MEASUREMENT OF STRUCTURE-BORNE NOISE FROM ROAD INPUT IN A MOTOR VEHICLE CABIN

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"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 (Thermal-Fluids)"

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This report is submitted in fulfillment of the requirements for the award Bachelor of Mechanical Engineering (Thermal-Fluids)

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DECLARATION

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

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ABSTRACT

Vehicle interior noise holds paramount aspect in determining its overall quality since it affects the level of acoustic comfort of the passengers. From various methods of measuring noise inside a vehicle cabin, a measurement technique has been developed in this project to measure the interior vehicle noise from road input. This project proposes a simple noise measurement technique which is direct noise measurement when test vehicle is running on the dynamometer, road and airborne noise measurement. The comparison between measured Sound Pressure Level (SPL) from road input and dynamometer input shows the contribution of structure-borne noise due to tire-road interactions and aerodynamic excitation. The comparison between measured SPL for total interior noise (at stationary condition) and SPL for road input shows the contribution of noise from road input, vehicle suspension system, and aerodynamic excitation. British Standard BS 6086:1981 on method of measurement of noise inside motor vehicle had been followed closely to ensure high accuracy of results obtained from the direct noise measurements method.

ABSTRAK

Bunyi dalam sesebuah kenderaan memainkan peranan penting dalam menentukan qualiti keseluruhan kenderaan tersebut disebabkan bunyi tersebut akan mempengaruhi keselesaan akustik para penumpang. Satu teknik ukuran bunyi baru telah diaplikasikan dalam project ini untuk mengukur bunyi dalam sesebuah kereta yang terhasil apabila kereta tersebut dipandu di atas jalan raya. Satu kaedah ukuran bunyi terus telah diguna dalam project ini apabila kereta ujian dipandu di atas dynamometer, jalan raya dan juga ukuran bunyi bawaan udara. Perbandingan antara bunyi yang diukur apabila kenderaan dipandu di atas jalan raya dengan bunyi yang diukur apabila kenderaan dibawa di atas dynamometer mempamerkan sumbangan bunyi dari interaksi tayar-permukaan jalan raya dan juga kesan aerodinamik ke atas struktur kenderaan.Perbandingan antara bunyi yang diukur apabila kenderaan dipandu di atas jalan raya dengan bunyi yang diukur apabila kenderaan berada dalam keadaan statik mempamerkan kesan sumbangan dari input jalan raya, sistem suspensi dan juga kesan dari aerodinamik kenderaan. Standard British BS 6086:1981 yang berkenaan dengan Kaedah ukuran bunyi dalam sesebuah kereta telah diaplikasikan dalam project ini untuk memastikan hasil dapatan daripada kajian ini adalah tepat.

TABLE OF CONTENTS

LIST OF FIGURE

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Vehicle interior noise increasing attracts attention from researchers and manufacturers since the past decades as it crucially affects the level of acoustic comfort of the passengers, especially for (luxury) sedans with pleasant low-noise engine sounds. Vibration caused by tires due to forces radiated by the road-tire interaction during rolling over a rough road surface is an important noise contribution in the vehicle cabin over a wide frequency range. This noise contribution to interior noise depends on the source levels and the reduction of noise from the exterior to the interior. The amount of acoustic discomfort in the passenger compartment generated by vibration is depends on the magnitude, frequency, direction and the duration of exposed vibration in the cabin (Junoh et al.).

In extend, this acoustic discomfort will affect the driver's emotions and decrease the level of driving concentration, for example by bothering driver's vision, thus at the same time promoting stress to the driver due to the generated noise. Furthermore, this undesired noise may interfere with speech communication between passengers and also can result in sleep disturbance of passengers during the night. Vehicle interior vibration and generated noise could alter the driver's driving focus which potentially leads to an accident.

Due to advancement in today's telecommunication in which most of (luxury) vehicles are equipped with interactive voice control, information and multimedia systems, and increased use of mobile phones, interior acoustic comfort is one of the main factors which attract the buyers in this extremely competitive automobile market of future design and sales (Douville et al., 2006).

Generally, this vehicle interior noise is classified into two types of detectable noise which are structure-borne and airborne noise. Structure-borne noise is generated when tires travel on a non-uniform road surface which causes structural excitation through the tire and suspension system into the vehicle body. This structural excitation generates noise throughout the vehicle instead of in the vicinity of the tire. Meanwhile, airborne noise is the noise radiated directly from the tires-road interaction, engine and other vibrating structures due to impinging sound pressure into the surrounding air.

1.3 PROBLEM STATEMENT

Vehicle interior noise crucially affects the level of acoustic comfort of passengers. At lower frequencies, the interior noise from road input is predominantly transmitted through structure-born route. A simple measurement method is therefore required to be proposed to measure structure-borne noise from road input in vehicle cabin, thus enable car manufacturers to determine the source of noise.

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1.4 OBJECTIVE

The main objective of this research is to measure the structure-borne noise in a motor vehicle cabin from tires-road interaction and to propose a simple technique to measure the noise in the vehicle cabin.

1.5 SCOPE

This research measures the Sound Pressure Level (SPL) in vehicle cabin at different RPM when driving on road. Then, the measured SPLs are decomposed into structure-borne noise by means of mathematical analysis. Factors that affect the vehicle interior noise is not the topic of research here and beyond the scope of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 VIBRATION

According to Hassan (2009), vibration is defined as motion or oscillations of particles or a body or a system which can be defined by displacement, velocity or acceleration of the particles from a position of an equilibrium point. Vibration occurs when a system is displaced from a position of stable equilibrium and when this happened; restoring forces such as elastic forces or gravitational forces tends to act on the system to return the displaced system back to the equilibrium or initial position. The system keeps moving forth and back across its position of equilibrium thus creating a periodic motion and can be deterministic or random in nature. Vibration is generally expressed in terms of frequency such as cycles per second or commonly known as Hertz (Hz), revolutions per minutes (rpm) and strokes per minute (spm).

Vibrations can be classified into three categories which are free vibration, forced vibration and self-excited vibration (Srinivas and Srinivas, 2004). Free vibration occurs when a system is allowed to vibrate freely in the absence of external force, meanwhile forced vibration occurs when an exciting force continuously act on a system which causes the system to vibrate at a desired frequency. On the other hand, self-excited vibrations are periodic and deterministic oscillations in which the systems begin to vibrate of their own accord spontaneously at its own natural or critical frequency. The energy supplying the self-excited system is gained from a constant source of power associated with the system which, owing to some mechanism inherent in the system that gives rises to oscillating forces (Ehrich, 2009). Most vibrations are undesirable be it in machines, structures, vehicle and etc. as they produce energy losses, induce fatigue, increase stresses and create passenger discomfort in vehicles.

2.2 EVALUATION OF NOISE

Generally, transmission paths of noise from road input are vital in the study of vehicle interior noise. Sound transmission into vehicle cabin is classified into two categories namely airborne noise or structure borne noise. Airborne noise is the noise that radiated directly from a vibrating structure due to impinging sound pressure into the surrounding air. In a vehicle, noise is transmitted into the cabin through leakages due to failure of sealing, for instance, around the door and window seals or grommets in the bulkhead (Harrison, 2004).

On the other hand, a structure borne noise is resulted from vibration of car structure which generates sound energy into the cabin when the tires travel on a non-uniform road surface. The noise is typically generated by the suspension mounting points, car engine, exhaust and other parts of a vehicle. Figure 2.1 shows the diagram of noise transmission path into the vehicle cabin.

For an much effective noise control treatment, separation of these vibro-acoustics path is vital to investigate the root causes of the generated noise since the reduction of noise transferred by different paths requires different solutions (Putra et al., 2012). According to Thompson and Dixon (2004), at higher frequencies, the noise is transmitted via airborne route into the vehicle cabin. Despite that, this airborne noise attenuates rapidly by 20dB/decade with the increasing frequency and is predominantly controlled by mass which causes the interior cabin noise lead by low frequency vehicle components. This study certainly aids vehicle manufacturers in optimizing and improve the structure of the parts to reduce the generated vibration and at the same time to decrease the noise in vehicle cabin to enhance acoustic comfort.

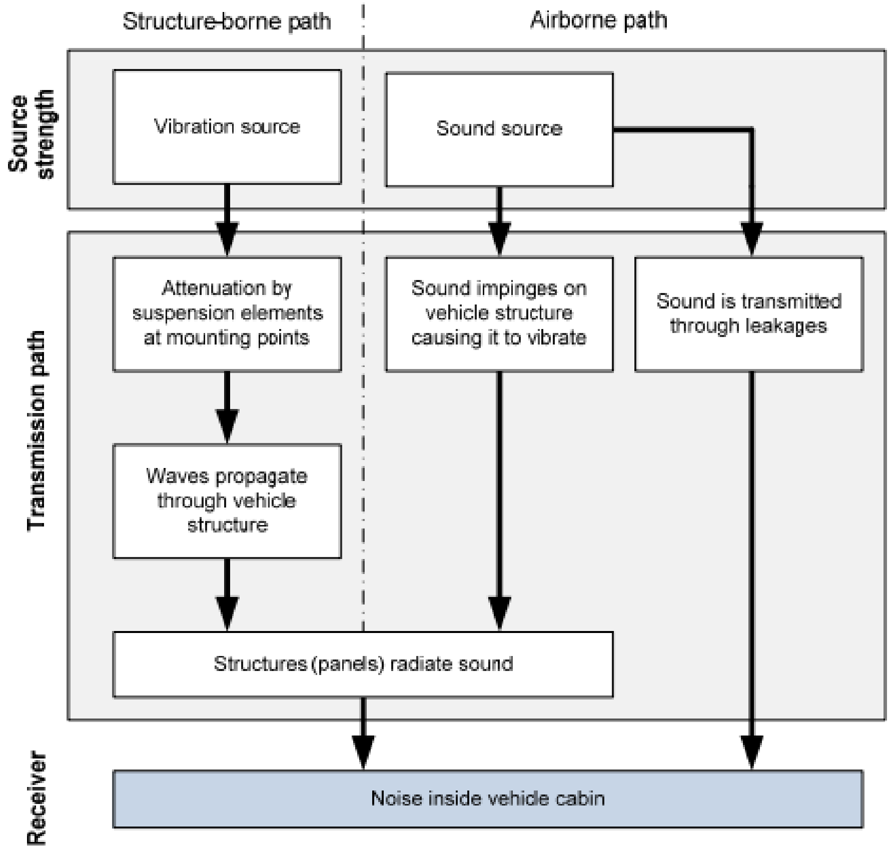

Figure 2.1: Diagram of noise transmission path (Putra et al., 2012)

2.3 EVALUATION OF VIBRATION

The main source of vibration in a vehicle is generally due to tires-road surface interaction, engine transmission during acceleration or deceleration of the car and mounting parts in vehicle's structure such as suspension and exhaust system. The generated vibration depends on the vehicle speed and could be felt in the steering wheel, seats or floor board which significantly affects vehicle interior acoustical comfort in the cabin. These sources are almost unavoidable, however, car manufacturer could overcome and reduce the magnitude, frequency, direction and also the duration of exposed vibration in the vehicle cabin after successfully identify the source of vibration and their transmission path into the car cabin.

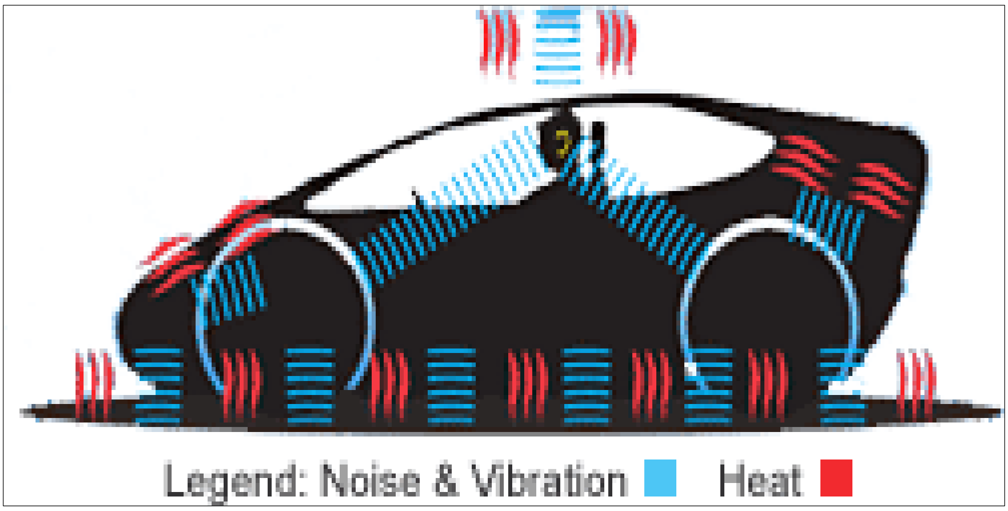

Figure 2.2: Car vibration and noise (Graf et al., 2002)

The total amount of vibration received by human over a period of time can be assessed by using vibration dose value (VDV) formula. Basically, VDV ($ms^{-1.75}$) is the measure of total exposure to vibration which magnitude, vibration exposure duration and frequency are taking into account. VDV can be defined as below:

$$VDV = \left(\int_0^T a(t)^4 dt\right)^{1/4}$$

Where VDV: Vibration dose value ($ms^{-1.75}$)

a (t): Frequency-weighted acceleration

T: Total period in seconds that the vibration occurred

2.3.1 Vibration Due to Tire-Road Interaction

The effectiveness noise reduction of the vehicle's engine and transmission by vehicle manufacturers had brought tire noise to become one of the most important sources of total traffic noise be it an interior or exterior noise. The noise produced by the tire-road interaction had become the most important source of vehicle noise for driving speeds above 40 km/h (Sandberg and Ejsmont, 2002). Tire noise is generated by several mechanisms which are tire wall vibration, air pumping and air resonant radiation in which the dominating noise source among these mechanisms is different for different frequency and speed ranges or for different road and tire conditions (Kim et al., 2007).

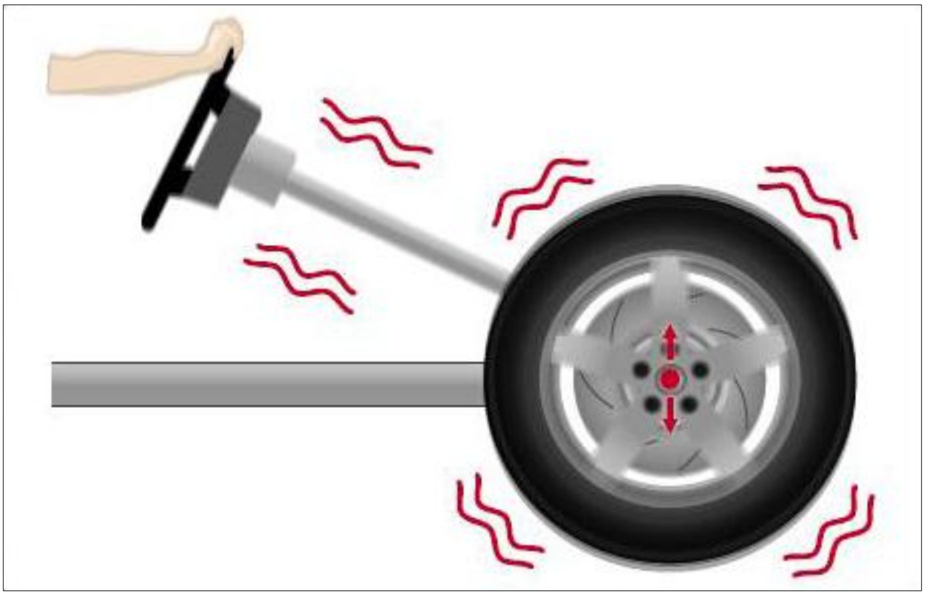

Figure 2.3: Vibration in tire (Kim et al., 2007)

According to Kim et al. (2007), the dominant noise generation mechanism for tire noise below 1 kHz is the tire wall vibration caused by collisions between the tread blocks and the road. At frequency above 1 kHz, all of these noise generation mechanisms have been considered as important contribution to the noise generation.

Tire wall vibration is the major source of tire noise at frequency below 1 kHz and this is due to several mechanisms as follow:

- Tire vibration is caused by the tire tread pattern which produces load modulation. According to Kim et al. (1997), the excitation force of tire vibration is solely due to the tire tread pattern only when the road surface is smooth that its wavelengths are less than those of tire pattern element (pitch length).

- Wheel rotation which causes deflection at the contact area also excites tire vibration. Basically, a tread element has a substantial vertical velocity before it contacts with the road surface and this velocity component is decreased to zero in a very short duration. In a nutshell, the decrease of this velocity component at the leading edge and the increase of velocity component at the training edge resulted in a huge deceleration and acceleration which become the source of tire vibration (Kim et al., 1997).

- Tire vibration is also due to the tire non-uniformity which excites carcass and tread vibration.

- Roughness of the road generates tire vibration in form of analogous to the vibrations produced by the tread pattern.

Generally, air pumping mechanism occurs when tire tread is compressed in radial, lateral and longitudinal directions due to the collisions of road surface with a portion of tire tread. These tread compressions at the leading edge forces and squeeze air out of the groove of the tire when the volume of the groove is reduced. Air pumping is a result of pumping, forcing and squeezing the air out of the tire groove (Hayden, 1971).

Furthermore, air resonant radiation occurs when a tread block at the trailing edge leaves the contact road surface, a Helmholtz resonator is formed due to the groove volume and groove opening (Nilsson, 1979). Helmholtz resonator can be described as the groove volume behaves like a spring and the air flow in the groove opening acts like a mass. There is an expansion of the groove volume and a fast inflow of air result when the groove opened at the trailing edge. According to Nilsson (1979), a high frequency at about 1000-2000 Hz tone bust is generated as the groove releases from the road contact.

Kindt et al. (2009) came up with a result that there is higher intensity of sound pressure level at both ends of a tire when rolling on the road surface. According to Kindt et al. (2009), the high intensity value at both ends is due to the horn effect. The area of contact of the tire and the road surface form a horn-like geometry which provides a significant amplification mechanism for sound sources. As a result, this amplification generates an increase in noise level of about 10-20 dB at around 1000 Hz. In extend, Graf et al. (2002) showed that the amplification owing to the horn effect reaches almost 4 dB at 200 Hz.

Nonetheless, research done by Saemann et al. showed that the radiated noise in the frequency range up to 500 Hz is independent of the tire tread pattern. They presented that the main noise contribution in the passenger compartment is due to the tire construction.

2.3.2 Vibration Due to Road Discontinuities

Vibration is highly dependent on the roughness of the road surface where the tires are rolling on, with the rougher the surface of the road generating more vibration. The term road discontinuities refers to the road pavement defects such as road cracking, potholes, rutting, sewer manholes and junctions between concrete road surface plates. Driving across these road discontinuities causes vibrational and acoustical discomfort to the passengers inside the vehicle. This interior noise can reach significant peak levels as a result of crossing such road discontinuity (Kindt et al., 2009).

At certain speeds, vibration of a vehicle is not only caused by the rolling tires, but also radiated by structure borne vibration which spread to the rim, suspension mounting points, and other parts of the vehicle body (O'Boy and Dowling, 2009). This vibration sources are caused by the uneven road surface and in other word, the up-and-down of the road surface. Nevertheless, this vibration source is also due to the road irregularities which generate sudden shock impact to the tires thus transmitted by solid mechanical transmission paths up to the passenger compartment.

Figure 2.4: Road cracks

Figure 2.5: Pothole

2.3.3 Vibration Due to Excitation of Suspension System and Engine Transmission

In automobiles, the interior noise of a vehicle cabin due to road input below 600 Hz is mainly due to structure-borne transmission path (Iwao and Yamazaki, 1996). Most of the road induced structure borne vibration and noise problems occur at frequency below 600 Hz are related to the dynamic characteristic of suspension and tire, where noise from the road can be characterized as a broadband noise source since it arises from the excitation of the tire rolling or contact on a random road profile. This generated broadband vibrations by the road irregularities are transmitted thru suspension, car structural and other solid parts up to the vehicle cabin (Park et al., 2001).

From the research conducted by Douville et. al. (2006), the most significant resonance of a typical suspension that can be observed on all frequency response function (FRF) is the natural frequency of the entire suspension at 24.4 Hz. They concluded that at this frequency, the entire suspension exhibit “wheel-hop resonance” in which it moves with a large-amplitude vertical displacement (z-direction) when encountered road irregularities. This dynamic characteristic of suspension is responsible for the road induced structure borne vibration and noise at lower frequency of 600 Hz and below.

2.4 ESTABLISHED MEASUREMENT TECHNIQUES

There are various methods to measure the structure-borne noise in vehicle cabin be it either by experimental analysis, engineering software noise simulation, emulated power train to simulate source of vibration and etc. Each of these methods had its pros and cons depending on the interest of research. Some of the research’s objective is to study the vibration transmission path into the vehicle cabin, while the others emulate vehicle vibration source before measuring the structure-borne noise in the cabin. Aforementioned above, structure-borne can also be measured by vehicle noise simulation software which could precisely decompose total interior noise in vehicle cabin into structure-borne and airborne noise.

2.4.1 Experimental Analysis of the Structure-borne Tire-road Noise Due to Road Discontinuities

An experimental analysis of road discontinuities induced structure-borne tire-noise interaction noise had been conducted by Kindt et al. (2009) to analyse the peak noise levels as a result of driving across road discontinuities. These road discontinuities are the deformations of road which are potholes, road cracks and etc. as well as the purposely man-made road irregularity for other purposes such as expansion joints, railway crossings, sewage holes and so on.

In this research, they designed and created a novel test setup at the K.U Leuven Noise and Vibration Engineering Laboratory in order to measure the structural and acoustic response of a tire rolling over a cleat. The cleat is used in this experiment to serve the purpose as the road discontinuities. This test setup is shown in the figures below.

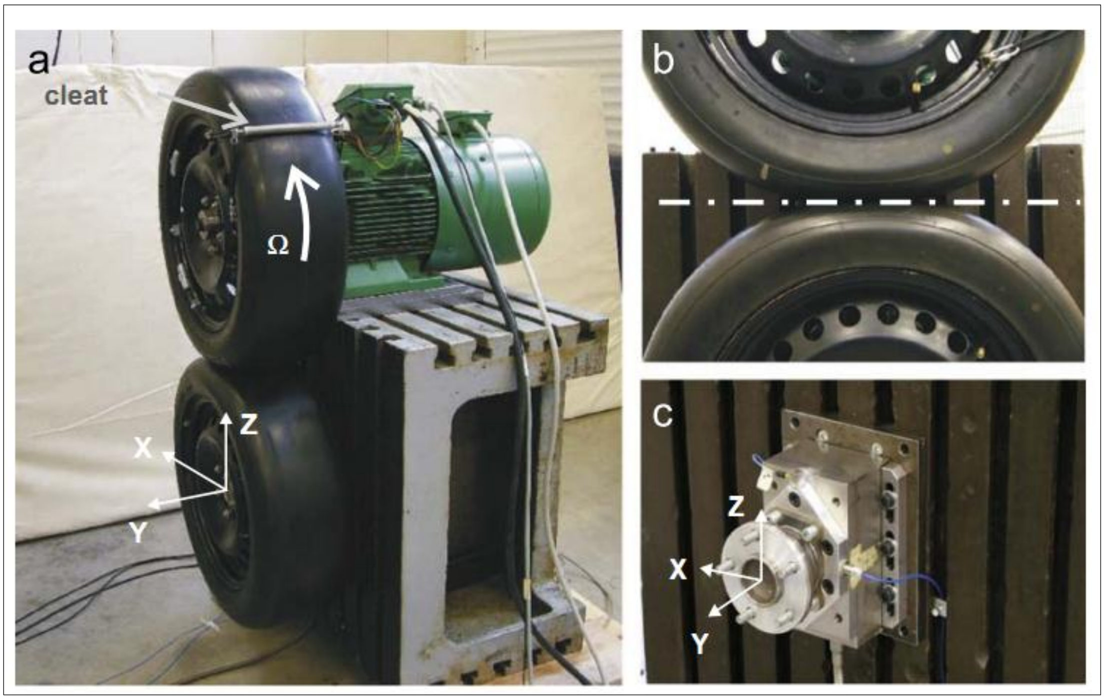

Figure 2.6: a) Test setup with two tires mounted. b) Static tire deformation due to preload. c) Multiaxial wheel hub dynamometer (Kindt et al., 2009)

As shown in the figure above, two identical tires are used in this experiment in which the upper tire is mounted on the induced motor and the second tire where