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Numerical sound prediction model to study tyre impact noise

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ABSTRACT

Impact noise is one of the mechanisms of vibratory origin that constitutes tyre/road interaction noise. When assessing a vehicle as a noise source, the impact sound mechanism is especially significant when obstacles are present on the driving surface. This document aims to enhance understanding of the impact noise phenomenon by presenting a two-step numerical model for studying the sound propagation of an accelerated tyre impacting a flat, rigid, and reflective surface: Firstly, a dynamic analysis of the contact is performed using the Finite Element Method. Then, the Boundary Element Method is used to perform an acoustic analysis with the vibration of the tyre surface as the sound source. The model has been successfully validated through a drop-test, where a tyre/rim assembly is dropped onto a ground surface. The validation was determined by comparing the predicted Sound Pressure Level measurements to those obtained from a circular microphone structure at various points during the drop-test.

1. Introduction

Technological advances in the automotive sector have enabled vehicle manufacturers to gradually reduce the sound emissions of their models [1]. Despite these advances, road traffic remains the leading cause of noise pollution with the greatest overall impact in urban and interurban environments [2]. The exposure to rolling noise could cause a range of issues such as annoyance [3], sleep disorders [4] and even cardiovascular disease [5].

It is therefore of vital importance to analyse in detail the different sound generation mechanisms that together constitute the vehicle as a source of noise [6]: the mechanical noise of the propulsion system, aerodynamic noise and the noise of the interaction of the tyre with the road. In urban areas, where the bulk of the population affected by noise pollution is concentrated, low driving speeds make the contribution of aerodynamic noise negligible. Engine and drive system noise of conventional vehicles predominate over tyre/road interaction noise below speeds of 30 *km/h*. However, the electrification of vehicles results in a drastic reduction in the noise of their propulsion systems [7].

The mechanisms of noise production generated by tyre/road interaction are divided into two groups [8]: aerodynamics of the emission zone and mechanical vibrations. Aerodynamic noise is associated with air pumping which produces noise above 1 *kHz* [9]. It is also related to Helmholtz and pipe resonances of the air mass vibrating in the tread cavities. Vibratory mechanisms predominate in the low and medium frequency ranges below 1 *kHz*. They are divided according to their method of excitation: due to adhesion phenomena, like stick-and-slip and stick-and-snap effects [10], or impact phenomena, caused by irregularities in the road.

Road characteristics also affect acoustic emission, whose most important factors are impedance [11], pavement ageing [12], texture [13] and mixture [14]. The study of these parameters results in new pavements and rubberized asphalts that mitigate noise emission [15]. Thus, particularly at low driving speeds, the total noise contribution of the vehicle tends to be drastically reduced. Nevertheless, there would still be specific situations where there is an increase in tyre/road interaction noise due to the presence of obstacles on the road surface which cause an impact noise. An example of this situation is the use of speed bumps over the road [16].

Models that study tyre/road interaction noise are classified as deterministic or statistical [17]. The statistical models are global regression models which use a large number of empirical data measurements such as the American TNM model [18] or the European CNOSSOS model [19]. On the other hand, the deterministic models are analytical or numerical models that study a specific sound production mechanism.

Among the deterministic models, the numerical Finite Element Method (FEM) has been used for the study of the behaviour of tyres and their mechanical characteristics. Xie and Yang [20] determined stress distribution both in radial and bias ply tyres, depending on

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the load they support and their inflation pressure. On the other hand, Wei et al. [21] analysed the vertical force–displacement characteristics of a tyre section. These studies model the tyre divided into several regions with different characteristics and properties.

The mechanical behaviour of the impact of a wedge on a tyre has been studied by Neves et al. [22] using an experimentally validated FEM model in order to evaluate the performance of a tyre in extreme situations. In this study, the experimental set-up involved fixing the wheel in a specific position, without replicating the effects of the suspension system, and dropping the impact mass on it. A similar test was performed by Gan et al. [23] by dropping a flat surface mass onto a tyre to analyse the impact of an aircraft during landing.

The propagation of tyre/road interaction noise can also be analysed using FEM techniques. Lafon et al. [24] started from an earlier statistical model to compare the sound propagation of a tyre geometry with a simplification of monopole sources. The road surface was modelled as a rigid surface whereas the absorption condition at infinity was achieved by means of the Perfectly Matched Layers condition. Another method to simulate the sound absorption condition at infinity is through the use of the Boundary Element Method (BEM) as performed by Biermann et al. [25]. The advantage of this method is its computational efficiency when calculating sound propagation in open space as it eliminates the need to discretise the air volume.

With regard to numerical models used for predicting impact sound, Behzada et al. [16] used a lumped quarter-vehicle model. In this model, the force applied to the tyre when it is driven over a speed bump profile is used to conduct a 3D FEM analysis to study the noise generated. The tyre-suspension assembly can also be modelled directly in 3D: Han et al. [26] simulated the passage of a tyre over a bar where the normal acceleration of its surface is used as a sound source.

Additional vibro-acoustic studies that combine FEM and BEM in other aspects of vehicle acoustics can also be found in the literature, such as the work from Citarella et al. [27], who studied the sound propagation of the structural vibration modes of a vehicle. Prior to this, Sung and Nefske [28] studied the noise inside the vehicle produced by the forces acting on the structure. Beyond road traffic, there are finite element vibro-acoustic studies on other types of vehicles: Yegao et al. [29] studied the acoustic footprint of a submarine and H. Djojodihardjo [30] analysed the behaviour of the lightweight structures of which space vehicles are made from.

This paper proposes a two-step deterministic model to study the impact noise of a tyre accelerated against a flat, rigid and reflective surface. It consists of a first FEM analysis that determines the vibration of the tyre, followed by a second analysis wherein this vibration is used as a sound source to study acoustic propagation using BEM. As a result, the sound pressure levels generated by the tyre are obtained and validated.

2. Methodology

2.1. Basic principles

The basic model describing the impact between the tyre and the road surface resembles a time-varying load and must be studied by means of a transient analysis. The dynamic response of the system is determined using the Equation of Movement (1) and is solved by the Finite Element Method.

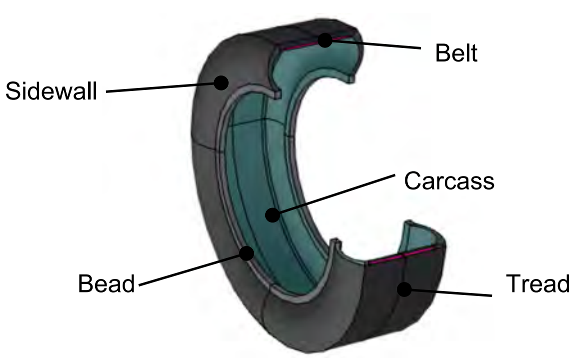

Fig. 1. Geometry and parts of the tyre.

Fig. 2. Tyre mesh.

Table 1
Characteristics of each part of the tyre geometry.

Part	Young's Modulus [MPa]	Poisson's Coefficient	Density [kg/m^3]	Type of Element
Sidewall	3.940	0.49	1140	Hexahedra and prisms
Tread	3.501	0.49	1120	Hexahedra and prisms
Bead	210,000	0.30	7800	Hexahedra and prisms
Belt	50	0.40	1110	Hexahedra and prisms
Carcass	300	0.38	1080	Quads (Surface)

$$M\ddot{u} + C\dot{u} + Ku = F \quad (1)$$

where u is the displacement field as a function of time, $\dot{u}$ and $\ddot{u}$ are respectively the velocity and acceleration fields, M is the mass matrix, C is the damping matrix, K is the stiffness matrix and F is the load vector.

The Fast Fourier Transform (FFT) is then applied to the acceleration $\ddot{u}$ of the surface of interest in a given time window. The acceleration, now in the frequency domain, is used as a boundary condition to relate the vibration of the body to sound pressure p according to Equation (2).

$$-n \cdot \left(-\frac{1}{\rho}\nabla p\right) = n \cdot \ddot{u} \quad (2)$$

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

The acoustic propagation is obtained using the Helmholtz Equation (3), whose solution involves frequency analysis using the Boundary Element Method.

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

where ω is the study angular frequency and c is the speed of sound.

2.2. Model

The vibro-acoustic model for impact noise prediction starts with the geometric characterisation of a radial tyre. This geometry is parameterised to be generated from the tyre width, aspect ratio and rim diameter values indicated in the metric ISO code for tyres [31]. This allows any type of tyre to be generated in a simple way. In turn, the geometry is divided into five parts as shown in Fig. 1.

Each of the parts has material characteristics obtained from [20] that define its inertial and linear elastic behaviour. These characteristics are summarised in Table 1 together with the type of element used.

The transient analysis to simulate the contact between the tyre and the surface is performed by means of FEM, using COMSOL®

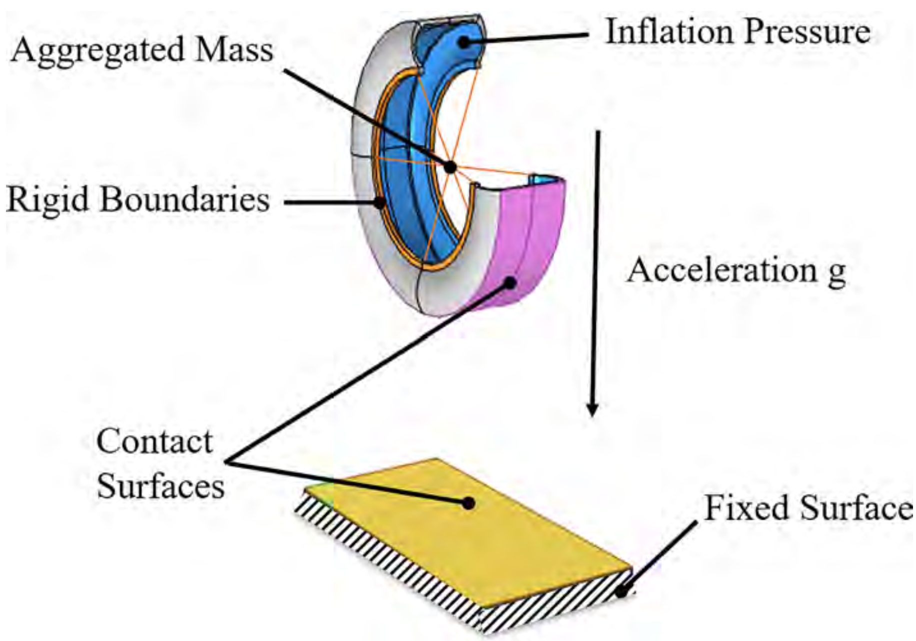

Fig. 3. Boundary conditions of the FEM analysis.

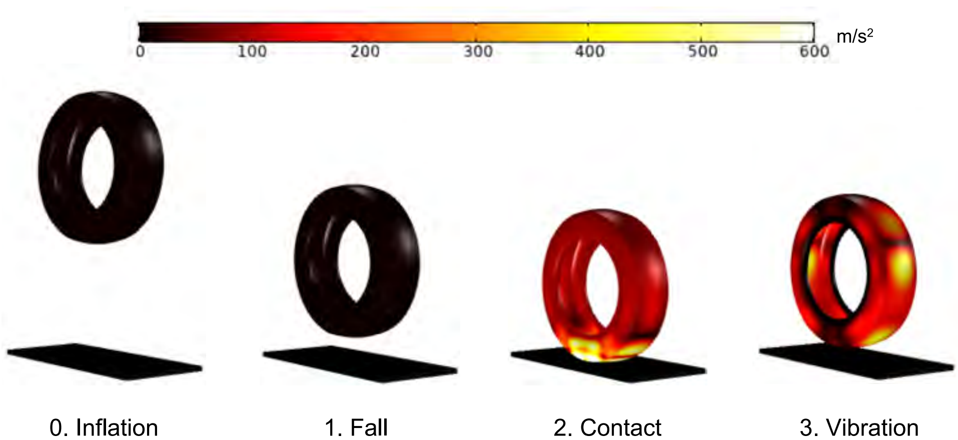

Fig. 4. Phases of the transient analysis in the FEM simulation.

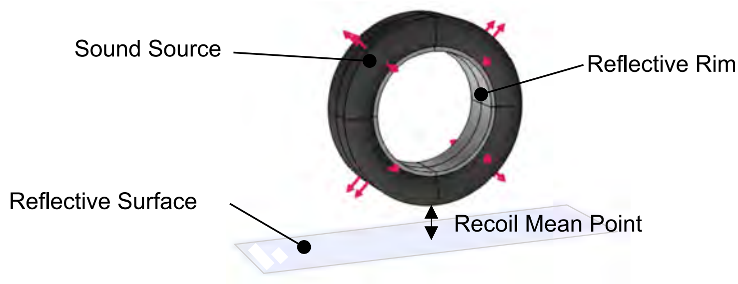

Fig. 5. Boundary conditions of the BEM analysis.

software. The model mesh has also been parameterised to be automatically generated for different tyre geometries. The meshing of the tyre volume is created by performing a circular sweep of the tyre section. The mesh used for the validation of this work, shown in Fig. 2, has 26,400 linear elements with a maximum size of 1 cm.

In the model, the tyre accelerates from rest in free fall by the effect of gravity to impact against a flat, rigid and fixed surface.

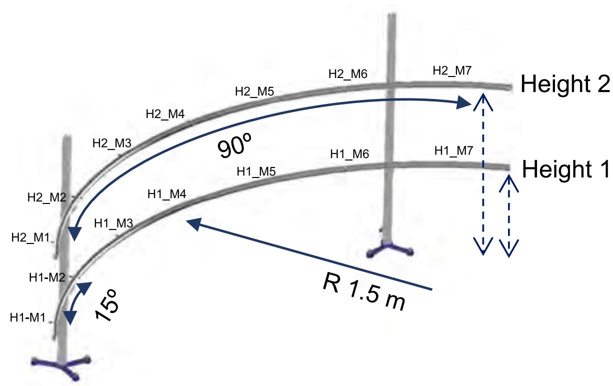

Fig. 6. Sketch of the acoustic array structure.

The contact between the flat surface and the tyre tread has been defined. Air pressure is modelled as a force per unit area normal to the inner surface of the tyre. In order to reduce computational cost, the force remains constant and equivalent to the inflation pressure as the variations of the volume during the impact are not significant. Air volume displacements inside the tyre are also not taken into account.

Rim modelling is achieved by defining the tyre surfaces that would be in contact with the rim, inner radial and outer lateral contour, as rigid. The mass of the rim is applied as a point mass of a constant value at the centre of gravity of these rigid bead surfaces [32]. The boundary conditions are shown schematically in Fig. 3.

The FEM analysis is performed in two distinct steps, firstly, a static analysis is performed to allow the tyre to acquire the stress and deformation state produced by the inflation pressure, and then, in a second step, the transient analysis of the drop test is performed.

During the transient analysis, the tyre increases its velocity until it makes contact with the flat surface, causing the tyre to impact and then recoil with the consequent vibration of the tyre surface. Fig. 4 shows different phases of the dynamic simulation with the plotting of the tyre surface acceleration.

Once the transient analysis has been solved, the FFT is applied to the acceleration field of the tyre surface. The FFT is performed

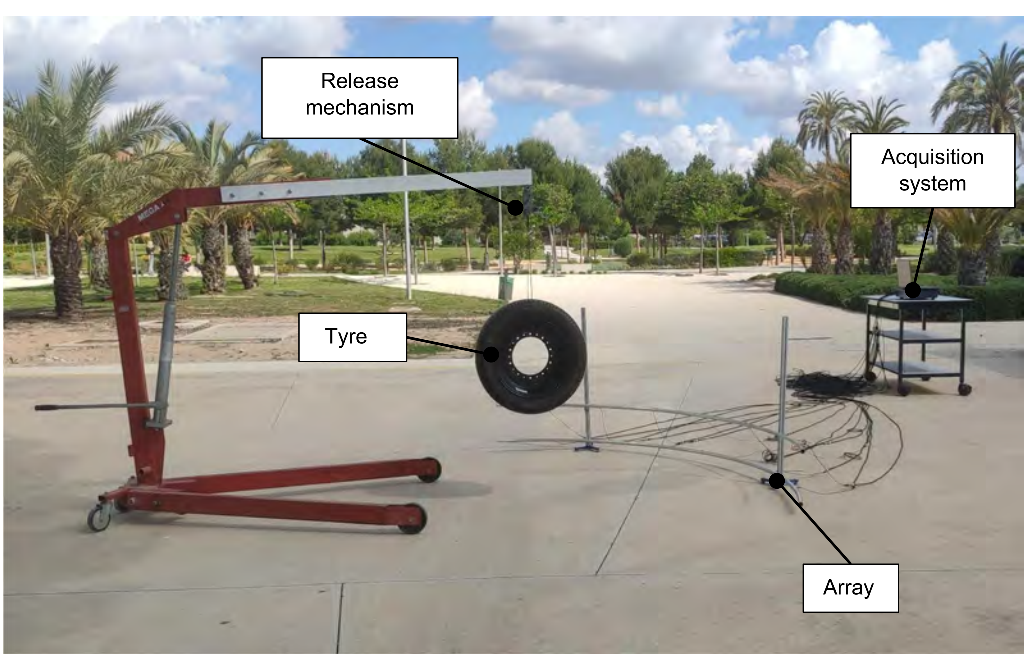

Fig. 7. Experimental set-up.

in a given time window (as indicated in point 4 below) starting from the instant of the simulation when the initial contact occurs. After applying the FFT, the values obtained must be scaled by the number of samples *SN* in order to maintain the original physical magnitude. The number of samples is defined, according to Equation (4), as the product of the time window used *TW* and the sampling frequency *SF*, inverse of the simulation time step *TS*.

$$SN = TW * SF = \frac{TW}{TS} \tag{4}$$

This frequency domain acceleration is mapped onto the stationary tyre geometry of the BEM analysis to be used as the sound source as described in Equation (2). In this analysis, the tyre is separated from the reflective surface at the mean distance of the recoil path after the contact produced in the transient analysis. The rim and the contact surface are now modelled as reflective surfaces as shown in Fig. 5.

3. Experimental set-up

Once the model is defined, an experimental set-up is designed to achieve empirical values that validate the results provided by the simulation. A microphone array has been built on a double-height circular structure that covers a 90° angle with a radius of 1.5 *m*. The pillars of the structure are grooved aluminium profiles that allow the height of the curved horizontal profiles to be adjusted. These curved profiles have been perforated to locate in each of them 7 microphones of ¼ inch diameter with a separation of 15°. A sketch of this structure is shown in Fig. 6.

The test tyre has the geometric dimensions of ISO code 205/55 R16. The tyre is mounted on a 13 *Kg* steel rim at an inflation pressure of 220 *kPa*. The assembly is lifted using a hydraulic workshop crane to which a profile has been fitted to extend the jib beyond the support base. The crane has a mechanical opening mechanism to drop the tyre due to the force of gravity.

To record the sound propagation of the impact of the tyre against a rigid and reflective surface, the tyre lifted by the crane is positioned at the geometric centre of the microphone array, as shown in Fig. 7. The tests are performed outdoors on a polished concrete floor in favourable atmospheric conditions [18] and no other reflective surfaces are located within a radius of less than 5 *m*.

The microphones used during the tests are Brüel & Kjær models 4935 and 4957, connected to an LMS SCADAS Mobile data acquisition system. The acquisition system was configured with a trigger

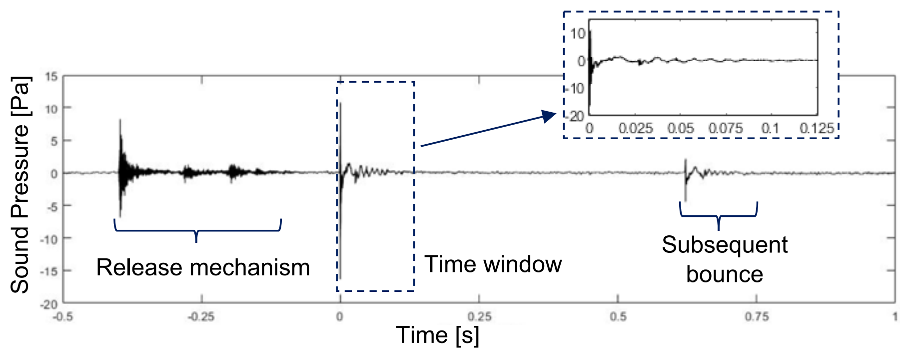

Fig. 8. Sound pressure recorded during a test.

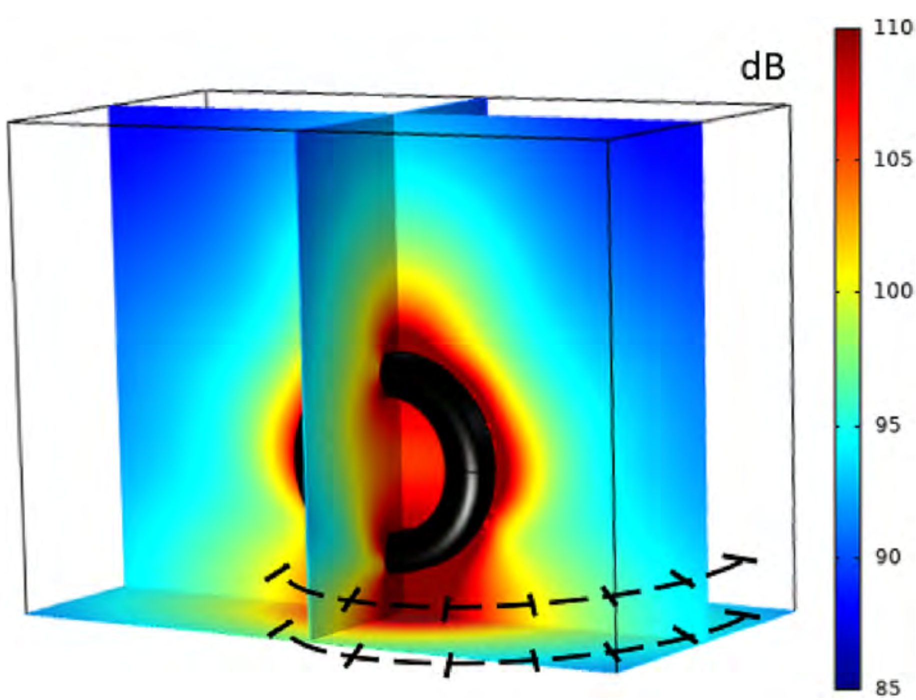

Fig. 9. Sound Pressure Level of the frequency analysis with the positioning of the measurement points superimposed.

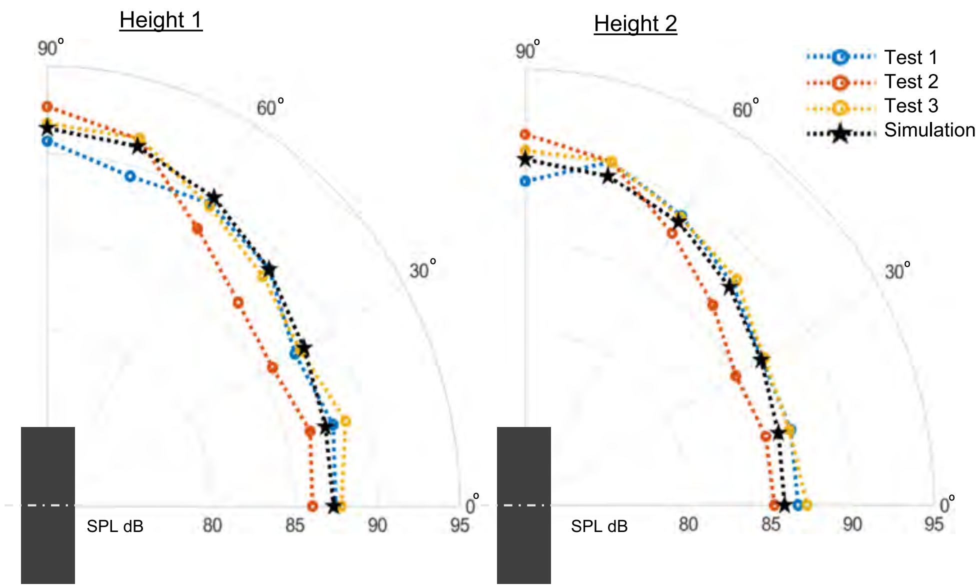

Fig. 10. Comparative polar graph of total SPL between tests and simulation.

to initialise the signal recorded as soon as a threshold sound pressure value is exceeded. The stored signal has a duration of 1 *s* after the trigger and 0.5 *s* before at a sampling rate of 25600 *Hz*. A time window is then defined to delimit the interval of interest for post-processing.

3.1. Validation

To compare the numerical model with experimental results, three free fall tests were performed from a height of 0.5 *m* between the floor and the lowest point of the tyre. The arches of the array were positioned at heights of 4 *cm*, the closest position to the ground that can be obtained, and 31 *cm*, the height of the centre of the tyre at the moment of impact. The array is oriented so that the microphones at 0° are aligned towards the axis of revolution of the tyre and those at 90° are perpendicular to the tread along its median plane. The background noise levels recorded during the tests do not exceed 55 *dB* at any time.

Fig. 8 shows the signal recorded by one of the microphones during the test. The trigger positions the pressure peak produced by the contact of the tyre with the ground at instant 0 *s*. It can be distinguished the previous sound generated by the release mechanism and a subsequent bounce of the tyre. A time window of 0.125 *s* is established after the contact which delimits the sound signal to be processed. This window is the value of the time constant in the *Fast* time weighting.

The dynamic simulation of the numerical model has been configured according to the characteristics of the test elements: tyre geometry, inflation pressure, rim weight, drop height and gravity acceleration value. The sampling frequency used during the simulation is 3000 *Hz*.

Subsequently, the FFT of the acceleration of the tyre surface is performed in a time window of 0.125 *s* starting from the instant of the simulation when contact between the tyre and the flat surface occurs. In the acoustic frequency simulation, a separation of 13 *cm* has been established between the tyre and the reflective surface, calculated as half the distance achieved in the tyre recoil of the dynamic simulation. The sound analyses are performed in increments of 8 *Hz*, inverse of the time window used, to thus obtain the full contribution from the 125 *Hz* to the 1000 *Hz* band. The total Sound Pressure Level (SPL) of the simulation is then calculated as the logarithmic sum of the contribution of each frequency analysis. Fig. 9 shows the sound propagation with the virtual positioning of the microphone array superimposed on the Sound Pressure Level.

The results simulated at the microphone locations are compared to the total SPL of the experimental signal in the same frequency range as in the numerical model. Fig. 10 show this comparison by means of a polar graph for each height of the microphone array.

The simulation results fall within the range marked by the experimental tests. The maximum deviation of the sample with respect to the mean of the tests is 1 *dB* for height 1 of the array and 0.85 *dB* for height 2.

The analysis of the horizontal directivity shows that the SPL achieved in the direction of the tread is 4 *dB* higher than on the tyre axis at both heights. Up to 1.4 *dB* can be due to the difference in distance between the tyre surface and the receiving microphone, while the rest can be explained by the greater stiffness of the tread with respect to the sidewall. On the other hand, the impact simulation shows an average SPL per microphone of 1.5 *dB*, higher at height 1 with respect to height 2, as height 1 is closer to the contact area of the tyre and the reflective surface.

4. Conclusions

A methodology has been developed to predict the impact noise of a tyre against a rigid and reflective surface, combining the Finite Element Method for the transient analysis of the contact and the Boundary Element Method for the sound propagation study.

The tyre is modelled as a radial type with a parameterized geometry, with isotropic elastic properties and a slick surface. The proposed model includes in a simplified form the effect of the rim and inflation pressure. The tyre is studied as a system isolated from the rest of the vehicle.

The simulations have been successfully validated in terms of total Sound Pressure Level by means of a drop-test of the tyre with rim around which an array of 14 microphones distributed at two heights has been positioned.

The contact model presented can be extended to study the sound generation of situations closer to actual driving conditions, such as including the effects of suspension or studying the impact against common road surfaces found in traffic such as speed bumps or imperfections in the road surface. In future works, efforts should also be made to consider the effect of inner air vibration modes on the model results.

This work presents an effective modelling that provides a deeper understanding of one of the phenomena which constitutes rolling noise. In brief, a numerical procedure to study the impact noise of a tyre has been addressed. The results provided by the model for a 205/55 R16 tyre are satisfactory since the sound emission in the field near the tyre is predicted very closely with the tests performed.

CRediT authorship contribution statement

Miguel Fabra-Rodriguez: Methodology, Software, Writing – original draft. **Ramon Peral-Orts:** Conceptualization, Writing – review & editing, Supervision. **David Abellan-Lopez:** Software, Investigation, Writing – review & editing. **Héctor Campello-Vicente:** Validation, Resources. **Nuria Campillo-Davó:** Formal analysis, Writing – review & editing.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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