomes more evident. In this section, the PIV velocity field and streamline pattern results are provided for the Baseline, Blunt and serrated NACA 65(12)-10 aerofoil at $U_0 = 30$ m/s for angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$. These plots allow the study of the interaction between the flow originating from the pressure side of the aerofoil and the vortex system introduced by the trailing-edge serrations.

At low angles of attack $\alpha = 0^\circ$ and $5^\circ$, compared with the results for the Baseline case in sub-plot (a) in Figs. 4.43 and 4.44, the velocity field and streamline pattern along tip position for all three different serrations show similar behaviour (c), (d) and (e) in Figs. 4.43 and 4.44), while the root-flow for serrated cases are similar to the blunt case (in sub-plot (b) in Figs. 4.43 and 4.44), i.e. moving upward through the valley. This was also observed in Figs. 4.11 and 4.13. However, at moderately high angles of attack, $\alpha = 10^\circ$, the use of serrations on the NACA 65(12)-10 shows a significant reduction in the wake TKE profile (Fig. 4.16) and Reynolds stress results (Figs. 4.31 and 4.32).

When increasing the angle of attack to $\alpha = 10^\circ$, in the velocity flow field results in Fig. 4.45, the flow over the pressure and suction sides of the Baseline and blunt cases show a reduced downward deflection. The results for the sawtooth serration cases with $\lambda = 24.8$ mm (large serration) for the tip- and root-locations (Figs. 4.45(c) and 4.45(d))
show that the tip-flow has a thicker boundary layer and wake width due to the increased effective chord-length, whereas the root-flow shows a strong upward deflection through the serration valley. These findings from the PIV results also correspond with the LDV results in Fig. 4.15. The results for the tip and root positions for the NACA 65(12)-10 aerofoil with a sharper sawtooth serration (λ = 9 mm) are shown in Figs. 4.45(e) and 4.45(f). For the high cambered NACA 65(12)-10 aerofoil, the flow in the vicinity of the serrations shows a strong upward movement at the tip-location. This is believed to be due to the flow moving over the suction surface of the serration through the serration valley. In general, the results for the NACA 65(12)-10 aerofoil with different sawtooth serrations at the angle of attack of α = 10° show that the flow along the tip-location of the serration follow the results for the Baseline case, while the root-flow moves upward within the valley (also observed in Fig. 4.15). This strong upward flow causes a three-dimensional flow before x/c = 0.2 (see Figs. 4.45(e) and 4.45(f)). Similar flow trends have been observed for the serration for NACA 65(12)-10 aerofoils with slotted-sawtooth trailing-edge in Figs. 4.45(g) and 4.45(h).

Figure 4.46 presents the velocity field and streamline pattern for the NACA 65(12)-10 aerofoil with and without different types of trailing-edge serrations at the angle of attack α = 15°. In the case of early separation at stall region (between 12° ≤ α ≤ 18° based on the force measurements in Chapter 3), the flow fields for the Baseline and blunt aerofoils (in Figs. 4.46(a) and (b)) show similar behaviour to each other. A large vortex (separation vortex) exists above the trailing-edge, originating from the separation on the suction side of the aerofoil. The use of serrations on the NACA 65(12)-10 aerofoil at the angle of attack α = 15°, especially for sharp serrations and the slotted-sawtooth (λ = 9 mm), show similar results to that of the NACA 0012 aerofoil. Serrations appear to have completely changed the wake flow field in the wake region from x/c = 0 to 0.2. As seen in Figs. 4.46(e) to (h), the use of sharp sawtooth and slotted-sawtooth
serrations shows that the flow from the aerofoil suction surface passes through the serration valleys causing a secondary small vortex (valley vortex), spinning in the opposite direction of the large separation vortex. Compare with the Baseline case, the results for the serrated cases show that the valley vortex has moved the center of the early separation vortex to an upward location (from 0.18c to around −0.2c). Using a larger sawtooth serration ($\lambda = 24.8$ mm) on the NACA 65(12)-10 aerofoil, in Figs. 4.46(c) and 4.46(d), shows the second valley vortex is absent but the upward shift of the wake can still be clearly seen.

The comparison of the larger ($\lambda = 24.8$ mm) and sharper ($\lambda = 9$ mm) serrations show that the location of the valley vortex depends strongly on the serration geometry. As observed in Fig. 4.18, the interaction of the two contra-rotating vortices causes significant reduction of the TKE in the wake, particularly within the region $x/c = 0$ to 1.0. This can be attributed to the shift of the early separation vortex-eye further upstream and higher level of dissipation as a results of the interaction between the two contra-rotating vortices. From the aerodynamic results shown in Chapter 3, the emergence of the new valley vortex, working against the strong separation vortex, can also improve the aerodynamic performance of the aerofoil by producing some lift, making the separation vortex smaller and changing its structure.

Figures 4.47 and 4.48 show the slice view of the velocity contours and the streamline pattern over the large sawtooth serrations ($\lambda = 24.8$ mm) for the NACA 65(12)-10 aerofoil at angle of attack $\alpha = 10^\circ$ and $15^\circ$. The results show the span-wise evolution of the vortices and horseshoe vortices more clearly. The results of the velocity field and streamline patterns for angle of attack $\alpha = 10^\circ$ (Fig. 4.47) show a clear gradual upward shift of the flow from the tip- to the root-plane along the span of the aerofoil. The boundary thickness and wake width also reduce when close to the root location. At the angle
of attack of $\alpha = 15^\circ$ (Fig. 4.48), the shape and location of the separation vortex change along the span over the serrations, forming a highly three-dimensional and periodic structure. The vortex is particularly large at the serration tip, with its centre near the root ($x/c = -0.1$) and becomes smaller whilst moving towards the tip-to-the-root-location. Results obtained using the sharp serrations ($\lambda = 9$ mm) show that apart from the separation vortex, valley vortex can also occur and remain mainly over the valley region and within $x/c = 0$ to 0.2. However, in the case of using wide serrations ($\lambda = 24.8$ mm) the valley vortex does not exist. Without the valley vortex, the valley shows much less effect for moving the separation vortex. The comparison between the results presented in this chapter and the aerodynamic forces included in Chapter 3 also show that the increase in the lift coefficient observed at 30 m/s at high angles of attack, particularly for sharp serrations ($\lambda = 9$ mm), can be attributed to the upward force caused by the emergence of the valley vortex and the changes consequently occurred to the early separation vortex. Therefore, it can be concluded that the size and location of the valley vortex can determine the level of lift increase compared to the Baseline aerofoil.

In summary, from the above discussion on the wake development and wake flow structure analysis, it can be inferred that for the Baseline aerofoil at high angles of attack with a straight trailing-edge, the flow is predominantly two dimensional, often with a strong early separation vortex appearing near the trailing-edge. However, for the case of serrated aerofoil tested at high angles of attack, the flow through the serration valley breaks the strong early separation vortex, giving rise to another smaller contra-rotating vortex that positions itself above every serration tooth in a periodic manner. These have also reported by [110, 115, 120].
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Figure 4.43: Velocity contours from PIV for NACA 65(12)-10 aerofoil at $\alpha = 0^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.44: Velocity contours from PIV for NACA 65(12)-10 aerofoil at $\alpha = 5^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm): (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm): (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.45: Velocity contours from PIV for NACA 65(12)-10 aerofoil at $\alpha = 10^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm); (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm); (e) tip position and (f) root position, slotted-sawtooth serration: (g) tip position and (h) root position.
Figure 4.46: Velocity contours from PIV for NACA 65(12)-10 aerofoil at $\alpha = 15^\circ$, $U_0 = 30$ m/s. (a) Baseline, (b) blunt, sawtooth serration ($\lambda = 24.8$ mm); (c) tip position, (d) root position, sawtooth serration ($\lambda = 9$ mm); (e) tip position and (f) root position, slotted-sawtooth serration; (g) tip position and (h) root position.
Figure 4.47: Slice view of velocity contours over the sawtooth serration ($\lambda = 24.8$ mm) for NACA 65(12)-10 at angle of attack $\alpha = 10^\circ$, $U_0 = 30$ m/s.
Figure 4.48: Slice view of velocity contours over the sawtooth serration ($\lambda = 24.8$ mm) for NACA 65(12)-10 at angle of attack $\alpha = 15^\circ$, $U_0 = 30$ m/s.
4.3 Wake energy content

The flow behaviour over the trailing-edge and in the wake region was studied in the preceding sections. In addition to the general velocity and turbulent kinetic energy information obtained using the PIV and LDV techniques, the frequency-energy content of the wake turbulence can also provide some valuable information, especially in the context of wake-interaction noise. The velocity and velocity fluctuation power spectral density (PSD) results have been obtained using a cross hot-wire probe, traversed within the wake. The velocity PSD ($\phi_{uu}$) results are provided for the NACA 0012 aerofoil and NACA 65(12)-10 aerofoil with and without a sawtooth serration with $\lambda = 9$ mm and $2h = 30$ mm and a slotted-sawtooth serration with $\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm and $H = 15$ mm, at different angles of attack ($\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$). The measurement of the velocity wake profiles has been carried out at two downstream locations, $x/c = 0.2$ and 0.5, (see Figs. 4.49(a) and (b)). For the serrated aerofoil case, measurements were performed at both the tip and root positions (see Fig. 4.49(c)). At each of the downstream locations, the velocity profiles were extracted along a vertical line containing 80 equi-spaced sampling points ($\Delta y/c = 0.003$) to accurately capture the flow behaviour within the wake region at the flow speed of $U_0 = 20$ m/s.
Figure 4.49: Chord-wise locations used along the tip and root planes of the serration for hot-wire measurements.
4.3. WAKE ENERGY CONTENT

4.3.1 Wake energy content for NACA 0012 aerofoil.

To better understand the changes to the velocity PSD within the wake region at different wake locations ($x/c$), the velocity PSD results, at each location, are normalized by the PSD results of the Baseline case. The dashed-lines shown in the contour plots indicate the location at which the TKE of the Baseline case peaks. The results for the NACA 0012 aerofoil with a sawtooth serration ($\lambda = 9 \text{ mm}$) at the wake location $x/c = 0.2$ and $x/c = 0.5$ for all four angles of attack ($\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$) are presented in Figs. 4.50 and 4.51.

The velocity PSD results at $x/c = 0.2$ in Fig. 4.50 show that the use of sawtooth serration does not have a strong effect on the velocity PSD at the angle of attack $\alpha = 0^\circ$. At the angle of attack of $5^\circ$, an increase in the velocity PSD can be found within the range $y/c \approx 0$ and $x/y \approx -0.07$, especially at high frequency range (2 kHz to 20 kHz). At a higher angle of attack of $\alpha = 10^\circ$, the region of increased velocity PSD only occurred at the location below the TKE peak location ($y/c \approx -0.075$). At high angles of attack, $\alpha = 15^\circ$, the velocity PSD shows a reduced area below the TKE peak location ($y/c$ between around $-1.2$ to $0$) over the entire range of frequency.

Figure 4.51 presents the velocity PSD at a further downstream location $x/c = 0.5$, at $\alpha = 0^\circ$. A region of increase in the velocity PSD can be seen at high frequency range (2 kHz to 20 kHz) at $y/c$ range of $-0.06$ to $-0.1$. At angle of attack $\alpha = 5^\circ$, a clear velocity PSD increase is also observed in the high frequency range from 2 kHz to 20 kHz, but the location in $y/c$ moves further away to the TKE peak location when compared with the results for lower angles of attack. At an angle of attack $\alpha = 10^\circ$, an increase in the velocity PSD can again be noted at high frequencies, but the $y/c$ range is smaller than that of the those for lower angle of attack ($\alpha = 5^\circ$). The results for $\alpha = 15^\circ$ show a similar trend to the upstream observations at $x/c = 0.2$ in Fig. 4.50, i.e. the use of serrations will
reduce the velocity PSD at most of the frequency range, especially at locations below the TKE peak location at high frequencies.
Figure 4.50: Normalised velocity PSD for NACA 0012 aerofoil with sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.2$ in the streamwise direction at angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (- - -) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
Figure 4.51: Normalised velocity PSD for NACA 0012 aerofoil with sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.5$ in the streamwise direction at angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (- - -) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
4.3.2 Wake energy content for NACA 65(12)-10 aerofoil

The normalized PSD results, at the tip and root locations, for the NACA 65(12)-10 aerofoil with a sawtooth serration ($\lambda = 9$ mm) at the wake locations $x/c = 0.2$ and $x/c = 0.5$ for all four angles of attack ($\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$) are presented in Figs. 4.52 and 4.53. The results for the aerofoil with a slotted-sawtooth serration ($\lambda = 9$ mm, $2h = 30$ mm, $d = 0.5$ mm and $H = 15$ mm) are presented in Figs. 4.54 and 4.55. The dashed-line shown in the contour plots indicates the location at which the TKE peaks in the Baseline case.

The relative velocity PSD ($\Delta\phi_{uu}$) results for the sawtooth serrated case are presented in Figs. 4.52 and 4.53. As shown in Fig. 4.52, at the near wake location $x/c = 0.2$, and at small angles of attack $\alpha = 0^\circ$, the emergence of two distinct high magnitude PSD regions above the peak TKE location, over the entire range of frequency centred around 50 Hz and 4000 Hz at $y/c = 0.45$ and 0.6 can be found for the tip position. For the case of the root-plane, the increase in the velocity fluctuations is slightly larger than that of the tip-plane. This is believed to be mainly due to the aerofoil geometry and that the high chamber aerofoil leads to an upward shift of the flow even at small angles of attack over the serration root plane, caused by the valley flow, as discussed in the previous sections. The upward flow also causes significant velocity PSD reduction in the areas along and below the TKE peak location over the entire frequency range. Similar trends have also been observed in the case of $\alpha = 5^\circ$. The areas of increased velocity PSD above the TKE peak location centred around 50 Hz and 4000 Hz at $y/c = 0.02$ and $y/c = 0.04$. The reduction areas centred at similar frequency at $y/c = −0.06$ and $y/c = −0.075$ for the serration tip position. For the root position, the velocity PSD decreased over the entire range of frequencies at $y/c$ below the TKE peak location (around $−0.02$). The velocity PSD results for the angle of attack $\alpha = 10^\circ$ is similar to that of the angle of attack $\alpha = 5^\circ$. However, at the angle of attack $\alpha = 15^\circ$, the trend in the velocity PSD completely changes. At the
locations above the TKE peak location, a clear velocity PSD reduction region occurs at around $y/c = 0.04$ over the entire frequency range. Below the TKE peak location, at the low frequency range (10 Hz to 700 Hz), an increase in the velocity PSD can be found at $y/c \approx -0.1$, while the rest of the region shows a reduction in the velocity PSD. At high frequency range ($f > 700$ Hz), the velocity PSD value increases at $y/c \approx -0.1$. As seen in Fig. 4.53, at further downstream locations, the velocity PSD results at $\alpha = 0^\circ$, 5° and 10° are similar to that of the near trailing-edge location ($x/c = 0.2$) in Fig. 4.52. In the case of $\alpha = 15^\circ$, the use of serrations resulted in a clear reduction in the velocity PSD values over wide frequency and $y/c$ ranges. The results for the slotted-sawtooth cases at the downstream location $x/c = 0.2$ and $x/c = 0.5$ are also presented in Figs. 4.54 and 4.55, respectively. As can be seen the results are very similar to those of the sawtooth serration case and no significant changes can be observed.

To conclude, the velocity PSD results collected within the wake of the NACA 65(12)-10 aerofoil have clearly shown that the use of serrations can lead to a reduction in the velocity energy spectrum. Of particular interest here is the possibility of suppression of the low frequency energy content of the wake turbulence structures using serrations. It can also be seen that the velocity PSD reduction level increases with angle of attack, which is consistent with the observations made from the results in Figs. 4.17 and 4.18. The velocity PSD results at $\alpha = 15^\circ$ for the sawtooth serrations and slotted-sawtooth serrations show that the energy content of the turbulence structures within the wake region for cambered aerofoils at high angles of attack can be reduced by more than 10 dB [99]. This implies that the use of serrations in configurations involving tandem aerofoils, such as rotor-stator and contra-rotating propellers, can results in stabilisation of the gap flow and significant reduction of wake-blade interaction noise. This will be the topic of discussion in the next chapter.
4.3. WAKE ENERGY CONTENT

Figure 4.52: Normalised velocity PSD for NACA 65(12)-10 aerofoil with sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.2$ at angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (---) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
Figure 4.53: Normalised velocity PSD for NACA 65(12)-10 aerofoil with sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.5$ at angles of attack $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (---) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
Figure 4.54: Normalised velocity PSD for NACA 65(12)-10 aerofoil with slotted-sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.2$ at angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (---) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
Figure 4.55: Normalised velocity PSD for NACA 65(12)-10 aerofoil with slotted-sawtooth serration for tip (left column) and root (right column) at location $x/c = 0.5$ at angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$ at $U_0 = 20$ m/s. Dashed-line (---) indicates the location of the TKE peak in the crosswise direction for the Baseline aerofoil.
4.4 Summary

A comprehensive experimental study has been carried out for the wake development of aerofoils fitted with different trailing-edge serrations. A symmetric NACA 0012 and cambered NACA 65(12)-10 were used in this study. The flow field results show that the use of serrations does not show a strong effect in the case of symmetric NACA 0012 aerofoil especially at pre-stall angles of attack. At high angles of attack, a clear wake TKE reduction can be found for the serrated NACA 0012 aerofoil at limited downstream wake locations from $x/c = 0.2$ to $x/c = 1.5$. Unlike the results for the symmetric NACA 0012 aerofoil, the use of serrations significantly affects the development of the wake deficit and the TKE value and peak location in the case of cambered NACA 65(12)-10 aerofoil. The velocity profiles vary notably between the tip- and root-planes, which would then cause significant shear stress between the tip- and root-flow planes. The wake deficit peak location shows an upward shift in the wake profiles at the root positions relative to the Baseline case with straight trailing-edge and the tip positions. This indicates that the flow originating from the pressure surface passes through the serration valleys moving upwards. The wake downwash flow turning angle for the root-plane is significantly smaller than that of the Baseline and tip-positions. The flow structure in the vicinity of the serrations at high angles of attack shows the occurrence of two fixed contra-rotating vortices for both the aerofoils. Furthermore, results have shown that the large vortex, due to the early separation of the flow on the suction surface of the aerofoil, is moved upwards and weakened by a secondary smaller periodic vortex originating from the flow passing through the serration valleys. The possibility of the flow moving from the pressure side to the suction side of the aerofoil around the serrations and through the serration valleys gives rise to the emergence of some horseshoe vortices leaving the aerofoil serrations and contra-rotating streamwise structures on the serrations. The emergence of horseshoe vortices from the serrations results in some turbulence structures.
in the near wake region after each serration tooth. This shows that the flow field over the serration and near-wake is highly three-dimensional with strong vortices present in both the span-wise and streamwise directions. This three-dimensional flow and vortices influence the turbulent energy decay within the wake region by increasing the flow mixing and bringing down the turbulence level significantly compared to the case with straight trailing-edge. The wake energy content results have also shown that the use of serrations can lead to considerable reduction in the velocity power spectrum at all angles of attack, particularly at high angles, where maximum aerodynamic performance is obtained. The possibility of reducing the turbulence level using serrations is a very interesting observation, particularly in the context of noise generated by wake-aerofoil interaction, such as contra-rotating propellers, rotor-stator configuration, etc.
The early sections showed that the implementation of trailing-edge serrations, such as sawtooth and slotted-sawtooth serrations, which have superior noise reduction efficiency [99], can also significantly reduce the wake turbulence intensity, particularly at high angles of attack, where maximum aerodynamic performance is obtained [3–5]. This significant rapid turbulent energy decay within the wake region is believed to be due to the three-dimensional flow originating from the serration tip and root planes. The possibility of reducing the turbulence level using serrations shows an option for a new technique for reducing noise generated by wake-aerofoil interaction. This will have industrial implications for applications involving multiple rows of aerofoils such as the contra-rotating propellers, rotor-stator configuration, etc.

To expand the existing knowledge and better understand the effect of using serrations on the aerodynamic and acoustic performance of aerofoils in tandem, detailed study of the wake development and surface pressure fluctuations have been carried out.
and presented in this Chapter. A comprehensive aerodynamic study using a cambered NACA 65-710 aerofoil with and without trailing-edge serration has been carried out using the two-dimensional Particle Image Velocimetry (PIV) technique. Thorough measurements have been also carried out for pressure coefficient distributions on the rear aerofoil. The effect of serrations on the noise generation for the tandem NACA 65-710 configuration has also been studied by studying the surface pressure fluctuations on the rear aerofoil using the remote sensing probe method. The experimental setup manufactured for the present study and the aerodynamic measurement techniques are discussed in Chapter 2. The aerodynamic performance results and the relevant discussions will be provided in the following sections.

5.1 Tandem aerofoil setup

The geometrical parameters of the tandem aerofoil configuration (see Fig. 5.2), such as the gap distances between the front and rear aerofoils ($W$), the streamwise distance between the centre-points of the aerofoils ($W_x$), vertical distance between the aerofoils centre-points ($W_y$), vertical distance in the wake region ($l$), angle of attack of front aerofoil ($\alpha_{\text{front}}$) and rear aerofoil ($\alpha_{\text{rear}}$) are provided in Table 5.2. Note that, $W_x$ and $W_y$ were defined based on the the locations where the the maximum turbulent kinetic energy is observed from the PIV results, obtained for the Baseline case of an isolated NACA 65-710 aerofoil.

The steady and unsteady surface pressures, ($C_p$ and $C_p'$), have been measured using a MicroDaq pressure scanner and remote sensing probes on both sides of the rear aerofoil, see Fig. 5.1. The pressure taps for the measurement of the pressure coefficient distribution were made from 1.6 mm diameter brass tubes with 0.4 mm pinholes with an angle perpendicular to the surface of the aerofoil to avoid any aerodynamic interference
between the pressure taps. The unsteady surface pressure fluctuation ($C_p'$) measurements are performed using remote sensing probes, which are connected between the brass tube to a remote microphone holder equipped with 34 Panasonic WM-61A microphones using plastic tubing with the inner and outer diameter of 0.8 mm and 3.6 mm. The details of the remote sensing method can be found in Chapter 2. The data was acquired by a National Instruments PX1e-4499 at a sampling rate of $2^{16}$ Hz and sampling time of 8 seconds, and processed using in-house routines developed in Matlab.

Figure 5.1: Tandem aerofoil setup in wind tunnel.

Table 5.1: Geometrical parameters of the trailing-edge serrations used in the current study.

<table>
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<th>Configuration</th>
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<th>$\lambda$ (mm)</th>
<th>$\lambda/h$</th>
<th>$\alpha_s$ (deg.)</th>
<th>$d$ (mm)</th>
<th>$H$ (mm)</th>
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Figure 5.2: Tandem aerofoil setup parameters.

Table 5.2: Tandem aerofoil setup parameters

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<th>Cases</th>
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<th>$\alpha_{\text{rear}}$ degrees</th>
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5.2 Isolated NACA 65-710 aerofoil aerodynamic measurements

The lift and drag measurements of the NACA 65-710 aerofoil at different angles of attack were carried out at the large wind tunnel facility at the University of Bristol. Tests were performed at a freestream flow speed of \( U_0 = 30 \) m/s. The details of the aerodynamic force measurement and the wind tunnel are provided in Chapter 2. The aerodynamic performance results are presented in Fig. 5.3. The figure shows both the lift and drag coefficients and the lift-to-drag ratio. As can be seen, the aerofoil is able to produce lift at zero angle of attack and has a linear behaviour up to about 7 degrees. The lift coefficient increases with the angle of attack until \( \alpha = 15^\circ \), and then rolls off. The value of the drag coefficient is generally low but then increases dramatically beyond \( \alpha = 0^\circ \), reaching 0.4 at the angle of attack of \( \alpha = 20^\circ \). According to the lift-to-drag ratio results, the aerofoil maximum performance is obtained at about \( \alpha = 8^\circ \), but has a plateau behaviour between \( 5^\circ < \alpha < 14^\circ \), providing lift-to-drag ratio of about 5. In order to perform a comprehensive study and cover all different operation regions of the aerofoil, we will study the flow characteristics and aerodynamic loading of the NACA 65-710, in both the isolated and tandem configurations, at the angles of attack of \( \alpha = 0^\circ, 5^\circ, 10^\circ \) and \( 15^\circ \).

Figure 5.3: Aerodynamic load of the isolated NACA65-710 aerofoil (a) Lift and drag coefficient (b) Lift-to-drag ratio.

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To better understand the effects of the trailing-edge serration on the wake development of the aerofoil, the flow measurements of a single NACA 65-710 aerofoil for the Baseline, blunt, two different sawtooth serrations ($\lambda = 9$ mm and $\lambda = 24.8$ mm) and one slotted-sawtooth serration ($\lambda = 9$ mm and $H = 15$ mm) configurations have been carried out using Particle Image Velocimetry. All serrations considered here have an amplitude of $2h = 30$ mm. The wake measurements were performed at angles of attack, $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ for the chord-based Reynolds number of $Re_c = 3 \times 10^5$, corresponding to the flow velocity of $U_0 = 30$ m/s. The fields of view used in our experiments covered the downstream locations $x/c = 0.2$ to $0.85$, relative to the trailing-edge of the Baseline case. The wake velocity profiles and the TKE results for the NACA 65-710 aerofoil at the downstream locations $x/c = 0.2$, $0.3$, $0.4$, $0.5$, $0.6$, $0.7$ and $0.8$ at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$ with and without trailing-edge serrations are presented in Figs. 5.4 to 5.11, respectively. The flow patterns and the turbulence kinetic energy (TKE) maps of the isolated aerofoil allows to choose the location of the rear aerofoil for the noise generation studies in section 5.5.

- Isolated NACA 65-710 aerofoil at $\alpha = 0^\circ$ and $5^\circ$

The wake velocity profiles for the Baseline and serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$ and $5^\circ$ are presented in Figs. 5.4 and 5.6, respectively. For the wide sawtooth serration ($\lambda = 24.8$ mm), in the near-wake region, $x/c = 0.2$ to $0.4$, it can be observed that the flow at the tip position of the sawtooth serration follows a similar wake profile to that of the Baseline, but with a slightly higher velocity deficit. The higher velocity deficit of the tip-flow is believed to be due to the larger effective chord-length of the tip-plane. At further downstream locations, between $x/c = 0.5$ to $0.8$, the tip-flow still follows a similar wake profile as the Baseline results. The root-flow, however, shows a very different behaviour in the whole wake region $x/c = 0.2$ to $0.8$, with is a smaller ve-
locity deficit, and the velocity dip location significantly moved upward along the vertical direction, which is believed to be caused by the jet flow through the serration valleys. When compared with the blunt trailing edge results, the root-flow results show a similar profile. For the sharp sawtooth serration ($\lambda = 9$ mm) and slotted-sawtooth serration, the results at the trailing-edge region ($x/c = 0.2$) show a similar trend to that for the wide sawtooth serration results. The differences between the wake velocity deficit and the deficit dip location of the tip and root-flows gradually disappear at downstream locations, but the velocity dip of the combined flow shows an upward shift in the vertical direction when compared with the Baseline case and clear downward variation when compared with the blunt trailing-edge results. It is, therefore, evident from the results that the serrations can significantly change the nature of the wake development for a cambered aerofoil, even at small angles of attack.

The turbulent kinetic energy (TKE) results for the NACA 65-710 aerofoil with serrated and unserrated trailing-edges at $\alpha = 0^\circ$ and $5^\circ$ are presented in Figs. 5.5 and 5.7, respectively. In the case of wide sawtooth serration ($\lambda = 24.8$ mm), at $\alpha = 0^\circ$, the TKE magnitude of the sawtooth serrated case is similar to that of the Baseline case but smaller than that of the blunt trailing-edge case. However, both the tip- and root-planes show different flow profiles to that of the Baseline case, with a weak double-peak trend in the near-wake region ($x/c = 0.2 - 0.5$), while the tip- and root-flow for the Baseline case only have a single deficit peak. Also, the root-flow shows a strong upward deflection behaviour in the vertical direction due to the valley flow through the serration root. The TKE results in the case of wide serrations at $\alpha = 5^\circ$ show similar trends to that of $\alpha = 0^\circ$ with a maximum of 20% reduction in the TKE magnitude. In the case of sharp sawtooth serrations ($\lambda = 9$ mm) and slotted-sawtooth serrations ($\lambda = 9$ mm and $H = 15$ mm) in Figs. 5.5(b) and (c), the TKE magnitude shows a similar trend as that of the wide sawtooth serration case, i.e. a similar behaviour to the Baseline but smaller than that of
the blunt trailing-edge results. At downstream positions, the turbulent kinetic energy pattern becomes two-dimensional, indicating that the tip- and the root-plane flows have merged and formed a fully developed wake flow. The results for different serrations in the case of the NACA 65-710 at $\alpha = 0^\circ$ have shown that the use of sharp and slotted-sawtooth serrations lead to a faster mixing of the tip- and root-plane flows and more rapid reduction of the TKE in the wake region. In the fully developed wake region, the TKE profiles show an upward turning of the peak location in the vertical direction compared to the Baseline case, and downward compared to the blunt case, which can be attributed to the effect of the serration valley flow on the wake structures. For $\alpha = 5^\circ$ in Figs. 5.7(b) and (c), in the case of sharp serration and slotted-sawtooth serration, the TKE magnitude reduction is observed to be around 30% for $\alpha = 5^\circ$. The reduction of the wake flow TKE is of great interest and can potentially lead to the reduction of unsteady loading on a rear aerofoil. This will be further discussed in Section 5.5.
Figure 5.4: Wake velocity profile for serrated and unserrated NACA 65-710 aerofoil at \( \alpha = 0^\circ \) and \( U_0 = 30 \) m/s.
Figure 5.5: Wake TKE profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 0^\circ$ and $U_0 = 30$ m/s.
5.2. ISOLATED NACA 65-710 AEROFOIL AERODYNAMIC MEASUREMENTS

Figure 5.6: Wake velocity profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 5^\circ$ and $U_0 = 30$ m/s.
Figure 5.7: Wake TKE profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 5^\circ$ and $U_0 = 30$ m/s.
Isolated NACA 65-710 aerofoil at $\alpha = 10^\circ$

The wake velocity profiles and TKE results for the NACA 65-710 aerofoil at $\alpha = 10^\circ$ with and without different serrations are presented in Figs. 5.8 and 5.9, respectively. The wake velocity profiles for the aerofoil with and without a wide sawtooth serration ($\lambda = 24.8$ mm) in Fig. 5.8(a) show that at higher angles of attack, the differences of the wake velocity deficit between the tip- and root-plane flows have increased, unlike the results at lower angles of attack especially for wide sawtooth serrations in the near trailing-edge region. The deficit of the tip-flow is higher than that of the Baseline with a downward deflection and the root-flow shows a significant reduction and an upward turning of the velocity deficit dip. These differences in the velocity deficit between the tip- and root-planes reduce moving further downstream. For sharp sawtooth and slotted-sawtooth serrations ($\lambda = 9$ mm), see Fig. 5.8(b) and (c), results show similar velocity wake profiles as the wide sawtooth serrated case in the near trailing-edge region ($x/c < 0.4$). The resultant flow is, however, different from the results for the wide sawtooth serration, merging together at around $x/c \approx 0.5$. After mixing, the resultant wake flow behaves similar to the Baseline flow but with a significant downward deflection.

Figure 5.9 presents the TKE results for the Baseline, blunt and different serrated cases at different axial locations at the angle of attack of $\alpha = 10^\circ$. In the wake TKE profile results for the wide sawtooth serration case ($\lambda = 24.8$ mm) in Fig. 5.9(a), a double-peak trend can be observed in both the tip-flow and the Baseline case in the near trailing-edge region ($x/c < 0.4$). The TKE magnitude of the tip-flow shows a much stronger peak on the pressure side of the aerofoil. Also, a clear downward deflection exists in the tip-flow results. For the root-flow of the wide sawtooth serration, unlike the tip-flow results, here only a single TKE peak exists and the magnitude of the TKE peak is smaller than both of the blunt and the Baseline cases. Furthermore, the TKE peak of
the root-flow shows a significant upward deflection when compared to the Baseline case. For sharp sawtooth ($\lambda = 9 \text{ mm}$) and slotted-sawtooth ($\lambda = 9 \text{ mm}, H = 15 \text{ mm}$) serrations, in the near wake region, $x/c = 0.2$ to $0.3$, slightly downward deflections in the tip-flow and upward deflections in the root-flow results are observed. However, while comparing against the blunt trailing-edge results, both the tip- and root-flow resulted in an apparent downward wake flow deflection. Furthermore, for both the tip- and root-flow, the TKE resulted in significant drop of up to $53\%$ over the whole range of the tip-flow and after only a short distance from the trailing-edge of the aerofoil ($x/c > 0.3$). This behaviour is believed to be mainly due to a strong root-flow and the planar interaction occurring between the tip- and root-flows in the vicinity of the trailing-edge, especially for the sharp sawtooth and slotted-sawtooth serration cases.
Figure 5.8: Wake velocity profile for serrated and unserrated NACA 65-710 aerofoil at \( \alpha = 10^\circ \) and \( U_0 = 30 \) m/s.
Figure 5.9: Wake TKE profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 10^\circ$ and $U_0 = 30 \text{ m/s}$. 
• Isolated NACA 65-710 aerofoil at $\alpha = 15^\circ$

The results for the wake velocity profiles for a NACA 65-710 aerofoil with and without trailing-edge serrations at the angle of attack $\alpha = 15^\circ$ are presented in Fig. 5.10. Unlike the results for smaller angles of attack, the results for all three serrations show the appearance of a large wake structure, indicating the presence of early separation on the suction side of the aerofoil. For wide sawtooth serration ($\lambda = 24.8$ mm) in Fig. 5.10(a), in the near trailing-edge region ($x/c < 0.4$), the velocity deficit at the serration tip is reduced in magnitude and the deficit dip angle turns downward while the root-flow shows a similar profile to that of the Baseline case with a smaller velocity deficit magnitude. The blunt trailing-edge results also follow the Baseline case quite well with smaller velocity deficit magnitude. The tip- and root-plane flows then converge together after $x/c = 0.6$ and the resultant flow shows a reduction in the velocity deficit when compared to the Baseline case. The range of velocity deficit reduction becomes smaller at further downstream locations ($x/c \geq 0.7$). In comparison to the blunt case, the results for serrated cases show a higher velocity deficit magnitude over the whole range of the wake. For sharp sawtooth and slotted-sawtooth serration results ($\lambda = 9$ mm and $\lambda = 9$ mm, $H = 15$ mm) in Figs. 5.10(b) and (c), the tip- and root-plane flows do not show a substantial difference in the whole wake region and the velocity deficit dip location for both tip- and root-planes slightly shift downwards in the vertical direction. Again, the velocity deficit shows a smaller value when compared with the Baseline case and this deficit range is higher than that of the blunt trailing-edge case.

Figure 5.11 summarizes the TKE results in the wake region of a NACA 65-710 aerofoil, set at the angle of attack of $\alpha = 15^\circ$, with different trailing-edge treatments. The TKE results of the wide sawtooth serration ($\lambda = 24.8$ mm) in Fig. 5.11(a) show a mild reduction of up to around 8% in the TKE magnitude compared to the Baseline aerofoil.
For sharp sawtooth ($\lambda = 9$ mm) serrated case in Fig. 5.11(b), a considerable reduction of the TKE magnitude can be found over both the tip- and root-planes at downstream locations $x/c > 0.3$. The TKE profiles for the serrated cases show a slight downward deflection when compared to the Baseline case. In Fig. 5.11(c), The wake TKE profiles for the slotted-sawtooth ($\lambda = 9$ mm and $H = 15$ mm) serrated case show that the use of serrations resulted in a clear reduction of about 28% above the aerofoil chord-line and 48% below the chord-line in the wake region. The TKE profiles for all serration cases have experienced significant growth compared to that of the blunt trailing-edge case. Results also show that in the case of high angles of attack, very little difference can be observed between different trailing-edge serrations. This indicates that the wake flow behaviour is primarily affected by the aerofoil early separation and that the trailing-edge type does not cause significant changes.

To summarise, the results presented in this section for a NACA 65-710 aerofoil have shown that the use of serration, particularly sharp ($\lambda = 9$ mm) and slotted-sawtooth ($\lambda = 9$ mm and $H = 15$ mm) serrations, can result in significant reduction of the energy content of the wake flow structures. Maximum TKE reduction was observed at relatively high angles of attack. This is of particular interest as most aerofoils are often operated at high angles of attack to achieve maximum aerodynamic performance. The possibility of the reduction of the wake flow energy content can have significant implications in terms of the steady and unsteady aerodynamic loading on downstream objects, such as an aerofoil in a tandem or cascade configuration, and aerodynamic noise generation mechanism.
Figure 5.10: Wake velocity profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 15^\circ$ and $U_0 = 30$ m/s.
Figure 5.11: Wake TKE profile for serrated and unserrated NACA 65-710 aerofoil at $\alpha = 15^\circ$ and $U_0 = 30$ m/s.
5.3 Tandem configuration: pressure coefficient distribution

In order to quantify the effects of trailing-edge serrations in a tandem aerofoil configuration, the pressure coefficient and the surface pressure fluctuations exerted on the rear NACA 65-710 aerofoil have been studied. The trailing-edge of the front aerofoil will be treated with different serrations, as discussed in the previous section. The mean pressure, pressure coefficient and \( C_{p_{\text{rms}}} \) pressure coefficient fluctuation are found from:

\[
P_{\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} P_i, \tag{5.1}
\]

\[
C_p = \frac{P_{\text{mean}} - P_{\infty}}{\frac{1}{2} \rho_{\text{air}} U_0^2}, \tag{5.2}
\]

\[
C_{p_{\text{rms}}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (C_{p_i} - C_{p_{\text{mean}}})^2}. \tag{5.3}
\]

where \( P \) is the static pressure at the point at which the pressure coefficient is being evaluated, \( P_{\infty} \) is the static pressure in the freestream, \( \rho_{\text{air}} \) is the freestream air density (air at sea level and \( 15^\circ \text{C} \) is considered, such that \( \rho_{\text{air}} = 1.225 \text{ kg/m}^3 \)) and \( U_0 \) is the freestream velocity.

Figure 5.12 presents the pressure coefficient distribution \( (C_p) \) on the rear aerofoil at the angles of attack, \( \alpha = 0^\circ, 5^\circ, 10^\circ \) and \( 15^\circ \), at different aerofoil separation distances of \( W = 0.3c, 0.5c \) and \( 1.0c \), with the front aerofoil fitted with sawtooth serration (\( \lambda = 24.8 \text{ mm} \)). At a low angle of attack \( (\alpha = 0^\circ) \), and a small gap distance \( (W = 0.3c) \), the
pressure coefficient results show that the use of serration can reduce the absolute value of the pressure coefficient at the leading-edge region \((x/c < 0.4)\) over both the suction and pressure sides of the aerofoil. The \(C_p\) values for root-plane then gradually converge to that of the Baseline case for \(x/c > 0.4\) and the tip-plane values became slightly higher than that of the Baseline case. At larger gap distance of \(W = 0.5c\), the \(C_p\) results show slightly larger reduction of the absolute value of \(C_p\) for the leading-edge region \((x/c > 0.4)\). Then, the value of the pressure coefficient for the suction side of the serrated case becomes close to the Baseline case for \(x/c > 0.4\). The values of the pressure coefficient for the pressure side of the serrated tip-plane show a continuous reduction for \(x/c > 0.4\). At the gap distance of \(W = 1.0c\), \(C_p\) in the serrated cases (both tip- and root-position) is observed to have been reduced over the whole chord of the aerofoil. To conclude, for the pressure side of the aerofoil (lower surface), with the gap distances of \(W = 0.3c, 0.5c\) and \(1.0c\), the results for the serrated cases (both the tip and root position) show an overall reduction in the absolute value of the pressure over the whole range the aerofoil, especially over the tip-plane.

At the angle of attack, \(\alpha = 5^\circ\) and the gap distances of \(W = 0.3c, 0.5c\), it can be seen that the pressure coefficient is slightly reduced on the suction side of the aerofoil (lower surface) for the serrated cases (both tip and root positions), while on the pressure side (upper surface), there is only a little difference between the Baseline and serrated cases. At the large gap distance of \(W = 1.0c\), on the suction side of the aerofoil, the difference between the pressure distribution of the Baseline and serrated case increases compared to the \(W = 0.3c\) and \(0.5c\) cases. Also, on the pressure side of the aerofoil, the pressure coefficient over the root-plane shows slight increase when compared to the Baseline case.

At a slightly higher angle of attack of \(\alpha = 10^\circ\), the use of the serrations on the up-
stream aerofoil has a very different effect on the rear aerofoil than those observed at lower angles of attack. Results for the gap distances of $W = 0.3c$, $0.5c$ and $1.0c$ show that the magnitude of the pressure on the suction side of the rear aerofoil in the leading-edge region ($x/c < 0.15$) increases significantly in the case of a serrated trailing-edge configuration, followed by a mild reduction over the chord range of $0.15 < x/c < 0.4$. The pressure distribution over the trailing-edge area of the rear aerofoil does not seem to be greatly affected. The pressure distribution on the pressure side of the rear aerofoil (bottom curves), is also observed not be significantly affected as a result of the trailing-edge serration on the front aerofoil. The significant changes to the pressure distribution between the small angles of attack ($\alpha = 0^\circ$ and $5^\circ$) and relatively high angle of attack ($\alpha = 10^\circ$) is consistent with the wake velocity and TKE observations in the previous section.

The results at a very high angle of attack of $\alpha = 15^\circ$ show that the pressure distribution over the rear aerofoil is very dependent on the gap distance due to the early separation on the front aerofoil and large separation wake interacting with the rear aerofoil. At small separation distances ($W = 0.3c$, $0.5c$), the use of trailing-edge serrations on the rear aerofoil does not seem to have a significant effect on the pressure distribution on the rear aerofoil, particularly over the leading-edge region. At large gap distances, however, the use of trailing-edge serrations on the front aerofoil leads to a significant increase in the absolute value of the pressure experienced over the suction side of the aerofoil over the whole chord length, particularly over the tip-plane. On the pressure side of the rear aerofoil, the serration causes a reduction in the static pressure over the aerofoil. An interesting observation here is that, despite the large gap distance, the pressure experienced over the tip- and root-planes remains significantly different. The effects of the interaction of the wake of NACA65-710 aerofoil with sharp ($\lambda = 9$ mm) and slotted-sawtooth serration ($\lambda = 9$ mm, $H = 15$ mm) trailing-edges on the pressure
distribution over the rear aerofoil in tandem configuration, with separation distances of $W = 0.3c$, $0.5c$ and $1.0c$ have also been studied in Figs. 5.13 and 5.14. Although the use of different trailing-edge serrations on the front aerofoil were observed to cause significant changes to the wake flow structure and the wake TKE patterns, the $C_p$ results on the rear aerofoil have shown that the pressure distribution trends for the different serration cases are fairly similar. Similar to the observations in Fig. 5.12, the absolute value of the pressure experienced on the suction side of the aerofoil at small angle of attack is seen to reduce, while it increases at high angles of attack, particularly at large gap distances. The comparisons also show that the slotted-sawtooth serration case has the most pronounced effect on the pressure distribution over the rear aerofoil, compared to the other two serrations.
5.3. TANDEM CONFIGURATION: PRESSURE COEFFICIENT DISTRIBUTION

Figure 5.12: Pressure coefficient distribution ($C_p$) for Baseline and sawtooth ($\lambda = 24.8$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$. 

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Figure 5.13: Pressure coefficient distribution ($C_p$) for Baseline and sawtooth ($\lambda = 9$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$.
Figure 5.14: Pressure coefficient distribution ($C_p$) for Baseline and slotted-sawtooth ($\lambda = 9$ mm, $H = 15$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$, and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$. 
Figures 5.15 to 5.17 present the root mean squared (\(rms\)) pressure coefficient distribution (\(C_{p_{rms}}\)) results over the rear aerofoil when different trailing-edge serrations, namely wide sawtooth serration (\(\lambda = 24.8\) mm), sharp sawtooth serration (\(\lambda = 9\) mm) and slotted-sawtooth serration (\(\lambda = 9\) mm and \(H = 15\) mm), have been applied to the trailing-edge of the front aerofoil. Results are presented for different angles of attack (\(\alpha = 0^\circ, 5^\circ, 10^\circ\) and \(15^\circ\)) and aerofoil separation distances (\(W = 0.3c, 0.5c\) and \(1.0c\)). All measurements were carried out at a wind speed of \(U_0 = 30\) m/s. Knowing that the noise generation from tandem aerofoil or aerofoils cascades is dominated by the interaction of the incoming wake turbulence from upstream aerofoils with the leading-edge and the front part of the downstream aerofoils, studying the energy content of the pressure experienced over the rear aerofoils, particularly in the leading-edge region can help the development of better and more robust noise control techniques.

The \(rms\) pressure results can also be categorised in the same way as the pressure and flow field sections. At low angles of attack (left column of Figs. 5.15 to 5.17) results show that the use of serrations on the upstream aerofoil generally increases the surface pressure experienced by the rear aerofoil, particularly over the pressure side. The increase in the experienced surface pressure fluctuations over the pressure side of the rear aerofoil compared to the Baseline tandem configuration is highest at \(\alpha = 0^\circ\) and reduces at \(5^\circ\). All results for these two angles of attack also show a typical decay with \(x/c\), which shows that the wake turbulence interaction causes maximum surface pressure fluctuations at the stagnation point and this will gradually reduce with the distance from the leading-edge.

At a higher angle of attack of \(\alpha = 10^\circ\) results change significantly. The \(rms\) pressure results at \(\alpha = 10^\circ\) show that the use of the trailing-edge serrations on the front aerofoil reduces the pressure fluctuations on the rear aerofoil considerably. The most important
observation is that the suction side of the rear aerofoil experiences the highest level of reduction over the whole chord of the aerofoil, which will accordingly lead to much less lift and drag fluctuations of the aerofoil and therefore much weaker noise generation mechanism. Also, results show that the maximum level of the reduction is perceived over the tip-plane of the serration. One can also infer from the results that the rms pressure reduction is greater for the aerofoil separation distances of $W = 0.5c$ and $1.0c$, which is in agreement with the TKE results discussed in Section 5.2.

At very high angles of attack ($\alpha = 15^\circ$), results show a very different behaviour. The pressure fluctuations experienced on the suction side of the rear aerofoil over the tip-plane is found to have been reduced, but the root-plane is very similar to the Baseline tandem aerofoil configuration. Compared with the results for $\alpha = 10^\circ$, the serrations have less effect at such high angles, which is consistent with the TKE and pressure observations in section 5.2. Finally, although the three different serrations have been found to have a fairly similar effect of the experienced surface pressure fluctuations on the rear aerofoil, the slotted-sawtooth serration has been the most effective in reducing the rms pressure in the leading-edge area at high angles of attack.

The root mean square (rms) pressure presented in Figs. 5.15 to 5.17 provided an opportunity to study the energy content of pressure fluctuations experienced on the rear aerofoil due to the interaction with the wake of an upstream aerofoil. The rms pressure can be regarded as the pressure fluctuations, averaged over all frequencies, which is exerted on the surface of the aerofoil. Although this is a very useful tool for understanding the effectiveness of the trailing-edge serrations on the control of wake turbulence interaction with the rear aerofoil, it does not provide any insight into the frequency energy content of the pressure exerted on the aerofoil. In the next section, the pressure power spectral density results will be provided as well as an analysis of
the energy content of the pressure experienced at different frequencies.
Figure 5.15: Fluctuations pressure coefficient distribution ($C_{p_{rms}}$) for Baseline and sawtooth ($\lambda = 24.8$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$. 
Figure 5.16: Fluctuations pressure coefficient distribution ($C'_{p_{rms}}$) for Baseline and sawtooth ($\lambda = 9$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$. 
Figure 5.17: Fluctuations pressure coefficient distribution ($C_{p}^{\prime\,\text{rms}}$) for Baseline and slotted-sawtooth ($\lambda = 9$ mm, $H = 15$ mm) serrated NACA 65-710 aerofoils at $\alpha = 0^\circ$, $5^\circ$, $10^\circ$ and $15^\circ$, at $U_0 = 30$ m/s with aerofoil separation distance of $W = 0.3c$, $0.5c$ and $1.0c$. 
CHAPTER 5. TANDEM AEROFOL CONFIGURATION

5.4 Tandem NACA 65-710 aerofoil flow pattern

The results in the Section 5.2 concerned the wake flow behaviour of an isolated NACA 65-710 aerofoil at different angles of attack, with and without trailing-edge serration. The results of the previous section, particularly the wake dip locations are to be used for determining the location of the rear aerofoil in the tandem configuration. It is, however, obvious that wake flow field in the case of tandem aerofoil configuration will be different due to the pressure field of the rear aerofoil. Therefore, before proceeding with the unsteady surface pressure measurements, we shall first present the tandem aerofoil flow pattern results.

In order to improve our understanding of the flow characteristics and the wake development in the gap region between the two aerofoils and the wake interaction with the rear aerofoil, the velocity flow field and TKE patterns are studied. The PIV measurements will be provided for the Baseline and two different sawtooth serrations (\(\lambda = 9\) mm and 24.8 mm) for the two NACA 65-710 aerofoils in tandem configuration (see Table 5.2). During the measurements, the aerofoils were mounted in the Low Turbulence Wind tunnel working section by a support frame and the PIV laser was placed under the working section with the bottom surface of the wind tunnel working section replaced with a clear window (see Chapter 2). A total number of 3 fields-of-view(FOV) PIV camera windows have been captured for the cases with the gap distance \(W = 0.3c\) and 0.5c (see Fig. 5.18(a)) and 4 FOVs windows for the cases with the gap distance of \(W = 1.0c\) (see Fig. 5.18(b))
5.4. TANDEM NACA 65-710 AEROFOIL FLOW PATTERN

Figure 5.18: Camera fields-of-view and laser sheet directions (arrow direction) (a) tandem aerofoil with the gap distance of $W = 0.3c$ and $0.5c$ (b) tandem aerofoil with the gap distance of $W = 1.0c$. 

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Figures 5.19 to 5.21 show the PIV results for the Baseline and sawtooth serrated \((\lambda = 9 \text{ mm and } 24.8 \text{ mm})\) NACA 65-710 aerofoil in the tandem configuration with the aerofoil gap distances of \(W = 0.3c, 0.5c\) and \(1.0c\), at the angle of attack of \(\alpha = 10^\circ\) under \(U_0 = 30 \text{ m/s}\). Based on the result presented in Section 5.2, clear TKE reduction can be found at high angles of attack. Therefore, results here are only presented at a single angle of attack \((\alpha = 10^\circ)\). The TKE profiles are presented for the Baseline, sawtooth tip- and root-planes. In Fig. 5.19, the gap distance between the two aerofoils is \(0.3c\). It can be observed that in the gap area, the wake TKE of the front aerofoils for the two serrated tip cases shows similar trends to that of the Baseline case while the serrated root cases show a clear upward shift. Around the rear aerofoil, on the pressure side of the aerofoil, no noticeable difference can be found between the Baseline case and the serrated cases. On the suction side of the rear aerofoil, a high TKE region \((TKE/U_0^2 > 0.12)\) can be observed in the results. The high TKE region for the large sawtooth serration case \((\lambda = 24.8 \text{ mm})\) show that at both the tip and root positions, the size of high TKE regions are similar to that of the Baseline case, but for the sharp sawtooth serration case \((\lambda = 9 \text{ mm})\), the high TKE regions are slightly smaller than that of the Baseline case. Also, on the suction side of the rear aerofoil, the shape of the TKE region \((TKE/U_0^2 > 0.005)\) for the Baseline case is slightly thicker than that of the two sawtooth serrated cases. Results have also confirmed that the vertical location of the rear aerofoil chosen based on the results in Section 5.2 for an isolated NACA65-710, falls very close to the velocity dip (highest TKE) of the front aerofoil.

The TKE contour plots for the tandem aerofoil configuration with the gap distance \(W = 0.5c\) are presented in Fig. 5.20. Similar to the results in Fig. 5.19, a clear upward and downward flow deflection over the serration root and tip planes can be seen. However, with the increase of the gap distance between the two aerofoils, a significant TKE reduction has been found in the wake gap, particularly in the vicinity of the leading-
edge of the rear aerofoil. The high TKE region, for the Baseline case, appears from the leading-edge to around 0.4c of the rear aerofoil while for the two serrated cases, this becomes much shorter. For the case of a large sawtooth serration (\( \lambda = 24.8 \) mm), the high TKE region can be found from the leading-edge to around 0.3c of the rear aerofoil, while that for the sharp sawtooth serration (\( \lambda = 9 \) mm) extends to about 0.35c. Furthermore, a noticeable reduction in both the TKE magnitude and high TKE region size can be observed in the further downstream locations of both sawtooth serration cases.

Figure 5.20 shows the TKE contour plots for the tandem aerofoil configuration with the gap distance of \( W = 1.0c \). Results show that the TKE value of the gap flow before interaction with the leading-edge of the rear aerofoil is much less than that with shorter gap distances. Also, the level of TKE reduction using sharp sawtooth cases increases with the gap distance. However, the TKE profiles around the rear aerofoils for serrated cases with the gap distance of \( W = 1.0c \) show that the use of serrations on the trailing-edge of the front aerofoil does not show a notable effect on the TKE distribution over the suction side of the rear aerofoil.
Figure 5.19: TKE profile for tandem NACA 65-710 aerofoil configuration at $\alpha = 10^\circ$ and $W = 0.3c$ at freestream velocity of $U_0 = 30$ m/s.
Figure 5.20: TKE profile for tandem NACA 65-710 aerofoil configuration at $\alpha = 10^\circ$ and $W = 0.5c$ at freestream velocity of $U_0 = 30$ m/s.
Figure 5.21: TKE profile for tandem NACA 65-710 aerofoil configuration at $\alpha = 10^\circ$ and $W = 1.0c$ at freestream velocity of $U_0 = 30$ m/s.
5.4. TANDEM NACA 65-710 AEROFOIL FLOW PATTERN

To further study the effect of trailing-edge serrations on the front aerofoil and the wake interaction with the leading-edge of the rear aerofoil, detailed TKE profiles at several locations within the wake and over the suction side of the rear aerofoil, as shown in Fig. 5.22, have been extracted from the PIV data and presented in Figs. 5.23 to 5.25. As before, results are presented for the gap distances of $W = 0.3c$, $0.5c$ and $1.0c$ at the angle of attack of $\alpha = 10^\circ$.

Figure 5.22: TKE measurement locations within the gap region and over the rear aerofoil.

Figure 5.23 shows the turbulence kinetic energy (TKE) results for the tandem configuration with a gap distance of $W = 0.3c$, at the locations shown in Fig. 5.22. Comparisons are provided between the Baseline and both of the tip and root position of the large sawtooth serration ($\lambda = 24.8$ mm; upper row of the plots) and the sharp sawtooth serration ($\lambda = 9$ mm; lower row of the plots). The TKE results at the location L2 ($0.1c$ upstream of the leading-edge of the rear aerofoil), show that both sawtooth serration cases cause an upward shift of the maximum TKE when compared to the Baseline case results, especially in the case of the root-plane. This is consistent with the observation in the previous section for an isolated aerofoil. The TKE magnitude of the two serrated
cases, especially over the tip-plane, is similar to that of the Baseline case, but with a shorter width over the y-axis, i.e. narrower shear layer. With regard to the TKE results over the rear aerofoil, the TKE results for the serrated cases show a narrower width compared to the Baseline case at L3 to L7. The magnitude of the TKE is also generally lower than that of the Baseline case, except for the wake centre, where they have comparable values. Results also show that the use of sharp sawtooth serration can lead to a more robust and long-lasting reduction in TKE within the wake and over the rear aerofoil. These results are again consistent with the observation made in Section 5.2 for an isolated NACA65-710 aerofoil.

The TKE results for the tandem aerofoil configuration with a slightly larger gap distance of \( W = 0.5c \) are presented in Fig. 5.24. As before, results are presented for the Baseline and serrated cases. As shown in the result of the TKE in the gap region (L1 and L2), for the large sawtooth serrated case, an upward shift can be found on the serration root-plane while a downward variation is observed on the serration tip-plane. For the sharp serrated case, the difference between the tip position and root position are less noticeable. Also, a significant reduction of the TKE magnitude can be observed in both two serration cases. Over the suction side of the rear aerofoil, between 0.25c (L5) to 0.65c (L7), a significant reduction of the TKE magnitude can be found from the results for both serration cases. The maximum TKE magnitude for the large sawtooth serrated case (upper row) is around 40% smaller than that of the Baseline case, while that for the sharp sawtooth serration case (lower row) is approximately 70% of the Baseline case. Results also show that the use of serrations results in a significant reduction of the width of the shear layer at downstream locations (L6 and L7).

The wake flow TKE results within the gap area and over the rear aerofoil for the case of \( W = 1.0c \) are presented in Fig. 5.25. As can be seen, within the gap region (lo-
cation: L1 and L2), the use of large sawtooth serration (upper row) leads to an upward and downward shift in the flow field over the tip- and root-planes, respectively. This is again in agreement with our earlier observations in Sections 5.2. Unlike the previous cases with smaller gap distances, in the case of the tandem aerofoil configuration with a large gap, the root- and tip-flow fields merge and form a more two-dimensional flow field in the downstream locations. Also, while a significant TKE reduction can be seen within the wake and just before the interaction with the leading-edge of the rear aerofoil, no noticeable changes are observed over the suction side of the rear aerofoil. One can finally also conclude from the results in this section that the use of the shear layer pattern from the flow-field results of an isolated aerofoil for placing the rear aerofoil has been relatively successful. Therefore, the same axial and vertical distances, as listed in Table 5.2 will be used for studies on the interaction of the wake flow from the front NACA65-710 aerofoil with the rear aerofoil and the unsteady aerodynamic loading exerted on the rear aerofoil. The unsteady aerodynamic loading results will be presented and discussed in the next section.
Figure 5.23: TKE results for tandem NACA 65-710 aerofoil configuration at $\alpha = 10^\circ$ and $W = 0.3c$ at freestream velocity of $U_0 = 30$ m/s. Black line: Baseline, red dashed line: serration root position, blue dash dotted line: serration tip position.
Figure 5.24: TKE results for tandem NACA 65-710 aerofoil configuration at \( \alpha = 10^\circ \) and \( W = 0.5c \) at freestream velocity of \( U_0 = 30 \text{ m/s} \). Black line: Baseline, red dashed line: serration root position, blue dash dotted line: serration tip position.
Figure 5.25: TKE results for tandem NACA 65-710 aerofoil configuration at $\alpha = 10^\circ$ and $W = 1.0c$ at freestream velocity of $U_0 = 30$ m/s. Black line: Baseline, red dashed line: serration root position, blue dash doted line: serration tip position.
5.5 Surface pressure fluctuations

As shown in the previous sections, the use of trailing-edge serration on the front aerofoil can lead to significant reduction of the turbulent kinetic energy in the aerofoil gap region and over the suction side of the rear aerofoil. As shown in the PIV contour plots and also the rms pressure distribution results, the flow separation over the suction side of the rear aerofoil is much larger than that over the pressure side. It can, therefore, be concluded that the main noise generation mechanism will be due to the turbulence interaction with the leading-edge area of the rear aerofoil and separated flow over the suction side of the aerofoil. Thus, in this section, we shall only concentrate on the aerodynamic performance exerted on the suction side of the rear aerofoil.

In order to further investigate the effectiveness of serration treatments for reducing aerodynamic loading and noise, surface pressure fluctuation measurements have been performed on the rear aerofoil using the remote sensing probe method, described in Chapter 2. Measurements have been carried out for the angles of attack $\alpha = 0^\circ, 5^\circ, 10^\circ$ and $15^\circ$, based on the wake TKE profiles observed in the previous section (see Figs. 5.4 to 5.11). In the tandem aerofoil configuration, the front aerofoil was fitted with Baseline and three different serrations. Three different gap distances between the two aerofoils have also been considered ($W = 0.3c, 0.5c$, and $1.0c$). Considering the effectiveness of the slotted-sawtooth serration for the reduction of the wake TKE at high angles of attack, results are only presented for this serration at $\alpha = 10^\circ$ and $15^\circ$. Results are presented for both the power spectral density (PSD) of the surface pressure fluctuations acting on the suction side of the rear aerofoil, at different chord-wise locations and the autocorrelation of the pressure signals collected at each location. While the surface pressure PSD can provide some useful information on the strength of the turbulent eddies passing over the rear aerofoil at different frequencies, the auto-correlation results can provide insight
into the life-span and the size of these turbulent structures. To avoid background noise contamination, due to the wind tunnel fan noise, a band-pass filter with a frequency range from 100 Hz to 5000 Hz has been applied to the signals collected by the surface pressure transducers. The autocorrelation results are obtained using Eq. 5.4.

\[
R_{p'_i p'_i}(\tau) = \frac{\overline{p'_i(x_i, t + \tau)p'_i(x_i, t)}}{p'_{i, rms}(x_i)},
\]

where \(p'\) is the surface pressure fluctuation obtained from the signal from pressure transducer, \(p'_{i, rms}\) is the root mean square of the pressure signal \(p'\), \(\tau\) represents the time delay between the pressure signals and the overbar denotes the time averaging.

Figures 5.26 and 5.27 show, respectively, the surface pressure PSD and pressure signal autocorrelation over the suction side of the rear aerofoil at different chordwise locations, with the gap distance of \(W = 0.3c\), at the angle of attack of \(\alpha = 10^\circ\). As mentioned earlier, the slotted-sawtooth serration is used for all discussions provided in this section. Results show that within the leading edge area \((x/c < 0.10)\), the use of the upstream serration leads to a considerable reduction of the pressure fluctuation energy experienced at low frequencies \((f_c/U_0 < 0.7)\). The use of serration also leads to an increase in the surface pressure PSD in the leading-edge area, though the high frequency part of the spectra, in general, experiences a sharp drop, and is not expected to contribute to the overall loading on the rear aerofoil. Further downstream, for the chordwise locations of \(x/c > 0.10\), the use of trailing-edge serration on the front aerofoil results in a significant reduction of the unsteady loading on the rear aerofoil over almost the whole frequency range of interest \(f_c/U_0 < 2\). The largest level of pressure PSD reduction (up to 8 dB) is observed within \(0.35 < x/c < 0.70\). This is also consistent with the TKE results observed in Fig. 5.23. Results also show that over these chordwise locations, the use of serra-
5.5. SURFACE PRESSURE FLUCTUATIONS

tions does not particularly change the high frequency part of the pressure spectra. The results observed here is of great interest as the noise radiated from the rear aerofoil is directly related to the unsteady pressure exerted on the aerofoil and the data here demonstrated that in the case of closely-placed tandem aerofoil configuration, the use of serration can significantly reduce the radiated noise. The pressure autocorrelation results in Fig. 5.27 also provide some interesting insight into the physics of the wake flow interacting with the rear aerofoil. Results show that the serration on the upstream aerofoil can slightly change the pressure autocorrelation results over the leading-edge area of the rear aerofoil \((x/c < 0.1)\). At further downstream \((x/c > 0.1)\), the serration does not seem to have any effect on the life-span of the turbulence structures. Also, results show that the signals detected at the leading-edge area \((x/c < 0.1)\), have a periodic nature with a Gaussian shape at \(\tau = 0\), due to the separated flow from the upstream aerofoil, while at the further downstream locations, the autocorrelation experiences a sharp exponential fall at \(\tau = 0\), followed by a less pronounced periodic behaviour at large \(\tau\), which can again be attributed to the flow circulation within the wake due to the flow separation from the front aerofoil. From the leading-edge data \((x/c < 0.10)\), one can also deduce that the recirculation time reduces slightly as a result of the use of serration on the front aerofoil. In general, despite the significant impact of the front aerofoil trailing-edge serration on the unsteady surface pressure PSD over the rear aerofoil, the serrations do not seem to greatly change the autocorrelation and therefore the life-span of the pressure signals.

The surface pressure PSD and autocorrelation results for the tandem aerofoil configuration with the separation gap of \(W = 0.5c\) are presented in Figs. 5.28 and 5.29. Unlike the \(W = 0.3c\) case, no pressure PSD reduction has been observed in the leading-edge area, but the pressure PSD is observed to reduce by 4 dB for the chordwise locations \(x/c > 0.10\). Maximum pressure PSD reduction is observed in the mid-chord region.
of $0.3 < x/c < 0.60$. Once again, although not as strong as in the case of small gap distance, results have shown that the use of trailing-edge serrations can change the overall unsteady pressure experienced by the rear aerofoil and therefore the unsteady lift and drag fluctuations of the aerofoil. The autocorrelation results show the same periodic behaviour with a Gaussian shape in the leading-edge area ($x/c < 0.10$) and a faster decaying exponential shape followed by a weaker periodic shape for the further downstream locations. The periodic nature of the pressure signal becomes stronger towards the trailing-edge of the rear aerofoil ($x/c > 0.50$), which can be attributed to the large flow separation on the rear aerofoil, as observed in the PIV contour plot in Fig. 5.20. As before, the use of an upstream aerofoil with serrated trailing-edge does not change the life-span of the flow structures interacting or travelling over the rear aerofoil.

The results for the tandem aerofoil configuration with a large separation distance of $W = 1.0c$ are presented in Figs. 5.30 and 5.31. Results show that the highest level of unsteady surface pressure exerted on the aerofoil occurs at around $x/c = 0.2$, both in case of Baseline and serrated tandem aerofoil configuration, which is consistent with the rms pressure results seen in Fig. 5.17. Results also clearly show that the use of serrations can lead to significant reductions in the unsteady surface pressure over the whole chord and the whole frequency range of interest. In particular, a pressure PSD reduction of up to 10 dB has been achieved within $0.15 < x/c < 0.5$, which has strong implications in terms of the aerofoil lift and drag fluctuations and radiated noise. The autocorrelation results show again the typical Gaussian behaviour near the leading-edge, an exponential decay in the mid-chord region, with a low-frequency periodic carrier wave pattern, which can be seen at all chordwise locations. As before, the periodic carrier wave pattern is strong in the vicinity of the leading-edge of the rear aerofoil, due to the wake flow from the front aerofoil and also near the trailing-edge of the rear aerofoil ($x/c > 0.5$), due to the large flow separation occurring over the suction side of the
aerofoil. Another interesting observation here is the autocorrelation result at $x/c = 0.35$, which shows a very sharp decay at $\tau = 0$, with almost zero correlation at larger time lags. The comparison of the autocorrelation data for the Baseline and serrated aerofoil cases shows again that the life-span and the size of the structure do not change significantly.

The surface pressure PSD and autocorrelation results at a stall angle of attack of $\alpha = 15^\circ$, and for different aerofoil gap distances of $W = 0.3c, 0.5c$ and $1.0c$ are presented in Figs. 5.32 to 5.37. Figures 5.32 and 5.33 show the results for the tandem aerofoil configuration with the smallest gap distance ($W = 0.3c$). The surface pressure PSD results show that the use of slotted-sawtooth serration on the front aerofoil can result in significant reduction of the experienced unsteady pressure on the rear aerofoil. A reduction of above 10 dB can be observed over the front part of the aerofoil ($x/c < 0.4$). A pair of tonal peaks can be seen at about $f_c/U_0 = 0.2$ and 0.4 in the leading-edge area ($x/c < 0.1$), which are due to the vortex shedding from the front aerofoil. Results also show that the implementation of the serration on the front aerofoil is more effective in reducing the broadband energy content of the wake structures than the tonal peaks. This, of course, makes sense as the vortex shedding from the upstream aerofoil originates from leading-edge separation and the trailing-edge treatment on the aerofoil cannot bring about any significant changes to the large flow structures within the leading-edge separated flow, as observed previously in Chapter 4. The pressure PSD spectra become more tonal in the trailing-edge region ($x/c > 0.6$), which is due to the large flow separation over the rear aerofoil, as seen in the PIV results in Fig. 5.10. The tonal peak occurs at about $f_c/U_0 = 0.23$, which corresponds to the vortex shedding frequency [1, 6, 7]. The autocorrelation results in the case of tandem aerofoil at $\alpha = 15^\circ$ are somehow different from those at $\alpha = 10^\circ$. A strong periodic carrier wave can be seen at all chord-wise locations which corresponds to the vortex shedding from either the front aerofoil (at small $x/c$) or the vortex shedding over the suction side of the rear aerofoil (at large $x/c$). Unlike the
\( \alpha = 10^\circ \) results, here the autocorrelations sharp exponential-type decay at around \( \tau = 0 \) in the leading-edge area and then a more Gaussian shape at the further downstream chord-wise locations. The level of correlation is also observed to increase with \( x/c \), which can be attributed to the large flow separation over the suction side of the rear aerofoil. The use of a serrated front aerofoil, however, does not seem to cause significant changes to the autocorrelation of the pressure signals collected over the suction side of the rear aerofoil in this configuration.

The results for the gap distance of \( W = 0.5c \) are presented in Figs. 5.34 and 5.35. Results have again shown that the use of upstream serrated aerofoil can lead to 5 – 8 dB reduction in the pressure PSD over the chordwise locations of \( x/c < 0.3 \). The level of pressure PSD reduction is observed to reduce with \( x/c \). The use of an upstream serrated aerofoil does not seem to have a significant effect on the pressure PSD near the trailing-edge of the rear aerofoil, but it also does not increase the pressure PSD at any locations or frequency ranges. The vortex shedding peaks observed previously in the case of \( W = 0.3c \) can again be seen here. The pressure PSD for the locations in the vicinity of the trailing-edge of the rear aerofoil (\( x/c > 0.65 \)) show a distinct peak at \( f c/U_0 = 0.2 \), which corresponds to the vortex shedding, and a sharp roll off at high frequencies. The autocorrelation results in the case of a tandem aerofoil configuration at stall do not show any particular changes to the life-span of the turbulence structures interacting with the leading-edge of the rear aerofoil or those travelling over the suction side of the aerofoil.

Finally, Figs. 5.36 and 5.37 present the pressure PSD and autocorrelation results for a tandem aerofoil configuration with a large gap distance of \( W = 1.0c \), with the aerofoils set a stall angle of \( \alpha = 15^\circ \). As discussed previously in Section 5.2, the effect of serration on the wake TKE diminishes gradually in the far downstream locations. The PSD results in Fig. 5.36 show that the use of a serrated front aerofoil, located
1.0c upstream of the rear aerofoil, has an only limited effect on the unsteady pressure exerted on the leading-edge area of the aerofoil. Results show that the serrations can reduce the pressure PSD by about 3 dB in the leading-edge area \((x/c < 0.1)\), but have a negligible effect further downstream \((x/c > 0.1)\). The autocorrelation results, on the other hand, show a very different behaviour to that observed previously. In the leading-edge area \((x/c < 0.1)\), the Baseline and serrated cases have a very similar Gaussian-shape decay, with a periodic pattern, due to the fully separated flow originating from the front aerofoil. Further downstream \((0.1 < x/c < 0.5)\), the pressure signals for the serrated cases show a sharp exponential decay at \(\tau = 0\), with small correlation at larger time lags, while for the Baseline case, the autocorrelation retains its Gaussian-shape. The level of correlation increases gradually with \(x/c\), which can again be attributed to the large flow separation over the aerofoil.
Figure 5.26: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 10^\circ$, $W = 0.3 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.27: Surface pressure fluctuation auto-correlation for locations on the rear aerofoil in tandem configuration at $\alpha = 10^\circ$, $W = 0.3 \ c$ and $U_0 = 30 \text{ m/s}$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.28: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 10^\circ$, $W = 0.5\ c$ and $U_0 = 30\ m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
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Figure 5.29: Surface pressure fluctuation auto-correlation result for locations on the rear aerofoil in tandem configuration at $\alpha = 10^\circ$, $W = 0.5 \ c$ and $U_0 = 30 \ m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.30: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 10^\circ$, $W = 1.0 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.31: Surface pressure fluctuation auto-correlation result for locations on the rear aerofoil in tandem configuration at $\alpha = 10^{\circ}$, $W = 1.0 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.32: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 0.3 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position
Figure 5.33: Surface pressure fluctuation auto-correlation result for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 0.3 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.34: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 0.5 \, c$ and $U_0 = 30 \, \text{m/s}$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.35: Surface pressure fluctuation auto-correlation result for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 0.5 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
Figure 5.36: Surface pressure fluctuation PSD for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 1.0 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position
Figure 5.37: Surface pressure fluctuation auto-correlation result for locations on the rear aerofoil in tandem configuration at $\alpha = 15^\circ$, $W = 1.0 \, c$ and $U_0 = 30 \, m/s$. Black line: Baseline, blue line: serration tip position, red line: serration root position.
In the engineering applications involving a pair or cascade of aerofoils, such as contra-rotating blades, rotor-stator systems, etc, the rear blades are subject to interaction with a periodic wake flow field from the front aerofoil. In our fixed tandem aerofoil configuration, this is equivalent to having the rear blade placed at different vertical locations relative to the wake of the front aerofoil. In the results presented up to now, the rear aerofoil was placed at the centre of the wake, where maximum turbulence and leading-edge interaction is expected to occur. In this part, the rear aerofoil was moved in the vertical direction, above and below the wake centre to study the effectiveness of using trailing-edge serration on the front aerofoil for reducing the unsteady aerodynamic force acting on the rear aerofoil (see Table: 5.1). The same tandem aerofoil configuration, set at angles of attack of $\alpha = 10^\circ$ and $15^\circ$, with the aerofoil gap distances of $W = 0.5c$ and $1.0c$, at the freestream flow speed of $U_0 = 30$ m/s is studied. Results are only presented for the slotted-sawtooth serration case. The surface pressure PSD on the suction side of the rear aerofoil for all four cases studied here are presented in Figs. 5.38 to 5.40. Each row shows the surface pressure PSD results at a different vertical distance ($l$) from the wake centre for different chordwise locations over the rear aerofoil. The middle row is always the case when the rear aerofoil is placed at the centre of the wake, as explained in the previous sections. The results, in general, follow the same trends observed in the previous sections. The most important observation here is that the use of an upstream aerofoil fitted with slotted-sawtooth serration always leads to the reduction of the surface pressure fluctuations acting on the surface of the rear aerofoil. From the cases studied here, no significant increase in the exerted unsteady aerodynamic loading have been observed. It can therefore be concluded that the use of trailing-edge serrations on the front aerofoil can lead to the reduction of the turbulent kinetic energy within the gap area, reduction of the unsteady surface pressure fluctuations on the rear aerofoil, which subsequently leads to the reduction of the unsteady aerodynamic loading acting.
on the rear aerofoil and the suppression of the aerodynamic noise from the rear aerofoil.
Figure 5.38: Surface pressure fluctuation results at selected locations on rear aerofoil from tandem NACA 65-710 aerofoils at \( \alpha = 10^\circ \), \( W = 0.5 \, c \) and \( U_0 = 30 \, \text{m/s} \) with front aerofoil fitted with a slotted-sawtooth serration (\( \lambda = 9 \, \text{mm}, \, H = 15 \, \text{mm} \)). Black line: Baseline, blue line: serration tip position, red line: serration root position.
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Figure 5.39: Surface pressure fluctuation results at selected locations on rear aerofoil from tandem NACA 65-710 aerofoils at $\alpha = 10^\circ$, $W = 1.0 \, c$ and $U_0 = 30 \, m/s$ with front aerofoil fitted with a slotted-sawtooth serration ($\lambda = 9 \, mm$, $H = 15 \, mm$). Black line: Baseline, blue line: serration tip position, red line: serration root position

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Figure 5.40: Surface pressure fluctuation results at selected locations on rear aerofoil from tandem NACA 65-710 aerofoils at $\alpha = 15^\circ$, and $U_0 = 30$ m/s with front aerofoil fitted with a slotted-sawtooth serration ($\lambda = 9$ mm, $H = 15$ mm). Black line: Baseline, blue line: serration tip position, red line: serration root position.
5.6 Summary

The aerodynamic characteristics of an isolated NACA 65-710 aerofoil and a pair of NACA 65-710 aerofoils in tandem configurations were studied experimentally. The application of trailing-edge serration treatments as a method to control the wake development and hence the noise generation from the interaction of the wake turbulence with the rear aerofoil in the tandem configuration was also studied. Results of the wake velocity profiles and the wake TKE profiles shown that for an isolated NACA 65-710 aerofoil, the use of trailing-edge serrations can lead to clear reduction of the energy content of the wake flow, especially in the case of sharp sawtooth serration ($\lambda = 9$ mm) and slotted-sawtooth serration ($\lambda = 9$ mm, $H = 15$ mm) at a high angle of attack ($\alpha = 10^\circ$).

In the case of tandem aerofoil configuration, significant reduction of the rms pressure coefficient $C_{p_{rms}}$ over the leading-edge region of the rear aerofoil also can be found when the front aerofoil is treated with trailing-edge serration. The wake topology of the tandem aerofoils configurations using the PIV technique also shows a significantly reduction of TKE value within the gap between the two aerofoils by using the trailing-edge serrations on the front aerofoil. Furthermore, the size of high TKE region in the leading-edge region of the suction side of the rear aerofoil for serrated cases show a significant reduction when compared to the Baseline case. The surface pressure PSD and autocorrelation results, collected over the rear aerofoil, been presented for the tandem aerofoil configuration at high angles of attack and different gap distance. Results have generally shown that the use of trailing-edge serration on the front aerofoil lead to clear reduction of the surface pressure PSD over the leading-edge area of the aerofoil and changes to the autocorrelation results of the pressure data, which indicates changes to the life-span and size of the structures passing over and interacting with the rear aerofoil.
For higher angle of attack $\alpha = 15^\circ$, the surface pressure PSD results show that the use of slotted-sawtooth serration on the front aerofoil can result in significant reduction of the experienced unsteady pressure on the rear aerofoil for the cases with the separation gap of $W = 0.3c$ and $0.5c$. Results also show that the use of the trailing-edge serrations can reduce the broadband energy content of the wake structures more effectively. The autocorrelation results of the pressure signals show that the use of a serrated front aerofoil, does not seem to cause significant changes in these configurations. For larger separation gap distance $W = 1.0c$, the PSD results show that the use of a serrated front aerofoil has an only limited effect on the rear aerofoil. The autocorrelation results, the Baseline case show a very similar behaviour to that of the serrated case at very leading-edge region. However, for further downstream, the comparison of the autocorrelation data for the Baseline and serrated aerofoil cases shows a significant reduction of the amplitude of the unsteady pressure experienced by the rear aerofoil, the life-span and the size of the structure do not change significantly.


6.1 Conclusion

A comprehensive experimental study has been carried out for the aerodynamic performance and wake development of aerofoils fitted with trailing-edge serrations. A symmetric NACA 0012 and cambered NACA 65(12)-10 were used in this study. The aerodynamic force and flow visualization results have been provided for a wide range of angles of attack.

Results have revealed the complexity of the flow field around the trailing-edge serrations and that the aerodynamic performance of the aerofoil and its wake behaviour can significantly alter, depending on the type of the aerofoil and serration used. Even though the $C_L - \alpha$ (i.e. lift coefficient vs angle of attack) curve trend is not affected by the serrations, results have shown that the use of serration changes the lift coefficient and the post stall characteristics of the aerofoil, particularly for cambered aerofoils. Surface flow visualization results for both the symmetric and cambered aerofoils clearly illustrated
the transition and re-attachment locations on the suction surface for a wide range of angles of attack.

The flow field results around the serration and within the wake region show that the serrations significantly affect the development of the wake deficit and its dip locations in the case of cambered aerofoils. Compared to the Baseline case the velocity profiles vary notably between the tip and root locations that would induce strong shear stress between the tip and root flow planes. The wake deficit dip location shows an upward shift in the wake profiles at the root locations relative to both the baseline case with straight trailing-edge and the tip locations. This indicates that the flow originating from the pressure surface passes has been deflected upward through the serration valleys. Similarly, the wake for the root locations are turning upward compared to that of the Baseline and serration tip locations. The flow structure in the vicinity of the serrations at high angles of attack shows two steady contra-rotating vortices for both the aerofoils. Results have shown that the large vortex, due to the early separation of the flow on the suction surface, is displaced upwards and weakened by a secondary smaller periodic vortex originating from the flow passing through the serration valleys. The possibility of the flow moving from the pressure side to the suction side of the aerofoil around the serrations and through the serration valleys gives rise to the emergence of contra-rotating streamwise structures on the serrations and some horseshoe vortices convecting away from the aerofoil serrations. The generation of horseshoe vortices from the serrations results in region of concentrated in the near wake after each serration tooth. As such the flow field over the serration and near-wake is predominantly three-dimensional with strong vortices present in both the spanwise and streamwise directions. This three-dimensionality and rich vortex structures influence the turbulent energy decay within the wake region by increasing the flow mixing and reduce the turbulence level significantly as compared with the straight trailing-edge case.
6.1. CONCLUSION

As shown from the single aerofoil study that the use of serrations can lead to considerable reduction in the velocity power spectrum along the mean camber-line at all angles of attack, particularly at high angles, where maximum aerodynamic performance is obtained. Even more, the possibility of reducing the turbulence level using serrations poses a very interesting observation, particularly in the context of noise generated by wake-aerofoil interaction, such as contra-rotating propellers, rotor-stator configuration, etc. Subsequently, the application of serration treatments from tandem aerofoil configuration as a method to control the wake development and hence the noise generation and radiation have been studied experimentally.

As expected, results of the flow analysis for an isolated NACA 65-710 aerofoil have shown that the mean velocity and the energy content of the wake flow can be reduced using trailing-edge serrations, especially at a high angles of attack ($\alpha = 10^\circ$ and $15^\circ$). In the case of a tandem aerofoil configuration, the use of trailing-edge serration on the front aerofoil can lead to significant reduction of the fluctuations of surface pressure coefficient $C_{p_{rms}}$ in the proximity of the leading-edge of the rear aerofoil, on the pressure side, and the entire suction side. The PIV wake topology results for the tandem aerofoil configuration show that the introduction of the serrations can significantly reduce the TKE level within the gap between the two aerofoils. The TKE wake profile results also show that in the leading-edge region of the suction side of the rear aerofoil, size of the elevated TKE region for serrated cases are smaller than that of the Baseline case. The use of serration on the front aerofoil also show a clear TKE reduction in the middle to further downstream region of the suction side of the rear aerofoil.

Considering the effectiveness of the trailing-edge sawtooth serration for the reduction of the wake TKE at high angles of attack ($\alpha = 10^\circ$ and $15^\circ$), the effect of wake flow interaction with a second aerofoil was studies by presenting the unsteady surface pres-
sure fluctuations over the rear aerofoil. The surface pressure power spectral density (PSD) and the autocorrelation of the pressure signals collected at each location on the rear aerofoil were investigated. The results for the angle of attack of $\alpha = 10^\circ$ show that the use of serrations on the front aerofoil can significantly reduce the unsteady surface pressure, up to 10 dB, especially for the tandem aerofoil configuration with a large separation distance ($W = 1.0c$). The pressure PSD and autocorrelation data for the Baseline and serrated aerofoil cases also show a significant reduction in the amplitude of the unsteady pressure experienced by the rear aerofoil, whereas interestingly the life-span and the size of the structure do not change significantly. At a higher angle of attack of $\alpha = 15^\circ$, strong pressure PSD reduction of up to 8 dB has been observed. However, the use of serrations does not seem to cause significant changes to the autocorrelation of the pressure signals collected over the suction side of the rear aerofoil in the results for separation distance ($W = 0.3c$ and $0.5c$). For larger separation distance, $W = 1.0c$, the comparison of the autocorrelation data for serrated and the Baseline cases show significant reduction of the amplitude of the unsteady pressure experienced by the rear aerofoil, the life-span and the size of the structure do not change significantly. The level of correlation increases gradually with $x/c$ over the aerofoil region $0.1 < x/c < 0.5$.

### 6.2 Future work

The results in this thesis showed that trailing-edge serration can lead to significant reduction of the energy content of the wake flow structures, particularly at high angles of attack, where maximum aerodynamic performance is achieved. The results also showed that the use of this technology in tandem aerofoil configuration can lead to significant reduction of the unsteady pressure fluctuations on a rear aerofoil. While the results in this thesis showed the great potential of trailing-edge serration in different sceneries, some issues remain outstanding and require further research. Here is a short list of
topics that warrant further investigations:

(a) the serrations observed to increase the mixing effects in the wake, which eventually leads to the reduction of the wake flow energy content. The underlying physics of this phenomenon is, however, unknown at large. Further experiments, including 3D PIV, is required to unravel the mechanisms leading to the reduction of the TKE within the wake domain.

(b) While the use of serrations on aerofoils at high angles of attack does not have a great acoustic benefit, the results here have shown that in tandem aerofoil configurations, it can significantly reduce the unsteady pressure fluctuations on an rear object. Far-field noise measurements are required to quantify the noise reduction capabilities of the technique.

(c) The results presented here can also be used as a benchmark for high-fidelity CFD (DES, LES) simulations. CFD results can help better understand the wake flow development in the case of aerofoils fitted with trailing-edge serrations at high angles of attack. The serration root flow has been observed to play an important role in the reduction of the energy content of the wake flow structures. High quality CFD simulations can help better understand the underlying physics of such phenomena observed in this thesis.
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