WIND NOISE SIMULATION OF THE A-PILLAR AND SIDE VIEW MIRROR USING GENERIC VEHICLE MODEL, DrivAer

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DEDICATION

This thesis is dedicated to
My beloved mother
My beloved father
My special youngest brother
Family members
That always make my life so meaningful and cheerful because of their love

This thesis also is dedicated to
a very responsible, kind-hearted, charming,
young talented manager
Tharveen a/l Puroshtuman

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ABSTRACT

Vehicle interior noise level has now become one of the indicators of driving comfort. However, the generation of noise is a complex phenomenon where it involves various sound sources with different ways of radiation. This research focuses on the generation of wind noise from the A-pillar and side-view mirror of a generic vehicle model known as DrivAer, based on the physical flow behaviour. The main objective of this study is to find the physical flow that causes the generation of A-pillar wind noise and to propose the relation between the A-pillar angles and length of side-view mirror with wind noise generation. This study is conducted numerically at a Reynolds number of $Re = 12.17 \times 10^6$, with respect to the length of DrivAer model. The noise source is obtained from the incompressible Unsteady Reynolds Averaged Navier-Stokes (URANS); and the noise radiation is predicted using an acoustic analogy based on Curle's equations. Reliability and validity of the calculations are tested by comparing the basic model with data of experimental studies from previous researchers, whereby the result indicates an almost similar outcome. A total of eight main cases have been studied. These cases include A-pillar cases of varying angles which are 61°, 58° (baseline case), 50° and 42°; and four side view mirror cases of varying gaps which are 180mm,190mm, 230mm and 240mm. Results have shown that increasing the A-pillar angle makes the sound pressure level louder. 84.33 dB is generated when the A-pillar angle is at 61° and 76.41 dB is generated when the A-pillar angle is at 42°. The formation of the A-pillar conical vortex formed along the A-pillar has been found responsible for the generation of the wind noise. In the case of different side-view mirror position, in which the A-pillar angle remains constant, results for all cases are almost the same according to the A-pillar sound pressure level and sound source level results, in which the noise generated is about 82 dB for all cases of side-view mirror.

ABSTRAK

Tahap kebisingan dalaman sesebuah kenderaan kini menjadi salah satu petunjuk terhadap keselesaan pemanduan. Walau bagaimanapun, penghasilan kebisingan merupakan fenomena yang kompleks di mana penghasilannya melibatkan pelbagai sumber bunyi dengan cara radiasi yang berbeza. Penyelidikan ini menumpukan kepada penjanaan kebisingan daripada A-pillar dan cermin sisi kenderaan generik yang dikenali sebagai DrivAer, berdasarkan kelakuan fizikal aliran angin yang melepasinya. Objektif utama penyelidikan ini adalah untuk mengenal pasti aliran fizikal yang bertanggungjawab kepada penjanaan kebisingan daripada A-pillar dan cermin sisi kenderaan, dan juga untuk menghubung kaitkan antara sudut A-pillar dan kepanjangan cermin sisi dalam penghasilan kebisingan angin. Kajian ini telah dijalankan secara numeral pada nombor Reynolds $Re = 12.17 \times 10^6$, berdasarkan kepada panjang model DrivAer dengan menggunakan persamaan *Unsteady Reynolds Averaged Navier-Stokes* (URANS) dan pengiraan kebisingan telah dilakukan dengan menggunakan teori Curle. Data kajian daripada model dasar telah dibandingkan dengan data kajian eksperimen yang telah dijalankan oleh penyelidik terdahulu untuk tujuan pengesahan dan kebolehpercayaan pengiraan. Data kajian telah menunjukkan hasil yang hampir sama seperti eksperimen yang telah dijalankan penyelidik terdahulu. Terdapat lapan jumlah keseluruhan kes yang dijalankan dalam kajian ini. Kes-kes tersebut adalah kes A-pilar dengan sudut yang berbeza iaitu 61°, 58° (model dasar), 50° and 42° dan juga empat kes yang melibatkan cermin sisi yang berlainan panjang iaitu 180mm,190mm, 230mm and 240mm. Hasil kajian mendapati bahawa semakin landai sudut A-pillar, semakin tinggi tahap kebisingan yang dihasilkan. 84.33dB tahap kebisingan telah dihasilkan oleh sudut A-pillar 61° dan 76.41dB dihasilkan daripada sudut A-pillar 42°. Kajian juga mendapati bahawa pembentukan konikal vorteks A-pillar sepanjang A-pillar memainkan peranan dalam penghasilan kebisingan angin. Bagi kes cermin sisi yang berbeza panjang pula, di mana sudut A-pillar ditetapkan pada sudut yang sama, hasil kajian mendapati kesemua kes menghasilkan tahap kebisingan yang hampir sama, di mana tahap kebisingan yang terhasil adalah dalam lingkungan 82 dB.

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LIST OF ABBREVIATIONS

CFD	-	Computational Fluid Dynamics
DES	-	Detached Eddy Simulation
DDES	-	Delayed Detached Eddy Simulation
LES	-	Large Eddy Simulation
URANS	-	Unsteady Reynolds Averaged Navier-Stokes
DNS	-	Direct Numerical Simulation
TUM	-	Technology University of Munchen
SVM	-	Side View Mirror
SPL	-	Sound Pressure Level
SSL	-	Sound Source Level
SEA	-	Statistical Energy Analysis
LBM	-	Lattice Boltzmann method
SST	-	Shear Stress Transport
PSD	-	Power Spectrum Density

LIST OF SYMBOLS

dB	-	Decibels
Hz	-	Hertz
A	-	Characteristics area of bluff body
L	-	Length, Lift force
D	-	Drag force
W	-	Width
H	-	Height
R	-	Distance of observer
U_∞	-	Upstream velocity
F	-	Force
u	-	Velocity
p	-	Pressure
St	-	Strouhal number
λ	-	Wavelength
Re	-	Reynolds Number
x	-	Streamwise direction
y	-	Crosswise direction
z	-	Spanwise direction
v	-	Kinematic viscosity of fluid
f	-	Frequency
C_o	-	Speed of sound

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CHAPTER 1

INTRODUCTION

1.1 Research Background

According to a fact, a healthy human ear is capable of hearing sounds with frequencies in the range of 20 Hz to 20 000 Hz. Nevertheless, the ability to hear sounds at higher frequency range declines with age. The frequencies above 20 000 Hz or 20 kHz is called as ultrasonic sound and it is inaudible to a human being. Meanwhile sounds lower than 20 Hz is known as the infrasonic sound, in which it cannot be heard, but can be felt only if it is sufficiently strong. Sound may be pleasant or unpleasant, in which unpleasant sound will be called as noise [1].

Noise that is known to cause annoyance, may lead to hearing impairment and may interfere communications. Nowadays, similar to the air and water pollutions, noise also has been recognised as a major environmental pollution. Rapid industrialisation of motorisation and aviation has clearly resulted in the rapid increases of noise pollution and it becomes of significant important. Not missed, Malaysia also always looking forward for a better way in reducing the nuisance from all possible noise sources. It was reported in *The Star*, a total of 132 complaints were lodged with the Environment Department (DOE) in 2015 about the noise pollution that comes from many sources such as construction, use of roads, railways and airports [2].

Basically, the noise level perceived by humans is depending on the surrounding possible noise sources as shown in Figure 1.1. Road traffic is the most common noise pollution source because it is the most pervasive, where their noise levels could achieved about 90 to 120 dB depends on the heaviness of the traffic. A survey on noise environment in Roorkee, India, conducted by Rajeev [3] also has found that 87 percent of the community from various ages are affected by the noise emanating from the automobiles.

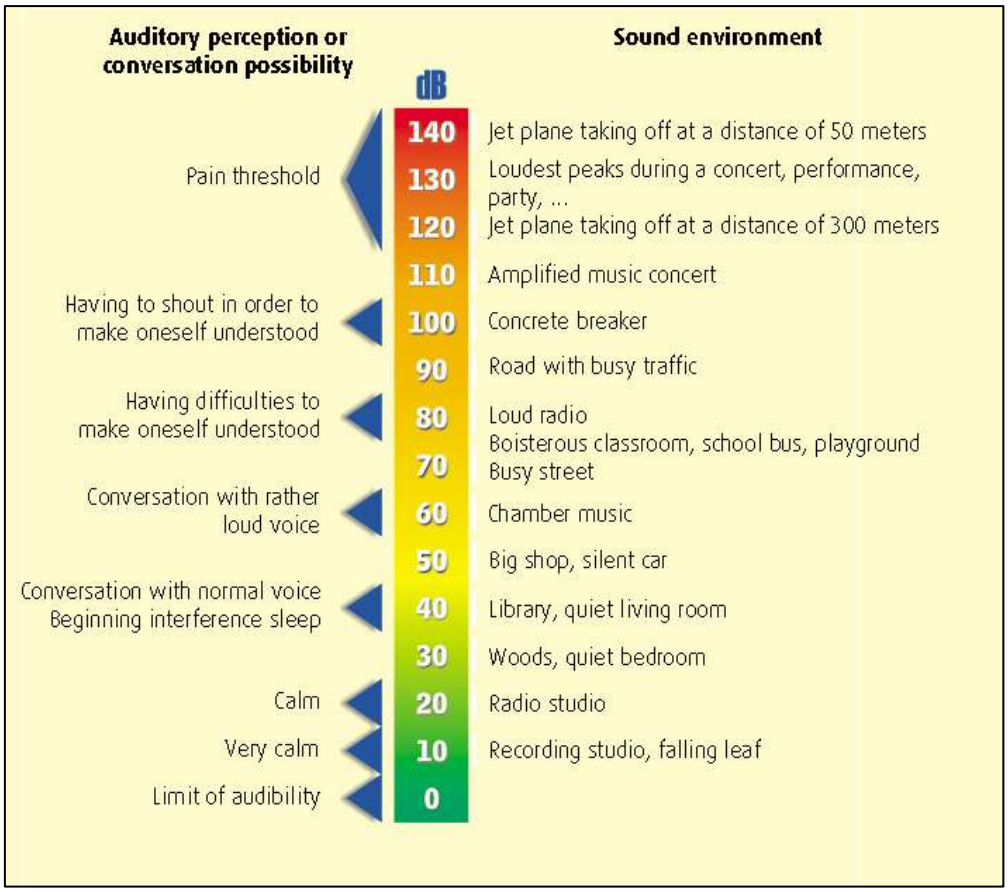

Figure 1.1 Noise level based on different situations

When it comes about the road traffic, passenger cars are seem to be one of the road vehicle that contributes significantly to the noise pollution. This is due to the number of passenger cars that outnumbers the other road vehicles especially at high speeds. One of the noise sources generated by passenger car is the aerodynamic noise. Aerodynamic noise is the mechanism of production of noise that arises almost entirely from the airflow instabilities. For moving vehicles, this is also known as the wind noise. The generation of wind noise is one of the crucial problem. Examples include the wind noise emitted from flow passes over pantograph system of high speed train when its speed exceeds 320km/h and the landing gear system of an aircraft. Also, the radiated noise from the aircraft undercarriage is one of the dominant noise source when an aircraft is in the final approach for landing [4, 5].

Deeply focusing on the passenger car problems, the noise emitted from a moving car is a total contribution mainly from three major noise sources. They are

from the engine (propulsion noise), tyre (rolling noise) and turbulent flow (wind noise). While cruising at high speed, mostly over 80km/h, the wind noise will dominates the total contribution of noise while the other two noise sources reduced significantly [6]. This is due to the fact that the wind noise increases as the speed of car increases. The increase in wind noise is proportional to the order of v^6, while the other two noise sources are proportional to the order of v^1 to v^3. Here, v is the cruising speed of the cars. Figure 1.2 clearly explains the situation based on the relationship between the speed of cars and its sound power level.

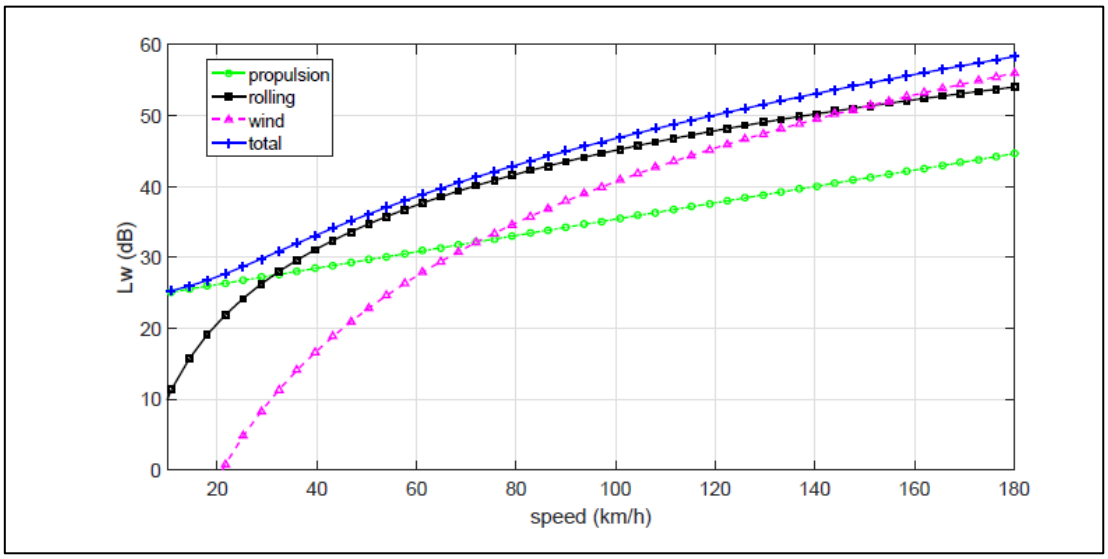

Figure 1.2 Relationship between the speed of car and the sound power level for each noise sources [7]

Theoretically, the change in sound power level with respect to the speed of the car for all type of noise sources can be estimated as follows [8, 9];

$$L_{w_{propulsion}}(v,a) = A_{propulsion} + B_{propulsion}\left(\frac{v - v_{ref}}{v_{ref}}\right) + C_{propulsion}.a \quad (1.1)$$

$$L_{w_{rolling}}(v) = A_{rolling} + B_{rolling}.\log_{10}\left(\frac{v}{v_{ref}}\right) \quad (1.2)$$

$$L_{w_{aero}}(v) = 10\log_{10}\left[\frac{A_{aero}\left(\frac{v^n}{c_0^{n-3}}\right)}{1\times 10^{-12}}\right] \quad (1.3)$$

Here A, B and C are constant. Those constant values are governed by the condition of the road, type of car and geometry. In the Equation (1.1) to Equation (1.3), a is the acceleration of the car, c_0 is the speed of sound and n is the type of wind sources. The type of wind sources are varied between the ranges of 4 to 8 that indicates the power level of sound. According to Lighthill [10] $n = 4$ indicates as monopole type of wind sources, $n = 6$ for dipole and $n = 8$ for quadrupole type of wind sources.

In a long driving trip, continuous exposure to wind noise can cause fatigue and discomfort to the vehicle occupants especially the driver. The characteristic of the wind noise of a passenger car depends on several factors. They are the shape of the car, its cruising speed, wind direction flow towards the car and the natural wind condition. Among all of those factors, the shape of the car is the most important and seen as the only controllable factor for the wind noise. Since 1921, car manufacturers have given a much focus on the design of the car to be more attractive and its aerodynamic performance in order to reduce the fuel consumption. However, on late 1960s, as the car's speed has progressively increased in line with high aerodynamic performance, researchers and engineers become aware that the wind noise is increasing with the speed. This is due to the wake generated around the exterior car component such as the A-pillar and the side view mirror. When the airflow passed around the A-pillar and the side view mirror, vortex is generated and the pressure fluctuations from the vortex shedding generate wind noise. Hucho [11] stated that when a car moving at 150 km/h with 5500 rpm engine speed, 78.5 dB from the total noise of 85 dB that are measured at the driver's ear, is generated by the wind noise. Therefore, it is important to control the generated wind noise in order to reduce the total noise generated by the car.

Studies of noise generation are particularly important for passenger comfort and also for reducing the environmental noise pollution. As passenger comfort becomes increasingly important, noise reduction has to be considered in the early

design process and need to be investigated numerically in the early design stage to avoid a poor design choices [6, 12]. Therefore, it is important to have a better understanding on the wind noise generation on a passenger car so that a practical method can be applied to reduce the noise being generated.

Recently, general investigations of the flow field around the A-pillar and side view mirror are strongly focused on simplified car models, such as the Ahmed body [13] and the SAE model [14]. Both models provide a better understanding on identifying and analysing the basic flow structures by reducing the interference effects between different areas of vehicles. Previous works based on the simplified models have provide many information on numerical and experimental that is suitable for the validation purposes for further study. However, the shape of this car is no longer relevant to the current car design, where a more aerodynamic shape is more prominent. In order to close this gap, the Institute of Aerodynamics and Fluid Mechanics of the Technical University Munchen (TUM), in cooperation with Audi AG and BMW Group have proposed a realistic generic car model, which is called the DrivAer [15].

DrivAer body is a general vehicle model that is purposely designed to have a similar exterior design feature to most production cars. The geometry which is made available to the public by TUM, has been used in many studies previously as a benchmark case. Thus, the DrivAer model will be used in this study as it reflects to a realistic production car. Many studies on DrivAer for the exterior aerodynamics have been done previously, but the study on the wind noise from the A-pillar and side view mirror of DrivAer is still not yet available. DrivAer, a sedan-typed car, is divided into three pillar that is known as the A, B and C pillar as shown in Figure 1.3. Therefore, current study is only focus on the A-pillar part in which side view mirror part also will be included.

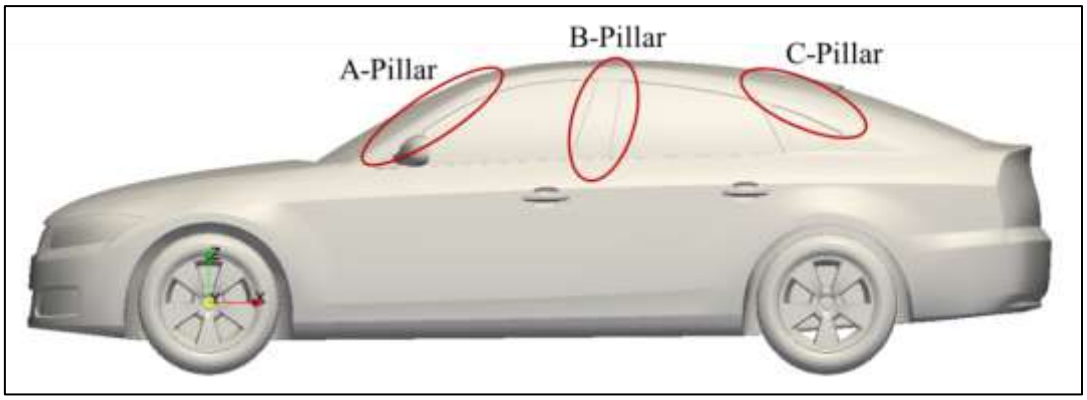

Figure 1.3 Three pillar configurations of DrivAer Fastback, a sedan-typed car model

1.2 Problem Statement

Due to the customers demand for a low level of cabin noise while at the same time keeping the cost of the car to a minimum, a study on the noise generation is needed in order to mitigate its noise source generation. At high speed, wind noise can dominates the total interior noise in which has caused discomfort for the passengers and the driver especially. Located near to the driver, A-pillar and side view mirror are the regions where the highly separated and turbulent flow are observed [14] and the relation and effects of the behaviour of flow over A-pillar and side view mirror on a realistic car are still not well understand.

The airflow around the A-pillar and side view mirror is very complex due to its turbulent nature and heavily governed by the unsteadiness behaviour of the fluids that thus contributes to the generation of wind noise at once [16] . Although, there are several studies on the wind noise generated by the flow over the A-pillar and side view mirror, there still a question on the reduction of noise level when the angle of A-pillar and length of side view mirror are varied on a real production car.

It is found that only several publications studied the wind noise associated with the flow from the A-pillar and side view mirror of a passenger car. Thus, the generation of wind noise over A-pillar and side view mirror is still not well understood especially

for the realistic production of car such as DrivAer model that would be used in this study. Nowadays, passenger comfort has becoming more important and therefore it is important to consider the automotive design in the early stage of process to make a reduction on noise for the car manufacturers as well as to cut the experimental cost and simultaneously improve its productivity and performance [17].

1.3 Research Objective

The objectives of this research are :

(a) To investigate the physical behaviour of wind generation on different slanted angle of the A-pillar and different length of the side view mirror of a realistic generic vehicle model called the DrivAer.

(b) To analyze the most relevant slanted angle of the A-pillar of DrivAer that generates the lowest noise level.

(c) To determine the best length of the side view mirror of DrivAer that produce the lowest level of wind noise.

1.4 Research Scope and Limitations

The scopes of this research are as follows:

1. A realistic generic vehicle model, DrivAer is chosen as the problem geometry with the focused will be given on the wind noise generation on the A-pillar and side view mirror based on the flow characteristics.

2. The noise sources are primarily due to the pressure fluctuations and fluctuating aerodynamic forces which are drag, lift and side force.

3. The sound sources are considered as compact when the sound wavelength, λ, is larger than the dimension of the body, D ($\lambda \gg D$).

4. Curle's equation is used in this study to calculate the noise radiation. In the Curle's equation, the noise generation due to pressure fluctuation on the surface of a rigid body is considered.

5. The research is only focused on the simulation method due to the complexity to separate the other noise sources from the wind noise in a real on road experiment.

This research is limited on noise generated from the A-pillar and side view mirror of symmetry body of the DrivAer model instead of a whole DrivAer body or other parts of car component such as the engine, radiator or tyres. The angle of A-pillar needs to follow the standard of its maximum and minimum of real production cars based on the standard for safety regulation as stated in Table 1.1 below. This is because the A-pillar angle and its width affect the structure of the rooftop of the production cars. Moreover, if the angle of the A-pillar is too small, the sunlight penetration would be directly to the driver and also to the front passenger.

Table 1.1 Standard European vehicles measurement regulations [18, 19, 20]

Measurement Description	**Mean**	**Min**	**Max**
A-pillar inclination from vertical (°)	57	40	61
Position of side view mirror (mm)	Must not projected more than 250 mm beyond the overall width of the vehicle measured without mirror.		

1.5 Significance of Research

Noise is not just unpleasant. It can be a major expense and productivity lost. With the increased speed of the vehicles, noise has become one of the environmental problems that need to be focused on. If this situation can be handled in a certain part, it would give a great impact on the driver and passenger while driving.

The study on wind noise radiated from the A-pillar and side view mirror of a realistic car can discover how much the level of noise propagated towards the driver. Reduction on noise level from A-pillar and side view mirror is expected to develop a comfort environment to the driver and passenger especially while driving at high speed and during a long journey. The study of wind noise generation based on the behaviour of flow that passing over the A-pillar and side view mirror may give the ideas to the designers and engineers to predict in advance their designed car at the early design stage.

Next, to signify the purpose of this study, studies about noise are not only understanding its propagation mechanism, but also to investigate the most effective method on controlling and reducing the noise. Based on the previous study, there are only several studies [14, 21–24] that systematically investigate the effects of changing the angle of the A-pillar and manipulating the length of side view mirror in order to mitigate its noise sources. However, the study only limited to simplified car model. With the current study, a more realistic car model is used, thus manufacturers able to focus on the best A-pillar angle and length of side view mirror that generate low level of noise.

The study would be beneficial due to the use of a realistic car model that able to explain a detailed flow structure around A-pillar and side view mirror that create noise, compared to a simplified car model such as SAE Type 4 model, used in most of the past studies. The realistic car model used in this study which is DrivAer, can provide a more reliable data or can be as a guideline for manufacturers on wind noise generation from the A-pillar and side view mirror.

1.6 Thesis Outline

This thesis is divided into six chapters. Chapter 1 provides basic introduction of the research by introducing the background of research, problem statement, the objectives of research, research scopes and limitations, and lastly the significance of research.

Chapter 2 discusses the literature review related to this study in detail including the review on the past studies which are important as a guideline for current study. Research gaps will be identified and highlighted based on the reviews.

Methodology for current study is explained in Chapter 3. It includes the methodology for flow simulation, noise calculation and sound transmission loss. Methods involved for flow simulation are the governing equations, turbulence model, wall function, problem geometry, computational domain, boundary conditions and computing machine. Method for noise calculation is explained starting from the basic acoustic analogy, followed by Lighthill's acoustic analogy, and finally the Curle's theory that is used in current study. Next, explanation for sound transmission loss method and finally the research flow is presented in a Gantt chart.

Chapter 4 describes the computational validation study for flow over DrivAer and the noise generated. This chapter is important in order to make sure that the method implemented in current study is correct and suitable for further progress by comparing the results from the validation case study with the previous available results. This includes the validation for flow simulation and noise calculation.

Chapter 5 presents the main findings of current study in which all the results obtained will be analysed and discussed. The results include the case of wind noise generated from both, the A-pillar and the side view mirror that are presented in the form of tables, graphs and flow visualisations.

Chapter 6 summarises the current study with conclusions and recommendation for future works.

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