

Developing a Statistical Model to Predict Tire Noise at Different Speeds

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ABSTRACT

Tire noise is caused due to the complex interactions between the rotating tire and the road surface at the tire/road interface. It is usually caused due to a combination of individual noise generation mechanisms, which can either be structural or air-borne. The influence of each of these noise generation mechanism may vary, depending on various conditions such as tire design, road surface and operating conditions. Due to the many variables that affect the noise generation mechanisms in tires, it is usually a very complex task to isolate and categorize those that are present in the overall tire/road noise spectrum. Various approaches are used to categorize noise generation mechanisms in tires. In this paper, a statistical model based on the assumption that the tire noise acoustic pressure at a specific frequency band is related to the vehicle speed, is used, in order to study tire noise at different speeds. Consequently, the variation of the speed coefficients with frequency bands is studied for a tire with two transverse slots cut into it, and an effort is presented here, to isolate the different noise generation mechanisms as structural or air-borne. While the goal of the statistical model is to indirectly isolate different noise generation mechanisms, the experimental studies presented here, directly attempt to isolate air-borne and structure-borne noise using a foam. Overall, the current study, tries to establish a trend for the variation of tire noise with tire speed, and also serves to reinforce the notion that statistical models can be used to isolate the different tire noise generation mechanisms.

CITATION: Gautam, P., Azizi, Y., and Chandy, A., "Developing a Statistical Model to Predict Tire Noise at Different Speeds," *SAE Int. J. Veh. Dyn., Stab., and NVH* 1(2):2017, doi:10.4271/2017-01-1507.

INTRODUCTION

Tire noise is a complicated phenomenon, caused due to a complex interaction between a tire and the road surface. It is important to be able to control tire noise, since it is one of the major sources of traffic noise [1, 2]. In order to control tire noise, it is first necessary to understand the underlying mechanisms. Tire noise may be classified in terms of whether the observer is inside the vehicle (in-vehicle) or outside the vehicle (pass-by). Furthermore, tire noise may propagate through the structure or through the ambient air and the classification of structure-borne and air-borne noise may be done using the means of propagation of the noise as well. The classification presented here is based on [3], which refers to the origin of the noise, i.e., low frequency structure-borne tire noise caused due to the structure of the tire, and the high frequency air-borne noise due to the response of air pockets to sudden changes in the structure. While structure-borne tire noise is generally caused by the vibration of the tire itself, the sidewalls, or the tread blocks, air-borne noise maybe be caused due to mechanisms such as air-pumping and resonance.

The importance of tire/road noise generation can also be determined in terms of frequency ranges. Since lower frequency noise are more energetic, they tend to transmit through structures. Therefore, for in-vehicle noise, it is necessary to control low frequency tire noise generation. Studies have suggested that the noise in the frequency range of 50 Hz to 2000 Hz is important for in-vehicle noise [4, 5, 6]. The frequency range of interest is similar for pass-by noise as well [7]. Consequently, any noise source that falls in this frequency range becomes significant and it is necessary to design the tire so that such noise sources are minimized, or the frequency of such sources are changed so that they become less significant.

Several attempts have been made to predict different noise generation mechanisms in tires. The modeling approach, however usually focuses on specific mechanisms and a complete model which can describe the overall tire noise generation has yet to be established [8, 9]. The modeling approach can be either purely statistical, purely deterministic or a hybrid of the two.

The speed coefficient approach discussed in this paper, as well as some results presented in [10, 11] are purely statistical models, where the variation of the tire noise with speed is studied and compared to generalized quantities. Purely deterministic models, from which numerical solutions are obtained, are based on approaches used to represent physical phenomena. The deterministic models may be used to predict either structure-borne noise [12, 13] or air-borne noise [14, 15, 16, 17]. Hybrid models are a combination of statistical and deterministic modeling approaches used by studies such as [18].

This paper mainly focuses on statistical modeling of tire noise, where speed coefficients are calculated from an experimental study. A tire with two hand-cut slots is used as the test tire and experimental studies are performed for six different tire speeds at a load of 800 lb. Speed coefficients are obtained for different frequency bands, using the sound power level data for different speeds. Additionally, a more direct approach is used to distinguish between air-borne and structure-borne noise, by filling the hand-cut slots with closed-cell foam. In doing so, the air pockets on the tire is removed and the resulting noise generated in theory, is only structure-borne. A comparison of the results between the direct experimental technique and the speed coefficient approach is made in order to study whether the statistical method can be used to draw meaningful conclusions with respect to the influence of different noise generation mechanisms.

Speed Coefficient Approach

The basis of the statistical model is that the different noise generation mechanisms affect the overall tire noise spectrum differently and hence, their relative impact on specific frequency bands change with speed. Consequently, a speed exponent and frequency band can be used to identify a specific mechanism from the overall spectrum. This assumption results in Eq. (1), which is a relation between the acoustic pressure and tire rotation speed.

Table 1. Ranges of speed exponents and frequency ranges for different tire/road noise generation mechanisms

	Speed exponent	Frequency
Structure-borne		
Radial vibrations		
- Carcass	2.0-3.0	100-500 Hz
- Tread block	3.0-3.5	100-500 Hz
Tangential vibrations		
- Tread block	3.0-5.5	> 1 kHz
Air-borne		
Air-pumping	4.0-5.0	1-3 kHz
Helmholtz resonances	0.0	1-2 kHz
Pipe resonances	0.0	500 Hz-3 kHz

$$p^2 = aU^n, \quad (1)$$

where p is the acoustic pressure, U is the tire speed, and a and n are constants. This form of the equation has also been used previously to identify the contribution of different mechanisms on the overall tire noise, by splitting the contribution of U^n at $n = 2, 4, 6$ [10]. This is based on the assumption that structure-borne noise has an $n \approx 2$

variation with tire speed, while air-borne noise results in higher values of n . However, it is more common to measure tire noise in terms of sound power level than in terms of acoustic pressure. Therefore, the relation is converted to log-log form.

In a log-log form, Eq. (1) is converted into an equation for the dependence of the sound pressure for a vehicle speed level as,

$$L_p = nL_s + b \quad (2)$$

Here, $L_p = 20\log_{10}\left(\frac{p}{p_{ref}}\right)$ is the sound pressure level,

$L_s = 10\log_{10}\left(\frac{U}{U_{ref}}\right)$ is the speed level for a reference tire speed of U_{ref} and b is a constant. It is important to note that while Eq. (1) is an n^{th} order polynomial, Eq. (2) is a linear equation. In this paper, Eq. (2) is used.

The speed coefficients can be useful to identify different noise generation mechanisms. However, the conclusions drawn from speed coefficients can be misleading in cases where multiple mechanisms may contribute to a specific noise frequency. Hayden [16] theorized that air-pumping has a speed coefficient of 4.0, based on the assumption that air-pumping noise generation sources are monopole in nature. Similarly, other studies have suggested that air-pumping mechanisms have a speed coefficient range of 4.0-5.0 [19]. Table 1 shows the classification presented in [8], based on a review of various studies. This is used as a reference for the comparisons in this paper.



Figure 1. The experimental setup inside the semi-anechoic chamber located at Bridgestone Americas Technical Center in Akron, Ohio.

EXPERIMENTAL SETUP

The experimental setup (Fig. 1) is located at the testing facility owned by Bridgestone Americas Technical Center in Akron, Ohio. The setup consists of a semi-anechoic chamber, where a road wheel drum, 10 ft in diameter, is used to drive the tire, fixed on a spindle and loaded using a load frame. As shown in Fig. 1, the drum surface contains a fine grit sandpaper, which ensures that the surface is not exciting the tire during rotation and any noise generated is because of the tire itself. This implies that the statistical model that is adopted in this paper is applied to study the speed coefficients for the noise generated by the hand-cut slots on the tire and not the road surface texture.