SUPERVISOR DECLARATION

"I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Automotive)"

Signature:	....
Supervisor:	DR CHENG SEE YUAN
Date:	....

EFFECT OF YAW ANGLE ON THE AERODYNAMICS PERFORMANCE OF REAR SPOILER – BY CFD STUDY

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This thesis is submitted to Faculty of Mechanical Engineering as a requirements to get award of
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DECLARATION

“I hereby declare that the work in this report is my own except for summaries and quotations which have been duly acknowledged.‟

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ABSTRACT

The aerodynamic performance of vehicle has become more and more important over the past few decades. The attention of vehicle stability has become another concern apart from fuel efficiency. A high speed travelling vehicle will become unstable when experiencing strong cross wind or cornering that can affect traffic safety. The proper installation of rear spoiler can help to stabilize the vehicle, particularly at the rear part. However, there are a few types of rear spoiler with different configurations. The purpose of this project is to investigate the effect of yaw angle on the aerodynamic performance of hatchback car using Computational Fluid Dynamics (CFD). The models are meshed and simulated by specific settings and boundary condition. The results obtained are drag, lift, pitch moment, and yaw moment coefficient. Drag coefficient is compared with wind tunnel results for validation. The findings show that model with non-slotted spoiler is most efficient to reduce drag and lift at 0° yaw angle. On the contrary, double-slotted spoiler shows the best result in yaw moment coefficient reduction.

ABSTRAK

Prestasi aerodinamik kenderaan telah menjadi lebih dan lebih penting untuk beberapa dekad yang lalu. Perhatian kestabilan kenderaan telah menjadi kebimbangan lain selain dari kecekapan bahan api. Sebuah kenderaan perjalanan berkelajuan tinggi akan menjadi tidak stabil apabila mengalami angin silang kuat atau memborong yang boleh menjejaskan keselamatan lalu lintas. Pemasangan spoiler belakang yang betul boleh membantu untuk menstabilkan kenderaan, terutamanya di bahagian belakang. Walau bagaimanapun, terdapat beberapa jenis spoiler belakang dengan configuration yang berbeza. Oleh itu, ia adalah penting untuk menentukan kesan prestasi aerodinamik spoiler belakang untuk kenderaan di bawah syarat-syarat rewang. Tujuan projek ini adalah untuk mengkaji kesan sudut rewang prestasi aerodinamik kereta hatchback menggunakan Dinamik Bendalir Komputasi (CFD). Model yang dihancurkan dan simulasi dengan tetapan yang khusus dan keadaan sempadan . Keputusan yang diperolehi adalah seretan, lif , masa padang , dan pekali momen rewang . Pekali seretan dibandingkan dengan keputusan terowong angin untuk pengesahan. Dapatan kajian menunjukkan bahawa model tanpa spoiler slot yang paling berkesan untuk mengurangkan seretan dan lif pada 0 ° sudut rewang . Sebaliknya , model dengan 2 slot menunjukkan hasil yang terbaik dalam masa rewang pengurangan pekali

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LIST OF SYMBOLS

V	=	velocity
Re	=	Reynolds Number
F	=	force
M	=	moment
A	=	reference area
l	=	reference length
ρ	=	density
C_f	=	force coefficient
C_m	=	moment coefficient
C_d	=	drag coefficient
C_l	=	lift coefficient
ψ	=	yaw angle
K	=	turbulent kinetic energy
L_{slant}	=	slant length
R	=	radius of curvature
Pa	=	pascal
L	=	length of model
μ	=	dynamic viscosity

LIST OF ABBREVIATION

CFD	computational fluid dynamics

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Aerodynamic performance of vehicle has become more and more important for the past few decades. Apart from a race car, the concern of aerodynamic performance has shifted to passenger car as well due to the advancement of high speed vehicle. The efficiency and safety of vehicle influence the consumer"s decision when buying a car. Fuel consumption is the primary concern for the development of automobiles. The drag force is the resistance that opposes the motion of a vehicle. Based on Leduc (2009), 65 percent of power is required to overcome the aerodynamic drag at 110km/h. Despite fuel consumption, vehicle stability at high speed also becomes another important factor to take into consideration. Under real driving conditions, drivers have to compensate for disturbance such as strong cross wind, undesired driver input, and road irregularities (Karnoop, 2013). A strong cross wind can contribute to great disturbance as such; it can affect the traffic safety.

1.2 PROBLEM STATEMENT

A high speed travelling vehicle will become unstable due to the effect of lift (Karnoop, 2013). Under normal condition, vertical force on a bluff body is positive and it tends to lift the vehicle. The decrease in rear wheel load as a result of Bernoulli's effect will increase the sensitivity of steering response to small disturbance, thus making the vehicle unstable as such over steer might occur. Rear spoiler mounted on the trunk of a car can alter the air stream at the rear body. Thus, supply under pressure for a vehicle, increase the body down force. Hence, lift is reduced (Tao, 2011). There is always an ambient wind and the wind is not aligned with the road along which vehicle is travelling causes the vehicle to operate at a yaw angle (Hucho & Sovran, 1993). Under yaw condition, yawing moment is significant. Yawing moment tends to force vehicle further away from the direction of wind and thus making the vehicle unstable.

A typical solution is to install rear spoiler. The rear spoiler can alter the air flow and helps to stabilize the vehicle under such condition (Chainani & Perera, 2008). Hence, it is important to study how rear spoiler helps to stabilize a vehicle under yaw condition. Based on Menon et al (2014), Ahmed body with 35 degree slant is used to represent the hatchback type car. Menon et al found that increasing spoiler slant length and minimizing curvature are most suitable in terms of aerodynamic performance. They concluded that rear roof spoiler can reduce drag and improve cross wind stability. However, there are few types of rear roof spoiler such as the one with a single-slotted or double slotted, which might have a different effect on aerodynamic performance under yaw condition. Spoilers with slots will allow air to flow beneath which alters the air flow. Therefore, it is important to determine different types of spoilers that carry different effect on the aerodynamic performance of a vehicle.

1.3 OBJECTIVE

The purpose of this research is to study the effect of yaw angle to the aerodynamic performance of the rear spoiler. The objectives of this research are:

1. To investigate the effect of yaw angle on the aerodynamic performance of the hatchback car with various spoiler configuration
2. To perform CFD simulation of hatchback car model flow using ANSYS fluent
3. To validate the CFD simulation results

1.4 SCOPE

The car model used in this study is a hatchback type car. Ahmed model with 35 degree slant angle at the rear is used to represent the hatchback type car. It will be placed in room temperature condition under the yaw angle of 0, 15, and 30 degrees respectively with the air velocity, V of 30 m/s. The corresponding Reynolds number, Re based on vehicle length is 3.28×10^5. Four cases will be tested accordingly. First, the Ahmed model with a 1/24 scale of a real car will be tested. The reason to scale down Ahmed body is due to the limitation of the wind tunnel. After that, the Ahmed model with spoilers will be tested. Aerodynamic performances to be analyzed are the drag, lift, pitching moment, and yawing moment respectively. The drag and lift results obtained from simulation will be compared with wind tunnel experiment under similar flow conditions for validation as the wind tunnel used only capable of obtaining drag and lift.

CHAPTER 2

LITERATURE REVIEW

2.1 AERODYNAMIC OF ROAD VEHICLE

The study of aerodynamics in vehicles has been focused on drag reduction due to fuel crisis of the early 1970s. However, the concern has been shifted to lift and side force in the recent year due to the importance of vehicle stability in the modern vehicle design. The vehicle stability is reduced in a crosswind situation as a result of the side effect caused by low drag shapes developed during the early 1980s. However, the concern on vehicle stability in crosswind has been considered by designers (Dominy, 2002).

Generally, there is a total of six basic forces and moments that acts on a vehicle body which comprises of three forces and three moments. Figure 2.1 shows the forces and moments axes of a vehicle.

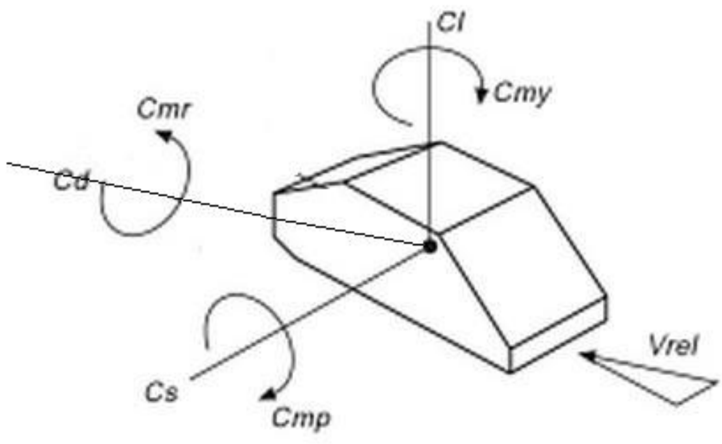

Figure 2.1: Forces and moments axes of a vehicle (Source: Dominy, 2002)

The force and moment coefficient are defined in Eq. (2.1) & (2.2) :

$$C_f = \frac{F}{\frac{1}{2}\rho \upsilon^2 A} \tag{2.1}$$

$$C_m = \frac{M}{\frac{1}{2}\rho \upsilon^2 Al} \tag{2.2}$$

Where F is force (lift, drag, and side), M is moment, ρ is air density, υ is velocity, A is reference area and l is reference length. The reference area is usually referred to frontal area in vehicle aerodynamic.

2.2 AERODYNAMIC PERFORMANCE

2.2.1 Drag

Drag is the force that a flowing fluid exerts on a body in the flow direction. Drag is normally undesirable. Reduction of drag often closed related to the reduction of fuel consumption in automobiles; improve stability and durability; and reduction of noise and vibration. There are a few factors that influence drag force. Density of fluid p, upstream velocity v, size, shape and orientation of the body are the main factors that affect the drag force of a body. Dimensionless number, drag coefficient C_d is used to represent drag characteristic of a body. Streamline body has a lower C_d compared to blunt body when moving at the same speed through a fluid (Cengel & Cimbala, 2006).

Drag force will directly affect the fuel consumption in automobiles. According to Hucho (1998), fuel consumption due to aerodynamic drag is more than 50% of the total vehicle energy at highway speed. Aerodynamic drag consists of skin friction drag and pressure drag. The pressure drag is more dominant and highly dependent on the vehicle geometry due to boundary layer separation and wake region at the rear part of a vehicle. It has been found that 40 % of drag force is concentrated at the rear of a vehicle (Menon et al., 2014). Therefore, the rear part design of a vehicle has great influence to the total fuel consumption.

2.2.1.1 Drag Reduction

The drag creation of a vehicle is closely related to the aerodynamic noise. The reduction of drag has directly reduced the aerodynamic noise with mutual benefits. However, this mutual benefit does not contribute to the dynamic stability of the vehicle. The rounded shapes and low drag designs cause the vehicle sensitive to crosswind in terms of side force and yawing moment (Dominy, 2012).

Two-dimensional consideration to describe the flow characteristic over the front of a vehicle is not sufficient to describe the rear flow. The flow structure at the rear of a vehicle is much more complicated. The magnitude of pressure and the energy and frequency are large influenced by the speed of vehicle, and the height and width of the tail. The flow structure at the rear surface is very different for hatchback, fastback, notchback and squareback. The flow structure for „squareback‟ is characterized by large, low pressure wake shown in Figure 2.2 below.

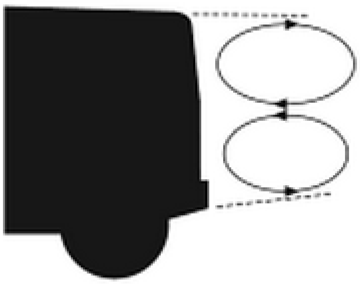

Figure 2.2: „Squareback‟ large scale flow separation (Source: Dominy, 2002)

The flow structure is very different if the rear surface slopes more gently as for the hatchback and fastback type. The low pressure on the upper surface draws the car upwards and leads to creation of intense, conical vortices at the „C‟ pillars as shown in Figure 2.3 below.

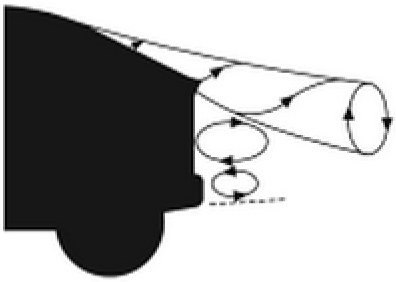

Figure 2.3: „Hatchback/Fastback‟ vortex generation (Source: Dominy, 2002)

These vortices cause the upper surface flow to remain attached to the surface over backlight angle of 30 degrees. Therefore, air is drawn down over the rear of the car that creates a resulting force in both lift and drag directions. The backlight angle is therefore absolutely critical for this type of vehicles (Ahmed et al., 1984). Figure 2.4 below shows the effect of backlight angle to the drag coefficient. From the figure, the drag coefficient decreases up until 10 degrees, but increases to maximum at about 30 degrees.

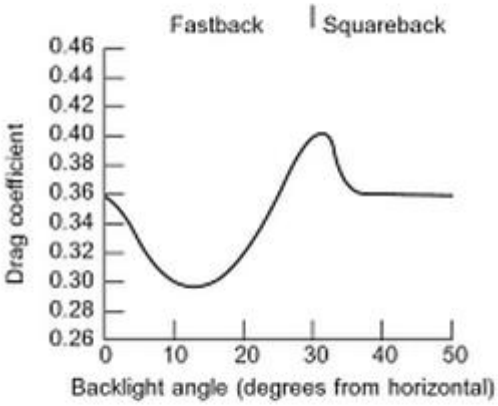

Figure 2.4: Influence of backlight angle on drag coefficient (Source: Dominy, 2002)

2.2.2 Lift and Pitch Moment

The effect of lift is unfavorable in the ground travelling vehicle. Under the free air condition, a symmetrical body will not produce lift. On the contrast, when the body is close to the ground, the body and its mirror image will form a narrowing channel between them. As a result, downforce will be produced. Simultaneously, flow resistance in the channel displaces more flow to the upper side of the body, resulting negative contribution of pressure which tends to produce an upward force. For a passenger car, the net force produced at the rear part of vehicle will often be upward force when the vehicle is travelling at high speed. The lift that concentrated at the rear of vehicle will cause pitching moment which will cause larger force at the front axle of vehicle. This phenomena is unfavorable as it might cause oversteer. Spoilers and inverted airfoils are often used to oppose the net force which in terms reducing the lift. To design an efficient spoiler or wing, the increase in drag must be minimum while producing downforce or reducing lift.

2.2.3 Side Force and Yaw Moment

Side force and yaw moment produced on cars are very likely to the lift and pith moment of a wing at an angle of attack (Hucho & Sovran, 1993). From the top view, a car can be treated as a blunt airfoil that can generate lift and pitch moment when the angle of attack is greater than zero. On the contrary, the car requires large yaw angle for side force and yaw moment to be produced. Yawing moment is generated due to the center of pressure of the area enclosed by the pressure distributions on the leeward and windward sides is located forward of the car length. Yaw moment of a vehicle can also be explained by the difference between longitudinal forces acting on the left and right hand sides of the vehicle or different lateral forces acting on the front and rear axles (Reif, 2014). Yaw moment is undesirable because it tends to turn the car away from the wind, causing the vehicle to become unstable.

Side force and yaw moment are highly dependent on the rear end shape of a vehicle. Figure 2.5 shows the yaw moment and side force coefficient for a family of cars with different rear end shapes.

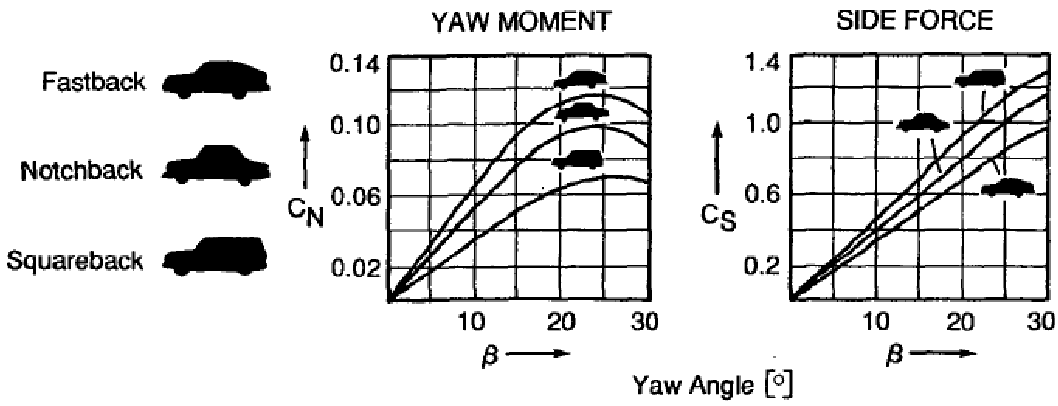

Figure 2.5: Yaw moment and side force coefficients for a family of cars with different rear end shapes (Source: Hucho & Sovran, 1993)

Based on the Figure 2.5, the yaw moment and side force increase linearly for yaw angle, ψ up to 20°. The increase of yaw moment and side force is mainly determined by the side view and cross-section shape of a vehicle. For example, a fastback type car will have a higher increase of the yaw moment compared to the squareback type car when the yaw angle increases. On the contrary, the side force is lower for the fastback car.

2.2.4 Yawing Stability

The aerodynamic stability of a vehicle is highly dependent on two different conditions. The first condition is that when a car is travelling at high speed in a straight line, then it experience lane change maneuverability. The second condition is the effect of steady crosswind and transient gusts. Both of these effects can be explained as the wind is not aligned with the road which the vehicle is travelling (Hucho & Sovran, 1993). Hence, the vehicle operates at a nonzero angle of yaw, producing side force and yaw moment. A free body diagram of vehicle operating at a nonzero yaw angle is illustrated in Figure 2.6.

Apart from gusts, driving conditions with yaw angle, ψ to reach maximum C_d are rare. The average value of yaw angle is less than 10 degrees for typical driving (Dominy, 2012). However, when passing bridge abutments and overtaking heavy vehicles, the influence of transient crosswind gusts is significant. In recent years, the car designs that have been focused on low drag and rounded body shapes can be particularly susceptible to crosswind. Moreover, the weight reduction to improve fuel efficiency increase yaw sensitivity, which in terms reduced the vehicle stability. The compensate aerodynamic changes can only be achieved at a very high cost or by addition of secondary parts such as spoilers.

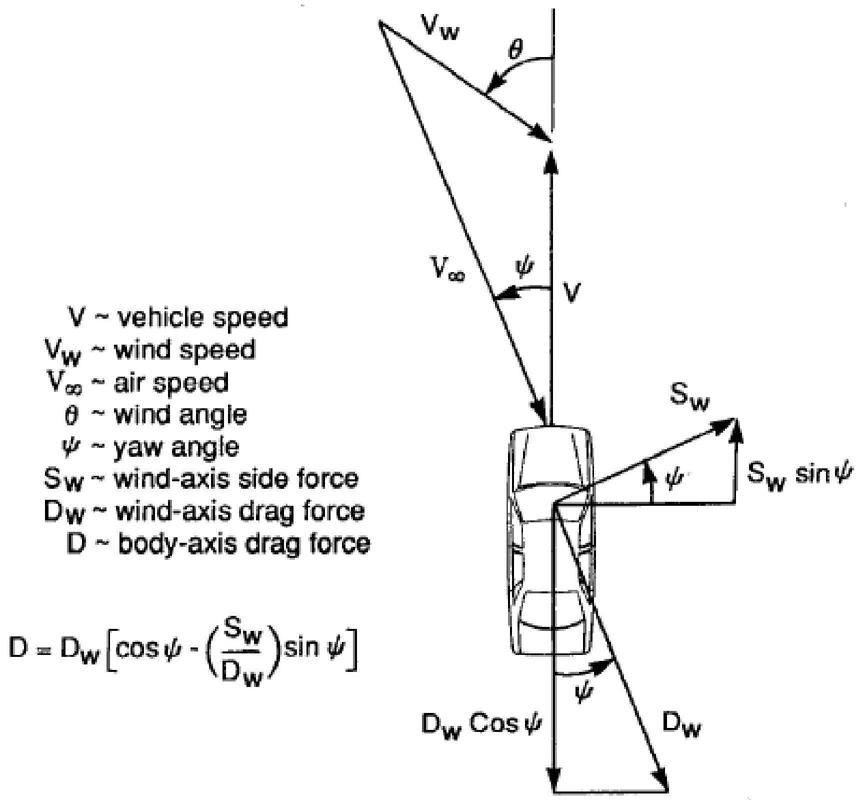

Figure 2.6: Body axis drag at nonzero yaw angle (Source: Hucho & Sovran, 1993)

2.3 SPOILER

The spoiler is commonly used to improve the aerodynamic performance of the vehicle. The spoiler can be divided into front spoiler and rear spoiler. The front spoiler is installed below the front bumper to decrease the air flow underneath vehicle. The decrement of air flow underneath vehicle will reduce aerodynamic drag and lift. On the contrast, the rear spoiler is installed at the rear part of vehicle commonly located on top of the trunk. The rear spoilers also known as "wings" installed on racing car usually are inverted airfoils that produce negative lift. Inverted airfoil can greatly increase down force which is needed by a racing car. As a result, it can provide traction and increase the stability of race car under high speed racing. Despite racing car, spoilers are also introduced into passenger car due to the increase of vehicle speed. Based on Kodali and Bezavada (2012), a rear spoiler can reduce the lift coefficient by 80% with a mere 3% increase in drag. A mid reduction in aerodynamic drag by installing optimized spoiler is proven by Hu and Wong (2011) after they studied the flow around a simplified high speed passenger car.

Refer to the Figure 2.7, the front part of the car has positive pressure while negative pressure appears on the rear part. The positive pressure part will produce downforce, therefore, the front spoiler will be installed at the bottom of the car to maximize the low pressure area under the car (Adams, 1992). On the contrary, the negative pressure part will produce a lift force. As a result, rear spoiler will be installed at the top of the car, normally at the top of trunk to maximize the high pressure area on top of the car.