# TRAILING-EDGE NOISE ATTENUATION OF AIRFOIL BY MEANS OF COMB-SERRATION AT LOW REYNOLDS NUMBERS

BY

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# ABSTRACT

Low Reynolds number flow is three-dimensional and intricate due to multiple vortical phenomena. This research contributes by investigating the impact of laminar Separation Bubble (LSB) on noise generated by passive control techniques. It also enhances the understanding of the efficiency of various trailing edge designs such as serrations, comb, comb-serrated, and porous configurations, across different flow conditions and Reynolds numbers, while also addressing the limitations of existing geometrical models for trailing edges. The study intends to examine the performance of different configurations, emphasizing their effect on flow structure and acoustic responses. The methodology of this study encompasses a combination of techniques that includes conducting 2D simulations using the SST model, performing 3D simulations using large eddy simulation, employing FW-H acoustic modeling, and utilizing an experimental PIV setup. These methods collectively provide a comprehensive and robust platform for in-depth exploration of the research objectives. The analysis of the NACA0015 airfoil's flow characteristics revealed the presence of laminar separation bubbles (LSBs) at low Reynolds numbers and angles of attack. Two types of flow patterns, with and without reattachment, were identified. On the suction side, Increasing the Angle of attack leads to a noticeable upstream shift of these points, while they move downstream along the pressure side. In 3D simulations, pressure distribution was symmetrical, with the maximum at the leading edge. No separation was observed except at the trailing edge tip. At higher angles of attack, the baseline airfoil experienced flow disturbances, laminar separation bubbles, and vortex shedding. The serrated, combed, and comb-serrated designs exhibited more stable flow patterns and fewer separation bubbles than the baseline, potentially reducing tonal noise. Conversely, the poro-serrated design led to distorted flow and an upstream-moving separation bubble, suggesting a possible increase in tonal noise. Moreover, results showed irregular broadband noise (300 - 600 Hz) with increased noise and shifting peak frequency as the Angle of attack rose. The serrated trailing edge design notably reduced noise levels by roughly 21 dB, especially for low frequencies. Comb-serration increased high-frequency noise by about 9 dB for angles of attack at 0, -1, and -2 degrees reduced approximately 9 dB for angles of attack at 1 degree and 2 degrees. On the other hand, the directivity pattern showed that the maximum noise level is observed to predominantly radiate at an azimuth angle of around 90 degrees for all the cases, ranging from 90 to 270 degrees, indicating that the majority of the source's acoustic energy is being emitted on the suction and pressure sides of the wing. In conclusion, the findings demonstrate that serrated and comb-serrated designs are beneficial in reducing noise levels, and that the Angle of attack can significantly impact both the noise level and directivity pattern.

# خلاصة البحث

تدفق أرقام رينولدز المنخفض ثلاثي الأبعاد معقد للغاية بطبيعته لتعدد أنواع الظواهر الدوامة. يساهم هذا البحث من خلال دراسة تأثير فقاعة الفصل الصفائحي (LSB) على الضوضاء الناتجة عن تقنيات التحكم السلبي. كما يحسن فهم كفاءة تصميمات الحواف الخلفية المختلفة مثل المسننات، والمشط، والمشط المسنن، والتكوينات المسامية، عبر مختلف حالات التدفق وأرقام رينولدز، مع معالجة القصور في النماذج الهندسية الموجودة للحواف الخلفية. الدراسة تهدف إلى فحص أداء تكوينات مختلفة، مع التركيز على تأثيرها على بنية التدفق والاستجابات الصوتية. منهجية الدراسة تشمل مزيجا من التقنيات، تتضمن إجراء عمليات محاكاة ثنائية الأبعاد باستخدام نموذج SST و عمليات محاكاة ثلاثية الأبعاد باستخدام LES، واستخدام نموذج صوتي FW-H وإعدادات PIV التجريبي. هذه الأساليب مجتمعة توفر منصة شاملة وقوية للاستكشاف المتعمق لأهداف البحث. كشف تحليل خصائص تدفق الجنيح NACA0015 عن وجود فقاعات الفصل الصفائحي (LSBs) عند أعداد رينولدز المنخفضة وزوايا الهجوم. تم تحديد نوعين من أنماط التدفق، مع وبدون إعادة الارتباط. من جهة الشفط، تؤدي زيادة زاوية الهجوم إلى تحول ملحوظ في الإتجاه الصعودي لهذه النقاط نحو المنبع، بينما تتحرك باتجاه نزولي على طول جانب الضغط. في عمليات المحاكاة ثلاثية الأبعاد، كان توزيع الضغط متماثلًا، مع حد أقصى عند الحافة الأمامية. لم يلاحظ أي انفصال إلا عند طرف الحافة الخلفية. عند زوايا الهجوم الأعلى، تعرض الجنيح الأساسي لاضطرابات التدفق، وفقاعات الفصل الصفائحي، وتساقط الدوامة. أظهرت التصميمات المسننة والمشطية والمسننة أنماط تدفق أكثر استقرارًا وفقاعات فصل أقل مقارنة بالأساس، مما يؤدي إلى تقليل الضوضاء النغمية. على العكس من ذلك، أدى التصميم المسنن المسامي إلى تدفق مشوه وفقاعة فصل تتحرك في اتجاه صعودي، مما يشير إلى زيادة محتملة في الضوضاء النغمي. علاوة على ذلك، أظهرت النتائج عدم انتظام ضوضاء النطاق العريض (300 – 600 هرتز) مع زيادة الضوضاء وتغير تردد الذروة كلما ارتفعت زاوية الهجوم. أدى تصميم الحافة الخلفية المسننة إلى تقليل مستويات الضوضاء بشكل ملحوظ بحوالي 21 ديسيبل، خاصة بالنسبة للترددات المنخفضة. أدى المشط المسنن إلى زيادة الضوضاء عالية التردد بنحو 9 ديسيبل لزوايا الهجوم عند درجات 0 و1 و2-، كما حقق انخفاضًا بنحو 9 ديسيبل لزوايا الهجوم عند درجة ودرجتين. من ناحية أخرى، أظهر نمط الاتجاه أن مستوى الضوضاء الأقصى يشع في الغالب بزاوية سمت تبلغ حوالي 90 درجة لجميع الحالات، وتتراوح من 90 إلى 270 درجة، مما يشير إلى أن غالبية مصدر الطاقة الصوتية للمصدر تنبعث على جانبي الشفط والضغط للجناح. في الختام، أظهرت النتائج أن التصميمات المسننة والمشطية مفيدة في تقليل مستويات الضوضاء، خاصة عند زوايا الهجوم العالية، وأن زاوية الهجوم يمكن أن يكون لها تأثير كبير على كل من مستوى الضوضاء ونمط الاتجاه.

# APPROVAL PAGE

The thesis of Mohamed Ibren Hassan has been approved by the following:

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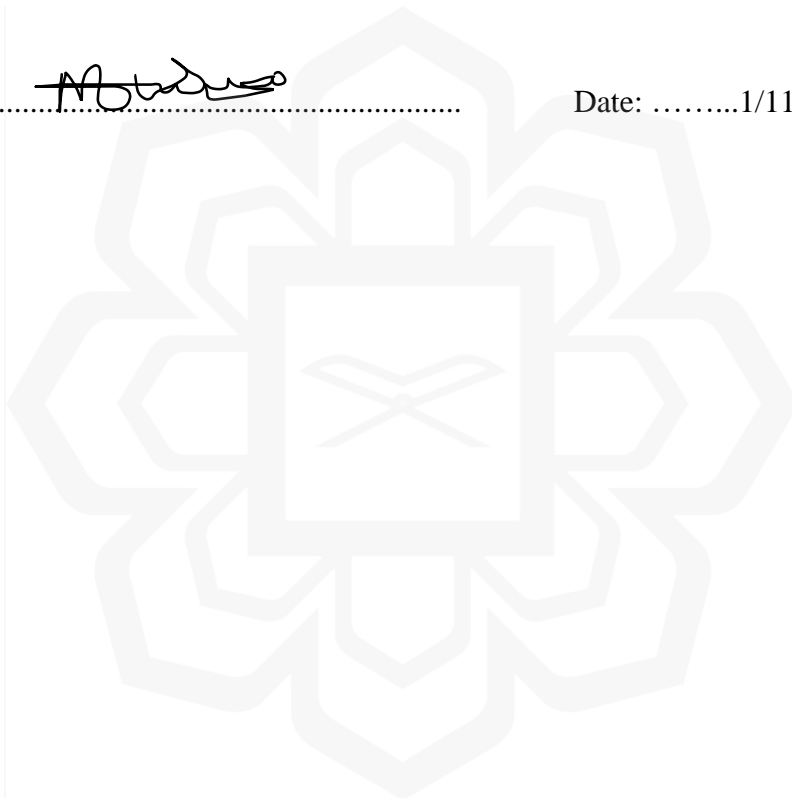External Examiner

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# DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mohamed Ibren Hassan

Signature ................................................................ Date: ……...1/11/2023…......

# ACKNOWLEDGEMENTS

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# LIST OF SYMBOLS

c        Chord Length

$C_d$       Drag Coefficient

$C_f$       Skin Friction Coefficient

$C_l$       Lift Coefficient

$C_p$       Pressure Coefficient

E        Porosity

$f_n$       Centre frequency of the broadband noise

$f_s$       Series of Secondary Tone

2h       Height of the sawtooth part

$l$        Extent of the porous region

$P'$       Normalized Pressure Fluctuation

$\Delta t$       Interval Time

U        Free-Stream Velocity

V        Normal Velocity

$\omega_z$       Spanwise Vorticity

$\Delta x$       Displacement

$\alpha$       Angle of attack

$\alpha_s$       Angle of ridges with respect to the flow direction

$\lambda$       Wavelength of the ridges

# LIST OF ABBREVIATIONS

| 2D | Two-Dimensional |
|---|---|
| 3D | Three-Dimensional |
| AOA | Angle of attack |
| BL | Boundary Layer |
| CAA | Computational Aeroacoustics |
| Cd | Drag Coefficient |
| CFD | Computational Fluid Dynamic |
| Cl | Lift Coefficient |
| DNS | Direct Numerical Simulation |
| dB | Decibels |
| FW − H | Ffowcs Williams–Hawkings |
| HLFC | Hybrid Laminar Flow Control |
| LBL | Laminar Boundary Layer |
| LE | Leading-Edge |
| LES | Large Eddy Simulation |
| LFC | Laminar Flow Control |
| LSB | Laminar Separation Bubble |
| MAVs | Micro Air Vehicles |
| MBT | Micro-Blowing Technology |
| NLF | Natural Laminar Flow |
| PTU | Programmable Timing Unit |
| PIV | Particle Image Velocimetry |

| | |
|---|---|
| RANS | Reynolds-Averaged Navier-Stokes |
| Re | Reynolds Number |
| SA | Spalart-Allmaras Turbulence Model |
| SGS | Subgrid-Scale |
| SPL | Sound Pressure Level |
| $SPL_{1/3}$ | Third Octave Sound Pressure Level |
| SST | Shear-Stress Transport |
| TS − WAVE | Tollmien–Schlichting wave |
| TE | Trailing-Edge |
| URANS | Unsteady Reynolds-Averaged Navier-Stokes |
| UAVs | Unmanned Aerial Vehicles |
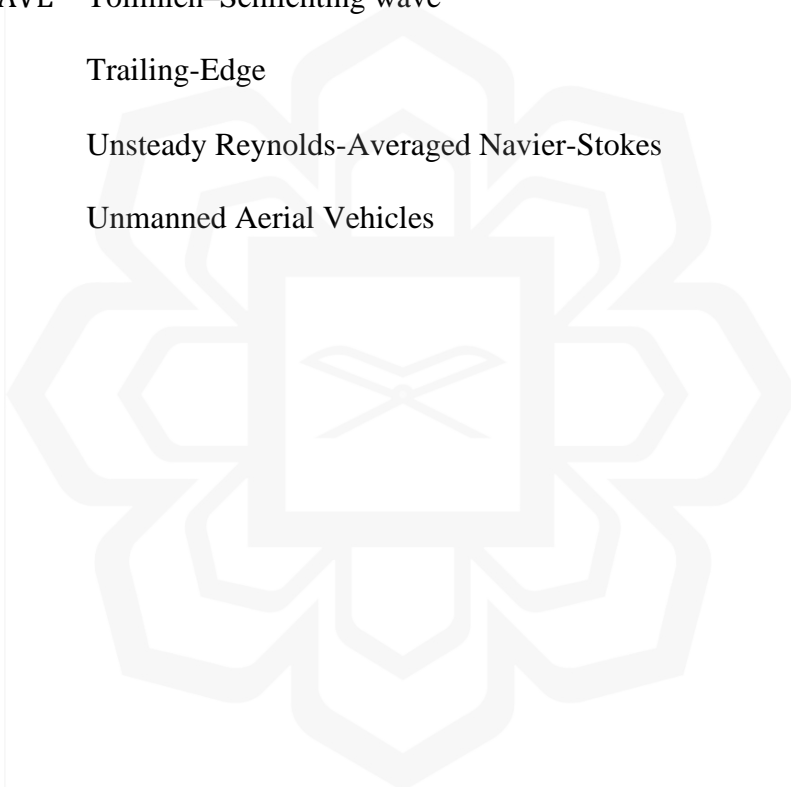
# CHAPTER ONE

# INTRODUCTION

## 1.1. OVERVIEW

The introduction chapter of this thesis includes a complete review of the study background, problem statement, research philosophy, scope, limitations, and objectives. This chapter commences with an overview of the introduction to the topic under consideration, followed by a concise description of the research problem and the reasoning for the suggested solution based on the philosophical approach of the study. The scope of the research is clearly defined, with a special focus on addressing the problem statement. The research objectives are then provided in a systematic and ordered way, offering a roadmap for the completion of the study. Finally, the chapter concludes with the outline of the thesis, offering a comprehensive summary of the organization and content of the research.

## 1.2. BACKGROUND OF THE STUDY

Noise pollution is a continuous issue that substantially influences the environment and the well-being of humans. Loud and undesired noises can induce disruption and stress and might be regarded as a severe environmental stressor. Research has found that airfoils operating within low to moderate Reynolds numbers ($R_e = 10^4 - 10^5$) are known to emit a unique sort of noise known as whistle-like tonal noise. This form of noise adds to the total environmental noise and is viewed as discomforting by people exposed to it (Wagner et al., 2007). Tonal noise may be experienced in several of circumstances, such as on blunt models and airfoil-like designs, buildings, fans, wind turbines, unmanned aerial vehicles (UAVs), and more. Given the widespread prevalence and effect of tone noise, it is vital to know the underlying mechanisms and situations that create it. This information may be utilized to design effective methods for limiting its impact and decreasing the related environmental and health hazards. Furthermore, understanding the behaviour of tonal noise can lead to the development of

new technology and ways to decrease noise pollution, increase human quality of life, and safeguard the environment.

Schumacher et al. (2014) first described the generation of discrete tonal noise from airfoil surfaces operating at relatively moderate Reynolds numbers (Schumacher et al. 2014). The tonal noise is a composition of broadband noise focused on a single frequency, and discrete tonal noise. The occurrence of tonal noise is influenced by the thickness of the Trailig-edge (TE) and the Boundary Layer (BL) displacement thickness, as evidenced by Ramirez and Wolf (Ramírez & Wolf, 2016). The noise generation can also be affected by various geometric factors, such as thickness, chord, profile, and Angle of attack. Other factors such as spanwise curvature and surface roughness also play a role but are subject to strict engineering constraints. Paterson et al. (1973) reported the presence of discrete and numerous tones in a ladder-like structural pattern, which is dependent on the frequency and free-stream velocity. Tonal noise with high intensity is often regarded as more disturbing than broadband noise. Arbey & Bataille (1983) ascribed the broadband contribution to the diffraction of pressure waves near the TE. The discrete frequencies are made of a primary frequency tone with the maximum intensity, and its respective secondary frequency tones are uniformly spaced, as indicated in Figure 1.1.
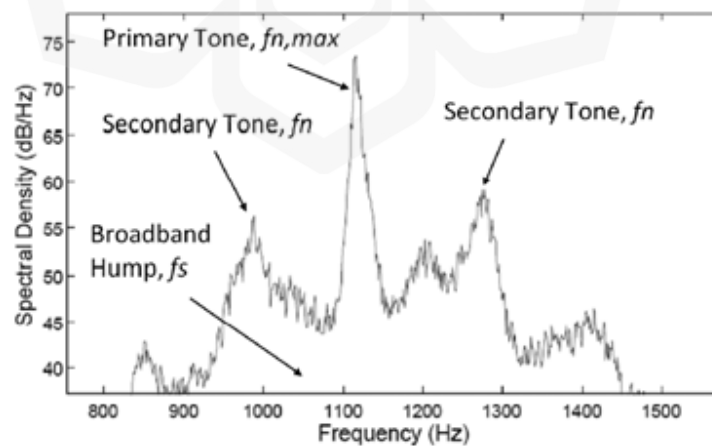


Figure 1.1 An example of noise spectra of an airfoil discrete tonal noise
(Arcondoulis et al., 2005)

The aviation industry has made tremendous progress in lowering the noise created by aircraft airfoils and helicopter blades via acoustically adapted materials and design improvements. Efforts to regulate fluid flow have led to the suggestion of strategies such as Laminar Flow Control (LFC), Natural Laminar Flow (NLF), and Hybrid Laminar Flow Control (HLFC) (Joslin, 1998). However, the practical implementation of NLF is hindered by its association with substantial pressure drag. Milestones have been made in the knowledge of flow physics, acoustic wave scattering, and noise propagation, leading to the introduction of various trailing-edge noise-reducing technologies (Joslin, 1998). These techniques are categorized into passive and active control approaches, with the former aiming to improve scattering conditions by altering physical and geometrical features of the TE and the latter acting on changing the flow structure through unsteady pressure fluctuations upstream of the trailing edge. Recently, numerous passive control approaches have been proposed and investigated, including using serrations, porous materials, finlets, surface treatments, shape optimization, morphing, and flexible materials. These strategies seek to increase aerodynamic performance while minimizing noise produced at the TE (Tze et al., 2016).

The study of silent flight in birds, notably the owl, has been a topic of continuous research in of aerodynamics. Figure 1.2 highlights the distinctive feather characteristics of the owl, which play a significant role in decreasing noise and contributing to the owl's reputation as the quietest flying bird. This has prompted contemporary research attempts to study the processes behind the owl's ability to fly so softly and to apply these results to numerous sectors, such as aviation. The attention to the owl's feather characteristics underlines the value of learning from nature and transferring these lessons into human technology. By acquiring a greater knowledge of the owl's quiet flight, researchers want to create more effective and efficient noise reduction solutions for many applications. This study primarily focuses on applying poro-serrated, serrated, combed, and comb-serrated trailing-edge designs to optimize the flow structure and minimize noise generation at the TE, as shown in Figure 3.4 – 3.12.
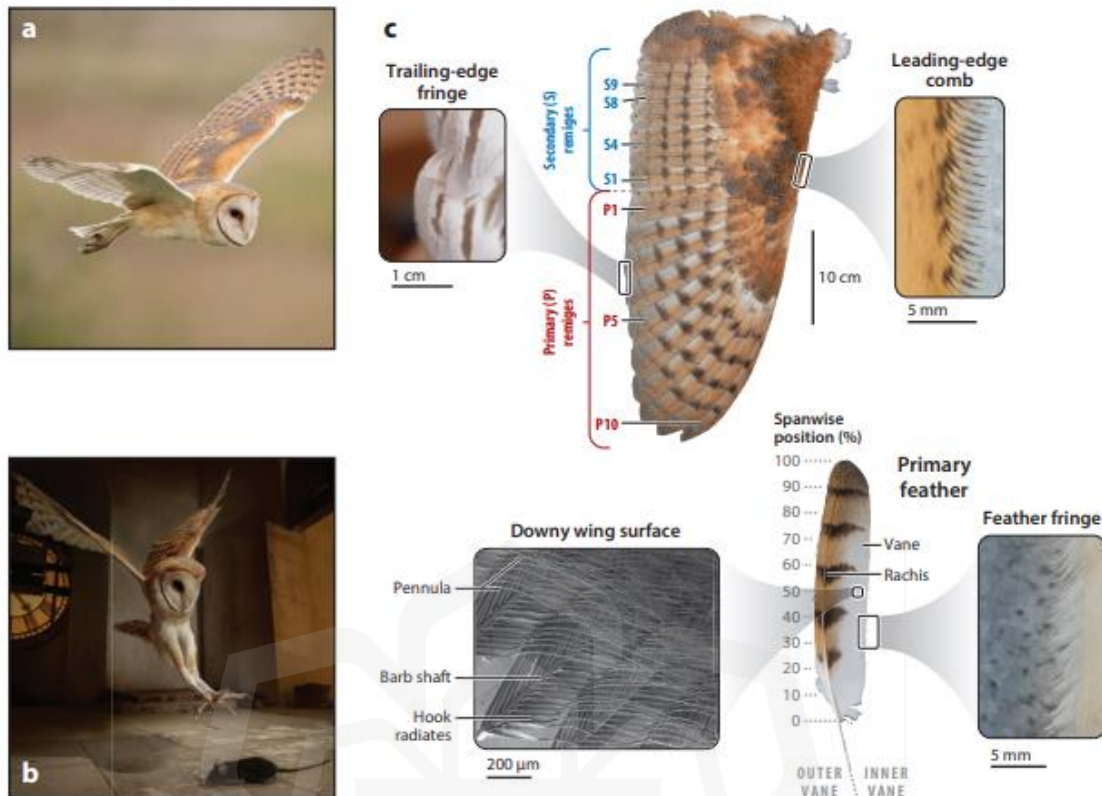
Figure 1.2 The Unique Feather Features of the Owl, Key to Its Silent Flight
(Jaworski & Peake, 2020).

## 1.3. STATEMENT OF THE PROBLEM

Aircraft noise has become a critical concern since the 1970s as the number of airports and commercial aircraft has increased. The adverse effects of aeroplane noise on human health have necessitated stricter regulations in the aviation sector. Although great progress has been achieved in decreasing jet engine noise, experts have advocated for more investigations into reducing noise from other aircraft elements. Various experimental, computational, and theoretical studies have focused on minimizing trailing-edge noise, with serrations being regarded as one of the most successful methods based on bio-inspired research. However, the efficiency of serrations, comb, and porous trailing edge is still not well understood. It is reliant on flow topology, and most experiments have been undertaken at low Reynolds numbers ($R_e \approx 10^4$). Furthermore, the collective impact of the serrated and comb design models has not been

thoroughly examined. Upon closer examination of owl feathers, it is evident that their shapes exhibit inconsistency. Consequently, it is imperative to delve comprehensively into this aspect to grasp its contribution to effective noise reduction. This is precisely why the comb-serrated model is being employed as one of the models in this study.

Additionally, there is a need to broaden the current understanding of the discrete tonal behaviour of NACA0015 airfoil, as relatively little experimental and numerical analysis has been undertaken at moderate Reynolds numbers and various angles of attack, which have more practical applications. Additionally, the NACA 0015 airfoil is preferred due to its utilization as a symmetric airfoil with increased thickness in compared to the more frequently employed NACA 0012 airfoil. Investigating the effect of this difference in thickness becomes essential in comprehending the distinctive tonal behavior exhibited by the NACA 0015 airfoil. The airfoil tonal emission is tied to the amplification of naturally existing instabilities inside the laminar boundary layer (LBL); however, these instabilities alone do not always contribute to tonal noise. Instead, the extent and location of the LSB also have an impact on the emitted tonal noise. Despite the viability of this finding, the fundamental physical reasons causing airfoil tonal noise still need to be fully understood.

The present research strives to thoroughly understand the tonal noise process and related physical phenomena by conducting wind tunnel tests and CFD simulations, evaluating the flow structure and tonal noise over an airfoil impacted by whistle tonal noise. Additionally, the study will evaluate the influence of passive flow control systems on airfoil noise emission and flow structure. Given the limited research on controlling airfoil tonal noise without negatively affecting flow structure, the study seeks to find effective methods to improve the noise performance and enhance the flow characteristics at relatively moderate Reynolds number ($1.7 \times 10^5$) and varying angles of attack ($-2 \leq \alpha \leq 2$ deg). The selection of Reynolds numbers and angles of attack for investigation is based on the observation that discrete tonal noise becomes more noticeable at lower Reynolds numbers and angles of attack, following previous research findings.

## 1.4. RESEARCH PHILOSOPHY

The scientific concept driving the analysis of airfoil tonal noise and its reduction is based on the knowledge of the link between the physics of flow and the generation of tonal noise. This research will tackle this problem by conducting flow visualization using wind tunnel experiments and CFD simulations to examine the flow structure and tonal noise mechanism over an airfoil under the effect of whistle tonal noise. It has been noted that the induced tonal radiation is dependent primarily on the Reynolds number and Angle of attack. Therefore, this research will examine the airfoil tonal emission at moderate Reynolds numbers and varied angles of attack that have more practical uses. In addition, the influence of flow control techniques on airfoil noise emission and flow structure needs to be explored. Therefore, this research will also attempt to conduct passive flow control over the NACA0015 airfoil to enhance its noise performance and flow characteristics. Overall, this study is motivated by the notion that a better understanding of the underlying physics of flow and tonal noise will lead to developing effective and efficient noise-reducing strategies for many practical applications.

## 1.5. RESEARCH OBJECTIVES

The main objectives of this research are:
1- To determine the influence of Reynolds number and angles of attack on the flow field structure over NACA0015 airfoil.
2- To investigate the noise emitted over NACA0015 airfoil at different angles of attack and a moderate Reynolds number.
3- To determine the effect of flow control techniques on the aerodynamic and flow field characteristics.
4- To evaluate effective noise-reducing methods for airfoil tonal noise based on passive techniques.

## 1.6. RESEARCH SCOPE

The study focuses on examining the link between the physics of flow and the generation of tonal noise over a NACA0015 airfoil as relatively little experimental and numerical