euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Numerical tyre impact model combining Finite Element and Boundary Element Methodologies.

Miguel Fabra-Rodríguez[1]*, Ramón Peral-Orts[1], Héctor Campello-Vicente[1], Nuria Campillo-Davó[1], Francisco Javier Simón-Portillo[1].

[1]Miguel Hernandez University, Elche, Spain.
*mfabra@umh.es

Abstract
In urban environments, the predominant noise emission is generated by the use of vehicles. Rolling noise, produced by the interaction between vehicle tyres and road surfaces, increases its importance as attenuation of the mechanical component's noise is achieved in modern vehicles. Vibratory phenomena, mainly due to impact mechanisms, are predominant in rolling noise at low and medium frequencies. To understand these better, this document presents a two-step numerical model: Firstly, a parameterised tyre is modelled to perform a dynamic study using the Finite Element Method. In this time-domain step, the tyre hits a rigid plain surface, then, the vibration over the tyre is transformed to the frequency domain through the Fast Fourier Transform. Secondly, this vibration is used as a sonorous source in a Boundary Element analysis to study sound propagation. This second study finally allows the sound directivity of the impact to be analysed at the frequencies of interest.

Keywords: Tyre noise, impact model, FEM, BEM.

1 Introduction

Road traffic is the noise source that affects the largest number of people [1]. The noise produced by traffic can be considered as the collective contribution of each of the vehicles that constitute traffic flow. The noise emitted by a vehicle is generated by different sub-sources [2] that can be grouped into three main categories: the noise generated by the engine and the traction system, the noise produced in the tyre-pavement interaction, and aerodynamic noise.
Advances in improved aerodynamics and optimisation of mechanical components have significantly reduced emissions in present vehicles [3]. In the case of hybrid-electric (VHEs) and electric (VEs) vehicles, the noise contributions of their mechanical components are practically reduced. Therefore, it is still necessary to know the physical mechanisms involved in the generation of rolling noise, since the noise emission generated in the tyre-pavement interaction is independent of the vehicle's propulsion system.
In general terms, the main mechanisms for generating rolling noise collected in the literature in this field [4] are divided into two groups: the mechanical vibrations of the tyre and the aerodynamics of the emission zone. Vibratory mechanisms predominate in the low and medium frequency range (below 1,000 Hz), which, in turn, are divided into impact mechanisms and adhesion mechanisms.
The impact of the tyre tread produces vibrations on the carcass that propagate through the sidewalls of the tyre. To study this phenomenon, this document proposes a model of the tyre using the Finite Elements Method (FEM) that allows the vibration on its surface after impacting on a rigid surface to be analysed. This vibration is then used as a sound source in a Boundary Element Method (BEM) frequency analysis to determine sound propagation.

2 State of the Art

The study of the mechanical behaviour of the tyre through Finite Elements has been widely studied in the bibliography: In [5] the distribution of stresses in tyres depending on the inflation pressure and the vertical load is studied. In [6] the stress and deformation of the different parts of a tyre are analysed while using a model of hyperelastic material. In [7] the vertical force-displacement characteristics of a wheel are studied using models of material obtained from tensile tests of specimens. These studies characterise the tyre through its different parts, applying specific material characteristics for each one of them.

Sound tyre propagation through FEM has been studied in [8], where the free-field absorbing condition is achieved through the Perfectly Matched Layer method and the road is modelled as a rigid surface. The sound power comes from a previous noise prediction model and then it is intended to achieve the same sound propagation produced by the wheel surface but simplifying it to equivalent monopole sources.

In [9] a Lagrangian mesh is used to simulate the behaviour of the wheel through a FEM analysis, where the non-rotational acceleration obtained is then mapped onto an Eulerian mesh that allows the study of acoustic propagation. This propagation is studied through BEM analysis, where the air over the wheel does not need to be discretised and the free-field condition is directly fulfilled. Besides that, in [10] the sound propagation of the wheel vibrations is achieved through a finite/infinite element approach.

Regarding tyre impact models that allow noise generation, in [11] and [12] the noise produced by the tyre after passing over a speed bump element is studied. In [11], using a lumped model of a quarter of a vehicle, the force acting on the wheel is obtained when it crosses a certain speed bump profile. This force is applied to the 3D FEM model of a tyre to study the emitted noise. In [12] the wheel, rim and suspension assembly are modelled directly in 3D and through a coupled FEM matrix system, the normal acceleration is used as a sound source to obtain the acoustic propagation in the time domain.

Beyond tyre noise, there are vibroacoustic studies such as [13] where the structural vibration modes of the chassis of a vehicle obtained by FEM are used in a BEM propagation analysis. Before, in [14] the interior noise of the vehicle produced by forces acting directly on its structure was studied with a coupled FEM model. Other contributions of vibroacoustic coupling applications are given in [15] for the hull of a submarine and in [16] for parts of space vehicles.

3 Methodology

3.1 Fundamentals

The dynamic response of a system of deformable solids subjected to variable loads over time is obtained using a transient dynamic analysis, where the inertial characteristics must be taken into account. Therefore, the displacement field u is a function of time and is governed by the Motion Equation (1).

$$M\,\ddot{u} + C\,\dot{u} + K\,u = F \tag{1}$$

Where M is the mass matrix, C is the damping matrix, K is the stiffness matrix and F is the loads' vector. In the Finite Elements Method, this equation is not solved directly, instead, their resolution involves using the appropriate numerical approach, such as virtual work principle.

In the next step, the Fast Fourier Transformation is applied to the displacement field u in a given time window to convert it into the frequency domain. The boundary condition of equation 2 links the displacement field u of the solid medium to the pressure field p of the air in the surfaces of interest.

$$-n \cdot \left(-\frac{1}{\rho}\nabla p\right) = (i\,\omega)^2 n \cdot\, u \tag{2}$$

Where n is the normal unit vector of the surface and ρ the density of the medium.

The acoustic propagation is governed by the Helmholtz Equation (3) solved through the Boundary Element Method in frequency-domain simulations.

$$\nabla^2 p - \left(\frac{\omega}{c}\right)^2 p = 0 \quad (3)$$

Where c is the speed of sound.

3.2 Model

The tyre geometry has been parameterised to be automatically generated by the three fundamental size values of the ISO metric code for tyres [17]:

- Tyre width in *mm*.
- Aspect ratio, which expresses the percentage ratio of the width and height of the sidewall.
- Diameter of the rim in *inches*.

Table 1 shows the parameters of the three chosen tyres. *Tyre 1* refers to a type of compact car, *tyre 2* refers to a type of truck and *tyre 3* refers to a type of sports car.

Table 1 - Size parameters of the three chosen tyres.

	Tyre 1	**Tyre 2**	**Tyre 3**
Width [*mm*]	205	265	265
Aspect Ratio	45	70	40
Rim [*in*]	16	17.5	21

Figure 1 shows the mesh of the three generated tyres.

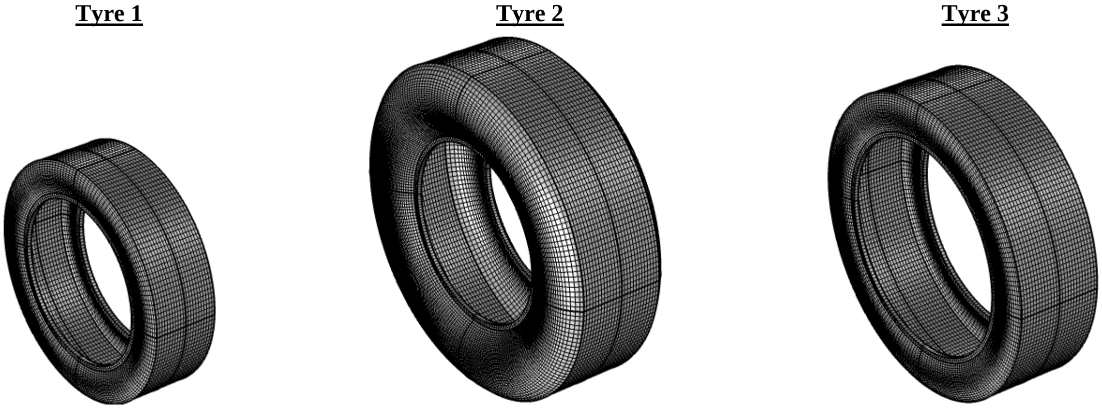

Figure 1 - Mesh of the three selected tyres.

In the first place, the transient dynamic simulation governed by equation (1) is performed through FEM. In this analysis, the tyre hits a rigid surface, for this, the tyre has an initial speed v_i equivalent to a free fall from one meter, at the same time, the acceleration of gravity g is also applied. Figure 2 shows in blue the inner surface of the tyre where an inflation load pressure of 200 *kPa* is applied. The rim is simulated the boundaries of the shoulder tyre (in yellow in Figure 2) by becoming non-deformable and applying a distributed mass of 15 *Kg* on them. The material considered [18] has uniform elastic properties throughout the whole tyre volume.

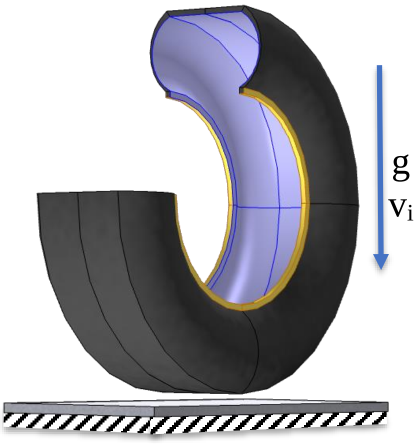

Figure 2 - Modelling of the FEM analysis with a three-quarter view of the tyre.

Once the transient analysis in the time domain has been solved, the FFT is applied to the field of displacements of the tyre to be able to use its outer surface as a sound source following equation (2). The BEM analysis is then performed to solve the Helmholtz Equation (3) and calculate sound propagation. Figure 3 shows the modelling of these acoustic simulations: A reflective plane acts as a floor and the ring element highlighted in blue simulates the presence of a tyre through its sound reflective characterisation.

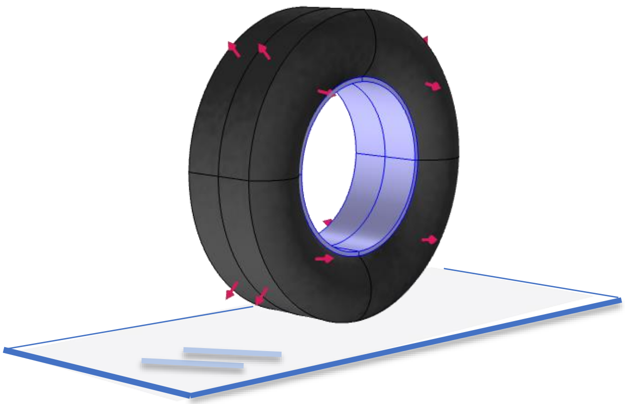

Figure 3 - Modelling of the BEM analysis.

4 Results

This section shows the results of the sound propagation of the different tyres, as well as the effect of the inclusion of grooves on the surface of the tyre is studied.

4.1 Sound propagation

An example of sound propagation obtained after the simulation of the impact is shown in Figure 4. The radiation planes have been marked over the plot of the results to visualise where the polar graphs are located. Arrows indicate reference angle 0 and the evaluation distance is 1 *m*. The vertical plane (black line) is set through the middle of the tread and centred on the ground, in turn, the transversal plane is placed through the centre of the tyre.

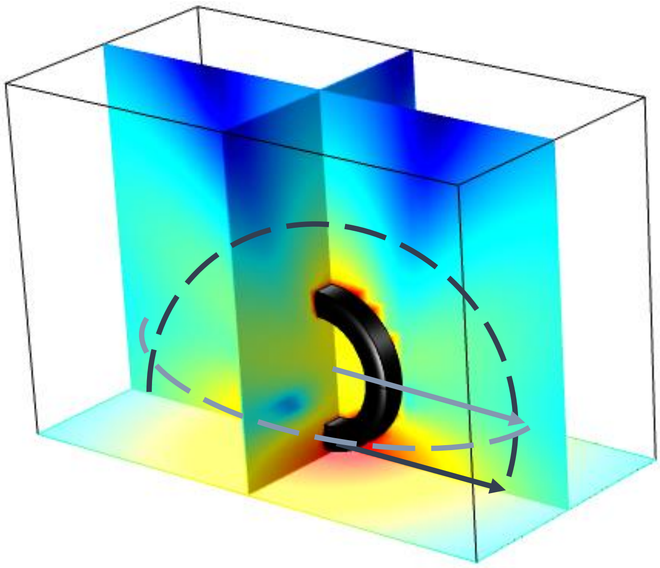

Figure 4 - Radiation evaluation planes over sound dispersion simulation.

The directivity of the sound propagation at 1000 *Hz* of the different simulated tyres can be studied across the polar graphs in Figure 5. This frequency has been considered because it belongs to the middle range of the audible spectrum and it is the reference frequency in loudness curves.
The sound pressure level achieved depends on the size of the tyre, with *tyre 3* being the largest and the one with the highest radiated energy, and *tyre 1* being the smallest and the one with the lowest energy.
In the vertical plane, the symmetrical lobes with the highest energy can be seen on the 0º axis. These lobes are produced by the highest amplitude vibration in the impact zone of the tyre against the reflective ground. The 90º lobe is due to the transmission of vertical vibrations produced on impact towards the upper part of the tyre.
In the transversal plane, the propagation is cross-shaped, reaching higher pressure levels in the axis at 90º (axial direction of the tyre).

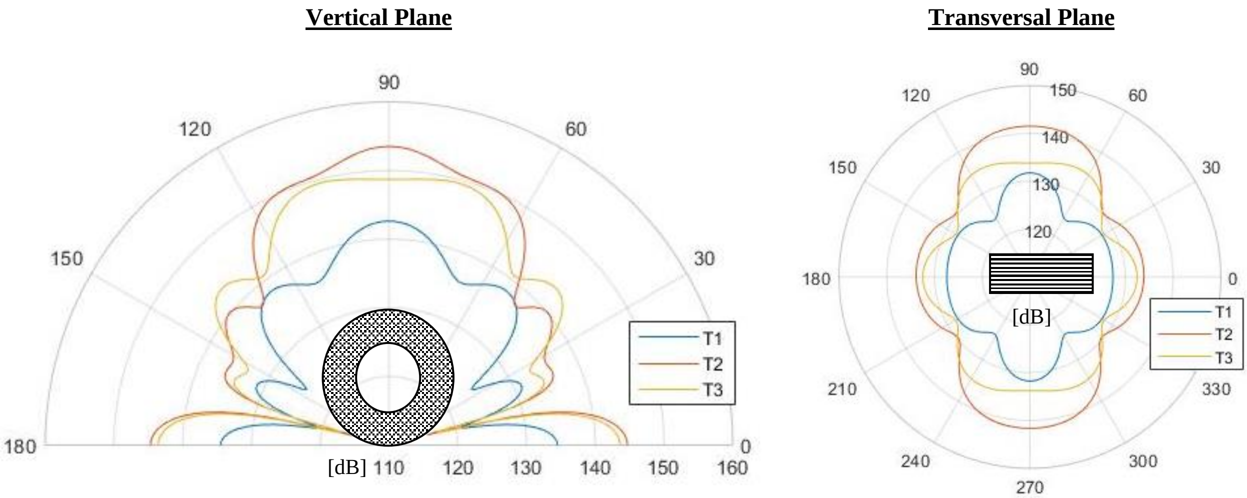

Figure 5 – Sound pressure level for different tyres at 1000 Hz polar charts.

4.2 Grooves Inclusion

The tyres have been initially modelled with a smooth surface for computation time reasons. Grooves have been included over the surface of *tyre 1* to study their effect on the impact simulation and its sound propagation.

Figure 6 shows the geometry of three modelled tyres: with the smooth surface called slick tyre, with three grooves and with four grooves

Figure 6 – Tyre 1 geometries with different surfaces.

Polar charts of the sound propagation at 1000 *Hz* of the different configurations of *tyre 1* are shown in Figure 7. The shape of the curves achieved in both the vertical and transverse planes are identical for the three surface geometries studied. The maximum difference in sound pressure level is 0.14 *dB* for the tyre with three grooves and 0.55 *dB* for the one with four grooves, both compared to the slick tyre.

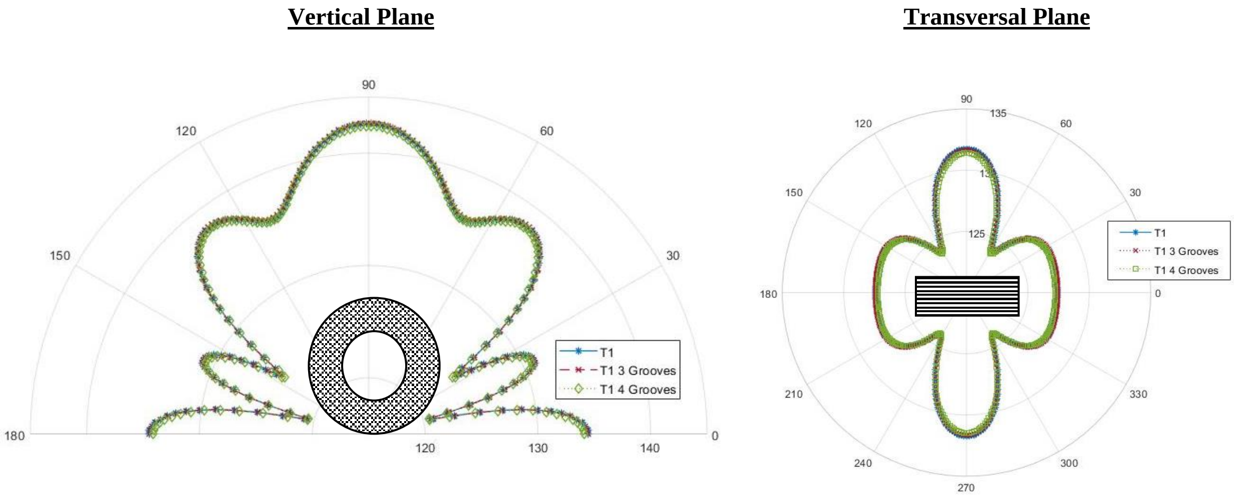

Figure 7 - Sound pressure level for Tyre 1 with different surfaces at 1000 Hz polar charts.

5 Conclusions

In this document, a generic model of tyre impact noise using a combination of the Finite Element and Boundary Element Methodologies has been presented. For this purpose, a variable geometry tyre from the standard size parameters has been modelled.
The simulations performed have reproduced the impact of a tyre in a free fall against the ground, where the vibration produced by the impact on its surface has been used as a sound source for the acoustic simulation.
The use of this model can be extended in the future to dynamic simulations of the road impact of a tyre-suspension assembly under rolling conditions. On the other hand, the sound propagation part also allows the incorporation of different acoustic properties to the ground.

The results performed in this study show that the acoustic propagation varies with the size of the tyre but including details on its surface such as considering the presence of grooves does not present substantial changes.
Current work is focused on model validation through a circular array of microphones and on the modelling of the tyre using different material properties such us the inclusion of orthotropic conditions.

References

[1] European Environment Agency, *Road traffic remains biggest source of noise pollution in Europe*, 2017.

[2] Nelson P. *Transportation Noise Reference Book,* Butterworths-Heinemann, 1987.

[3] Sancho, S.; Gaja, E.; Peral-Orts, R.; Clemente, G.; Sanz, J.; Velasco-Sánchez, E. Analysis of sound level emitted by vehicle regarding age. *Applied Acoustics*, Vol 126, 2017, pp 162-169.

[4] Sandberg, U.; Ejsmont, J.A. *Tyre/road noise reference book,* Kisa, Sweden: Informex, 2002.

[5] Xie, Y.; Yang, Q. Tyre–pavement contact stress distribution considering tyre types. *Road Materials and Pavement Design*, Vol 20, 2018, pp 1899-1911.

[6] Wei, L.; Liu, H.; Chen, H.; Zhao, Z. Finite element analysis of cross section of TBR tire. *Mechanics of Advanced Materials and Structures,* Vol 27 (17), 2018, pp 1509-1517.

[7] Conradie, J.M.; Els, P.S.; Heyns, P.S. Finite Element Modelling of Off-Road Tyres for Radial Tyre Model Parameterization. *Proceeding of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering,* **vol 230 (4), 2016.**

[8] Lafont, T.; Stelzer, R..; D'amico, R.; Bertolini, C.; Kropp, W. Modeling Tyre Noise in FE Simulations for Pass-By Noise Predictions. *Conference: Noise and Vibration Emerging Methods*, 2018.

[9] Yintao, W.; Feng, X.; Fuqiang, Z.; Xiang, D. Simulation of Rolling Noise Based on the Mixed Lagrangian–Eulerian Method. *Tire Science and Technology*, Vol 44 (1), 2016, pp 36-50.

[10] Biermann, J.; Estorff, O.; Petersen, S.; Schmidt, H. Computational Model to Investigate the Sound Radiation from Rolling Tires. *Tire Science and Technology,* Vol 35 (3), 2007.

[11] Behzada, M.; Hodaeia, M.; Alimohammadib, I. Experimental and numerical investigation of the effect of a speed bump on car noise emission level. *Applied Acoustics, Vol* 68(11-12), 2017, pp 1346-1356.

[12] Han, M., Lee, C.; Park, Tae. Vibro-Acoustic Response in Vehicle Interior and Exterior Using Multibody Dynamic Systems Due to Cleat Impacts. *International Journal of Automotive Technology,* Vol 21 (3), 2020 pp 591-602.

[13] Citarellaa, R.; Federicoa, L.; Cicatiellob, A. Modal acoustic transfer vector approach in a FEM–BEM vibro-acoustic analysis. *Engineering Analysis with Boundary Elements,* Vol 31(3), 2007, pp 248-258.

[14] Sung, S. H.; Nefske, D. J.; A Coupled Structural-Acoustic Finite Element Model for Vehicle Interior Noise Analysis. *Journal of Vibration and Acoustics,* Vol 106 (2), 1984, pp 314-318.

[15] Yegao, Q.; Jinpeng, S.; Hongxing, H.; Guang, M. Structural vibration and acoustic radiation of coupled propeller-shafting and submarine hull system due to propeller forces. *Journal of Sound and Vibration,* Vol 401, 2017, pp 76-93.

[16] Djojodihardjo, H. Vibro-acoustic analysis of the acoustic-structure interaction of flexible structure due to acoustic excitation. *Acta Astronautica*, Vol 108, 2015, pp 129-145.

[17] ISO 4000-1:2015, *Passenger car tyres and rims - Part 1: Tyres (metric series)*.

[18] Flores-Moreno, R.; Martínez-Rodríguez, A.; Valerio-Pacheco, Gelasio.; Reyes-Cruz, V.L.; Laffita-Leyva, A. Determinación de propiedades físico-mecánicas del material componente de un neumático de tractor. *Revista Ciencias Técnicas Agropecuarias,* Vol 19 (3), 2010, pp 57-61.