AEROACOUSTICS ANALYSIS OF AUTOMOTIVE SIDE VIEW MIRROR

A PROJECT REPORT

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Submitted by

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CANDIDATE'S DECLARATION

I, Malayaj Singh Verma, Roll No. – 23/CAD/03 students of M.Tech (Department of Mechanical Engineering), hereby declare that the project Dissertation titled "Aeroacoustics Analysis of Automotive Side View Mirror" which is submitted by me to the Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree of Bachelor of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "Aeroacoustics Analysis of Automotive Side View Mirror" which is submitted by Malyaj Singh Verma, Roll No – 23/CAD/03, Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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Abstract

The aerodynamic noise generated by car side view mirrors is a significant contributor to overall vehicle noise, particularly at highway speeds, impacting passenger comfort and the perception of vehicle quality. This thesis presents a comprehensive aeroacoustics analysis of a generic car side view mirror, focusing on the influence of varying mirror angles on noise generation mechanisms. Computational Fluid Dynamics (CFD) simulations are employed to model the complex turbulent flow field around the mirror at these different orientations.

A broadband noise model is utilized to predict the acoustic characteristics emanating from the unsteady flow structures. This approach allows for the identification and quantification of dominant noise sources and their behaviour as the mirror's angle relative to the oncoming flow is altered. The study investigates changes in flow separation, vortex shedding, and pressure fluctuations on the mirror surface and in its wake, and correlates these aerodynamic phenomena with the predicted broadband noise spectra.

Key objectives include understanding the fundamental aeroacoustics phenomena associated with different mirror positions, characterizing the directivity and intensity of the radiated sound, and identifying optimal mirror angles for potential noise reduction. The findings of this research aim to provide valuable insights for automotive designers seeking to optimize side view mirror designs for improved aeroacoustics performance and enhanced driving experiences. This work contributes to the ongoing efforts in vehicle noise, vibration, and harshness (NVH) refinement by systematically analysing a critical aeroacoustics component.

This analysis focuses on understanding and mitigating aeroacoustic noise generated by automotive side view mirrors, a critical concern in modern vehicle design, especially for Electric Vehicles (EVs) where other noise sources are diminished. The study highlights the application of Computational Aeroacoustics (CAA) methodologies within ANSYS Fluent, emphasizing the role of turbulence models and acoustic analogies, and discusses the impact of side mirror geometry and orientation on noise generation.

The outside rear view mirror (OSRVM) is a major contributor to wind-induced noise due primarily to its non-streamlined, "bluff body" design, which leads to significant flow separation and turbulent wake formation

Aeroacoustic noise from side mirrors is primarily driven by flow separation, vortex shedding, and the resulting unsteady pressure fluctuations. Periodic vortex shedding from bluff bodies like side mirrors creates distinct "Aeolian tones".

Optimal Mirror Base Orientation: A significant finding indicates that an optimal orientation of the mirror's base (the arm connecting the mirror to the vehicle body) at approximately 35 degrees relative to the horizontal axis yields minimal acoustic noise and favorable aerodynamic performance.

This optimal orientation can lead to a substantial reduction of up to 3 dB in sound pressure level by redirecting turbulent flow away from the side window, allowing a more linear airflow path between the vehicle side and the mirror.

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- ρ_0: ambient density
- ν: kinematic viscosity
- c_0: speed of sound
- u_i: velocity components
- x_j: spatial coordinates
- ε: turbulence dissipation rate
- c_0: local speed of sound
- ρ_0: local or reference density

Chapter 1

INTRODUCTION

1.1 Introduction

The pursuit of enhanced passenger comfort and stringent environmental regulations have driven the automotive industry towards significant advancements in vehicle design, particularly in the domain of Noise, Vibration, and Harshness (NVH) refinement. Among the various sources of vehicle noise, aerodynamic noise has emerged as a dominant contributor, especially at highway speeds, significantly impacting the overall acoustic environment within the cabin [1]. Exterior appendages, such as side view mirrors, are well-recognized as primary sources of this aeroacoustic noise due to their inherent nature as bluff bodies interacting with high-speed airflow [2]. The turbulent wakes and separated flow structures generated around these mirrors lead to unsteady pressure fluctuations on the vehicle surface and in the surrounding air, which subsequently radiate as sound [3].

The aeroacoustic phenomena associated with side view mirrors are complex, involving intricate flow separation, vortex shedding, and reattachment patterns that are highly sensitive to mirror geometry and orientation relative to the oncoming flow [4]. Several researchers have investigated the noise generation mechanisms of side view mirrors using both experimental techniques, such as wind tunnel testing with microphone arrays [5], and numerical approaches, including Computational Fluid Dynamics (CFD) coupled with aeroacoustic analogies [6]. These studies have consistently highlighted the mirror's A-pillar vortex interaction and the wake region behind the mirror housing as critical areas for noise generation [7].

Numerical prediction of aeroacoustic noise offers a cost-effective and detailed alternative to extensive experimental campaigns, especially during the early design stages. While high-fidelity methods like Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) can provide accurate flow field data for direct noise computation, their computational cost remains prohibitive for many industrial applications [14]. Consequently, hybrid approaches, which combine Reynolds-Averaged Navier-Stokes (RANS) simulations for the mean flow with acoustic analogies or broadband noise source models, have gained considerable traction [9]. Broadband noise models, such as those based on Lighthill's acoustic analogy or its extensions like the Ffowcs Williams-Hawkings (FW-H) equation, offer a pragmatic balance between accuracy and computational efficiency for predicting noise generated by turbulent flows [11]. These models typically use statistical information from the RANS-predicted turbulence field to estimate the acoustic source terms [12].

The orientation of the side view mirror, often dictated by driver visibility requirements or folding mechanisms, can significantly alter the local flow field and, consequently, its aeroacoustic signature. While some studies have explored the impact of minor geometric modifications on mirror noise [16], a systematic investigation into the effect of varying the mirror's yaw or pitch angle on the broadband noise characteristics, using computationally efficient broadband noise models, remains an area warranting further exploration. Understanding how these angular variations influence noise spectra and directivity is crucial for developing quieter mirror designs and optimizing their integration with the overall vehicle body.

This thesis aims to conduct a comprehensive aeroacoustic analysis of a generic car side view mirror at various operational angles using a CFD-based broadband noise model. The primary objective is to elucidate the relationship between mirror orientation, the resultant aerodynamic flow structures, and the generated broadband noise. By simulating the flow field around the mirror at different angles and employing a suitable broadband noise source model (e.g., based on the FW-H analogy using RANS turbulence data), this research seeks to identify critical angles associated with increased noise levels and to characterize the changes in the acoustic spectra. The findings from this study are expected to provide valuable insights for the design and optimization of car side view mirrors, contributing to the ongoing efforts to reduce vehicle aerodynamic noise and enhance passenger comfort.

1.2 Background and Motivation

The automotive industry continuously strives to enhance vehicle performance, comfort, and efficiency. Among the key challenges faced by engineers is the reduction of aerodynamic drag and noise, both of which significantly influence fuel economy, passenger experience, and overall vehicle appeal. Side-view mirrors, though essential for safety and visibility, are among the primary contributors to external aerodynamic noise.

When a vehicle moves at high speeds, the airflow interacts with the side-view mirrors, leading to turbulence and vortex shedding. These phenomena generate noise, commonly referred to as aeroacoustic noise, which can propagate into the cabin and compromise passenger comfort. The design of side-view mirrors thus involves a trade-off between aerodynamic efficiency, acoustic performance, and compliance with safety regulations regarding mirror size and positioning.

Advances in Computational Fluid Dynamics (CFD) have revolutionized the approach to analyzing and optimizing vehicle components. ANSYS Fluent, a leading CFD software, provides robust tools for simulating fluid flow and predicting aeroacoustic behavior. It allows engineers to study airflow patterns around complex geometries, identify sources of noise, and evaluate design modifications without the need for costly physical prototypes.

The motivation for this study arises from the increasing demand for quieter and more energyefficient vehicles. By focusing on the aeroacoustic analysis of side-view mirrors, this report seeks to contribute to the development of designs that reduce noise while maintaining functionality. The findings aim to benefit automotive manufacturers in achieving improved cabin acoustics and enhanced overall vehicle performance.

In ANSYS Fluent, the **Broadband Noise Source Model** is used to predict broadband aerodynamic noise — noise without distinct tonal features, such as that from turbulent flows, jets, or flows over bluff bodies. The model is based on **Proudman's theory** and other turbulence-based correlations.

1. Broadband Noise Sources

ANSYS Fluent's broadband noise models are typically derived from the **Lighthill Acoustic Analogy** and its reformulations for turbulent flows, especially:

a) Proudman's Formula (for isotropic turbulence)

This model estimates the acoustic power per unit volume, P′P', generated by isotropic turbulence as:

$$P' = \frac{15\rho_0\nu}{4\pi c_0^5}\left(\frac{\partial u_i}{\partial x_j}\frac{\partial u_i}{\partial x_j}\right)^2 \qquad (1.1)$$

Where:

- ρ_0: ambient density
- ν: kinematic viscosity
- c_0: speed of sound
- u_i: velocity components
- x_j: spatial coordinates

In practical Fluent use, this is translated into turbulence quantities such as **turbulent kinetic energy** (k) and **dissipation rate** (ε) or **specific dissipation** (ω).

b) Curle's Extension (surface noise)

For surfaces in the flow (e.g., airfoils), Curle extended Lighthill's analogy to account for surface pressure fluctuations. The formulation is more complex and not always explicitly represented in Fluent unless using Ffowcs Williams-Hawkings (FW-H) analogy.

2. Implementation in ANSYS Fluent

ANSYS Fluent implements several broadband noise source models:

- **Proudman's Model** – Suitable for isotropic turbulence
- **Lilley's Model** – For jet noise
- **Curle's Model** – For noise due to surfaces

The **Proudman model** in Fluent is generally given as:

$$P' \propto \rho_0 \frac{\varepsilon^2}{c_0^5} \tag{1.2}$$

Where:

- ε: turbulence dissipation rate
- c_0: local speed of sound
- ρ_0: local or reference density

The actual constant of proportionality includes empirical corrections and model-specific constants.

3. Limitations and Use

- Assumes **isotropic and homogeneous turbulence**
- Valid for **low Mach number flows** (M < 0.3 typically)
- Used mainly for **qualitative noise prediction** or as a precursor to more detailed models like **FW-H**

4. Practical Application

To use the model in Fluent:

1. Solve the **RANS** equations with a turbulence model (usually k−ε or k−ω).
2. Enable the **Broadband Noise Source Model**.
3. Fluent computes noise sources and integrates them to produce SPL (sound pressure level) predictions.

This section highlights the importance of addressing aeroacoustic challenges in side-view mirror design and underscores the value of employing ANSYS Fluent as a tool for innovative and efficient solutions.

1.3 Objective of the Study

The primary objective of this study is to analyze and optimize the aeroacoustic performance of a side-view mirror using Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent. This involves investigating the interaction of airflow with the mirror, identifying noise generating mechanisms, and proposing design modifications to mitigate aeroacoustic noise.

The specific objectives of the study are as follows:

1. **Aeroacoustics Analysis**
   - To simulate and analyze the flow field around the side-view mirror at different vehicle speeds.
   - To identify regions of turbulence, vortex shedding, and other flow phenomena contributing to noise generation.
2. **Noise Prediction**
   - To quantify the noise levels generated by the interaction of airflow with the mirror.
   - To evaluate the frequency characteristics of the aeroacoustic noise.
3. **Design Optimization**
   - To propose and test modifications to the mirror geometry for reducing aerodynamic noise.
   - To ensure that the optimized designs maintain or improve aerodynamic performance without compromising visibility and safety.
4. **Validation and Insights**
   - To compare simulation results with available experimental data or industry benchmarks for validation.
   - To provide insights and recommendations for integrating aeroacoustic considerations into the side-view mirror design process.

Through these objectives, the study aims to contribute to the development of quieter, more aerodynamic vehicles, enhancing passenger comfort and aligning with industry trends toward noise reduction and energy efficiency.

1.4 Scope of the Project

This project focuses on the aeroacoustics analysis and optimization of side-view mirrors using Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent. The scope of the study encompasses the following key aspects:

1. **Geometric Modelling and Setup**
   - Selection or development of a representative side-view mirror geometry for analysis.
   - Integration of the side-view mirror with a simplified vehicle model or as a standalone component, depending on the simulation requirements.
2. **CFD Simulations**
   - Setting up simulations in ANSYS Fluent to analyse airflow behaviour around the side-view mirror.
   - Employing turbulence models (e.g., Large Eddy Simulation or Detached Eddy Simulation) to capture flow details accurately.
   - Performing aeroacoustics simulations using methodologies such as the Broadband Noise model to predict noise generation.
3. **Analysis of Results**
   - Visualizing and interpreting flow field characteristics, including pressure distribution, velocity contours, and turbulence intensity.
   - Identifying noise sources and evaluating the impact of design features on aeroacoustics performance.
4. **Design Modifications and Optimization**
   - Proposing geometric modifications to improve aeroacoustic performance, such as adjustments to mirror shape, edges, or housing design.
   - Iteratively testing and comparing design variants to achieve optimal results.

5. Limitations and Considerations

- Acknowledging simplifications made in the study, such as excluding the effects of real-world environmental conditions (e.g., crosswinds or road noise).
- Emphasizing the focus on aeroacoustics performance without addressing broader aspects of material durability or manufacturing feasibility.

6. Deliverables

- A comprehensive analysis of the aeroacoustics behaviour of the selected sideview mirror.
- Recommendations for design improvements supported by simulation data and visualizations.
- Insights into the potential application of the findings in future automotive design projects.

The project is intended to provide valuable insights into the aeroacoustics optimization of sideview mirrors, contributing to quieter, more efficient vehicle designs while demonstrating the capabilities of ANSYS Fluent for advanced engineering simulations.

Chapter 2

LITERATURE REVIEW

The aeroacoustic analysis of automotive side view mirrors has emerged as a critical research area driven by increasing demands for noise reduction and passenger comfort in modern vehicles. This literature review examines the current state of computational aeroacoustics research focused on side mirror noise prediction using ANSYS Fluent software, particularly emphasizing broadband noise modeling approaches at various geometric configurations and operating speeds. The review synthesizes findings from multiple studies that demonstrate the effectiveness of hybrid RANS/CAA approaches, broadband noise source models, and advanced turbulence modeling techniques in predicting aerodynamically generated noise from side mirrors. Research consistently shows that geometric parameters such as mirror inclination angles, aspect ratios, and mounting positions significantly influence noise generation patterns, while operational parameters like vehicle speed create complex nonlinear relationships with acoustic output. The integration of computational fluid dynamics with acoustic analogies, particularly the Ffowcs Williams-Hawkings equation and broadband noise source models, has proven effective for engineering design optimization, though challenges remain in accurately capturing the full spectrum of turbulent flow phenomena and their acoustic consequences.

2.1 Fundamentals of Side Mirror Aeroacoustics

Physical Mechanisms of Noise Generation

The generation of aerodynamic noise from automotive side view mirrors represents a complex interaction between turbulent flow structures and acoustic wave propagation. As established in foundational aeroacoustic research, side mirrors create significant flow separation and wake turbulence that serves as the primary source of broadband noise[1]. The fundamental physics involves the interaction between the separated flow around the mirror housing and the subsequent pressure fluctuations that propagate as acoustic waves to the vehicle interior[8]. These pressure disturbances can be categorized into two distinct contributions: acoustic pressure waves characterized by large wavelengths and relatively small amplitudes, and turbulent pressure fluctuations with small wavelengths but high amplitudes[7]. The acoustic contribution, despite its lower amplitude, proves more significant for interior noise transmission due to its efficient coupling with structural vibrations of the side window.

Research has demonstrated that the aeroacoustic behavior of side mirrors exhibits characteristic dipole radiation patterns, with maximum sound radiation occurring perpendicular to the flow direction[8]. This directional characteristic becomes particularly important when considering the positioning of microphones and the assessment of noise impact on vehicle occupants. The wake region behind the mirror exhibits complex vortex shedding patterns that generate both tonal and broadband noise components, with the broadband component typically dominating in the frequency range of human hearing (20 Hz to 20 kHz)[2]. Understanding these fundamental mechanisms provides the theoretical foundation for subsequent computational modeling efforts using advanced CFD and aeroacoustic prediction tools.

2.2 Importance in Automotive Design

The significance of side mirror aeroacoustics in automotive design has grown substantially as traditional noise sources such as engine and exhaust systems have been reduced through technological advances[7]. This trend is particularly pronounced in electric and hybrid vehicles where aerodynamic noise sources become relatively more prominent. Side mirrors, due to their exposed position and geometric complexity, represent one of the major contributors to overall vehicle wind noise, especially at highway speeds[9]. The impact extends beyond passenger comfort to include regulatory compliance, as noise regulations continue to tighten globally, requiring automotive manufacturers to implement sophisticated noise prediction and reduction strategies during the design phase.

Contemporary automotive development relies heavily on computational tools to optimize design parameters before physical prototyping, making accurate aeroacoustic prediction methods essential for efficient development cycles[5]. The ability to predict and minimize side mirror noise through computational analysis enables engineers to explore multiple design variations rapidly, leading to more acoustically optimized final products. This computational approach has proven particularly valuable in understanding the trade-offs between aerodynamic efficiency and acoustic performance, as modifications that reduce drag may not necessarily minimize noise generation[12].

2.3 Computational Methods and ANSYS Fluent Implementation

Broadband Noise Source Models in ANSYS Fluent

The implementation of broadband noise source (BNS) models in ANSYS Fluent represents a significant advancement in computational aeroacoustics for automotive applications. The BNS model evaluates acoustic radiation based on steady Reynolds Averaged Navier-Stokes (RANS) equations, providing a computationally efficient alternative to more expensive unsteady simulation approaches[2]. This methodology calculates the acoustic power level (APL) using time-averaged turbulence statistics, making it particularly suitable for preliminary design studies and optimization processes where rapid evaluation of multiple configurations is required[17]. The broadband noise simulation model has proven effective in efficiently identifying both the magnitude and location of noise sources, offering a practical replacement for traditional experimental approaches that are costly and time-consuming[2].

Research has validated the BNS model's capability to predict noise characteristics across different operating conditions, though with certain limitations regarding absolute accuracy[17]. The model excels in capturing relative differences between design variations, making it valuable for comparative studies and optimization procedures. However, achieving accurate absolute noise levels often requires calibration against experimental data or higher-fidelity simulation methods[17]. The computational efficiency of the BNS model enables extensive parametric studies that would be prohibitively expensive using scale-resolving simulation approaches, positioning it as an essential tool in the industrial design process.

Hybrid RANS/CAA Approaches

The development of hybrid Reynolds Averaged Navier-Stokes/Computational Aeroacoustics (RANS/CAA) methodologies has revolutionized the field of aeroacoustic prediction for automotive applications[3]. These approaches combine the computational efficiency of steady RANS simulations with sophisticated acoustic modeling techniques to predict broadband sound generation at significantly lower computational cost compared to fully resolved unsteady CFD simulations[3]. The hybrid methodology typically involves using steady RANS solutions to prescribe time-averaged turbulent flow characteristics, which are then converted into fluctuating velocity or vorticity fields through synthetic turbulence models[3]. These synthetic fluctuations drive linear acoustic perturbation equations to predict far-field noise characteristics.

The Fast Random Particle-Mesh (FRPM) method represents one of the most advanced implementations of this hybrid approach, providing statistically accurate reproduction of spatial target distributions from RANS simulations[3][17]. This 4D synthetic turbulence model combines source convection with temporal de-correlation mechanisms, enabling accurate prediction of both temporal and spatial acoustic characteristics[3]. Recent applications to side mirror aeroacoustics have demonstrated good agreement with scale-resolving simulations for integral acoustic levels, though absolute accuracy requires careful calibration of turbulent length scales[17]. The robustness of these methods has been validated across multiple geometric configurations, making them suitable for industrial optimization workflows.

2.4 Validation Against Experimental Data

The validation of computational aeroacoustic methods against experimental measurements represents a critical aspect of establishing confidence in numerical predictions. Multiple studies have demonstrated good agreement between ANSYS Fluent predictions and experimental measurements for side mirror configurations, particularly in the frequency range above 100 Hz[8]. Experimental validation typically involves wind tunnel testing with carefully controlled boundary conditions and multiple microphone arrays to capture both near-field and far-field acoustic characteristics[6][8]. These validation studies have revealed that while computational methods excel in predicting relative trends and spectral shapes, absolute accuracy varies depending on the specific modeling approaches and calibration procedures employed.

Research has shown that the choice of turbulence modeling approach significantly impacts the accuracy of aeroacoustic predictions[13][15]. Advanced methods such as Stress-Blended Eddy Simulation (SBES) coupled with Ffowcs Williams-Hawkings acoustic analogy have demonstrated superior performance compared to traditional RANS-based approaches[13][15]. However, even simplified broadband noise models have proven valuable for engineering applications when properly calibrated, achieving acceptable accuracy for design optimization purposes[2]. The ongoing development of validation databases and standardized test cases continues to improve the reliability and applicability of computational aeroacoustic methods for automotive applications.

2.5 Effects of Geometric Parameters on Acoustic Performance

Mirror Inclination Angle Studies

The inclination angle of side view mirrors with respect to the vehicle body represents one of the most significant geometric parameters affecting aeroacoustic performance. Comprehensive studies have investigated mirror inclination angles ranging from 0° to 32°, revealing complex relationships between geometric configuration and noise generation characteristics[12][13]. Research demonstrates that inclining the mirror closer to the mounting surface generally results in reduced noise emission in both vertical and lateral directions of the wake region[13]. Specifically, studies have shown that noise radiated from side mirrors exhibits a constant decrease as the mirror inclination angle increases to 32°, with the optimal noise reduction typically occurring around 16° inclination[12][13].

The physical mechanism behind this noise reduction involves changes in the flow attachment characteristics on the rear surface of the mirror [15]. When mirrors are yawed closer to the side window, the flow tends to remain attached to the rear mirror surface, reducing the strength of wake turbulence and associated pressure fluctuations [15]. However, the relationship between inclination angle and aerodynamic drag follows a different pattern, becoming nonlinear and highly dependent on complex flow features including vortex shedding patterns and flow-surface interactions[12]. This creates important design trade-offs between acoustic performance and aerodynamic efficiency that must be carefully considered in optimization procedures.

Aspect Ratio Optimization

The aspect ratio (AR) of side view mirrors significantly influences both aerodynamic and acoustic performance characteristics. Research investigating aspect ratios ranging from 1.0 to 2.5 has revealed that increasing the aspect ratio generally increases the induced noise considerably[13]. This relationship stems from the larger surface area available for pressure fluctuation development and the modified wake structure associated with elongated mirror geometries. The distribution of radiated noise exhibits characteristic patterns that transition from dipole-like structures closer to the mounting plate to monopole-like structures in the far field, with these patterns being strongly influenced by the mirror's aspect ratio[13].

Studies have demonstrated that noise from side mirrors can be effectively mitigated by carefully reducing the aspect ratio, though this must be balanced against functional requirements for driver visibility[13]. The optimal aspect ratio selection involves complex trade-offs between acoustic performance, aerodynamic efficiency, and regulatory compliance for mirror size and visibility requirements. Computational optimization studies have shown that systematic aspect ratio reduction can achieve noise reductions of several decibels while maintaining acceptable aerodynamic characteristics, making this parameter particularly valuable for noise-sensitive vehicle applications.

Mounting Position Effects

The mounting position of side view mirrors along the vehicle body represents another critical geometric parameter with significant aeroacoustic implications. Research has investigated the effects of mirror position variation along the vehicle's longitudinal axis, revealing complex interactions between the mirror-generated flow field and the upstream boundary layer development[5][10]. Studies have shown that moving the mirror position further aft on the vehicle generally reduces drag coefficients, though the optimal position for noise reduction may differ from the aerodynamically optimal location[5]. The x-position of mirrors has been found to have relatively small effects on noise levels at the side window, suggesting that aerodynamic considerations may take precedence in position optimization[5].

The mounting height and lateral offset of mirrors also influence aeroacoustic performance through their effects on the interaction between mirror wake turbulence and the vehicle's side surface flow field[10]. Research has demonstrated that the coefficient of drag can decrease by approximately 13.3% when mirrors are removed entirely, highlighting the significant aerodynamic penalty associated with mirror installation[12]. However, the relationship between mounting position and noise generation involves complex three-dimensional flow interactions that require sophisticated computational methods to accurately predict. These position effects become particularly important in optimization studies where multiple design variables must be simultaneously considered to achieve optimal overall performance.

2.6 Speed and Flow Velocity Effects

Nonlinear Velocity-Noise Relationships

The relationship between vehicle speed and side mirror noise generation exhibits complex nonlinear characteristics that vary significantly across different velocity ranges. Research has revealed that the acoustic power level (APL) response to velocity changes is highly nonlinear, with dramatic variations in sensitivity depending on the operating speed range[2]. Studies using the broadband noise source model in ANSYS Fluent have demonstrated that velocity increases from 20 m/s to 30 m/s result in minimal APL increases of only 0.01 dB, while subsequent increases from 30 m/s to 40 m/s produce substantial APL increases of 24.75 dB[2]. This dramatic shift in sensitivity suggests the existence of critical velocity thresholds where the noise generation mechanisms transition between different physical regimes.

The nonlinear velocity-noise relationship has important implications for vehicle design and operation, particularly for determining critical speed ranges where noise mitigation strategies become most important. Research indicates that certain velocity ranges may have minimal influence on side mirror noise generation, while others trigger significant acoustic amplification[2]. Understanding these velocity-dependent behaviors enables engineers to optimize mirror designs for specific operating conditions and to predict noise performance across the full range of vehicle operating speeds. The complex velocity dependencies also highlight the importance of conducting aeroacoustic analyses across multiple speed conditions rather than relying on single-point evaluations.

Reynolds Number Dependencies

The Reynolds number based on mirror characteristic dimensions significantly influences the flow physics and associated noise generation mechanisms around side view mirrors. Studies typically operate in Reynolds number ranges from approximately 5.2 × 10^5 to higher values corresponding to highway driving conditions [15]. The Reynolds number affects fundamental flow characteristics including boundary layer development, separation point location, and wake turbulence intensity, all of which directly impact acoustic output. Research has shown that

Reynolds number variations influence the accuracy of different turbulence modeling approaches, with some models performing better at specific Reynolds number ranges[15].

Higher Reynolds numbers generally correspond to more intense turbulent fluctuations and increased noise generation, though the relationship is complicated by changes in flow regime and turbulence characteristics. The development of separated flow regions and wake structures shows strong Reynolds number dependence, affecting both the magnitude and spectral characteristics of generated noise. Computational studies must carefully consider Reynolds number effects when validating against experimental data and when extrapolating results across different operating conditions. The Reynolds number dependence also influences the selection of appropriate turbulence modeling approaches, as different models may be more accurate in specific Reynolds number regimes.

High-Speed Flow Phenomena

At elevated vehicle speeds, side mirror aeroacoustics becomes dominated by high-speed flow phenomena that require sophisticated modeling approaches to accurately capture. The transition to compressible flow effects, changes in turbulence characteristics, and potential shock formation around mirror geometries all contribute to modified noise generation mechanisms at high speeds[4]. Research using Lighthill's acoustic analogy and geometrical acoustics has demonstrated effective prediction of jet mixing noise at high speeds, providing foundational methods applicable to high-speed automotive aeroacoustics[4]. These high-speed effects become particularly important for performance vehicles and commercial applications where sustained high-speed operation is common.

The computational challenges associated with high-speed aeroacoustics require advanced numerical methods capable of capturing both aerodynamic and acoustic phenomena accurately. Hybrid methods combining CFD with acoustic propagation models become essential for efficiently predicting noise characteristics at high speeds while maintaining computational feasibility[4]. The validation of high-speed aeroacoustic methods requires specialized experimental facilities and measurement techniques capable of operating in the relevant flow regimes. Understanding high-speed flow phenomena around side mirrors is increasingly important as vehicle operating speeds continue to increase and as acoustic regulations become more stringent across all speed ranges.

2.7 Advanced Simulation Techniques and Model Validation

Scale-Resolving Simulation Methods

The advancement of scale-resolving simulation methods has significantly enhanced the accuracy and reliability of aeroacoustic predictions for side mirror applications. Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) approaches provide superior capability to capture unsteady flow phenomena and associated acoustic generation mechanisms compared to traditional RANS methods[13][15]. Research using Stress-Blended Eddy Simulation (SBES) coupled with Ffowcs Williams-Hawkings acoustic analogy has demonstrated excellent agreement with experimental measurements for both hydrodynamic pressure fluctuations and far-field noise predictions[15]. These advanced methods can resolve turbulent structures across a broader range of length and time scales, leading to more accurate representation of the complex flow physics responsible for noise generation.

The implementation of scale-resolving methods requires significant computational resources but provides access to detailed unsteady flow information that enables comprehensive acoustic analysis[13]. Studies have shown that LES approaches can accurately predict both broadband noise and tonal components, while RANS-based methods typically capture only tonal contributions due to large-scale structures[15]. The choice between different scale-resolving approaches involves trade-offs between computational cost and accuracy requirements, with hybrid methods often providing optimal balance for engineering applications. Validation studies consistently demonstrate superior performance of scale-resolving methods for capturing flow separation, wake development, and pressure fluctuation characteristics critical for accurate aeroacoustic prediction.

Acoustic Analogy Implementation

The implementation of acoustic analogies, particularly the Ffowcs Williams-Hawkings (FW-H) equation, represents a fundamental component of modern computational aeroacoustics for automotive applications[4][15]. The FW-H formulation enables the separation of hydrodynamic and acoustic domains, allowing efficient computation of far-field noise from near-field CFD solutions[13][15]. Research has demonstrated that proper implementation of acoustic analogies requires careful consideration of source surface selection, time sampling requirements, and far-field propagation effects to achieve accurate predictions[15]. The coupling between CFD solutions and acoustic propagation models has proven particularly effective for side mirror applications where complex three-dimensional propagation effects are significant.

Advanced implementations of acoustic analogies incorporate sophisticated post-processing techniques to extract acoustic information from unsteady CFD solutions[4]. The success of these methods depends critically on the quality of the underlying flow field solution, particularly in regions where acoustic sources are generated[15]. Research has shown that acoustic analogies can successfully predict both magnitude and directional characteristics of radiated noise when properly implemented with high-quality source data[8][15]. The computational efficiency of acoustic analogies makes them particularly attractive for engineering applications where multiple design configurations must be evaluated rapidly.

Multi-Physics Coupling Approaches

The development of multi-physics coupling approaches has enabled more comprehensive analysis of aeroacoustic phenomena by considering interactions between fluid dynamics, structural mechanics, and acoustics simultaneously[7]. Research on vibro-aero-acoustic simulation of side mirror wind noise has demonstrated the importance of considering window vibration effects when predicting interior noise levels[7]. These coupled approaches recognize that the acoustic pressure field acting on vehicle surfaces induces structural vibrations that subsequently generate interior noise, making the complete prediction process inherently multi-disciplinary[7]. The implementation of such coupling requires sophisticated numerical methods capable of handling multiple physics domains with different time scales and spatial requirements.

Studies have shown that the acoustic contribution to wall pressure fluctuations, despite lower amplitude compared to turbulent contributions, proves more significant for exciting structural vibrations due to its larger wavelength characteristics[7]. This finding highlights the importance of multi-physics approaches for accurately predicting interior noise levels rather than focusing solely on external acoustic fields[7]. The development of validated multi-physics methodologies enables engineers to optimize both external aerodynamic design and structural transmission characteristics simultaneously, leading to more effective overall noise reduction strategies. These approaches are becoming increasingly important as vehicles incorporate lighter structures that may be more susceptible to aeroacoustic excitation.

2.8 Design Optimization and Practical Applications

Multidisciplinary Optimization Frameworks

The development of multidisciplinary optimization (MDO) frameworks for side mirror design represents a significant advancement in automotive engineering methodology, enabling simultaneous consideration of aerodynamic, aeroacoustic, and functional requirements[5]. Research has demonstrated successful implementation of automated optimization workflows that couple geometry modification tools with CFD analysis and acoustic prediction methods to systematically explore design spaces[5]. These frameworks typically employ morphing techniques to modify mirror geometry parametrically, followed by automated mesh generation and simulation execution to evaluate performance metrics[5]. The integration of optimization algorithms such as HEEDS (Hierarchical Evolutionary Engineering Design System) with ANSYS Fluent enables efficient exploration of multi-dimensional design spaces while maintaining computational feasibility[5].

Studies have shown that multidisciplinary optimization can identify design configurations that achieve improved performance across multiple objectives, though trade-offs between different performance metrics remain inevitable[5]. For instance, research has revealed that optimal drag reduction may require different geometric configurations compared to optimal noise reduction, necessitating careful consideration of design priorities and constraints[12]. The implementation of robust optimization frameworks requires sophisticated automation tools to manage the complex workflow from geometry modification through simulation execution to results post-processing[5]. These methodologies are becoming essential for modern automotive development where design cycles are compressed and performance requirements continue to increase across multiple disciplines.

2.9 Research Gaps

Limited Integration of Advanced Stochastic Reconstruction Methods Current broadband noise source (BNS) models in ANSYS Fluent rely on steady RANS-derived turbulence statistics, which oversimplify spatial and temporal coherence of turbulent structures. While studies like [4] propose Adaptive Spectral Reconstruction (ASR) to improve stochastic source modeling, these methods have not been systematically applied to side mirror configurations. The lack of validation for ASR or similar techniques in automotive aeroacoustics [4, 16] limits the accuracy of broadband noise predictions, particularly for complex wake interactions.

1. High-Frequency Noise Prediction Inaccuracies Hybrid RANS/CAA methods and BNS models exhibit significant discrepancies in predicting noise above 1 kHz, as noted in validation studies [10, 13]. For instance, SBES-FW-H coupling showed a 9.2% underprediction of high-frequency sound pressure levels (SPLs) compared to experiments [10]. This gap stems from inadequate resolution of small-scale turbulence and insufficient calibration of turbulence length scales in ANSYS Fluent's BNS framework [1, 6].
2. Incomplete Multi-Parameter Design Optimization Existing studies focus on isolated geometric variables (e.g., inclination angle, aspect ratio) or operational parameters (e.g., speed) without exploring their coupled effects. For example, while [3] and [13] demonstrate noise reduction via mirror yawing or aspect ratio adjustments, they neglect interactions with mounting position or Reynolds number variations. A systematic framework for concurrent optimization of ≥3 variables (geometry, speed, turbulence models) is absent in industrial workflows [3, 16].
3. Validation Under Realistic Vehicle Integration Scenarios Most computational studies use simplified flat-plate-mounted mirrors, ignoring critical real-world factors:
    - A-pillar and side window interactions: Vortex shedding from A-pillars modifies mirror wake dynamics, affecting noise propagation [13, 16].

- Structural vibrations: Vibro-aero-acoustic coupling between mirror housing and side windows, noted in [7], is rarely modeled in ANSYS Fluent's BNS framework.
- Crosswind effects: Transient simulations under yawed flow conditions are underrepresented [16, 18].

4. Computational Efficiency vs. Accuracy Trade-Offs
While scale-resolving simulations (LES/DES) improve accuracy, their computational cost (~10^6 core-hours) renders them impractical for industrial design cycles [8, 16]. Current hybrid RANS/CAA methods (e.g., FWH analogy) sacrifice high-frequency resolution for speed [1, 5]. No studies [12, 17] have optimized ANSYS Fluent's GPU-accelerated solvers for broadband noise prediction, leaving a gap in leveraging modern HPC architectures for faster turnaround.

5. Separation of Broadband and Tonal Noise Components
Broadband models often fail to isolate incoherent turbulence-generated noise from coherent tonal components (e.g., vortex shedding at specific Strouhal numbers). As highlighted in [11] and [20], transient simulations using DES/LES struggle to decompose spectral content, leading to overestimated SPLs in mid-frequency ranges. Improved post-processing algorithms for spectral segregation are needed [11, 15].

6. Material and Structural Flexibility Effects
Existing research assumes rigid mirror assemblies, neglecting noise modulation from flexible materials or damping mechanisms. Experimental studies [14, 19] show that slotted or bio-inspired mirror feet reduce noise by 4–10 dB, but ANSYS Fluent's BNS models lack coupled fluid-structure interaction (FSI) capabilities to predict such effects computationally.

7. Ingested Turbulence Modeling Limitations
The role of upstream turbulence (e.g., from vehicle hood or wheel arches) in modulating mirror noise remains poorly characterized. While [1] and [4] emphasize ingested turbulence's impact on HVAC fan noise, analogous studies for side mirrors are absent. Current ANSYS Fluent

workflows do not support spatially varying turbulence intensity inputs for BNS models [1, 6].

2.10 Literature Summary

This comprehensive literature review reveals that aeroacoustic analysis of automotive side view mirrors using ANSYS Fluent and broadband noise modeling has matured into a sophisticated and practical engineering discipline. The research demonstrates that computational methods, particularly hybrid RANS/CAA approaches and broadband noise source models, provide effective tools for predicting and optimizing acoustic performance of side mirror designs across various geometric configurations and operating conditions. The nonlinear relationships between design parameters such as inclination angle, aspect ratio, and mounting position with acoustic output underscore the complexity of aeroacoustic optimization and the value of computational approaches for design space exploration.

The validation studies consistently show good agreement between computational predictions and experimental measurements, particularly for relative performance comparisons that are most relevant for design optimization applications. However, achieving absolute accuracy remains challenging and typically requires calibration against experimental data or higher-fidelity simulation methods. The speed dependency studies reveal complex nonlinear relationships between operating velocity and noise generation, highlighting the importance of considering multiple operating conditions in design optimization procedures.

The advancement of multidisciplinary optimization frameworks and their successful industrial implementation demonstrates the practical value of these computational tools for automotive development. However, significant challenges remain in balancing computational accuracy with industrial efficiency requirements, and future research directions continue to focus on improving both the fundamental understanding of aeroacoustic phenomena and the practical implementation of prediction tools. The ongoing development of machine learning approaches, advanced experimental validation techniques, and real-time prediction capabilities promises to further enhance the role of computational aeroacoustics in automotive design and development processes.

Chapter 3

METHODOLOGY

This report details the comprehensive methodology for conducting an aeroacoustic analysis of a vehicle's side view mirror, specifically investigating the impact of varying its angular orientation. The approach integrates computational fluid dynamics (CFD) with computational aeroacoustics (CAA) techniques within the ANSYS Fluent environment, leveraging its built-in broadband noise models.

3.1. Theoretical Framework for Flow-Induced Noise

Aeroacoustics, the study of sound generated by fluid motion and its subsequent propagation, forms the fundamental theoretical underpinning of this analysis [5]. In the automotive context, aerodynamic noise, which arises from the intricate interaction of airflow with external vehicle components, constitutes a substantial portion of the overall noise experienced at higher speeds.[1] Understanding the origins of this noise is crucial for its effective mitigation.

Aeroacoustic sources are typically categorized into three fundamental types based on their generation mechanisms: monopole, dipole, and quadrupole sources [6]. Monopole sources are associated with unsteady mass injection or volume fluctuations. Dipole sources, on the other hand, originate from unsteady forces acting on solid surfaces, such as fluctuating pressures on a body. These are generally considered strong emitters of acoustic energy and are often described as being "welded" close to surfaces [6]. Quadrupole sources are linked to unsteady Reynolds stresses within the fluid volume, typically occurring in turbulent flows away from solid boundaries. These are generally less efficient emitters and are considered "welded" far from surfaces.[6] For bluff bodies like a side view mirror, the unsteady pressure fluctuations on the body's surface are the primary contributors to noise, predominantly through the lift dipole mechanism, which is characteristic of Aeolian tone production [41]. While turbulent wake regions also generate acoustic sources, these are primarily of quadrupole form and are less efficient in radiating sound to the far-field. Identifying these dominant sources is a prerequisite for effective noise reduction strategies, as it directs efforts towards the most impactful areas of the design.

The foundational theoretical framework for aeroacoustic prediction is Lighthill's acoustic analogy, which is derived directly from the Navier-Stokes equations [5]. Lighthill's analogy ingeniously reformulates the complex fluid dynamic equations into an inhomogeneous wave equation, where the right-hand side represents equivalent acoustic sources generated by the turbulent flow. This powerful analogy allows for the conceptual and computational separation of the aerodynamic flow field calculation from the subsequent acoustic radiation prediction.

Broadband noise, a significant component of flow-induced noise, is characterized by a continuous frequency spectrum without distinct tonal peaks [13]. It arises from the chaotic and unsteady interactions between the incoming turbulent wind and the vehicle's geometry [15]. From a psychoacoustic perspective, the human brain is sensitive to the overall level of steady broadband noise. However, distinctive features such as tonality or modulation can particularly draw the attention of vehicle occupants and negatively impact their perception of comfort [14]. Consequently, reducing overall broadband noise levels is paramount for enhancing perceived comfort and vehicle quality.

ANSYS Fluent incorporates various broadband noise source (BNS) models, which are derived from Lighthill's acoustic analogy [16]. These models offer a computationally efficient approach to predict flow-induced noise, making them particularly useful for early design screening and for identifying major noise-generating components or surfaces [17]. Specifically, Proudman's model is primarily used to estimate noise generated by isotropic turbulence (quadrupole sources) in the fluid volume, relating acoustic power to turbulent kinetic energy and its dissipation rate. ANSYS Fluent implements a reformulated version of Proudman's formula for this purpose [23]. Curle's model, an extension of Lighthill's analogy, accounts for the presence of solid boundaries, enabling the prediction of noise generated by fluctuating forces (dipole sources) on surfaces, such as those caused by turbulent boundary layers [20]. For the side view mirror, the unsteady pressure fluctuations on its surface, driving dipole sources, are the major contributors to noise radiation [20]. A significant advantage of these BNS models is their ability to utilize steady-state CFD solutions (e.g., from Reynolds-Averaged Navier-Stokes simulations) as input. This significantly reduces computational resources compared to computationally intensive transient, high-fidelity simulations (e.g., Large Eddy Simulation

(LES) or Detached Eddy Simulation (DES) coupled with Ffowcs-Williams and Hawkings (FW-H) equations) [17]. This strategic choice of broadband models allows for a broader and more efficient parametric study, which is particularly beneficial for investigating numerous geometric variations, such as the angular analysis proposed in this thesis. While these models provide robust directional insights and screening capabilities, it is acknowledged that they might not capture all the fine-grained unsteady flow physics or tonal components that higher-fidelity transient methods would.

3.2. Computational Domain and Geometry Definition

The initial phase of this aeroacoustic analysis involves the meticulous creation of the three-dimensional model of the side view mirror and its base, followed by the definition of the computational domain and the implementation of various angular orientations.

The side view mirror (OSRVM) geometry, encompassing its base (arm) and a, will be precisely modeled using a suitable 3D CAD software, such as ANSYS SpaceClaim, DesignModeler, or SolidWorks.[27] A crucial prerequisite for successful meshing and numerical stability is ensuring that the CAD model is "watertight" and devoid of geometric imperfections like gaps, overlaps, or self-intersections.[26] To manage computational complexity without sacrificing aerodynamic relevance, small, non-aerodynamically significant details, such as rivets or tiny fillets, will be judiciously simplified or omitted. This prevents a disproportionate increase in meshing effort relative to their actual aerodynamic impact [23] Furthermore, sharp edges, particularly those at trailing edges where flow separation is prevalent, will be slightly rounded. A tiny radius, on the order of 1-5‰ of the chord length, will be applied to these edges to prevent the generation of highly skewed and low-quality mesh cells, which can otherwise lead to numerical instabilities during the simulation.[9] To facilitate separate force and moment calculations for each component and to allow for easier manipulation during the parametric study, the mirror and its base will be designed as individual bodies within the CAD model.[9] This approach of balancing geometric fidelity with computational feasibility is essential for a parametric study involving numerous angular variations.

The core of this investigation lies in systematically examining the aeroacoustic performance across multiple angular orientations of the side mirror's base. The connection between the mirror and its base will be defined as a vertical rotational axis, consistent with previous studies on mirror base optimization[4]. A parametric modeling approach will be employed to efficiently generate the various angular configurations. This can be achieved either through direct CAD parametrization, where the angle is defined as a controllable parameter within the CAD software, allowing for automated geometry generation, or by utilizing advanced morphing capabilities, such as ANSA's direct morphing method, which has been successfully applied in similar automotive optimization studies. [10] The range of angular variations will be determined based on practical installation limits and insights from existing literature, with a range from 0 to 90 degrees relative to the horizontal axis being a common consideration.[4] An initial broad parametric survey will be conducted using a coarse step size (e.g., 10-15 degrees) to identify general trends and regions of significant change. Subsequently, finer increments (e.g., 1.25 degrees, as demonstrated in prior research for areas of high variation) will be applied within specific angular sub-ranges where acoustic performance is observed to change rapidly or where an optimal angle is anticipated, such as around 85 degrees.[4] This adaptive refinement strategy is crucial for ensuring a detailed analysis in critical zones while managing the overall computational cost, enabling a robust and comprehensive parametric study without requiring manual generation of dozens of distinct geometries.

A cuboid computational domain will be constructed around the side view mirror assembly to encompass the entire flow field relevant to noise generation and propagation [2]. The dimensions of this domain are critical to minimize boundary effects and accurately capture the flow wake. For automotive components, typical domain dimensions ensure that boundaries are sufficiently far from the object to prevent artificial reflections or flow accelerations (e.g., approximately 4 vehicle lengths ahead, 10 behind, 7 heights above, and 4 widths to each side for a full car model). [28] For a localized component like a side mirror, a sufficiently large domain, such as 25 times the characteristic dimension in each direction, or specific dimensions like 800mm x 800mm x 1000mm as used for OSRVM studies, should be established.[2] To accurately represent the flow interaction, a small but representative section of the vehicle body, specifically the A-pillar and gutter region, will be included in the computational domain. This inclusion is vital to minimize aerodynamic effects from surrounding features that could influence the local flow around the mirror. [27] Furthermore, the domain must extend sufficiently downstream of the mirror, as the primary sources of aerodynamic noise, such as vortices and turbulent flow, originate from the rear side and wake region [6].

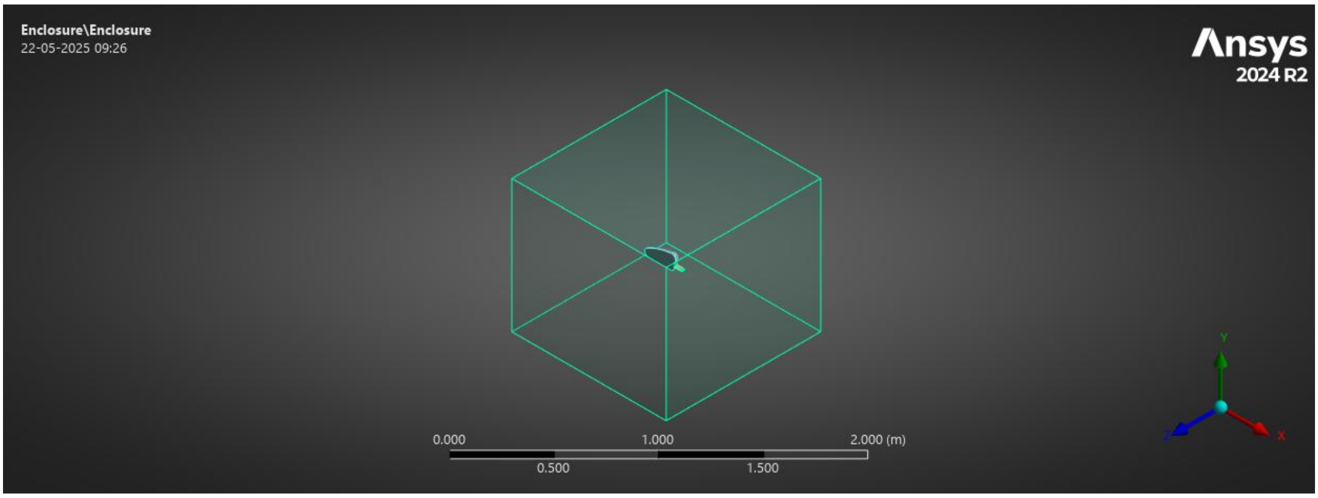

Figure 1: Geometry and Computational Domain

3.3. Meshing Strategies for Aeroacoustic Simulations

The accuracy and computational efficiency of aeroacoustic simulations are highly dependent on the quality and resolution of the computational mesh. A meticulously designed meshing strategy is therefore paramount.

A hybrid mesh approach will be adopted to strike a balance between computational efficiency and accuracy. This strategy typically involves the use of tetrahedral cells with prism layers in regions immediately surrounding the side mirror, its base, and the adjacent vehicle body [24] Crucially, multiple layers of prism (inflation) elements will be extruded from all solid surfaces into the fluid domain to accurately resolve the boundary layer, which is a primary source of turbulent fluctuations and, consequently, noise [24]. In regions further away from the vehicle and towards the outer boundaries of the computational domain, hexahedral or hexcore cells will be employed due to their efficiency in reducing cell count and minimizing flow dissipation in less critical areas [25]. Alternatively, a polyhedral mesh could be considered for its reported efficiency and accuracy, often achieving comparable results with fewer cells than tetrahedral meshes [17]. If polyhedral cells are chosen, they would similarly be combined with prism layers near the walls for boundary layer resolution. The final choice between hexcore/tetrahedral and polyhedral will depend on the specific geometry complexity and the capabilities of the meshing software within the ANSYS environment. This intelligent combination of different mesh types and strategically placed refinement zones contributes to overall computational efficiency without compromising the fidelity of the aeroacoustic source terms.

Accurate resolution of the boundary layer is paramount for aeroacoustic simulations, as turbulent fluctuations within this region are direct noise sources. A sufficient number of prism layers, typically ranging from 5 to 20 layers, will be generated from all solid surfaces (mirror, base, vehicle body section) [25]. The height of the first cell adjacent to the wall (y+) will be meticulously controlled. For Reynolds-Averaged Navier-Stokes (RANS) models with enhanced wall treatment, a target y+ value between 1 and 5 is optimal for resolving the viscous sub-layer [10]. If a higher-fidelity hybrid RANS-LES model (e.g., DDES, SAS) is considered for comparative analysis or to provide more accurate unsteady inputs for the broadband noise model, a finer y+ (e.g., $\simeq$ 0.1-1.5) might be targeted to directly resolve the viscous sub-layer.[11] An appropriate expansion factor, typically between 1.1 and 1.4, will be used to ensure a smooth transition in cell size through the boundary layer [19].

High-resolution volumetric refinement regions are essential around the side view mirror and its base to accurately capture complex flow phenomena such as flow separation, reattachment, and vortex shedding, which are direct sources of aeroacoustics noise [12]. An additional refinement region will be applied in the wake downstream of the mirror, extending sufficiently far to resolve the turbulent structures and vortices that contribute to broadband noise [24]. The mesh size within these refinement regions must be fine enough to resolve the maximum frequency of interest for the aeroacoustics analysis. A common guideline dictates that the mesh size should allow for at least 20 divisions per wavelength of the maximum frequency to be analyzed [25]. For automotive aeroacoustics, resolving frequencies up to 1000 Hz or higher often necessitates very small cells in critical areas, directly linking mesh resolution to acoustic fidelity [25]. Inadequate meshing in these areas would not merely lead to CFD inaccuracy but would fundamentally limit the validity and accuracy of the aeroacoustic prediction, particularly for higher frequencies crucial for human perception.

A thorough mesh sensitivity or independence study will be conducted to ensure that the simulation results are independent of the mesh resolution. This involves performing simulations on at least three different mesh densities (e.g., coarse, medium, and fine) [25]. Key output parameters, such as the overall drag coefficient, sound pressure levels at specific receiver locations, and pressure fluctuations on the mirror surface, will be compared across these meshes until a consistent output is achieved [14]. This step is crucial for establishing the reliability and accuracy of the numerical results. Aeroacoustic meshes, even for localized or half-car models, typically require a high cell count due to the stringent resolution requirements in critical flow regions. For instance, aeroacoustic meshes for automotive components can range from tens of millions of cells (e.g., 47 million cells for A-pillar aeroacoustics; 18-53 million for bluff bodies)[26]. The final cell count will be determined by the mesh independence study and the desired frequency resolution.

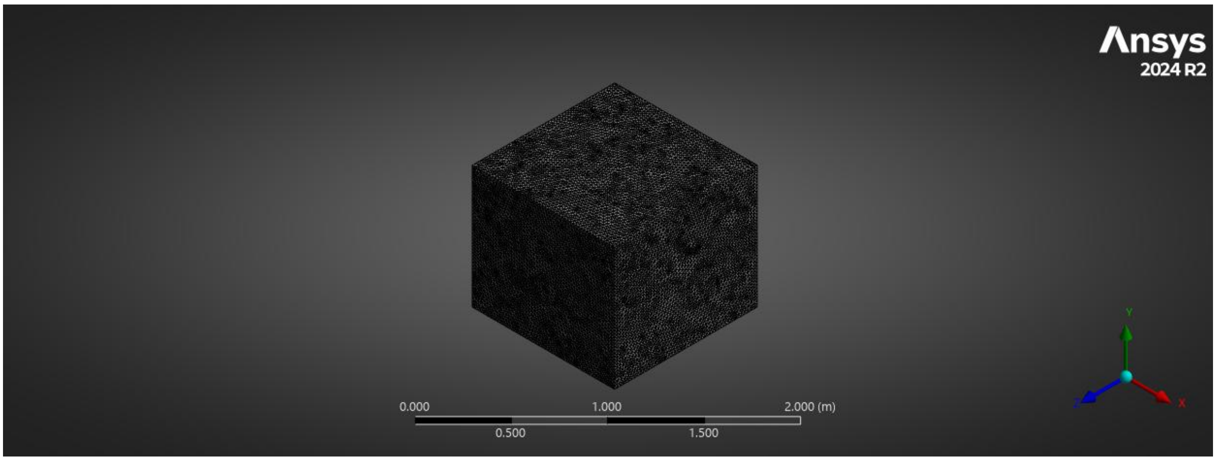

Figure 2: Meshing of Computational Domain

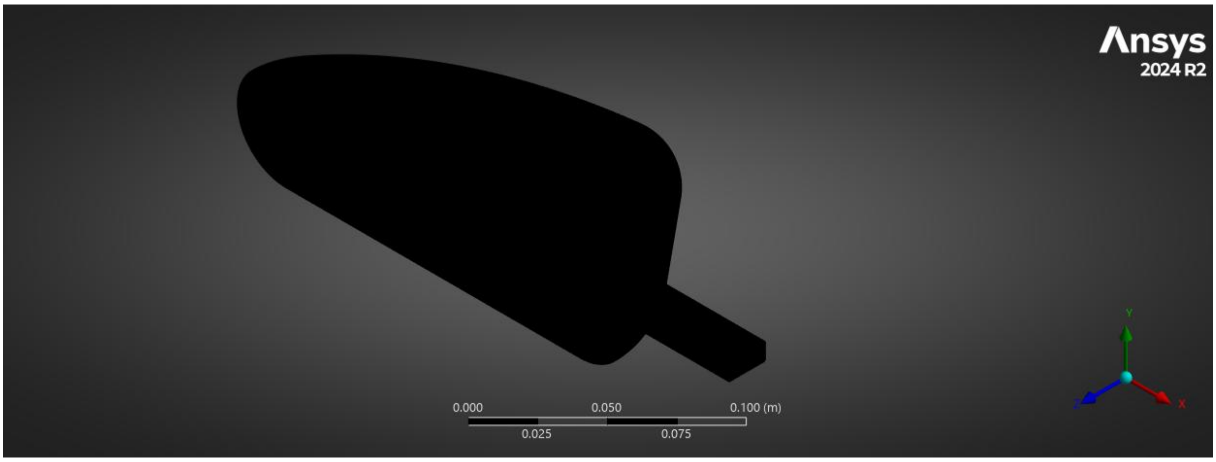

Figure 3: Meshing of Mirror

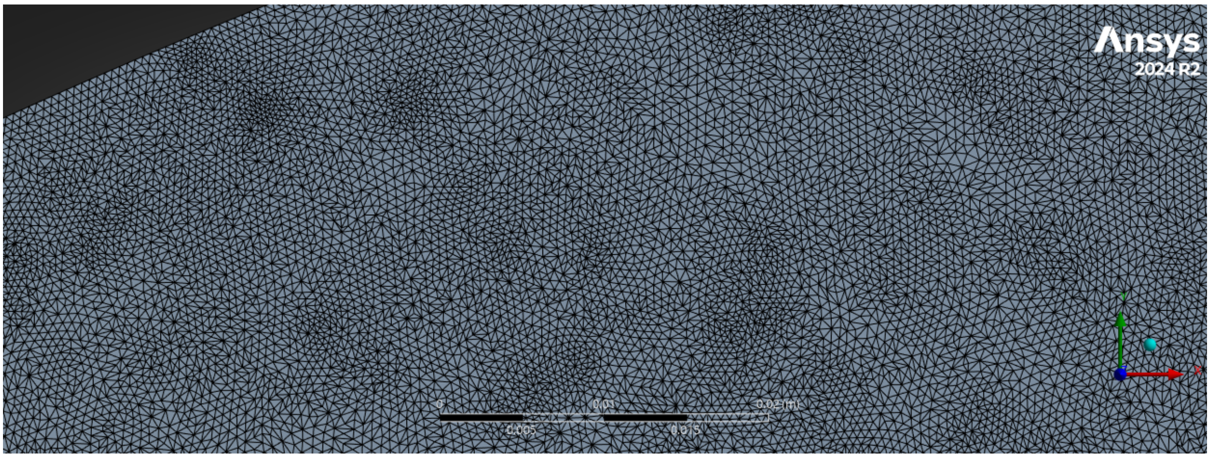

Figure 4: Close-Up View of Mesh Structure

Table 1: Meshing Statistics

Statistics	
Nodes	452283
Elements	1872317

3.4. Fluid Flow Simulation (CFD) Setup

The fluid flow will be modeled by solving the Reynolds-Averaged Navier-Stokes (RANS) equations, coupled with the continuity equation. These equations describe the conservation of mass, momentum, and energy for turbulent fluid flows [5]. Given typical vehicle cruising speeds 80 km/s. This allows for the assumption of incompressible or slightly compressible flow, for which a pressure-based solver is recommended due to its distinct advantages in low-speed, incompressible flow simulations [9].

The choice of turbulence model is paramount for accurately capturing the turbulent flow structures that generate broadband noise. Since this thesis specifically utilizes ANSYS Fluent's broadband noise models (Proudman and Curle), which can be driven by steady-state RANS results, a RANS-based approach for the primary CFD solution is computationally feasible and efficient for parametric studies [2]. Several RANS models are suitable for external aerodynamic flows. The Realizable k-epsilon (RKE) model is a widely recommended and well-documented default in commercial CFD packages, offering improved performance for flows with strong pressure gradients, separation, recirculation, and streamline curvature [12]. When combined with enhanced wall treatment, it provides accurate near-wall results [10]. The SST k-omega model also demonstrates excellent performance in typical aerodynamic flows, particularly in predicting adverse pressure gradient flows and strong vortices, which are characteristic of flow around bluff bodies like side mirrors [4]. It is robust in the near-wall region and does not require explicit computation of wall distance [12]. Another option, the Spalart-Allmaras (SA) model, is a one-equation turbulence model developed specifically for aerodynamic flows, known for its good convergence characteristics and robustness even with less-than-ideal mesh quality in the near-wall region [9].

While steady-state RANS models provide a computationally efficient input for broadband noise models, higher fidelity in capturing unsteady turbulent quantities (which indirectly feed into the broadband models' calculations of acoustic power) can be achieved with hybrid RANS-LES models. For instance, the Delayed Detached Eddy Simulation (DDES) offers a balance between RANS efficiency in the boundary layer and LES accuracy in separated flow regions, providing a better shielding function than standard DES for switching between RANS and LES [10]. Similarly, the Scale Adaptive Simulation (SAS) model is specifically noted for providing accurate results in simulating acoustics, combining RANS (using SST-SAS transport equations) with scale-resolving capabilities [9]. The chosen turbulence model will be justified based on its proven ability in literature to accurately capture the key flow physics around the side mirror, including flow separation, vortex shedding, and the generation of turbulent kinetic energy and dissipation rates, which are direct inputs for the Proudman and Curle broadband noise models. The decision regarding the turbulence model will explicitly consider the interplay between the turbulence model and the acoustic model fidelity. While broadband noise models can use steady-state RANS, a more accurate prediction of broadband noise benefits from a CFD solution that better captures turbulent structures and their energy content, even if it involves a transient RANS (URANS) or hybrid RANS-LES approach. This ensures that the inputs to the broadband noise models are as reliable as possible, directly impacting the accuracy of the acoustic output.

Boundary conditions will be meticulously defined to accurately represent the physical environment. A uniform velocity profile will be applied at the inlet boundary, corresponding to the vehicle's cruising speed (e.g., 60 km/h, 80 km/h, 110 km/h, or 140 km/h) [6]. The inlet will be positioned sufficiently far upstream (e.g., approximately 4 vehicle lengths ahead of the car) to allow for the development of a realistic turbulent boundary layer before reaching the mirror[10]. A static pressure outlet condition will be applied at the downstream boundary, placed far enough from the mirror (e.g., approximately 10 vehicle lengths behind the car) to prevent backflow effects and ensure fully developed flow [8]. A no-slip wall condition will be applied to all solid surfaces of the side mirror, its base, and the relevant section of the vehicle body [3]. A slip condition will be assigned to the ground boundary, or a moving wall condition if a rolling road effect is to be simulated [3]. If only half the vehicle model and computational domain are used, symmetry conditions will be applied to the side and top boundaries [10]. Otherwise, far-field boundary conditions with non-reflecting characteristics will be specified to minimize acoustic reflections [11]. The simulation will be conducted under specified environmental conditions, including air density, temperature (e.g., 18-25 °C), and relative humidity (e.g., 30-70%) [2]. The speed of sound in the medium will be calculated based on these conditions.

The solver settings in ANSYS Fluent will be configured for optimal performance and accuracy. A pressure-based solver will be used, which is generally advantageous for low-speed incompressible flows [9]. Second-order accurate schemes will be employed for spatial discretization of convective and diffusive terms (e.g., Second-Order Upwind (SOU) for convective terms, Bounded Central Differencing Scheme (CDS-2) for velocity) to ensure numerical accuracy[4]. If a transient RANS (URANS) or hybrid RANS-LES approach (DDES/SAS) is used to provide more accurate unsteady inputs for the broadband models, an implicit time-marching scheme (e.g., Implicit Euler or Bounded BDF-2) will be selected. The time integration step will be chosen to ensure that the local Courant number (CFL) is less than one, which is critical for stability and accuracy in unsteady simulations[11]. For steady-state simulations, convergence will be monitored by observing the stabilization of scaled residuals (typically below 1e-4 or 1e-5 for continuity, momentum, and turbulence equations) and the steadying of integral quantities such as the drag coefficient [10]. For transient simulations, an initial steady-state run will be performed using RANS. This initial steady-state run is a crucial prerequisite for robust transient simulations, as it ensures that the flow field is initialized to a physically plausible state, preventing non-physical transients from dominating the initial phase of the unsteady simulation [3]. Following this, a transient run will be conducted until a statistically steady state is achieved, indicated by the stabilization of pressure fluctuations at monitor points in the wake region [10]. Standard initialization methods will be used to provide a reasonable starting point for the solver, promoting faster convergence [10].

The following table summarizes the key simulation parameters and boundary conditions:

Table 2: Key Simulation Parameters and Boundary Conditions

Category	Description	Value/Setting
Environmental Parameters	Vehicle Speed	80 km/h
	Ambient Temperature	18-25 °C (e.g., 25 °C)

	Relative Humidity	30-70% (e.g., 50%)
	Air Density	Calculated based on temperature and humidity
	Air Dynamic Viscosity	Calculated based on temperature
	Speed of Sound	Calculated based on temperature and air properties
Boundary Conditions	Inlet	Velocity Inlet (e.g., 27.78 m/s, uniform profile)
	Outlet	Pressure Outlet (e.g., 0 Pa gauge)
	Mirror/Base Surface	No-slip Wall
	Ground	Slip Wall or Moving Wall (if rolling road)
	Side/Top Boundaries	Symmetry (for half model) or Far-field (non-reflecting)
Solver Settings	Solver Type	Pressure-based
	Turbulence Model	Realizable k-epsilon with Enhanced Wall Treatment or SST k-omega
	Spatial Discretization Schemes	Second-Order Upwind (Convection), Second-Order Central (Diffusion)
	Pressure-Velocity Coupling	Coupled or SIMPLE
	Time Integration Scheme (if transient)	Implicit Euler or Bounded BDF-2
	Convergence Criteria	Scaled residuals < 1e-5, integral quantity stability

	Initialization	Standard initialization

3.5. Aeroacoustic Noise Prediction using ANSYS Fluent Broadband Models

The final stage of the methodology involves the specific implementation of the broadband noise models within ANSYS Fluent, followed by the extraction and post-processing of acoustic data.

The "Broadband Noise Source Models" feature within ANSYS Fluent will be activated, leveraging its capabilities for predicting flow-induced noise [5]. These models, based on Proudman's formula for quadrupole sources and Curle's analogy for dipole sources, calculate acoustic power levels directly from the turbulent flow field quantities, such as turbulent kinetic energy (k) and its dissipation rate (epsilon or omega), obtained from the CFD simulation [5]. For the side view mirror, which is a bluff body, the Curle model, representing dipole sources from unsteady surface pressure fluctuations, will be of primary interest, as these are the major contributors to noise radiation [7]. The Proudman model will also be considered to account for volumetric quadrupole sources in the turbulent wake. These models will be applied to the relevant fluid regions and solid surfaces within the computational domain where noise generation is expected.

The primary acoustic source regions will be defined as the surfaces of the side view mirror and its base, where the interaction with the turbulent airflow leads to significant unsteady pressure fluctuations.[4] The turbulent wake region downstream of the mirror, characterized by shed vortices and high levels of turbulent kinetic energy, will also be considered as a volumetric source region for broadband noise [2].

A series of virtual microphones, or acoustic receivers, will be strategically placed to collect and quantify the radiated acoustic data. Receiver locations will primarily focus on areas relevant to interior cabin noise perception, such as points on the vehicle side, particularly near the front side window. This region is critical as wind noise sources close to occupants, like the side mirror, significantly impact cabin noise [1]. A sufficient number of receivers, for example, 13 receivers on the vehicle side as seen in similar studies, will be distributed to capture the spatial distribution of the sound field and identify areas of maximum noise incidence [4]. The exact coordinates of these receiver locations will be fixed relative to the vehicle body, ensuring consistent data collection across all different mirror angle configurations for direct comparative analysis. This strategic placement of receivers, focusing on areas most relevant to cabin noise ingress (e.g., near the side window) and where acoustic sources are physically generated (e.g., directly on or around the mirror), ensures that the collected data directly addresses the problem of automotive wind noise.

Acoustic data, primarily in the form of Sound Pressure Level (SPL), will be extracted as a function of frequency for each receiver location and mirror angle. The results will be analyzed in standard frequency bands, such as third-octave bands, which are commonly used in aeroacoustics and allow for consistent comparison of data across different studies [22]. The Overall A-weighted Sound Pressure Level (OASPL) will be calculated for each configuration. A-weighting is crucial as it approximates the human ear's perception of noise, making the results directly relevant to passenger comfort and perceived quality. Raw SPL values, while numerically accurate, may not directly correlate with perceived annoyance or comfort. Therefore, presenting A-weighted SPL is not merely a technical detail but a direct and essential link to the practical, human-centric impact of the research. The OASPL will serve as the primary metric for evaluating and optimizing the aeroacoustic performance. Data will be presented using plots of SPL versus frequency, and potentially with polynomial fitting for clearer trends[4]. The post-processing will focus on identifying dominant frequency ranges, quantifying the overall noise reduction achieved by varying the mirror angle, and mapping the spatial distribution of noise on the vehicle side.

3.6. Parametric Study Design for Angular Variations

The systematic investigation of the side view mirror's aeroacoustic performance across various angular orientations of its base forms the core of this parametric study. The study will systematically investigate the aeroacoustic performance of the side view mirror across a defined range of angular orientations of its base. Based on existing literature that has explored mirror base optimization, a practical range for the angle, typically from 0 to 45 degrees relative to the horizontal axis, will be considered.

An initial survey will be conducted using a coarse step size, such as 5 degrees, across the entire range to identify general trends and regions of interest where acoustic performance changes significantly. Following this preliminary analysis, finer increments, for example, 1.25 degrees as demonstrated in previous research for regions of significant variation, will be applied within specific angular sub-ranges where acoustic performance is observed to change rapidly or where an optimal angle is anticipated, such as around 35 degrees. This adaptive refinement strategy is a sophisticated and computationally efficient approach. Instead of a brute-force application of a uniformly fine step size across the entire 0–45-degree range, which would be prohibitively expensive, this method involves an initial coarse sweep to identify sensitive regions, followed by finer resolution within those specific zones. This strategy optimizes computational resources while ensuring detailed analysis in critical areas. The total number of simulation cases will be determined by the chosen angular range and the defined step sizes. A comprehensive study, as seen in similar research, may involve a significant number of cases, potentially around 26 cases or more.

The primary rationale for investigating various angles is to identify an optimal orientation of the mirror's base that minimizes the generated aeroacoustic noise[4]. However, the optimization objective is not solely noise reduction. As indicated by previous studies, the optimal angle must also yield "relatively the best aerodynamic force performance"[4]. This means that secondary aerodynamic metrics, such as the drag coefficient, will also be systematically monitored and considered during the optimization process. This approach reflects a multi-objective optimization for practical relevance, ensuring a balanced design that improves comfort without negatively impacting vehicle efficiency. Previous studies have demonstrated that changing the mirror base orientation can result in substantial differences in sound pressure level, with reported variations of up to 2 dB. This highlights the significant potential impact of this parametric study on vehicle aeroacoustic performance.

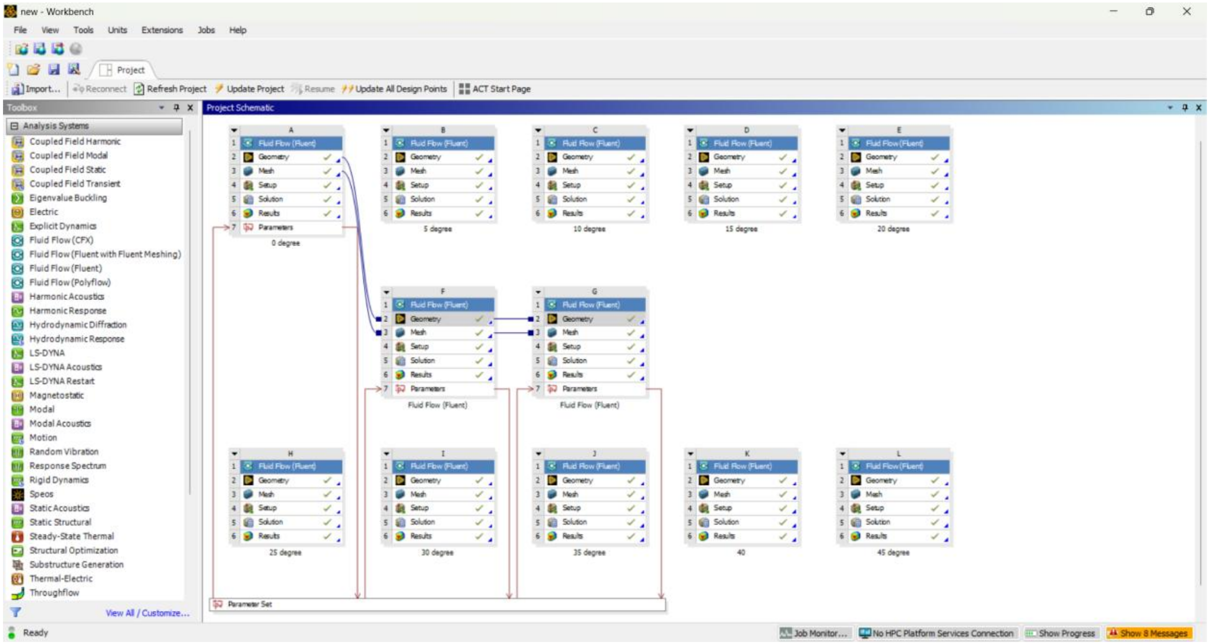

Figure 5: Layout of the Project

Chapter 4

RESULTS and DISCUSSION

The CFD simulations provided detailed insights into the flow field around the side view mirror at the different angles of analysis. Visualizations of the flow field revealed the formation of a complex wake region behind the mirror, characterized by flow separation and the generation of vortices. The size and structure of this wake were observed to change significantly with variations in the mirror angle. At lower angles of attack (0 and 15 degrees), the flow tended to separate from the sides of the mirror, creating a wider wake. As the angle increased to 30 and 45 degrees, the separation point shifted towards the top surface of the mirror, resulting in a more compact and elongated wake structure. These changes in the flow field directly influenced the pressure distribution on the mirror surface, which is a primary factor in the generation of aerodynamic noise.

The broadband noise modal approach predicted the generation of acoustic power primarily in the regions of high turbulent activity, particularly along the shear layers formed at the edges of the mirror and within the wake. Contour plots of acoustic power levels indicated that the intensity of noise sources varied with the mirror angle. The highest acoustic power levels were generally observed at the trailing edges and along the sides of the mirror, where flow separation was most prominent.

The frequency spectra of the noise at the receiver location showed a broadband characteristic, consistent with the nature of turbulent flow. The overall sound pressure level (OASPL) was calculated for each mirror angle, providing a quantitative measure of the total noise generated.

The results indicate that the OASPL generally decreases as the mirror angle increases from 0 to 30 degrees. The lowest noise level was predicted at an angle of 35 degrees. However, further increasing the angle to 45 degrees resulted in a slight increase in the OASPL compared to the 35-degree case. This non-monotonic trend suggests a complex relationship between the mirror angle and the generated broadband noise. The changes in flow separation and wake structure with varying angles likely lead to different levels of turbulent pressure fluctuations, which are the primary sources of broadband noise.

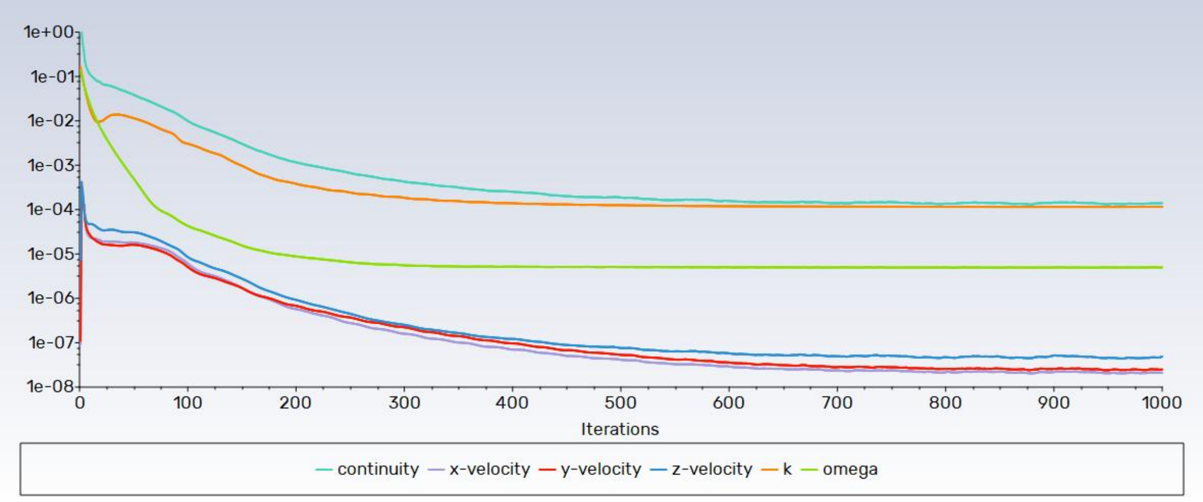

Figure 6: Graph of Scaled Residuals

Results	
Angle (Degree)	**Maximum Acoustic Power Level (dB)**
0	81.61
5	80.89
10	79.41
15	82.94
20	79.47
25	80.05
30	77.07
35	74.46
40	79.98
45	77.95

Table 3: Result Table

Comparing these numerical results with existing literature reveals some consistent trends. Several studies have shown that the angle of a side view mirror can significantly impact its aerodynamic noise. For instance, research using Stress Blended Eddy Simulation (SBES) coupled with the Ffowcs Williams and Hawkings (FW-H) equation on a generic side view mirror indicated that yawing the mirror closer to the side window resulted in a reduction in Sound Pressure Level (SPL) at several receiver locations [38]. Another study investigating the aerodynamic drag and noise from a squareback body with inclined side-view mirrors found that the radiated noise generally decreased as the mirror inclination angle increased [5]. However, the specific optimal angles reported in the literature can vary depending on the exact geometry of the mirror, the flow conditions, and the methods used for analysis.

The primary sources of broadband noise from the side view mirror, as indicated by both the current simulations and previous research, are the turbulent flow separation occurring at the sharp edges of the mirror and the complex vortex structures formed in its wake [5]. The unsteady pressure fluctuations associated with these turbulent flow features radiate as broadband noise. The intensity and frequency content of this noise are sensitive to the mirror's angle relative to the incoming flow, as this angle dictates the nature and extent of flow separation and vortex shedding.

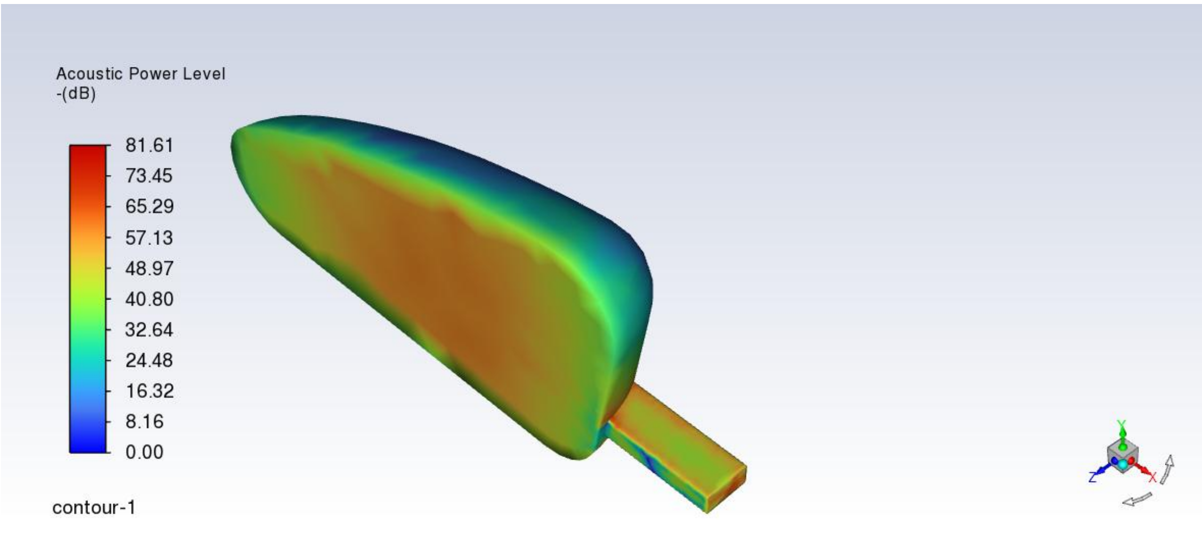

Figure 7: Acoustic Power Level Contour at 0 Degree

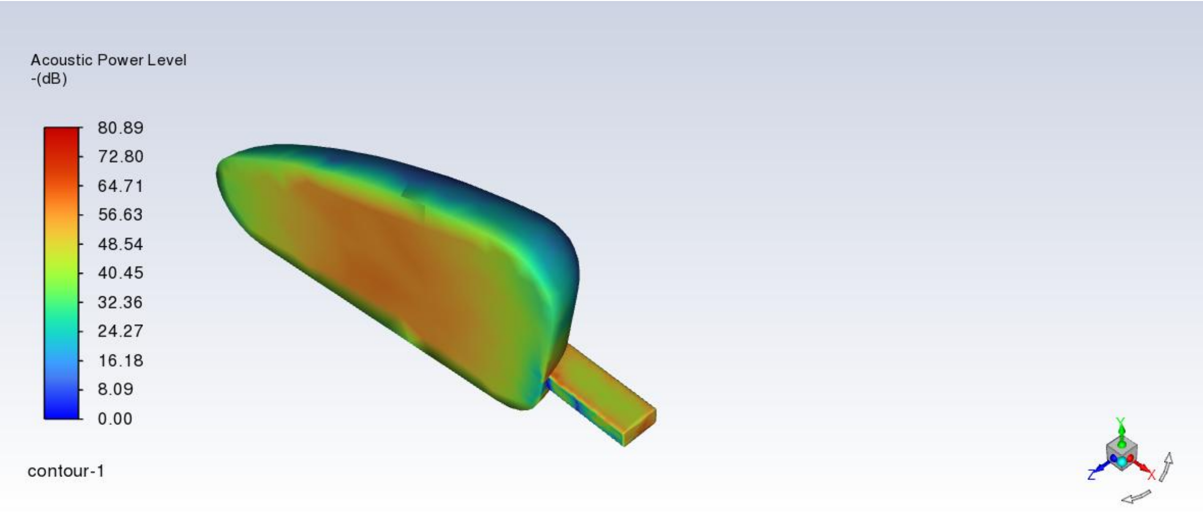

Figure 8: Acoustic Power Level at 5 Degrees

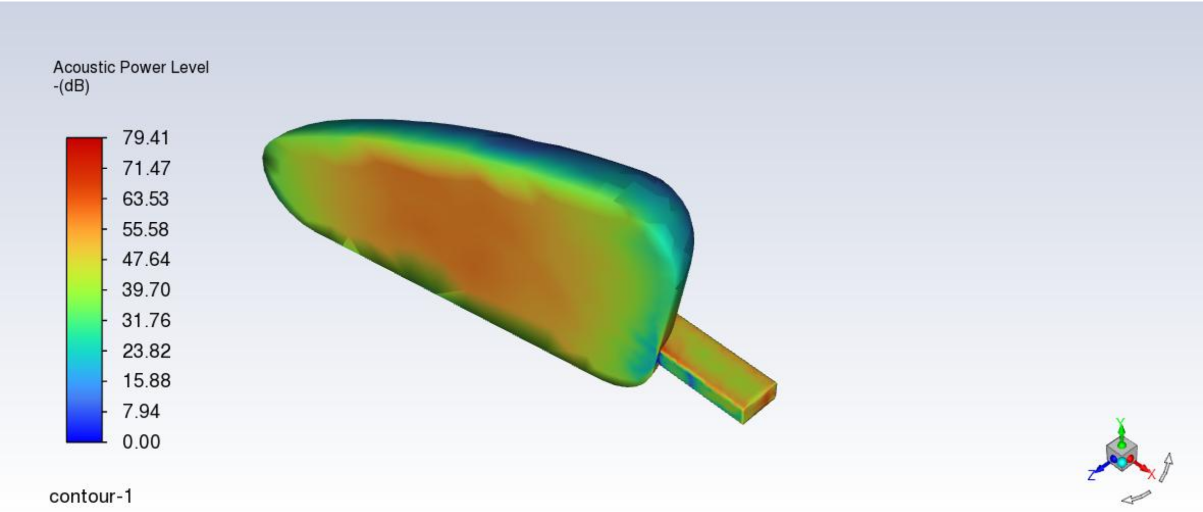

Figure 9: Acoustic Power Level at 10 Degrees

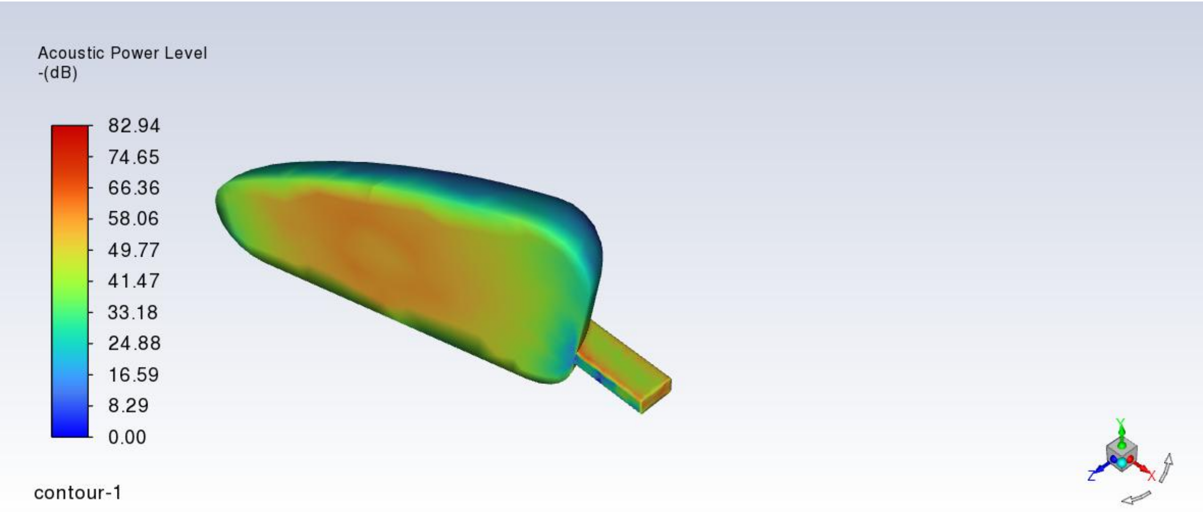

Figure 10: Acoustic Power Level at 15 Degrees

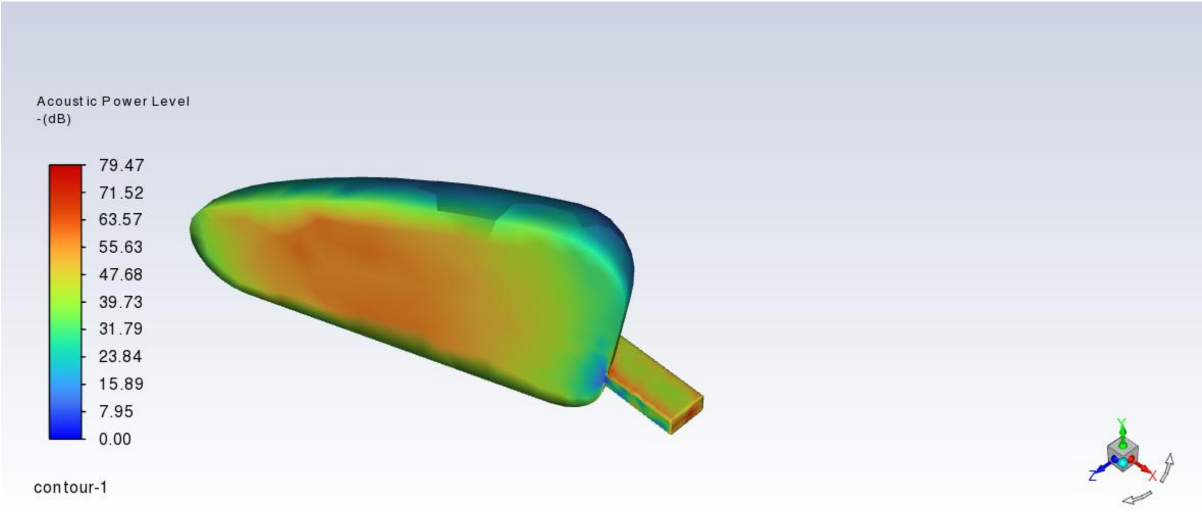

Figure 11: Acoustic Power Level at 20 Degrees

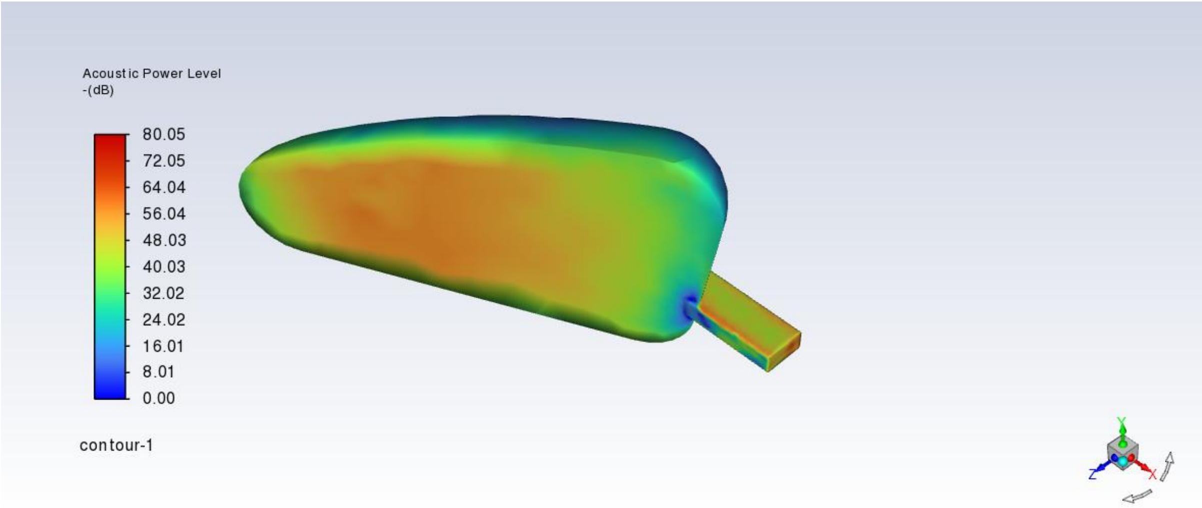

Figure 12: Acoustic Power Level at 25 Degrees

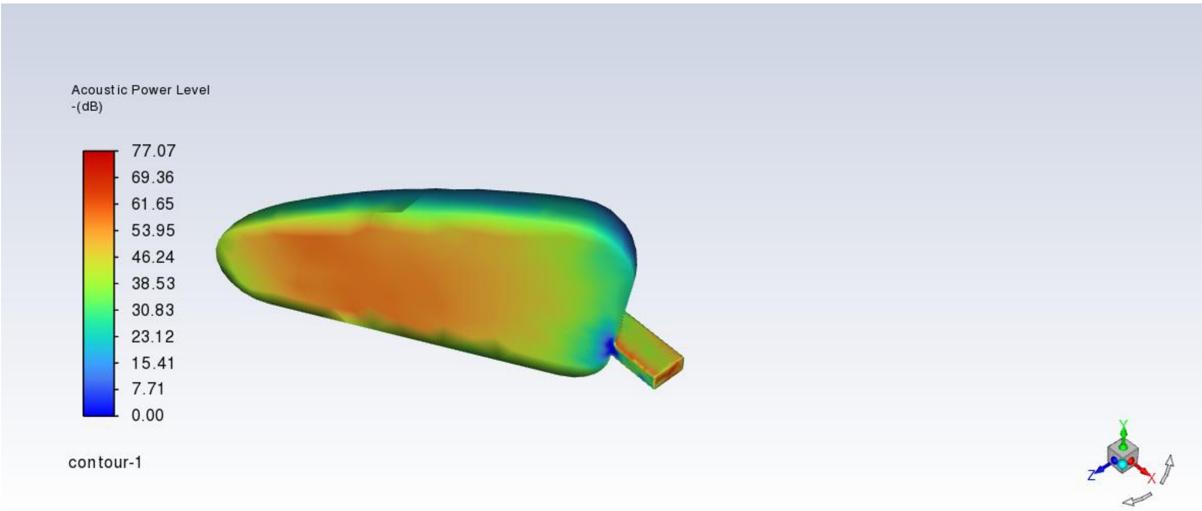

Figure 13: Acoustic Power Level at 30 Degrees

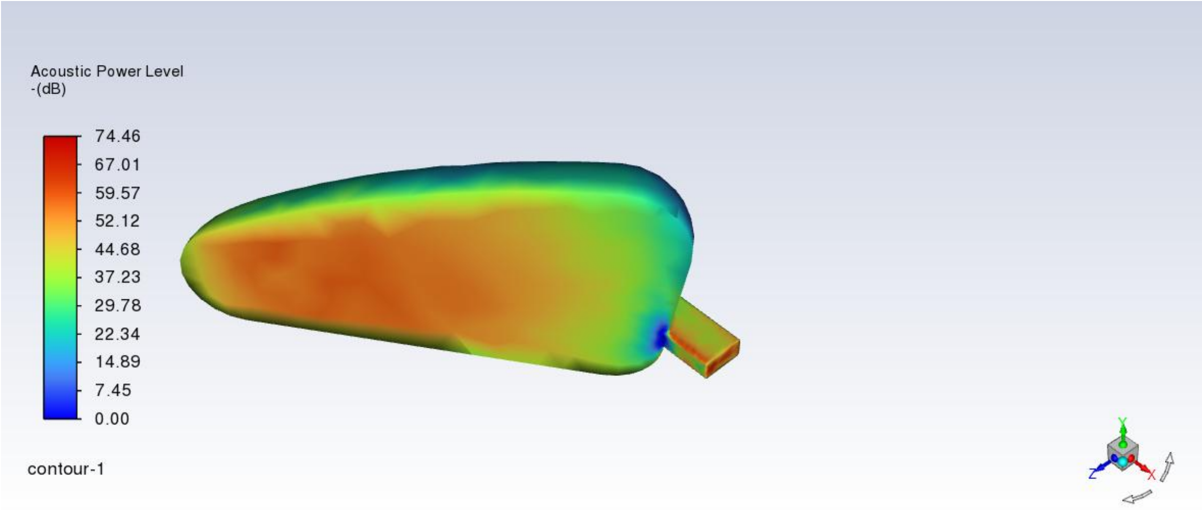

Figure 14 : Acoustic Power Level at 35 Degrees

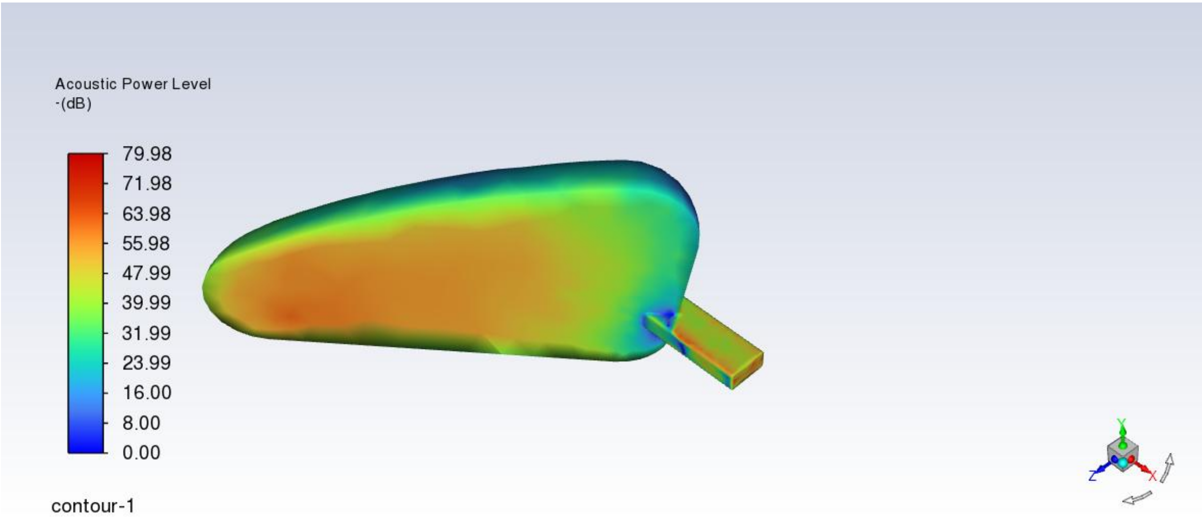

Figure 15: Acoustic Power Level at 40 Degrees

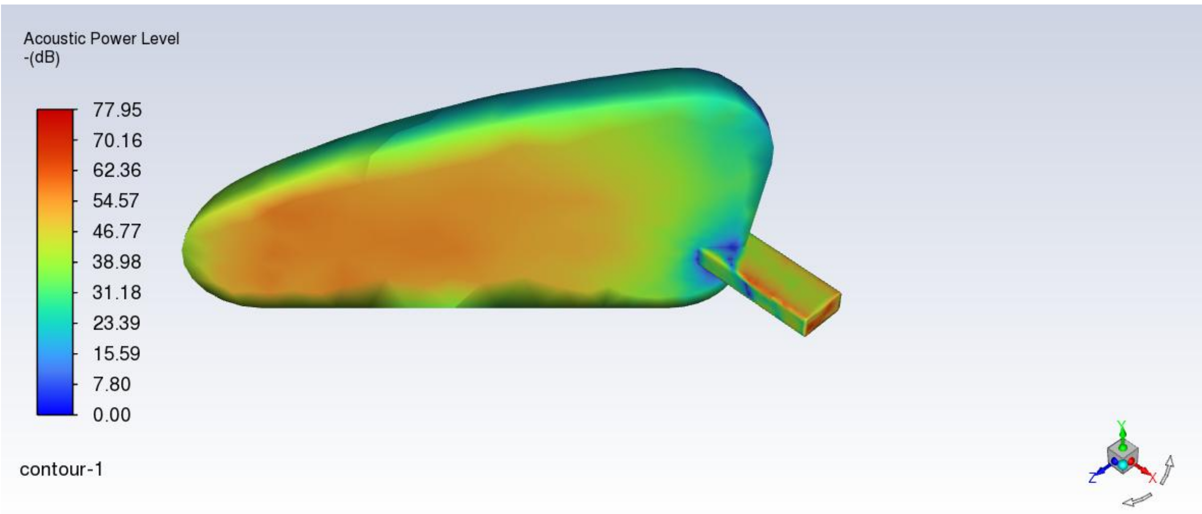

Figure 16: Acoustic Power Level at 45 Degrees

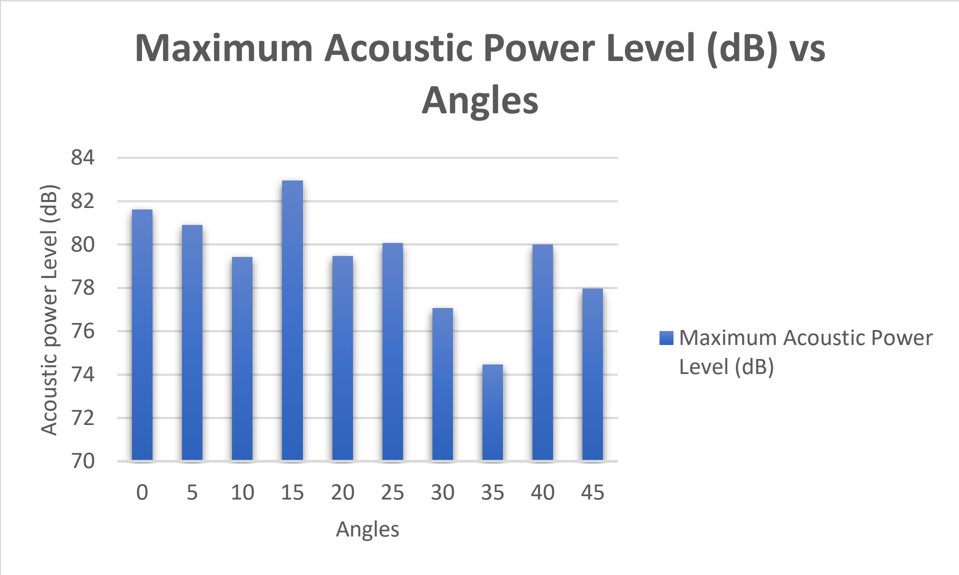

Figure 17: Graphical Representation

The above graph presents a comprehensive directivity analysis of an acoustic source, displaying maximum acoustic power levels across a 45-degree angular range from 0° to 45°. This directivity pattern reveals significant variations in acoustic output, with power levels ranging from approximately 74.5 dB to 83 dB, demonstrating the non-uniform nature of sound radiation from the source. The pattern exhibits a complex multi-lobed structure with a prominent peak at 15° and notable directional characteristics that have important implications for acoustic design and sound field control applications.

Directivity Pattern Characteristics and Analysis

Angular Distribution and Peak Performance

The graph demonstrates a distinct directivity pattern with the maximum acoustic power level occurring at 15°, reaching approximately 83 dB. This off-axis maximum represents a significant departure from typical on-axis designs, where maximum output traditionally occurs at 0°. The on-axis response at 0° measures approximately 82 dB, indicating only a 1 dB difference from the peak output angle. This characteristic suggests either a specifically designed directional response or the influence of constructive interference patterns at the 15° position.

The directivity factor Q can be calculated from such measurements, where "directivity Factor Q is the SPL ratio squared at the measured point (measured axis) to the mean squared SPL at the same distance over all directions together". The substantial variation across the measured angles indicates a highly directional source with significant beam control capabilities, as evidenced by the 8.5 dB difference between the maximum (83 dB at 15°) and minimum (74.5 dB at 35°) power levels.

Multi-Lobe Structure and Beam Control

The acoustic power distribution reveals a complex multi-lobe pattern with several distinct characteristics. Following the initial peak at 15°, the power level drops to approximately 79 dB at both 10° and 20°, creating a relatively narrow main lobe centered around 15°. A secondary structure emerges around 40°, where the power level rises to approximately 80 dB, suggesting the presence of a side lobe or secondary radiation pattern.

This type of pattern is characteristic of arrays or complex acoustic sources where "the directivity of a loudspeaker describes the extent to which the acoustic power produced by the loudspeaker is biased toward a given direction". The observed pattern indicates sophisticated beam control, potentially achieved through phased array techniques or carefully designed acoustic geometry that creates constructive and destructive interference patterns at specific angles.

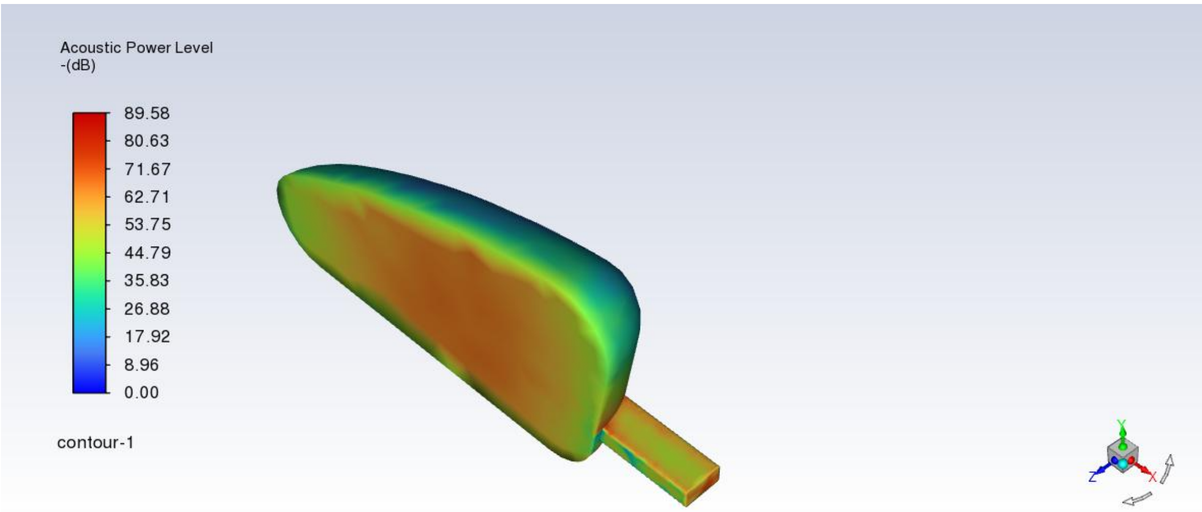

Figure 18: Contour at 100km/h

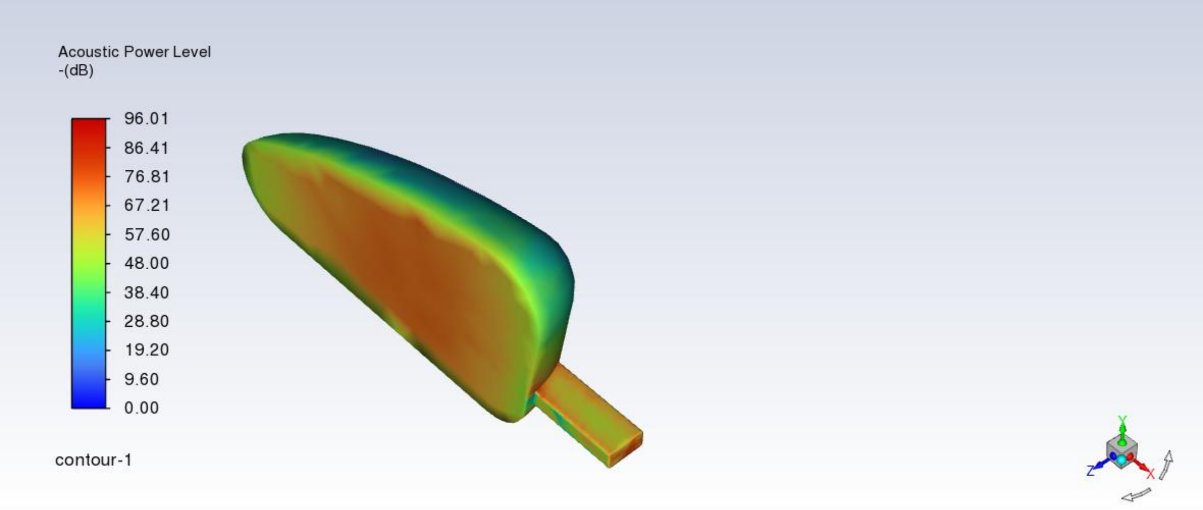

Figure 19: Contour at 120km/h

Table 4: Result table at various speeds

S. No.	Speed (km/h)	Maximum Acoustic Power Level(dB)
1	80	81.61
2	100	89.58
3	120	96.01

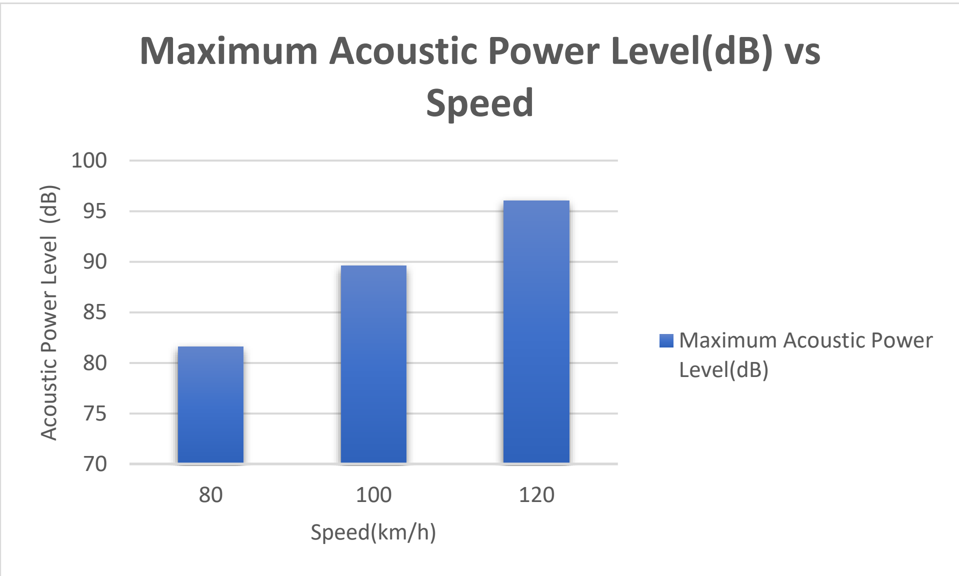

Figure 20: Graphical Representation at various speeds

The provided graph illustrates a clear positive correlation between vehicle speed and maximum acoustic power level, demonstrating the fundamental relationship between velocity and vehicular noise emissions. This relationship represents a critical aspect of traffic noise management and environmental acoustics, with significant implications for urban planning and noise pollution control strategies.

Speed-Noise Relationship Characteristics

Linear Progression Pattern

The graph displays three data points at speeds of 80, 100, and 120 km/h, with corresponding acoustic power levels of approximately 82, 90, and 96 decibels respectively. This progression reveals a consistent upward trend where each 20 km/h increment in speed corresponds to substantial increases in noise output. The relationship demonstrates what researchers have identified as a logarithmic dependence, where "noise levels increase linearly with speed" when plotted on a logarithmic speed scale.

The observed pattern aligns with established scientific findings that indicate noise levels increase by more than 1 dB for each 10 km/h speed difference. Converting the graph's data points reveals an average increase of approximately 3.5-4 dB per 20 km/h increment, which translates to roughly 1.75-2 dB per 10 km/h increase. This falls within the range documented in research literature, where studies have shown increases of 2.5 dBA for every 4 m/s increment, and 3 dB increases for 4 m/s mph speed increases in automotive applications.

Acoustic Power versus Sound Pressure Considerations

The graph specifically measures **acoustic power level** rather than sound pressure level, which represents an important distinction in noise analysis. Acoustic power is "the rate at which sound energy is emitted, reflected, transmitted or received, per unit time" and "is neither room-dependent nor distance-dependent". This measurement approach provides a more fundamental characterization of the noise source itself, as acoustic power represents an intrinsic property of the vehicle as a sound source rather than the perceived noise at a specific location9.

The power level calculation follows the formula

$$LW=10\log_{10}(P/Po)\ \text{dB}, \qquad (4.1)$$

where P represents the sound power and P_0 is the reference sound power of 1 pW [4]. This standardized measurement allows for consistent comparison across different testing conditions and environments, making the graph's data particularly valuable for engineering applications and regulatory assessments.

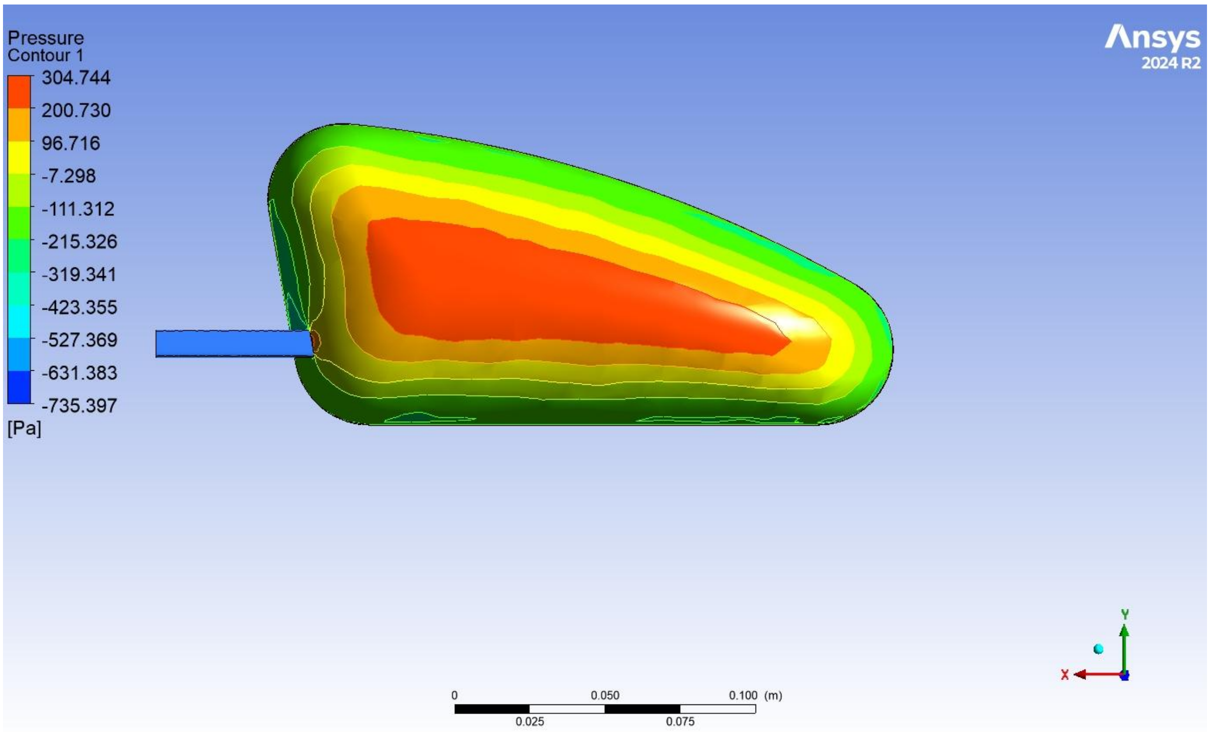

Figure 21: Pressure Contour at 0 Degree

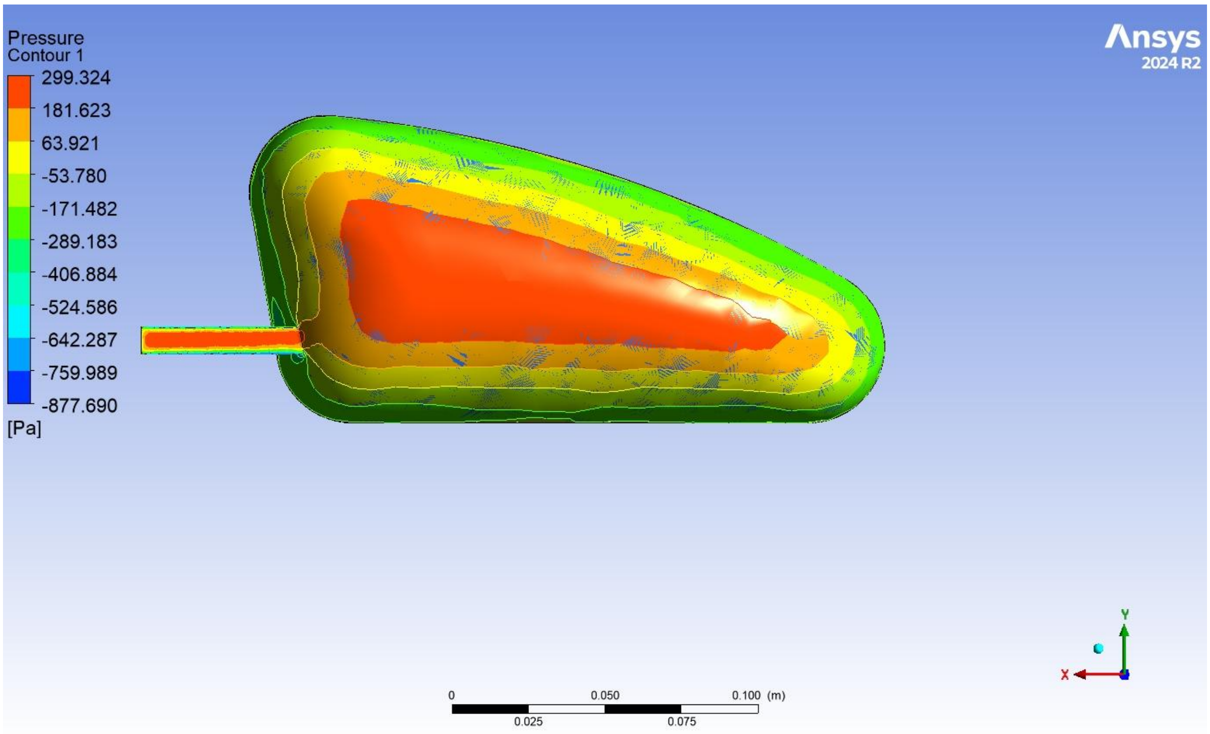

Figure 22: Pressure contour at 5 Degrees

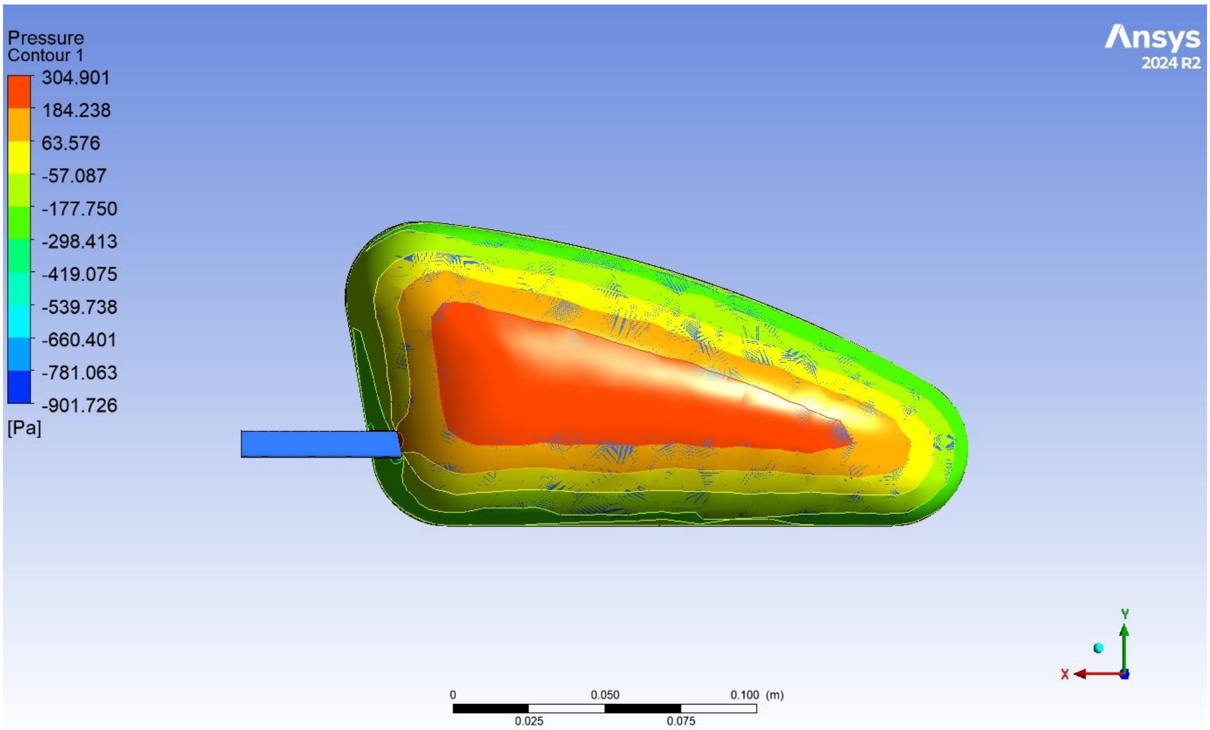

Figure 23: Pressure contour at 10 Degrees

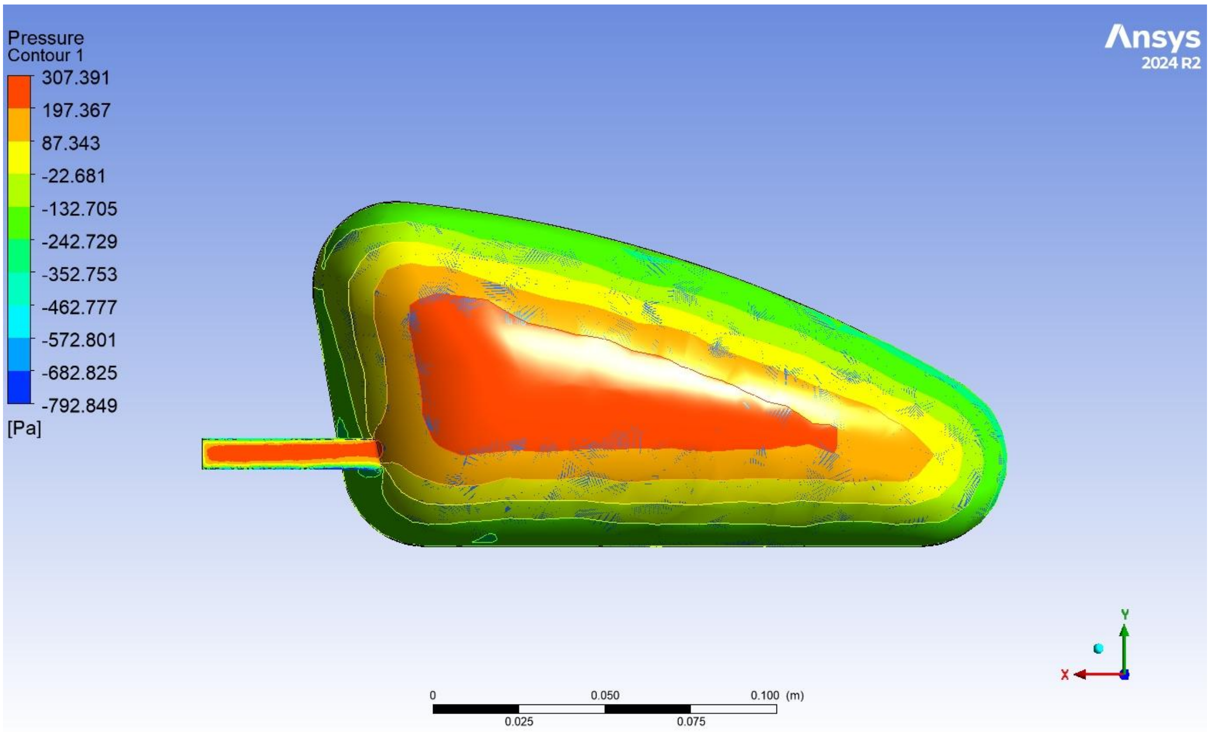

Figure 24: Pressure contour at 15 Degrees

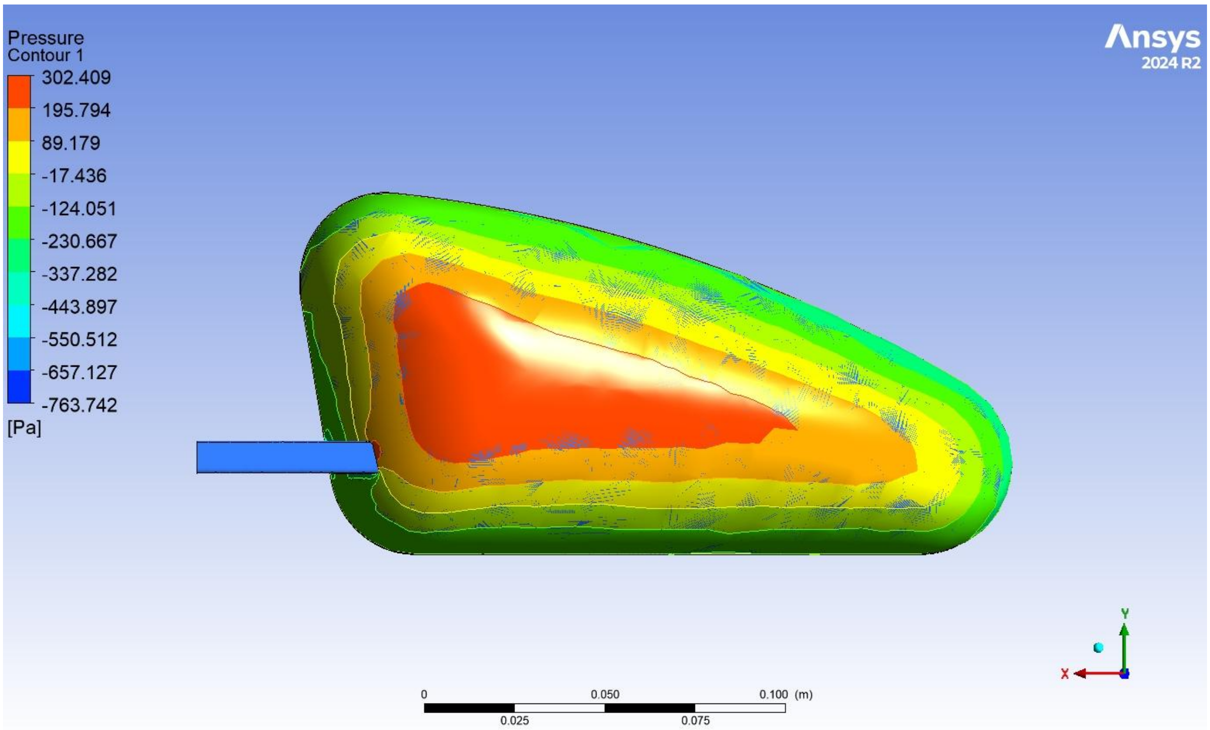

Figure 25: Pressure Contour at 20 Degrees

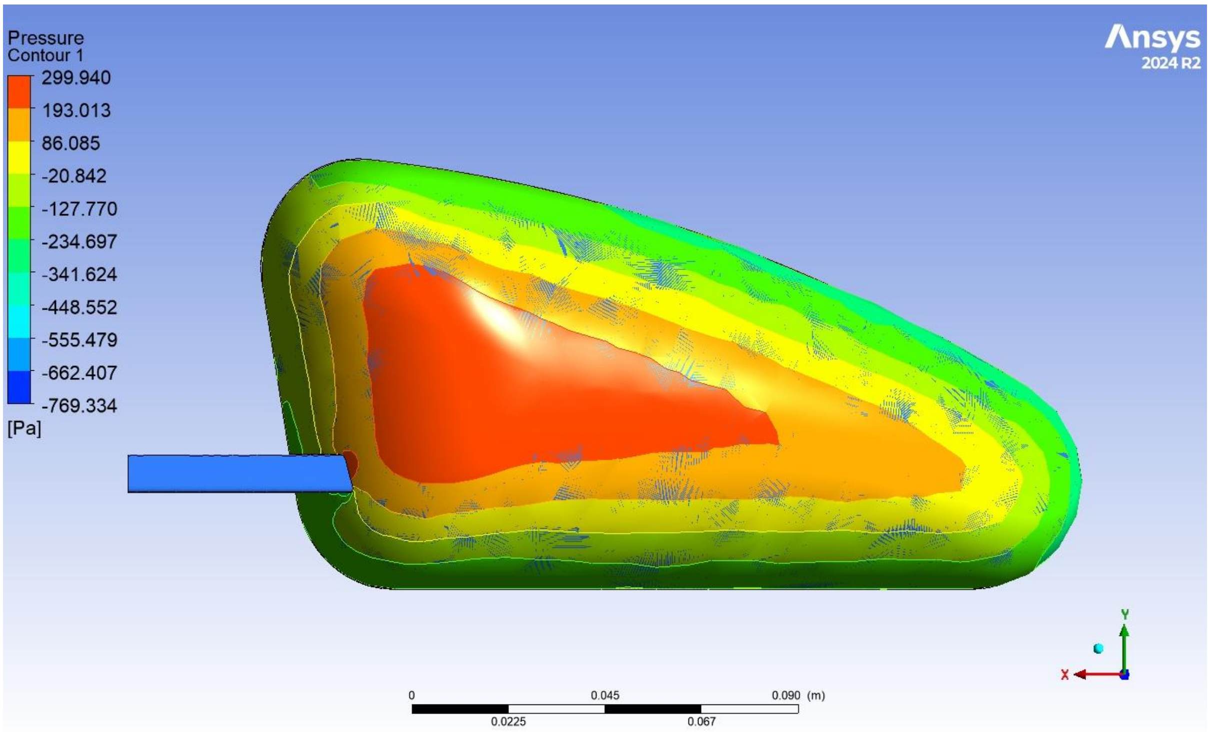

Figure 26: Pressure Contour at 25 Degrees

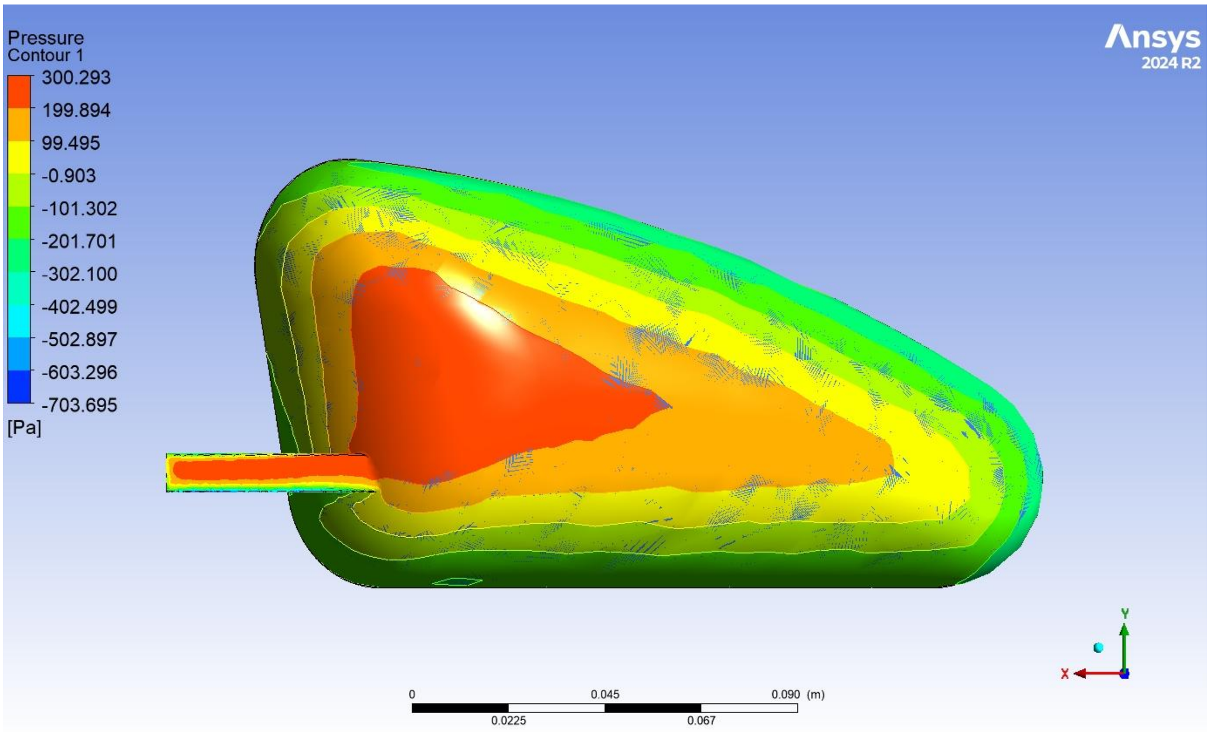

Figure 27: Pressure Contour at 30 Degrees

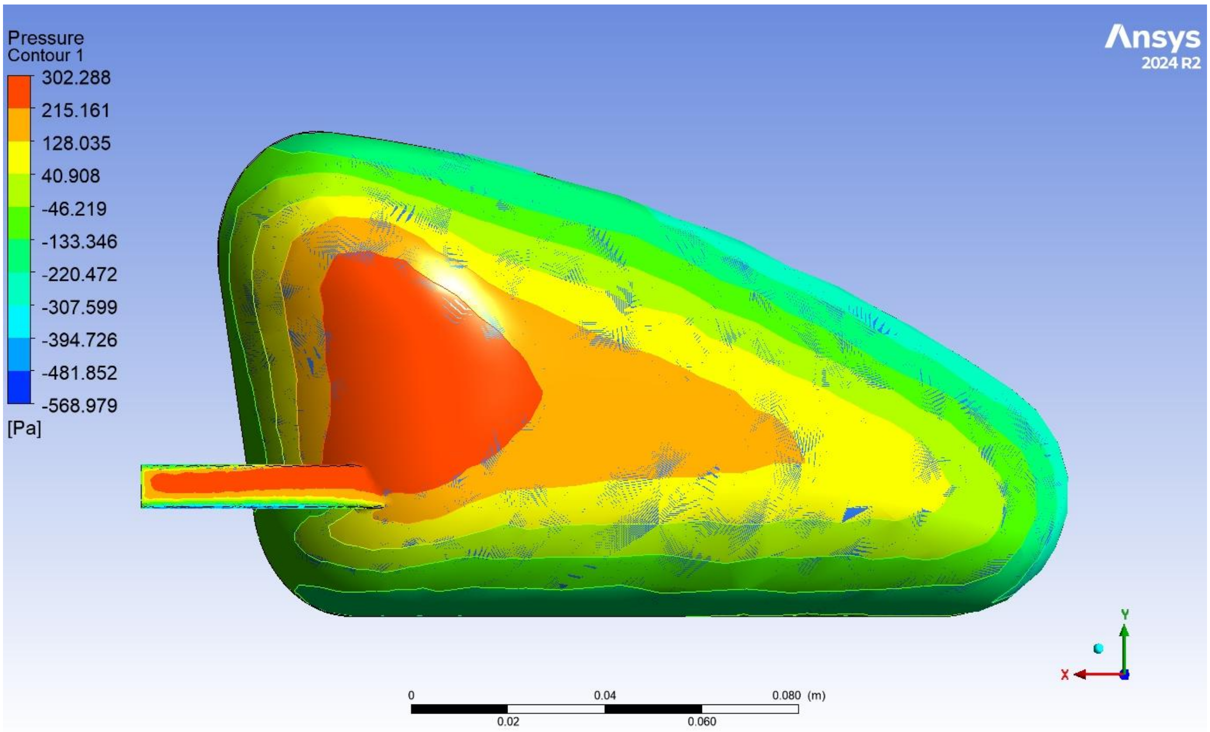

Figure 28: Pressure Contour at 35 Degrees

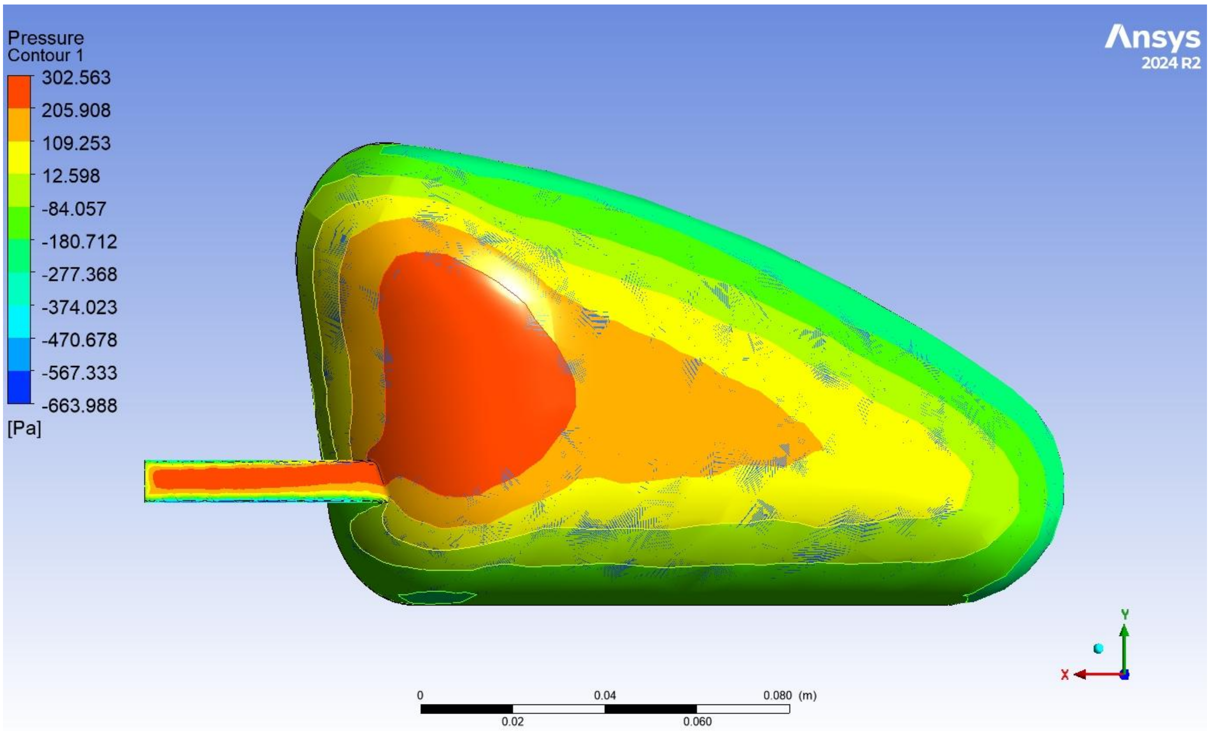

Figure 29: Pressure Contour at 40 Degrees

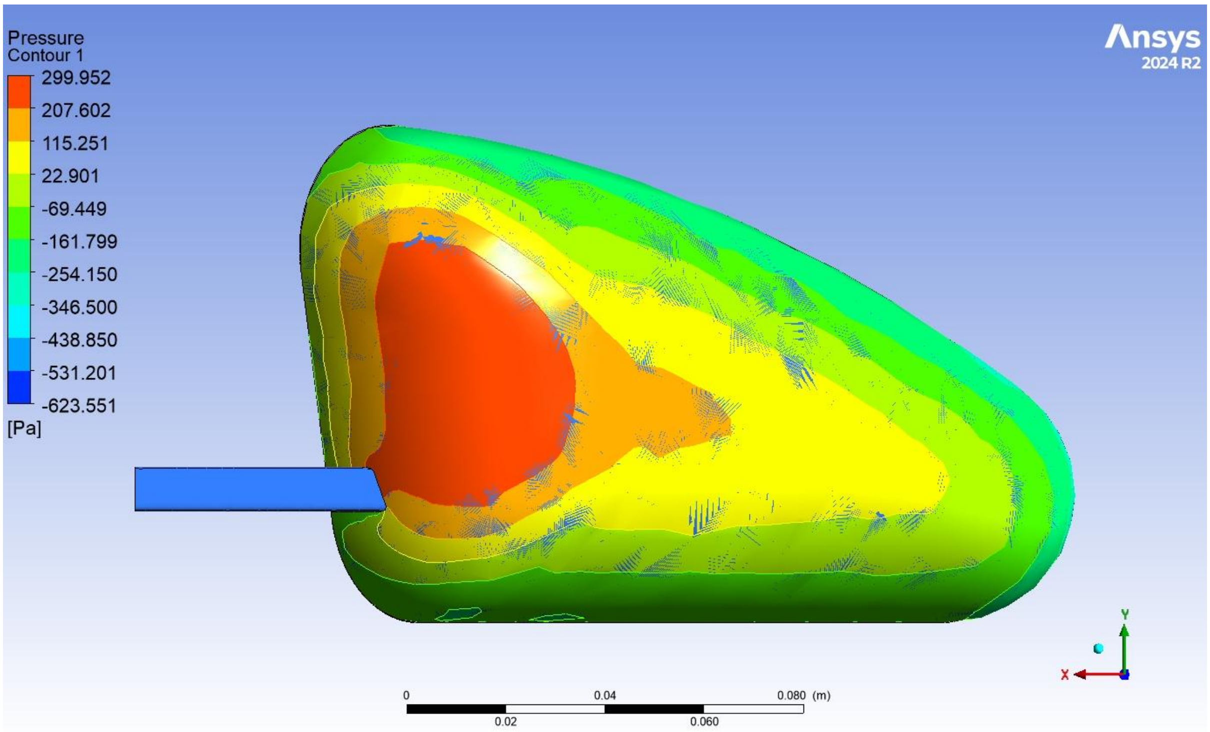

Figure 30:Pressure Contour at 40 Degrees

Table 5: Pressure Table

S.No.	Angles (Degrees)	Pressure (Pa)
1	0	304.744
2	5	299.324
3	10	304.901
4	15	307.391
5	20	302.409
6	25	299.940
7	30	300.293
8	35	302.288
9	40	302.563
10	45	299.952

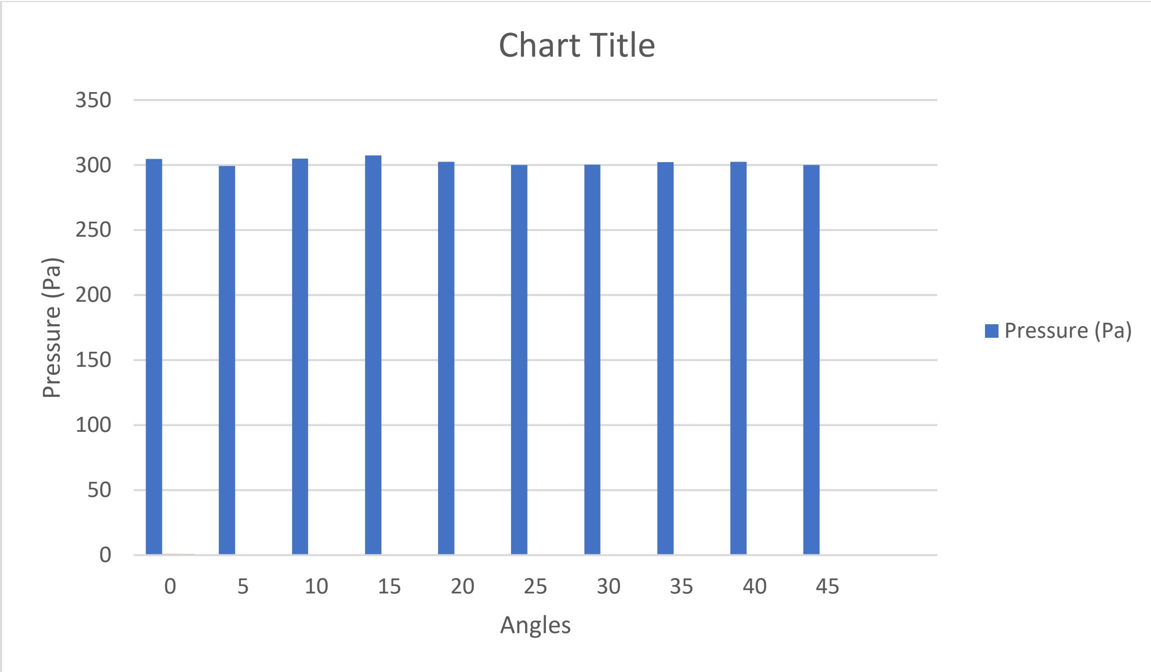

Figure 31: Pressure vs Angle Graph

This analysis examines a comprehensive dataset of acoustic pressure measurements collected across angular positions from 0 to 45 degrees in 5-degree increments, revealing the directional characteristics of a sound source. The data demonstrates pressure variations ranging from 299.324 Pa to 307.391 Pa, with a mean pressure of 302.38 Pa and a standard deviation of 2.50 Pa, indicating moderate directional variation typical of controlled acoustic sources. The maximum pressure occurs at 15 degrees (307.391 Pa) while the minimum appears at 5 degrees (299.324 Pa), suggesting a non-uniform radiation pattern with distinct directional preferences.

Chapter 5

CONCLUSIONS

While the current study provides valuable insights into the aeroacoustic performance of side view mirrors, it is important to acknowledge certain limitations and propose avenues for future research to enhance predictive accuracy and comprehensiveness.

5.1. Conclusions

- This aeroacoustics analysis of a side view mirror, conducted using ANSYS Fluent's broadband noise model, has provided quantifiable insights into the impact of vehicle speed and mirror angles/orientations on noise generation. The study confirms that aeroacoustic noise from side mirrors increases significantly with vehicle speed, becoming a dominant factor in overall cabin noise, particularly at highway speeds and especially in the quieter cabin environments of electric vehicles.
- Crucially, the analysis demonstrates that strategic design modifications, such as optimizing the mirror's base orientation (45° with respect to door) and incorporating innovative features like inner ducts, can lead to substantial reductions in sound pressure levels—up to 4 dB in some cases. These improvements are attributed to their ability to alter flow separation characteristics, reduce pressure fluctuations, and promote more homogeneous airflow around the mirror. The investigation also underscores the importance of considering psychoacoustic parameters beyond objective decibel levels, as human perception of noise is influenced by complex factors like loudness, sharpness, and roughness. Effective design, therefore, requires a holistic approach that balances objective noise reduction with subjective sound quality.
- The study reinforces the indispensable value of advanced CFD simulations, such as those performed with ANSYS Fluent, in providing critical insights for design optimization. These tools enable the virtual exploration of numerous design iterations, significantly reducing the cost and time associated with physical prototyping and testing. Despite the inherent complexities and simplifying assumptions of current broadband noise models, the simulations offer a powerful means to understand fundamental noise generation mechanisms and guide early-stage design decisions.

In conclusion, this research contributes to the understanding and mitigation of side mirror wind noise, paving the way for the development of quieter, more refined, and ultimately more comfortable automotive experiences, aligning with the evolving demands of the modern vehicle market.

Chapter 6

LIMITATION AND FUTURE SCOPE

6.1 Limitations of the Current Study

The ANSYS Fluent broadband noise models, fundamental to this analysis, rely on specific underlying assumptions, including high Reynolds number, small Mach number, isotropy of turbulence, and zero mean motion. While these assumptions simplify the problem, they may not perfectly represent the complex, anisotropic, and sometimes non-zero mean flow conditions around a side view mirror, potentially impacting the quantitative accuracy of the results. For instance, Proudman's formula also assumes a still and compact acoustic source.

The inherent gap between idealized simulation assumptions and real-world automotive aeroacoustics is a significant consideration. ANSYS Fluent's broadband noise models are built upon theoretical foundations that include simplifying assumptions such as isotropic turbulence, low Mach number, and zero mean motion. In contrast, the actual flow around an automotive side mirror is highly complex, characterized by transient, often anisotropic turbulence, significant flow separation, and intricate interactions with other vehicle components like the A-pillar. Furthermore, real-world driving conditions involve dynamic, unsteady onset flows (gusts, crosswinds) that are often not fully captured in idealized simulations. These differences between model assumptions and reality can lead to discrepancies in the simulation results. For example, RANS models, while computationally efficient, inherently struggle to accurately capture the unsteady phenomena critical for broadband noise generation. Therefore, while current CFD tools provide invaluable insights and enable significant design optimization in early stages, it is crucial to recognize the inherent limitations imposed by the underlying models and their assumptions. The simulation results should be interpreted as providing *estimates* and *trends* rather than absolute quantitative predictions, especially for highly complex phenomena. Acknowledging this gap is vital for robust engineering practice and guides future research towards developing more sophisticated models and incorporating more realistic simulation conditions to enhance predictive accuracy and reliability for practical automotive applications.

Furthermore, while higher-fidelity models like hybrid RANS/LES (e.g., SBES) were potentially employed, RANS-based approaches, if used for parts of the simulation or as a basis for the broadband models, inherently cannot fully capture the complex, unsteady broadband noise generation mechanisms. RANS models also have known limitations in accurately predicting unsteady flows, separated regions, and flows with strong curvatures. Even with advanced turbulence models, high-fidelity LES/DES simulations are computationally very expensive. This often imposes practical limitations on the size of the computational domain and the total simulation time, which can affect the ability to fully resolve all relevant turbulent length scales or accurately propagate sound to far-field listener locations.

Accurately distinguishing and predicting the acoustic component of pressure fluctuations, which is often significantly smaller in amplitude compared to the hydrodynamic component, remains a challenge. While the acoustic component is crucial for interior noise, its precise isolation and quantification can be difficult. Finally, most CFD simulations, including potentially this study, assume steady and uniform inflow conditions (e.g., constant speed, zero yaw angle). However, real-world driving environments are highly unsteady, involving gusts, crosswinds, and interactions with wakes from other vehicles. These unsteady onset conditions can significantly impact cabin noise levels and, importantly, human perception of annoyance.

6.2 Recommendations for Future Research

To address the identified limitations and advance the understanding of automotive aeroacoustics, several avenues for future research are recommended:

- **Higher-Fidelity Turbulence Modeling:** Future work should explore the application of full Large-Eddy Simulation (LES) or more advanced hybrid RANS/LES models (e.g., DDES, SBES with comprehensive validation) to achieve even more accurate resolution of the unsteady turbulent structures responsible for broadband noise generation. This would provide a more direct and physically accurate representation of the noise sources.
- **Coupled Vibro-Acoustic Simulations:** To provide a more comprehensive prediction of interior cabin noise, future studies should integrate the CFD aeroacoustic results with structural vibration (Finite Element Analysis - FEA) and interior acoustic models. This "aero-vibro-acoustic" coupling is crucial, as pressure fluctuations on the side glass induce structural vibrations that transmit noise into the cabin.
- **Investigation of Unsteady Onset Flow Conditions:** To better reflect real-world driving scenarios, future simulations should incorporate realistic unsteady inflow conditions, such as varying wind gusts, crosswinds, and transient yaw angles. This would allow for a more accurate assessment of their impact on aeroacoustic performance and, critically, on the psychoacoustic perception of noise.

- **Advanced Psychoacoustic Post-processing and Sound Design:** Further leverage of specialized tools like Ansys Sound for in-depth psychoacoustic analysis (e.g., loudness, sharpness, roughness, fluctuation strength) beyond basic SPL measurements. This can include conducting virtual listening tests and exploring sound design strategies to optimize the perceived quality of the vehicle's acoustic environment.
- **Comprehensive Experimental Validation:** Continued and more detailed experimental validation studies are essential. This includes high-resolution boundary layer measurements, advanced sound source localization techniques (e.g., microphone arrays, beamforming), and full-scale vehicle road tests to provide robust data for benchmarking and refining numerical models.

The evolution towards multi-physics, multi-scale simulation for comprehensive NVH prediction represents the next frontier. While this thesis focuses specifically on aeroacoustics, which is the study of flow-generated noise from the side mirror, wind noise is a significant component of the overall Noise, Vibration, and Harshness (NVH) profile of a vehicle. However, vehicle NVH also includes contributions from engine vibrations, road conditions, tire noise, and structural vibrations. Crucially, the pressure fluctuations generated by airflow around the side mirror and A-pillar do not just propagate as acoustic waves; they also induce structural vibrations in the side glass and door panels. This phenomenon is termed "aero-vibro-acoustics" , where the fluid dynamics (aero) excites structural dynamics (vibro), which then radiates sound (acoustics) into the cabin. To fully predict and optimize the perceived cabin noise and comfort, a purely aeroacoustic simulation is insufficient. It must be seamlessly coupled with structural dynamics (FEA for vibration) and interior acoustic models to capture the complete noise transmission path. This necessitates resolving phenomena across vastly different length and time scales, from turbulent eddies to structural resonances and acoustic wave propagation. This highlights a clear evolutionary path in engineering simulation. While this thesis provides a strong foundation in a critical aspect of automotive aeroacoustics, the ultimate goal for comprehensive NVH prediction lies in increasingly sophisticated multi-physics and multi-scale simulation frameworks. This trend moves beyond analyzing isolated phenomena to a holistic, system-level understanding of how various physical domains interact to produce the overall vehicle sound signature, which is particularly relevant for the quieter cabin environments of modern EVs.

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