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Feasibility Study for the Development of Small Scale Low Speed Wind Tunnel for Supermileage Prototype Car

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Abstract

This paper presents the design and construction of a small-scale low-speed open circuit wind tunnel suitable for experimental testing and analysis of aerodynamic phenomena. The wind tunnel is specifically designed for low-speed applications, focusing on flows within velocities of 35 meters per second with turbulence conditions below 10 percent. The design process of a wind tunnel involves considerations such as dimensions, design parameters, and instrumentation to ensure accurate flow measurements, with key components including a settling chamber, contraction section, test section, diffuser, and drive system working together to remove disturbances, create uniform flow, minimize blockage effects, and generate required airflow for accurate aerodynamic testing. This paper highlights the design considerations, key components, construction techniques, and the significance of the wind tunnel for aerodynamic testing, validation of simulations, and education. The designed wind tunnel is capable of producing controlled and repeatable low-speed flow conditions, making it suitable for a wide range of applications, including aerodynamic testing of scaled- down models, validation of Computational Fluid Dynamics (CFD) simulations, and educational purposes. The small-scale design allows for cost-effective construction and operation while maintaining reliable results.

Keywords: *Contraction, Diffuser, Test Section, Settling Chamber, Wind Tunnel*

1.0 Introduction

The efficient design of a car involves multiple factors, and among them, the significance of aerodynamic performance cannot be overlooked. While theoretical knowledge and software testing are employed to create models and evaluate their aero- dynamic capabilities, it is crucial to validate their performance in the presence of real physical forces. This necessitates the utilization of wind tunnels.

A wind tunnel serves as a valuable tool in aerodynamic research, enabling the examination of the impact of wind on the surface of solid objects. Typically, a wind tunnel comprises components such as a motor, fan unit, settling chamber, contraction cone, test section, and diffuser. This setup accurately simulates the drag effects experienced by a moving object in a controlled environment. The primary objective of a wind tunnel is to analyze the aerodynamic performance and efficiency of a model, aiding in the design process by identifying areas for improvement or correction.

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This study specifically focuses on determining the optimal design specifications for a wind tunnel dedicated to testing vehicles for supermileage, particularly under low-speed conditions. Additionally, the study aims to enhance the existing basic design employed for the supermileage vehicle.

2.0 Literature Survey

R. D. Mehta and P. Bradshaw[1] in "Design Rules for small low speed wind tunnels" discuss the design guidelines for a low-speed open return wind tunnel and its components. The authors emphasize the advantages of utilizing a centrifugal blower type over an axial suction fan-type wind tunnel. They specifically highlight the benefits of open-circuit tunnels, which include space and cost savings, as well as reduced vulnerability to temperature changes. The use of centrifugal blowers is preferred due to their ability to deliver optimal performance across a wide range of loads. However, the authors also acknowledge the disadvantages of open-circuit tunnels, such as pressure differences and spurious jets, which can be mitigated by obstructing the tunnel outlet.

P. Bradshaw and R. C. Pankhurst[2] in "The design of low speed wind tunnels" present a thorough exploration of aerodynamic and structural design considerations from the viewpoint of aspiring tunnel designers. The paper delves into contemporary practices and showcases distinctive characteristics of numerous existing tunnels through illustrations and data, encompassing approximately thirty representative tunnels of varying ages. While the primary emphasis is on low-speed tunnels constructed using wood, the principles and considerations discussed can be extrapolated to inform the design of larger or higher-speed tunnels.

Jewel B Barlow *et al.*[3] in "Low speed wind tunnel testing" put forth a proposal to address secondary flow issues in the corners of rectangular contractions. They suggest the installation of a 45-degree fillet at the beginning of the contraction, resulting in an octagonal shape, which helps minimize such problems. The length of the test section in wind tunnels primarily focused on aeronautical research varies between one to two times the major dimension of the section. Due to the high speed involved, there are significant power losses within the test section. Therefore, by keeping the test section length short, power can be conserved. However, it should be noted that contractions do not provide a uniform velocity distribution at the beginning of the test section. To address this, a settling chamber length of approximately 0.5 times the inlet diameter is commonly employed.

R. D. Mehta[4] in "Turbulent boundary layer perturbed by a screen" investigated the effects of screens on turbulent flow, specifically turbulent boundary layers. The research found that screens can reorganize the turbulence and reduce its thickness, making it less prone to separation. Plastic screens differ from metal screens in their aerodynamic properties. The inclination of the screen affects the pressure drop coefficient and causes an overshoot in mean velocity near the boundary-layer edge. Screens with an open-area ratio below 0.57 produce prominent ripplings. Screens with open-area ratios below 0.5-0.6 result in unstable flow with spatial and temporal variations. Metal screens generate higher non uniformities compared to plastic screens in regions beyond the boundary layer due to differences in their weaving properties.

Mauro S. *et al.*[5] in "Small-Scale Open-Circuit Wind Tunnel: Design Criteria, Construction and Calibration" constructed a small-scale open-loop wind tunnel and conducted qualification tests using a Particle Image Velocimetry experimental setup. The experimental results revealed that the wind tunnel had a test section flow velocity of 6 m/s, accompanied by a relatively low turbulence level of approximately 0.4 percent. However, a slight increase in turbulence level was ob- served along the test section. The highest measured turbulence intensity, reaching around 1 percent, was found at the outlet of the test section. The researchers attributed this increase in turbulence intensity to the interaction between the fan flow structure and the flow-field within the test section. To mitigate this issue, they proposed extending the length of the wind tunnel and incorporating a settling chamber between the first diffuser and the fan section, which could potentially alleviate the undesired turbulence levels.

J. H. Bell and R. D. Mehta[6] in "Contraction Design for Small Low- Speed Wind Tunnels" developed a design procedure for small, low-speed wind tunnels, employing an iterative approach to optimize the performance of contractions. The procedure initiates by utilizing a three-dimensional numerical panel method to calculate the potential flow field and pres- sure distributions along the contraction walls. Subsequently, these pressure or velocity distributions are inputted into two- dimensional boundary layer codes to analyze the behavior of the boundary layers along the walls. The study demonstrates that, for successful designs of small, low-speed contractions, assuming a laminar boundary layer starting from stagnation conditions at the contraction entry and remaining laminar throughout the passage is a valid assumption. This assumption is supported by comparing the predicted boundary layer data at the contraction exit with the measured data from existing wind tunnels. The results indicate that the measured boundary layer momentum thicknesses at the exit of four existing contractions, including two three-dimensional contractions, were found to be within 10 percent of the predicted values, with the predicted values generally being lower. Among the investigated contraction wall shapes, the design based on a fifth-order polynomial was selected for implementation in a newly designed mixing layer wind tunnel.

J. E. Sargison *et al.*[7] in "Design and Calibration of a wind tunnel with a two dimensional contraction" undertook the redesign of a laboratory wind tunnel for the purpose of conducting turbine blade cooling experiments. The main focus of their redesign was the two-dimensional contraction section, which was shaped using a sixth-order polynomial. This research paper provides an overview of the design optimization process, in which Computational Fluid Dynamics (CFD) was employed to model the contraction. The utilization of CFD enabled the exploration of a wider range of shapes, ultimately leading to the selection of a sixth-order polynomial profile. The study focused on varying two key parameters of the profile: the location of the point of inflection and the curvature at the contraction inlet. The investigation revealed that the most favorable outcome, characterized by a uniform velocity profile at the inlet to the working section and the prevention of flow separation within the contraction, was achieved when the point of inflection was positioned as far downstream as possible.

Ahmed D. E. and Eljack E. M.[8] in "Optimization of Model Wind Tunnel Contraction using CFD" utilized a sixth-order polynomial profile with six conditions to determine the polynomial coefficients. The study considered five different inflection points and performed numerical simulations at a Reynolds number of 1.3 x 106. The optimization parameters focused on were the boundary layer thickness, static pressure, and secondary flow. The results indicated that moving the inflection point downstream resulted in reduced boundary layer thickness and improved flow quality towards the test section exit. However, it also led to increased static pressure drop across the contraction and poorer flow characteristics at the test section inlet. Consequently, the researchers concluded that the optimal position for the inflection point was in the center of the contraction, resulting in an optimal profile represented by a fifth-order polynomial. This configuration achieved a balance by reducing boundary layer thickness and improving flow quality while avoiding excessive static pressure drop and unfavorable flow characteristics at the test section inlet.

Miguel A., *et al*.[9] in "Design Methodology for a Quick and Low Cost Wind Tunnel" introduced a method for the rapid design of affordable wind tunnels suitable for low-speed applications in the fields of aeronautics and civil engineering. The proposed methodology enables designers to obtain a quick and approximate estimation of the wind tunnel size based on the given main design parameters. Additionally, guidelines are provided for selecting the secondary design parameters. To address cost considerations in both design and construction, the authors suggest the utilization of a multi-fan power plant and rectangular duct sections. These measures aim to optimize efficiency while minimizing expenses associated with the wind tunnel project.

Y. Hussain *et al.*[10] in "Design, Construction and Testing Of Low Speed Wind Tunnel With Its Measurement and Inspection Devices" have successfully designed, manufactured, and constructed a low-speed open circuit wind tunnel. The paper is divided into two parts, with the first part focusing on design calculations, simulations, and the construction process, while the second part covers testing and calibration. The wind tunnel features a test section with a cross-sectional area of 0.7 x 0.7 m^2 and a length of 1.5 m. It is capable of achieving a maximum speed of approximately 70 m/s when the test section is empty. To ensure minimal flow disturbances, three screens are strategically placed within the wind tunnel. The design philosophy is extensively discussed, and the methods used for wind tunnel calculations are outlined. ANSYS simulations are employed to validate the absence of flow separation along the wind tunnel. The paper provides a detailed account of the construction steps undertaken, showcasing the significant progress made in bringing the wind tunnel to completion.

Mahesh K. Panda and Amiya K. Samanta[11] in "Design of Low Cost Open Circuit Wind Tunnel-A Case Study" de- signed a low-cost open circuit wind tunnel to achieve a flow velocity of 25 m/s at the test section. They utilized a straight- walled contraction instead of a curved one, compensating for it by increasing the length of the contraction. The test section was a square with a side length of 500 mm, and the exit diffuser transitioned from a square to an octagon with a side length of 311 mm. The power requirement and pressure drops in the test section were calculated based on these design parameters. The study provides a concise account of the design process, focusing on cost-effectiveness and achieving the desired performance for the wind tunnel.

Alaa A. Kareem *et al.*[12] in "Aerodynamic Study Of Low-Speed Wind Tunnel Contraction Section : Design and Manufacturing" aimed to improve the visualization capabilities of an existing subsonic open-section smoke tunnel located at AL- Nahrain University/College of Engineering. The focus was on modifying the contraction section to optimize airflow properties within the test section. The analysis compared the original contraction section with several suggested new profiles, represented by different polynomial orders (6th, 7th, 8th, 9th, and 10th). Emphasizing the 9th-order profile, the study conducted experiments with four different inflection points (0.5L, 0.55L, 0.6L, and 0.65L), using a scaled-down model of the original smoke tunnel to validate the numerical results. This allowed direct observation of the new contraction's impact on the flow within the test section. The findings indicated that the most optimal contraction configuration for the targeted smoke tunnel was a 9th-order wall profile with an inflection point located at 0.65L and a length of 0.93m. These results highlight the improvements achieved by the modified contraction section in enhancing the visualization capabilities of the smoke tunnel.

Zelieus Namirian *et al.*[13] in "Modeling and Wind Flow Analysis of an Open Type Subsonic Wind Tunnel" focused on designing a small open-circuit wind tunnel, specifically an Eiffel Type, for subsonic low-speed aeromechanics research. The main objective was to replicate real-world airflow conditions accurately and measure aerodynamic forces and pressure distribution. The study involved fabricating various components of the wind tunnel, including the Test Section, contraction cone, diffuser, drive system, and settling chamber. The project was successfully completed, providing a valuable tool for conducting aero-mechanics research.

R. A. Siregar and K. Umurani[14] in "Laboratory Development of low speed wind tunnel for educational purposes" described the design and development of a low-speed open-type wind tunnel for educational purposes. The wind tunnel is capable of achieving wind speeds up to 20 m/s, with a maximum turbulent intensity of 5 percent. The test chamber has dimensions of 0.4 x 0.4 m^2 and is equipped with a 0.7 m axial fan driven by a 3 hp motor. The wind tunnel was found to be suit- able for both demonstrations and research applications.

Cattafesta L. *et al.*[15] in "Fundamentals of Wind-Tunnel Design". The paper emphasizes the importance of wind tunnels as tools for acquiring data on flow characteristics over scaled or full-scale models. It explores the research objectives and specific measurement requirements that guide the design process, while taking into account limitations posed by factors such as space, budget, and power. The guidelines provided encompass key components of wind tunnels, including flow conditioners, contraction sections, test sections, diffusers, drive systems, and optional elements. Furthermore, the paper briefly outlines procedures for facility characterization, including the assessment of flow uniformity, turbulence intensity, and background noise and vibration levels. The publication serves as a comprehensive resource for understanding the design considerations and processes involved in constructing low-speed wind tunnels.

Nelton Koo Chwee Yang[16] in "Design of Wind Tunnel (Fluid Flow Analysis)" designed and fabricated a small-scale low-speed wind tunnel for conducting experiments on the drag coefficient of a sphere. The wind tunnel design was created using Computer-Aided Drawing (CAD) with Solid Work software. Experimental measurements of the drag force on the sphere were conducted using an integral balance system, while the velocity of the air stream was measured using a Pitot tube. Classical equations of fluid mechanics were applied to process the collected data and determine the drag coefficient. Visual observations of the fluid flow around the sphere were obtained using white smoke, and flow analysis in the test section was demonstrated using strings. The experimental results were compared with existing published data within the tested range to evaluate their accuracy and validity.

3.0 Methodology

In the feasibility study and conceptual design phase, extensive research was conducted to gain a comprehensive under- standing of different types of wind tunnels, their purpose, typical configurations, and the underlying aerodynamics principles. Based on the specific size and velocity requirements, design constraints were identified. Moving on to the detailed design procedure, each component of the wind tunnel was carefully designed according to the established requirements and guide-lines obtained from the literature survey.

The main components of a wind tunnel include the settling chamber, flow straighteners, contraction, test section, diffuser, and drive system. The arrangement of these components depends on the type of driving unit and the desired outcomes of the wind tunnel. Factors such as budget constraints and the conditions required in the test section also influence the design. The contraction, choice of fan, diffuser, and settling chamber, which may incorporate honeycombs and screens, are designed in accordance with the specifications of the test section. Different layouts for open return suction wind tunnels are available, allowing flexibility in the overall design.

The contraction plays a crucial role in accelerating the air-flow from the settling chamber to the test section at the desired velocity. It minimizes cross-sectional velocity variance and ensures flow uniformity. The size and shape of the contraction determine the turbulence levels, velocity increase, and pressure drop. The optimal contraction ratio, which is the ratio between the entrance and exit section areas, depends on the specific application. The length of the contraction is carefully considered to minimize boundary layer growth and mitigate the effects of Gortler vortices.

The settling chamber is of utmost importance as it significantly influences the flow quality before it enters the contraction section. It is responsible for slowing down the flow, reducing turbulence, and smoothing out any irregularities caused by the fan. The design of the settling chamber can range from a simple duct of constant section for low flow quality requirements to the incorporation of

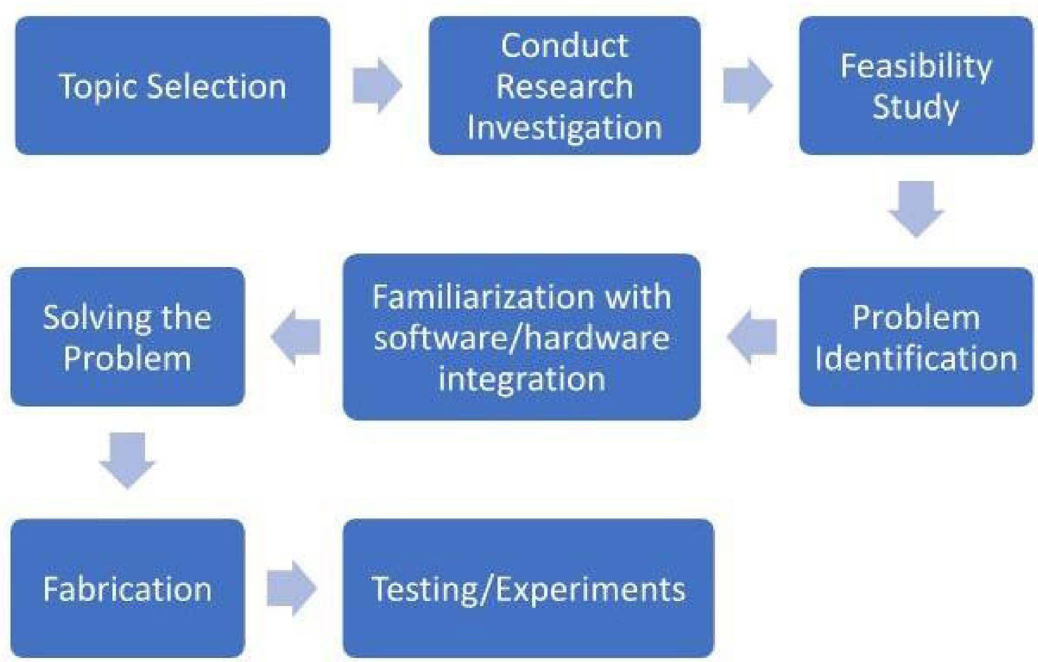

Figure 1. Flowchart of Methodology.

flow straighteners, such as honeycombs and screens, for high-quality flow.

Flow straighteners, including honeycombs and screens, are employed to improve flow uniformity and decrease turbulence levels at the contraction inlet. Honeycombs help straighten the airflow, and different types are available. Hexagonal honey- combs are known to have the lowest pressure loss. Screens further enhance turbulence reduction by breaking up large-scale eddies into smaller ones. The design parameters for screens include wire diameter, mesh size, and porosity.

The test section's size is determined by the operating speed and the desired flow quality. It dictates the maximum size of the test models and the achievable Reynolds number. The shape of the test section, such as rectangular, circular, or hexagonal, is chosen based on the intended purpose of the wind tunnel. The design of the test section emphasizes ease of accessibility for installing test models and instrumentation, ensuring steady and uniform flow velocity with minimal turbulence.

The diffuser, positioned after the test section, is responsible for decelerating the flow and recovering static pressure, thereby reducing the load on the drive system. A gradual increase in the diffuser's cross-sectional area from the inlet to the outlet is essential to prevent flow separation. The design parameters for the diffuser include the area ratio, diffuser angle, wall contour, and cross-sectional shape. It is recommended to keep the diffuser angle below 5 degrees to ensure optimal flow steadiness.

Lastly, the drive system determines how the working fluid flows through the wind tunnel and varies depending on the operational modes. Fans and compressors are commonly used. Axial and centrifugal fans/blowers, driven by a shaft or belt, are suitable for low-speed wind tunnels. Compressors, on the other hand, provide high pressure ratios and are preferred for high-speed wind tunnels.

By carefully considering these design aspects and adhering to the established guidelines, a well-designed wind tunnel can be created to fulfill specific testing requirements in the field of aerodynamics and fluid mechanics.

4.0 Summary and Conclusions

In conclusion, the development of a small-scale low-speed wind tunnel for a supermileage prototype car is a significant step towards optimizing the vehicle's aerodynamic performance. This project aimed to create a controlled testing environment to evaluate and improve the car's efficiency by reducing drag and increasing fuel efficiency. Through the development process, several key objectives were achieved. First and foremost, the construction of the wind tunnel provided a controlled

Parameter	Value
Test section Width*Height	340 * 340 mm^2
Test section length	880 mm
Test section aspect ratio	1
Pre Test Section Stabilisation allowance	200 mm
Contraction Intlet Width*Height	840 * 840 mm^2
Contraction Exit Width*Height	340 * 340 mm^2
Contraction ratio	6
Contraction Length	1000 mm
Contraction Curve	5th order polynomial

Figure 2. Result of dimension of Test Section.

Parameter	Value
Diffuser inlet Width*Height	340 * 340 mm^2
Diffuser Outlet	Circle of diameter 550 mm
Diffuser angle	4.7636^0
Diffuser Length	1260 mm
Settling Chamber Length	396 mm [60 + 168 +168]
Overall wind tunnel length	3536 mm (Approx.)

Figure 3. Result of dimension of Diffuser.

and repeatable testing environment, allowing for accurate measurements of aerodynamic forces acting on the prototype car. This enabled the identification of areas of high drag and provided valuable data for further design iterations. The wind tunnel also facilitated the testing of various aerodynamic modifications, such as streamlined body shapes, wheel fairings, and optimized vehicle components. These modifications were essential for achieving better aerodynamic efficiency, reducing drag, and ultimately improving fuel economy. By systematically testing and refining these design elements, the development of the wind tunnel contributed to the overall enhancement of the supermileage prototype car. Moreover, the small scale of the wind tunnel allowed for cost-effective and accessible testing, making it suitable for development projects with limited resources. This

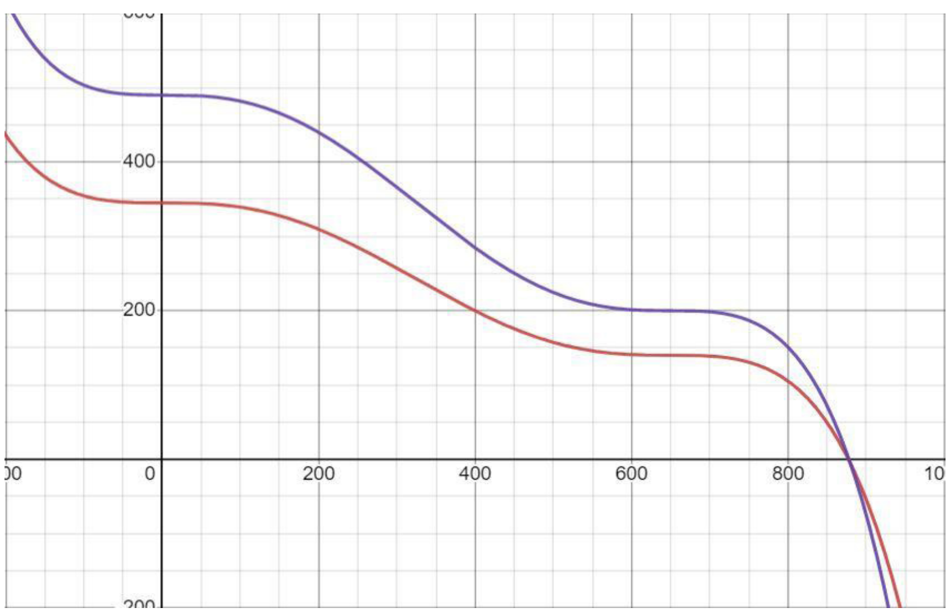

Figure 4. Fifth order curve for contraction.

affordability and scalability make it a valuable tool for educational institutions, research facilities, and small-scale engineering teams working on supermileage projects.

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Appendix