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THE INFLUENCE OF TYRE CAVITY ON ROAD NOISE: A THEORETICAL AND EXPERIMENTAL COMPARISON

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Abstract. *Consumers are increasingly linking the vehicle quality to its vibroacoustic comfort, considering this an important factor in purchasing decisions. Most of vehicle noise are related to powertrain, wind and tyre/road interaction, which is currently the most important source of noise. In this sense, the present work aims to study how the tyre cavity resonances influences the interior noise due to the vibration transmission across the wheel and the suspension system into the vehicle compartment. First, two analytical models are presented to estimate the tyre cavity resonance frequencies. Then, road tests are performed to correlate the experimental results with the analytical models and theoretical concepts. Through the measurements was verified that tyre cavity resonances are the main contributions to the interior noise. Complementarily, applying the multiple coherence function it was confirmed that the noise measured in the microphones has a high correlation with the vibration measured in the suspension knuckles, proving that the interior noise is prominently originated by structural transmission.*

Keywords: *tyre/road noise, tyre cavity resonance, vehicle interior noise*

1. INTRODUCTION

With the elevated competition in the automotive industry and the demand for acoustic comfort from customers, NVH (noise, vibration and harshness) performance is increasingly being recognized as an important vehicle quality factor. Wang (2010) states that consumers usually associate vehicle quality to its vibroacoustic comfort. Problems related to noise and vibration affect the occupants' comfort, inducing stress, fatigue and feelings of insecurity. Therefore, the understanding of the vibroacoustic energy transmission to suit the market demands is a great challenge for the automotive industry, significantly influencing the vehicle overall image.

Most of vehicle noise sources are related to powertrain, wind and tyre/road interaction. The SPL (sound pressure level) in the vehicle is mainly determined by air-borne transmission through the structure and by structure-borne sound transmitted into the car body. The vibrating structure then radiates noise into the vehicle compartment. In the past, engine noise was the most relevant for vehicular noise, but with the advancement of NVH technology, nowadays it is possible to identify noise sources and reduce the noise and vibration transmission from the engine and aerodynamic sources to the passenger compartment (Chanpong et al., 2014; Mohamed, Wang and Jazar, 2013). As summarized by Sandberg and Ejsmont (2002), the same cannot be stated for tyre/road noise. The progress for this source has been much slower, making tyre/road interaction currently the most important source of vehicle noise for driving speeds above 40 km/h. Besides the slower progress, Kindt *et al.* (2009) affirms that the tendency towards wider tyres and larger wheel diameters has also contributed to increased importance of tyre/road noise.

Although the tyre wheel assembly present cavity, tyre structure and wheel modes, Mohamed and Wang (2015) point out that tyre cavity resonance is the one that spreads the mostly energy through the passenger chamber and thereby contributes to the increased level of annoyance (noise is loud and noticeable). According to Fernàndez (2006), when a vehicle is travelling on a road the contact forces between the tyres and the road surface vary with time due to the motion of the car and the roughness of the road and the tyre pattern. The forces acting on the tyre deform the tyre tread resulting in an acoustic field being excited within the air cavity of the tyre. The resulting pressure inside the tyre is quite high at the cavity resonances, increasing the energy transmission from the road-tyre contact surface through the tyre to the wheel axle and thus to the vehicle body itself.

Considering this, the present work analyzes how the tyre cavity resonances influences the interior noise due to the vibration transmission across the wheel and the suspension system into the vehicle compartment. The problem will be evaluated in two different parts. First, it will be presented conclusions from previous studies and two models for tyre cavity analysis analytically. Then, road tests will be performed in order to correlate the experimental results with theoretical concepts and analytical results. A commercial tyre of size 185/60R15 was used for the analytical and experimental approach.

2. TYRE CAVITY RESONANCES

2.1 Background

The first study related to the effects of tyre cavity resonances was published by Sakata *et al.* (1990), where they observed an acoustic resonance mode in the tyre cavity that significantly influences the structure-borne interior noise. Moreover, Sakata *et al.* (1990) presented other contributions on the topic, such as:

a) The tyre deflected generates two acoustic modes compared to a corresponding acoustic mode at the near frequencies in an undeflected tyre.
b) Only the first cavity resonance affects road noise (considering deflected tyres the first two modes will affect).
c) The cavity resonance is virtually unaffected by the cross-sectional shape of the tyre, being more important the circumference of the tyre at its cross-section center.
d) The cavity resonances is virtually unaffected by the tyre inflation pressure.
e) Filling a tyre with polyurethane foam can attenuate the effects of cavity resonance.

Since then, many authors have investigated the phenomenon by theory, simulations and experiments. However, the tyre/road interaction remains with much progress to be made, being the most important source of vehicle noise.

2.2 Undeflected tyre model

Thompson (1995) pointed out that through the knowledge of tyre geometries, approximations have been developed to allow the calculations of the resonance frequencies. As shown in Fig. 1, the undeflected tyre model is the simplest case for modeling the tyre cavity resonance. Sakata *et al.* (1990) simplify the tyre cavity for a torus in the theoretical model. As the wavelength is much larger than the cavity cross sectional dimensions to low frequencies, the sound in the tyre cavity can be treated as a plane wave.

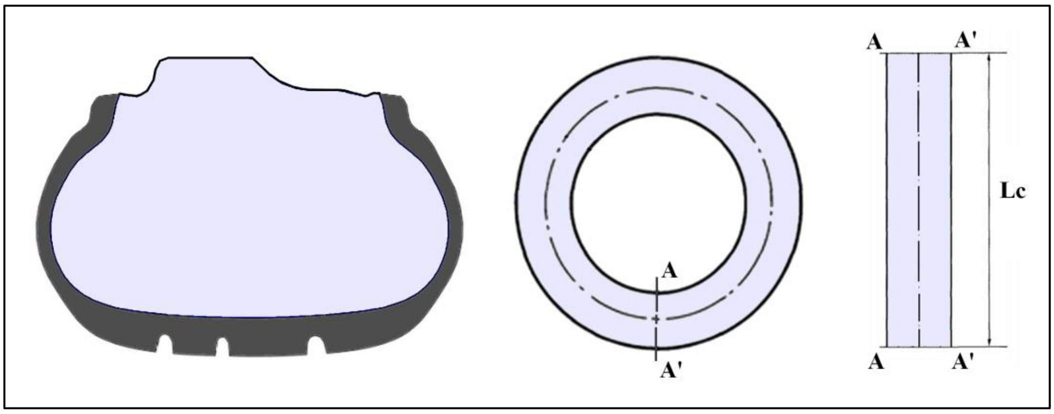

Figure 1. Undeflected tyre cavity model

Based on these premises, Sakata *et al.* (1990) defined a mathematical expression (Eq. 1) that gets precise predictions of the natural frequencies in the tyre cavity.

$$f_{\mathrm{i}} = i \cdot \frac{c}{L_{\mathrm{C}}} \tag{1}$$

where f is the i^{th} resonance frequency, i is the order of the cavity resonance, c is the sonic speed and L_C the length of the tyre circumference at its cross-section center. Using the Eq. 1, the first cavity resonance frequency of the 185/60R15 tyre (c = 343 m/s, L_c = 1.46 m) is 234.9 Hz.

Next, the result of the analytical solution was compared with a finite element simulation, that were performed with the Siemens LMS Virtual.Lab software (using a real model of tyre cavity). Through this approach, the first cavity resonance frequency of the 185/60R15 tyre is 233.5 Hz, proving that the Eq. 1 presents a precise prediction of the natural frequencies in a tyre cavity. Figure 2 shows the two acoustic mode shapes of the undeflected tyre cavity in 233.5 Hz.

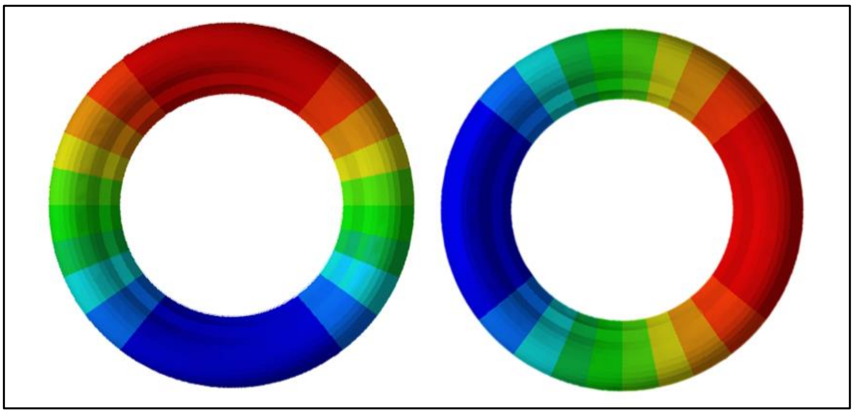

Figure 2. First two acoustic mode shapes of the undeflected tyre cavity

2.3 Deflected tyre model

The development of the model for the deflected tyre cavity is more complicated than the undeflected tyre. Although Sakata *et al.* (1990) had already observed the effect of the deflected tyre in his study, it was Thompson (1995) who developed an analytical expression for the acoustic resonance frequency of the deflected tyre. In his study, Thompson (1995) stated that under deflection the tyre cavity is no longer a constant cross section, and then a small cross section appears in the area where the tyre contacts the road surface, as shown in Fig. 3. This contact patch causes a break in the tyre symmetry, which produces two modes identified as the horizontal shape mode and the vertical shape mode.

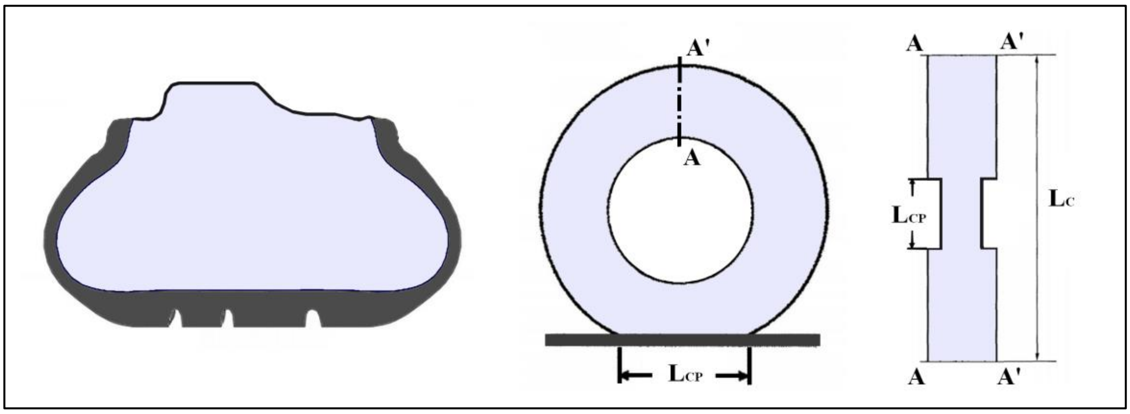

Figure 3. Deflected tyre cavity model

Unlike the undeflected tyre model, the best approach for the deflected tyre is modeling the tyre as a finite length tube with a constriction. Equations (2) and (3) predict, respectively, the horizontal natural frequency (f_h) and the vertical natural frequency (f_v) of the tyre cavity.

$$f_{\mathrm{h}} = \frac{c}{L_{\mathrm{C}} + (1-m)\cdot L_{\mathrm{CP}}} \tag{2}$$

$$f_{\mathrm{v}} = \frac{c}{L_{\mathrm{C}} - (1-m)\cdot L_{\mathrm{CP}}} \tag{3}$$

where c is the speed of sound, L_C is the median circumferential length of the tyre cavity, L_{CP} is the contact patch length, m is the ratio of the cross sectional area in the contact patch S_{CP} to the undeflected cavity cross sectional area S, S_{CP} is the cross sectional area in contact patch and S is the undeflected cross sectional area. Using Eq. 2 and 3, the horizontal and vertical tyre cavity resonance frequencies of the loaded 185/60R15 tyre (c = 343 m/s, L_C = 1.46 m, L_{CP} = 0.115 m, m = 0.75) are, respectively, 230.4 Hz and 239.6 Hz.

Comparing these expressions to that for the undeflected tyre, the lower frequency (f_h) for the deflected tyre is less and the higher frequency (f_v) is higher than the undeflected tyre cavity resonance frequency. The higher resonance frequency excites the knuckle in the z-direction (vertical) due to the road input while the lower resonance frequency excites the knuckle in the x-direction (horizontal). As outlined by Sakata *et al.* (1990), only these first two modes of the tyre cavity resonance (considering the deflected tyre) could amplify tyre/road noise into cabin. Yamauchi and Akiyoshi (2002) also made an important contribution in this field, identifying that as the speed of the vehicle increases, the f_h is getting lower and f_v is increasing.

Thompson (1995) also pointed out that the determination of the cavity resonance frequencies for the deflected tyre using finite element simulation has had limited success. For this reason, road tests were performed to compare with the results of the deflected tyre model.

3. EXPERIMENTAL PROCEDURE

The road tests were performed in a compact vehicle, equipped with 15x6"steel wheels and commercial tyres of size 185/60R15 with air pressure of 32 psi. With regard to speed, measurements were first made at a constant 75 km/h, since under these conditions tyre/road noise stands out. Then, coast-down tests were performed to evaluate the variation of tyre cavity resonance frequencies with respect to speed. The coast-down test consisted of launching the vehicle from 120 km/h with the engine ungeared, while recording the speed (besides the noise and vibration) until the vehicle reaches 20 km/h.

The LMS Scadas Mobile measurement hardware and the LMS TestLab software were used, respectively, for data acquisition and analysis. During the measurements there were two occupants in the car, a driver and a passenger taking care of all the equipment, the experimental notes and procedure. For measurements the vehicle was instrumented with microphones and accelerometers. For the noise measurements two microphones were used, positioned at the height of the driver's right ear and driver's left ear, as indicated in Fig 4a. The interior noise will be presented as an average of the two microphones. Accelerometers were used to measure the longitudinal, vertical and lateral acceleration components of front suspension knuckles (Fig. 4b) and rear suspension knuckles (spindle acceleration)

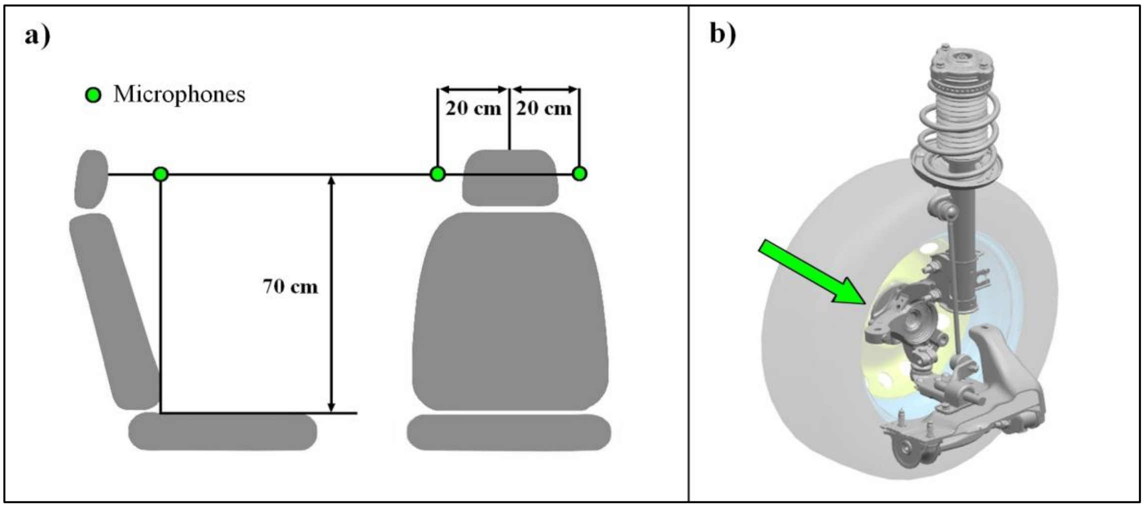

Figure 4. a) Position of the microphones in the driver's seat. b) Position of the accelerometers in the front suspension knuckles

4. RESULTS AND DISCUSSION

The graph presented in Fig. 5 shows the SPL for the vehicle constant at 75 km/h. It is possible to clearly identify the two peaks referring to the tyre cavity resonance frequencies. As highlighted in green, the 1/3 octave band with center at 250 Hz is the one with the highest noise level, thus indicating that the tyre cavity is the main source of interior noise. This condition is in accordance with Sandberg and Ejsmont (2002), in which they indicated that tyre/road interaction is currently the most important source of vehicle noise for driving speeds above 40 km/h.

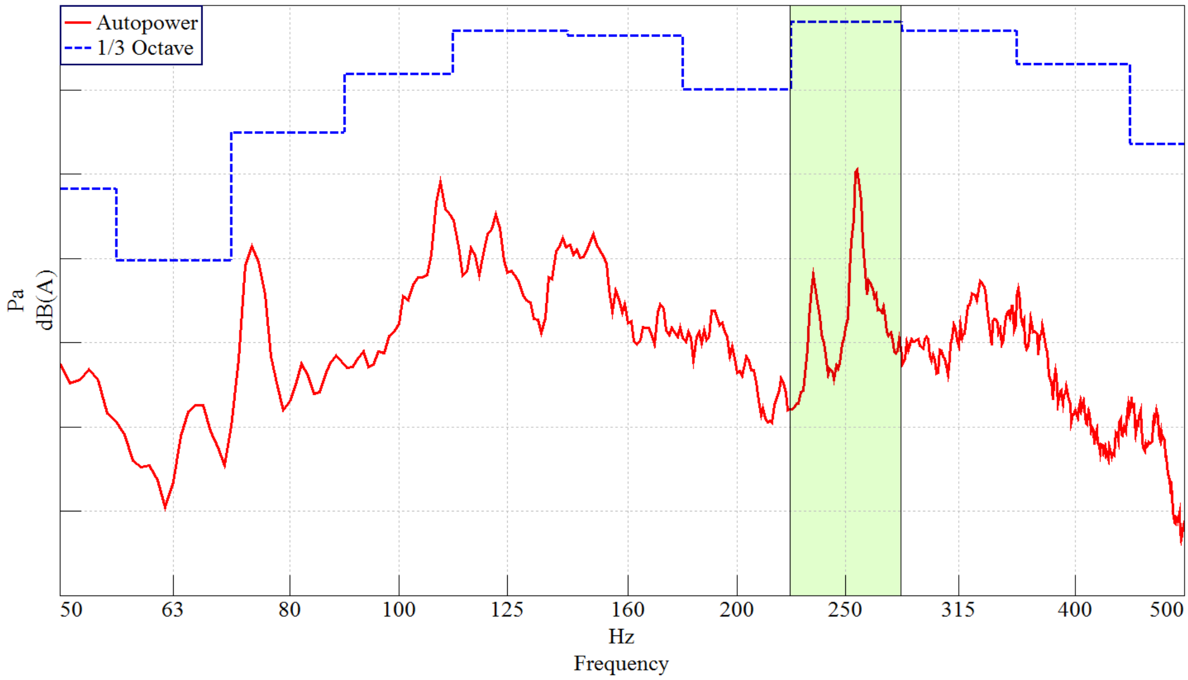

Figure 5. Interior SPL at the driver's ear position

Another way to demonstrate the influence of tyre cavity on road noise is through the multiple coherence function. It indicates how much the noise measured in the microphones is correlated to the vibration measured in the wheel knuckles, that is, the fraction of noise that is originated by structural transmission. The closer the coherence function is to the value 1, the higher the correlation between the measurements analyzed. In the frequency range of interest, as highlighted in Fig. 6, the coherence function presents values close to 0.94 and 0.97, indicating a high influence of the tyre cavity on road noise.

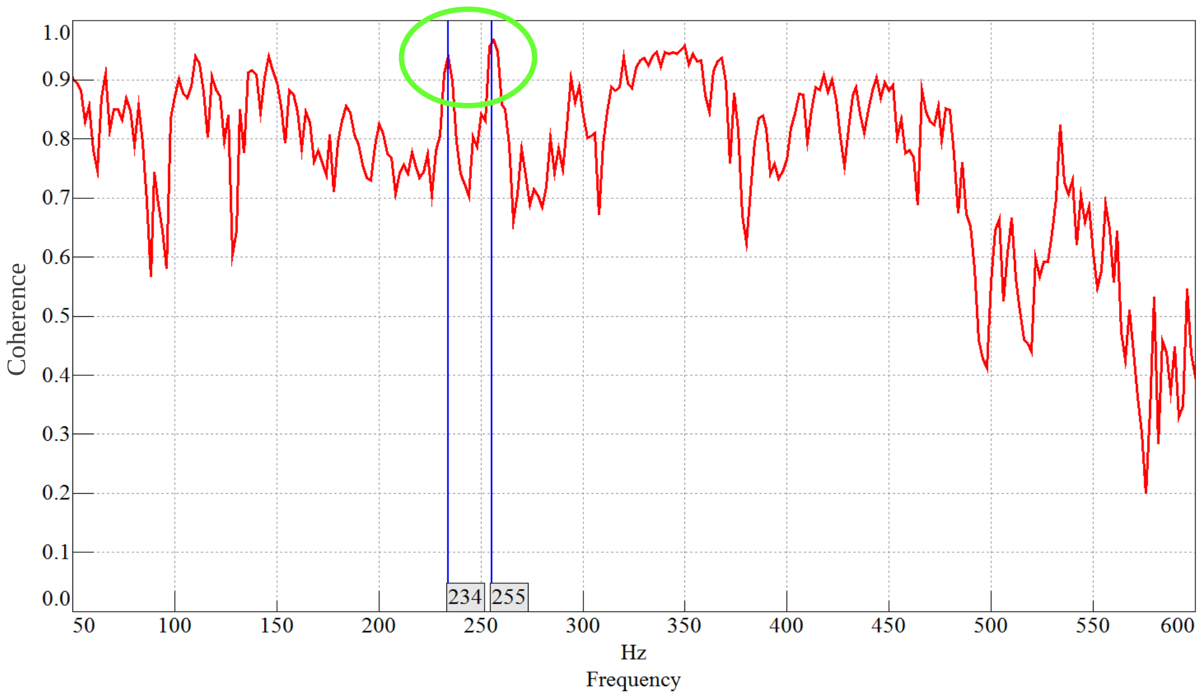

Figure 6. Multiple coherence function

Analyzing Fig. 6, it can also be inferred that despite some variations, the interior noise below about 500 Hz correlates very well with the vibration measured in the suspension knuckles. This fact confirms that up to this frequency range the interior noise is mainly determined by structural transmission.

Lastly, Figure 7 shows the coast-down test result. The colormap shows a relation between speed, frequency and SPL, helping to identify resonance frequencies. It can be clearly seen that f_h is getting lower and f_v is increasing as the speed of the vehicle increases, certifying what was theoretically predicted by Yamauchi and Akiyoshi (2002).

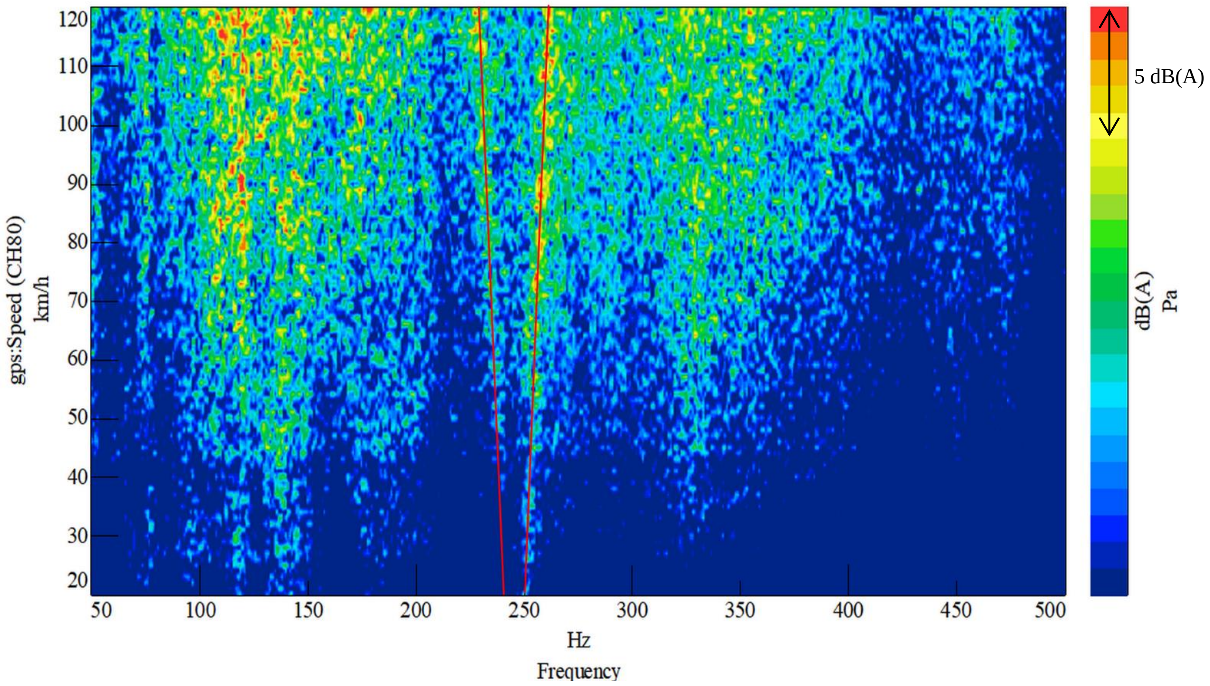

Figure 7. Colormap graph of the coast-down test

As found through the analytical approach of the tyre 185/60R15, the first cavity resonance frequency of the undeflected tyre is 234.9 Hz and the horizontal and vertical tyre cavity resonance frequencies of the deflected tyre are, respectively, 230.4 Hz and 239.6 Hz. Figure 8 shows in detail the frequencies highlighted in red lines in the colormap of Fig. 7, where is shown the variation of the tyre cavity resonance frequencies with respect to speed in the road tests. It can be concluded that the two approaches have the same tendency, but that the frequencies of the experimental results are slightly higher than the analytical results (approximately 10 Hz).

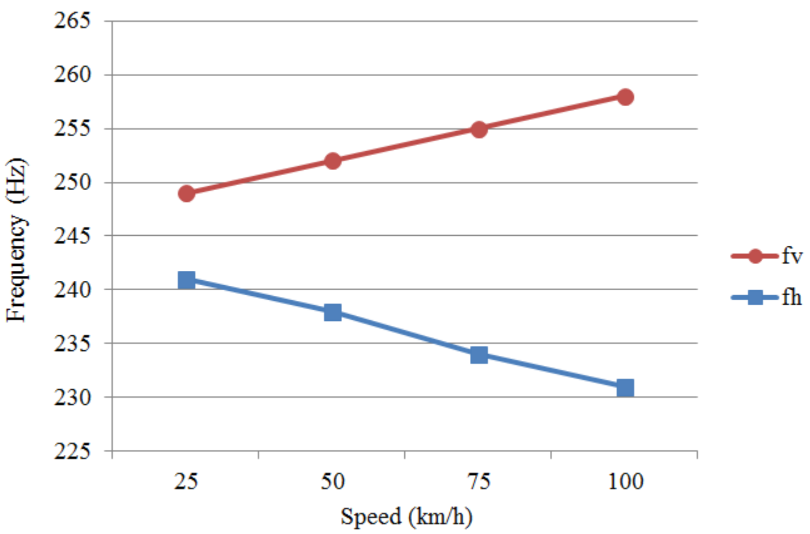

Figure 8. Variation of the tyre cavity resonance frequencies with respect to speed

As seen in the analytical approach, the speed of sound in the air is a very important parameter for determining the tyre cavity resonance frequencies. Thus, the increase in temperature that occurs in the road tests can be an explanation for the difference of these results, since it can directly influence the speed of sound inside the cavity.

5. CONCLUSIONS

The influence of the tyre cavity on road noise was verified by analytical and experimental analysis. Initially, an analysis of the undeflected tyre was performed, which corresponds to the simplest model to analyze the tyre cavity. The analytical results were verified by finite element simulation, providing a precise result. For the deflected tyre model, which is more complex and close to the real one, an analytical approach and road tests were performed.

Through the interior noise measurements it was verified that tyre cavity resonances are the main contributions to the interior noise. Then, applying the multiple coherence function it was possible to indicate that the noise measured in the microphones has a high correlation with the vibration measured in the suspension knuckles, proving that noise measured in the interest frequency range is prominently originated by structural transmission. Finally, through the results of the coast-down test it was possible to infer as the speed of the vehicle increases, f_h is getting lower and f_v is increasing.

The arguments given above prove that the work was able to satisfactorily correlate the results of road tests with theoretical concepts and analytical results, showing the important influence of the tyre cavity on road noise.

6. ACKNOWLEDGEMENTS

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