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Design and Analysis of a Split Spoiler to Optimize Downforce and Turbulence

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Abstract - *The split spoiler design represents a significant advancement in vehicle aerodynamics, improving downforce, stability, and handling at high speeds. By introducing a second, slotted wing positioned at a downward angle, the redesigned spoiler increased downforce from 1094.32 N to 1342.34 N at 300 km/h, while maintaining turbulence intensity at a manageable level, rising slightly from 0.1032% to 0.109903%. Simulations conducted in SolidWorks highlighted the design's ability to moderate turbulence, enhance airflow reattachment, and optimize the lift-to-drag ratio, improving traction and reducing wake instability. These aerodynamic gains lead to better cornering stability, shorter stopping distances, and enhanced safety in dynamic driving conditions. While the design increases drag slightly, its benefits in stability and performance outweigh this drawback. Future improvements could focus on reducing drag further and incorporating lightweight materials for greater efficiency. This research demonstrates the potential of advanced spoiler designs to improve the stability, safety, and overall performance of high-speed vehicles.*

Key Words: **Downforce, Split Spoiler, Aerodynamics, Turbulence Intensity, Computational Fluid Dynamics (CFD), Vehicle Stability**

1. INTRODUCTION

Aerodynamics is a critical factor in determining a vehicle's performance, particularly at high speeds, where forces like drag and lift significantly affect stability, handling, and fuel efficiency. Spoilers are essential aerodynamic components that shape airflow around the vehicle to reduce lift and generate downforce. This downforce enhances grip by increasing the vertical load on the tires, which is vital for improved traction during high-speed cornering and braking. However, achieving higher downforce often comes at the expense of increased drag and turbulence, necessitating a careful balance for optimal performance.

This study focuses on designing and analysing a split spoiler system that improves downforce while minimizing turbulence. A split spoiler consists of two separate aerodynamic surfaces, strategically placed to optimize airflow and manage pressure distribution. By introducing a slotted lower wing at a different angle to the original design, this configuration aims to reduce turbulence and enhance aerodynamic efficiency.

Using a BMW M4 Coupe as a case study, the original spoiler, which generates 1098.55 N of downforce at 300 km/h, was redesigned to incorporate a split-spoiler configuration. The redesigned system increased downforce to 1342.34 N with a minimal rise in turbulence. This paper examines the theoretical principles behind the split spoiler, details the design and simulation process, and evaluates its impact on overall vehicle performance.

2. CONVENTIONAL(BASELINE) DESIGN OF SPOILER

In our initial design, a simple rear car spoiler was modelled using SolidWorks and subjected to airflow analysis.

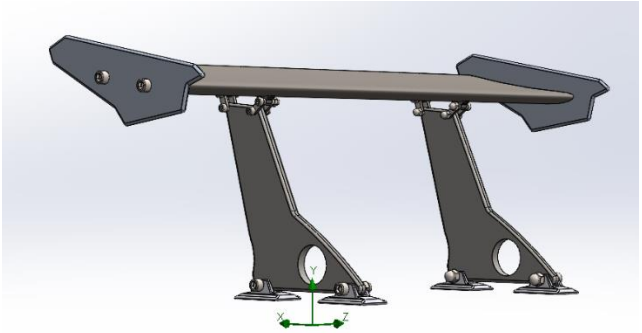

Fig. 1 Baseline(conventional) design of rear spoiler

The results indicated a turbulence intensity of 0.1032% and a downforce of 1094.32 N at a wind speed of 300 km/h. This design effectively utilized basic aerodynamic principles, generating downforce by creating a pressure difference above and below the spoiler.

The downforce (F_L) is governed by the equation

$$F_L = 1/2 * \rho v^2 / (C_L * A) ,$$

Where:
air density (ρ),
velocity (v),
lift coefficient (C_L),
and reference area (A) are key factors.

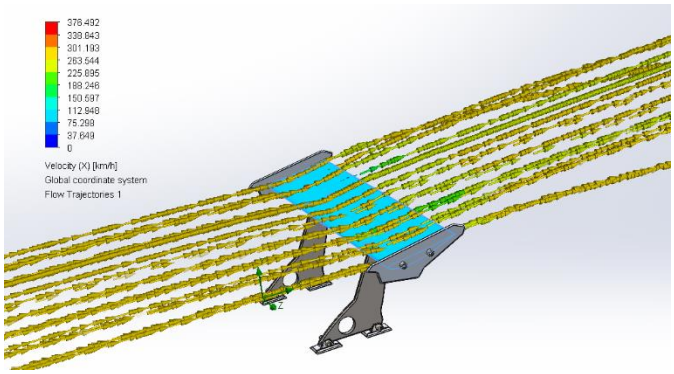

Fig. 2 Air flow through spoiler

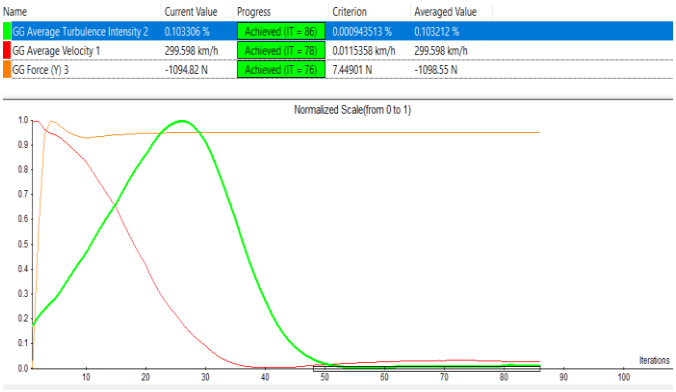

Fig. 3 Flow simulation result

While the spoiler provided improved traction, stability, and braking performance by increasing vertical tire load, its effectiveness was limited due to turbulence and inefficient airflow management at higher speeds.

To enhance performance under the same wind speed, a split spoiler design is proposed. This improved configuration incorporates a second wing positioned beneath the primary aero foil, angled downward with slotted gaps to better manage airflow. The slotted design moderates turbulence and encourages airflow reattachment, reducing wake instability and increasing aerodynamic efficiency. By optimizing the lift-to-drag ratio, the split spoiler achieves higher downforce while maintaining acceptable levels of turbulence and drag. This advanced design is more suitable for high-speed conditions, as it offers enhanced traction, better cornering stability, and shorter stopping distances compared to the original spoiler. Adopting the split spoiler design would be a significant step forward in maximizing aerodynamic performance and overall vehicle handling.

3. DESIGN AND SIMULATION PROCESS

To develop the new split spoiler design, SolidWorks CAD software was used to model and simulate its aerodynamic performance. The base spoiler was initially designed using standard aerofoil geometries with well-documented aerodynamic properties, ensuring that the shape provided a reasonable starting point for airflow control. The redesigned split spoiler introduced a secondary wing positioned beneath the main wing. This secondary wing was angled downward and incorporated slotted gaps to enhance airflow reattachment and reduce turbulence. The combination of these two elements allowed for improved pressure distribution and a more efficient generation of downforce without excessively increasing drag.

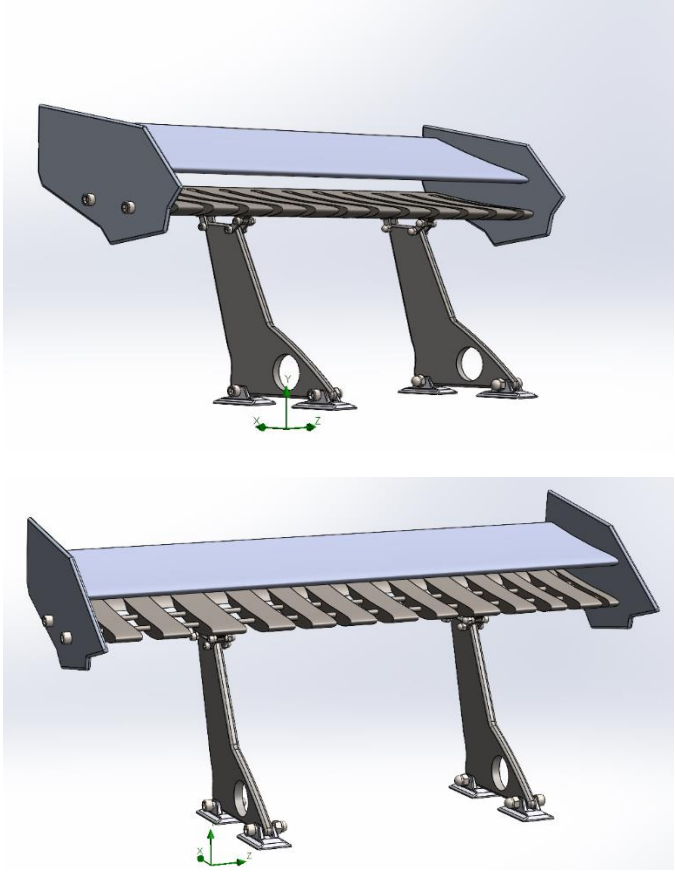

Fig. 4 New design of split spoiler

Simulation Setup:

After the design was finalized, computational fluid dynamics (CFD) simulations were conducted to analyse airflow behaviour around the spoiler. Key boundary conditions were set for the simulation, with airspeed specified at 300 km/h, corresponding to an inlet velocity of 83.33 m/s. A high-resolution mesh was generated around the spoiler to accurately capture the complex airflow patterns, particularly in regions prone to turbulence and flow separation. The k-ε turbulence model, a widely used approach for resolving turbulent flows in aerodynamic studies, was selected to simulate the interaction of air with the spoiler surfaces and the wake region behind the car.

Airflow simulation insights for rear spoiler:

The rear spoiler plays a crucial role in managing the airflow over the back of the car, which is an area prone to lift and turbulence. By incorporating the split spoiler design, the airflow was directed more effectively, reducing wake turbulence and improving pressure recovery behind the vehicle. This resulted in a stronger and more stable downforce generation while minimizing drag penalties. The slotted lower wing helped reattach airflow that would otherwise separate, maintaining smooth flow lines and reducing the likelihood of chaotic vortices.

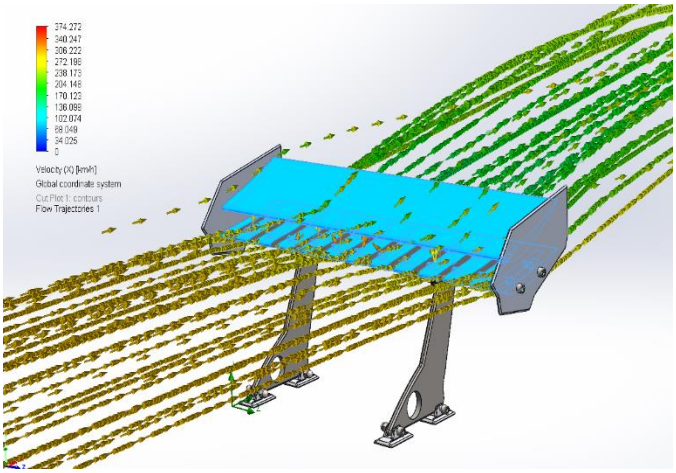

Fig. 5 Air flow around the new spoiler design

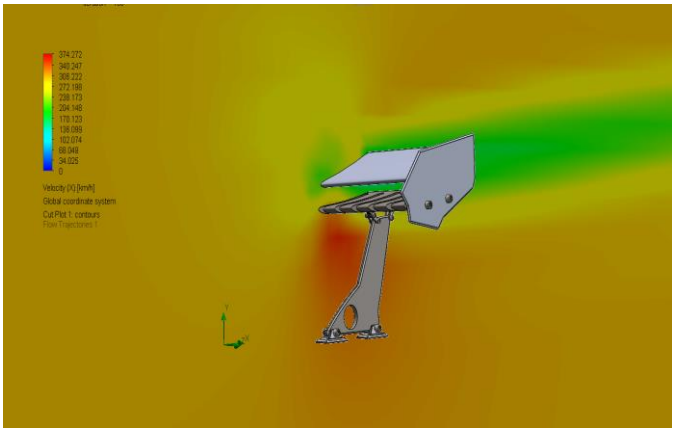

Fig. 6 cut section plane of air flow simulation

Simulation Outputs and Analysis:

The simulation provided valuable insights into several aerodynamic factors. Pressure distribution maps revealed how the spoiler's shape managed high and low-pressure zones, contributing to the generation of downforce.

The redesigned split spoiler showed a more uniform pressure distribution compared to the original design, indicating effective airflow management. Flow velocity streamlines visualized the behavior of air as it passed over and beneath the spoiler. These streamlines demonstrated improved airflow reattachment in the split spoiler, particularly due to the slotted design, which helped channel and stabilize airflow in critical areas. Turbulence intensity was also evaluated, showing a slight increase compared to the baseline design, but this was within acceptable limits for maintaining vehicle stability.

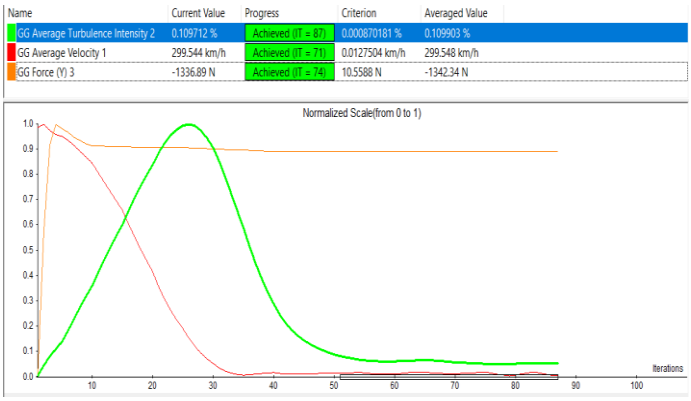

Fig. 7 New design flow simulation result

4. METHODOLOGY AND CALCULATIONS

- **Baseline Design Parameters:**

Downforce (F_L): 1098.55 N

Airspeed (v): 300 km/h (83.33 m/s)

Turbulence Intensity (T_I): 0.103212%

Wing Area (A): 0.5 m^2 (assumed)

Air Density (ρ): 1.225 kg/m^3

From the lift equation:

$$C_{Lold}=2F_L/\rho v^2 A$$

Substituting values:

$$C_{Lold}=2(1098.55)/1.225(83.33)^2(0.5)$$

$$=0.319$$

- **New Design Parameters:**

Downforce (F_L): 1342.34 N

Turbulence Intensity (T_I): 0.109903%

New lift coefficient:

$$C_{Lnew}=2F_L/\rho v^2 A$$

$$C_{Lnew}=2(1342.34)/1.225(83.33)^2(0.5)$$

=0.39

- **Lift-to-Drag Ratio**

A drag coefficient C_D of 0.034 for the baseline and 0.036 for the new design:

$$L/D_{old} = C_{Lold}/C_D$$

=0.319/0.034=9.38

$$L/D_{new} = C_{Lnew}/C_D$$

=0.390.036=10.83

- **Turbulence Analysis**

Impact of Turbulence

Turbulence intensity (T_I) quantifies fluctuations in airflow velocity, calculated as:

$$T_I = u'/U$$

Where:

- u' Root mean square of velocity fluctuations
- U: Mean flow velocity

T_I=Root Mean Square of Velocity Fluctuations/ Mean Flow Velocity×100

Lower turbulence intensity indicates smoother airflow, while moderate increases are acceptable if accompanied by significant aerodynamic benefits. The slotted design of the split spoiler promotes flow reattachment, reducing separation zones and wake turbulence. Turbulence intensity increased marginally from 0.103212% to 0.109903%. This increase is within acceptable limits for maintaining stability.

The implementation of the improved split spoiler design impacts several areas of vehicle performance beyond aerodynamics. While the increased downforce slightly raises drag, leading to a minor reduction in fuel efficiency, it significantly enhances handling and stability during high-speed maneuvers by improving tire traction. This improved grip allows the vehicle to maintain better control during cornering and braking, reducing stopping distances and ensuring more precise handling. Additionally, the increased stability and braking performance contribute to overall safety, making the vehicle more responsive and reliable under dynamic driving conditions, particularly in critical or emergency scenarios.

5. IMPLEMENTATION ON VEHICLE PERFORMANCE

To evaluate the impact of the redesigned split spoiler, the BMW M4 Coupe was selected as the case study vehicle due to its weight of 1,680 kg and its baseline spoiler performance, which closely aligns with the older spoiler design used in this study. The original spoiler on the BMW M4 generates a downforce of 1098.55 N at a speed of 300 km/h, with a coefficient of drag (C_D) of 0.34. These characteristics make it a suitable candidate for implementing the new split spoiler design, allowing for a direct comparison of aerodynamic and performance improvements. The redesign aims to enhance downforce while maintaining manageable levels of drag and turbulence, ensuring better stability and handling at high speeds.

IMAGE :- BMW M4 coupe

(taken from: - https://www.acschnitzer-us.com)

- **Impact of New Downforce**

The additional downforce translates to improved tire grip. This enhances cornering performance and braking efficiency:

Weight on Tires (New)=

Vehicle Weight+ Downforce

New Tire Load=(1680*9.81)+1342.34

=17510.34

- **Cornering Force:**

For cornering friction force play vital role

Frictional force at the tires is proportional to vertical load:

$F_{friction}$= μ*Tire Load

Assuming μ=0.9 (friction coefficient for performance tires):

Calculated Frictional force of BMW M4 coupe is nearly 15268N

$F_{friction}$(new)=0.9*17510.34

=15759.3 N

The increase in cornering force (5.1%) improves handling significantly.

Using the BMW M4 Coupe as an example, the redesigned split spoiler demonstrated significant performance improvements compared to its assumed older spoiler.

Downforce increased by 22.2%, rising from 1098.55 N to 1342.34 N at a speed of 300 km/h, enhancing tire grip and stability. Although turbulence intensity saw a slight rise of 6.5% (from 0.103212% to 0.109903%), it remained within manageable levels.

Additionally, the frictional force on the tires increased by 5.1%, from 15,268.1 N to 15,759.3 N, contributing to improved braking and cornering performance. These results highlight the enhanced aerodynamics and overall handling capabilities provided by the new design.

6. CONCLUSION

The split spoiler design offers significant improvements in aerodynamic performance, demonstrating an increase in downforce from 1094.32 N in the original design to 1342.34 N at a wind speed of 300 km/h. This enhancement is achieved through the introduction of a second, slotted wing positioned at a downward angle, which effectively moderates turbulence and ensures better airflow reattachment.

The slight increase in turbulence intensity, from 0.1032% to 0.109903%, is an acceptable trade-off, as it is accompanied by a substantial boost in vehicle stability, handling, and cornering performance. This advanced design highlights how innovative aerodynamic solutions can transform vehicle dynamics under high-speed conditions.

One of the key benefits of the split spoiler lies in its efficient airflow management. The slotted configuration reduces wake turbulence and enhances pressure recovery, contributing to a better lift-to-drag ratio. By increasing the lift coefficient (C_L) without significantly affecting the drag coefficient (C_D)the design provides superior traction and grip during high-speed manoeuvres. The reduction in vortex generation around the vehicle results in smoother airflow, improving overall aerodynamic efficiency. These improvements directly impact braking performance by shortening stopping distances and enabling more precise and responsive handling, particularly in challenging driving scenarios.

Although the split spoiler delivers outstanding aerodynamic and safety benefits, future research can explore further enhancements. For example, minimizing drag while maintaining or increasing downforce could improve fuel efficiency, making the design more practical for everyday vehicles. Refinements to the slotted configuration, coupled with the use of lightweight materials, could further optimize the performance and adaptability of the spoiler. This study emphasizes the critical role of innovative spoiler designs in advancing vehicle stability, safety, and efficiency, making it a valuable step forward in automotive aerodynamics.

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