A Simulation Methodology for Tire/Road Vibration Noise analysis

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Abstract: A new methodology for simulating tire/road vibration noise is presented in this paper, which is is based on the Mixed Lagrange–Euler Method and Pseudo Excitation Method(PEM). A non-rotational acceleration field is constructed by mapping the acceleration of the Lagrange mesh onto the Euler mesh. Using this acceleration field as the acoustic source, the rolling noise can be predicted numerically using the Boundary Element Method (BEM) and Finite Element Method (FEM). In addition, a Pseudo Excitation Method(PEM) is proposed to simulate effect of road surface profile on the tire noise., which transfers the road elevation power spectral density(PSD) to the sum of harmonic excitation. A frequency domain analysis can be conducted to obtain the dynamical response of the tire on the real road and a sound emission analysis can be performed to get the sound field excited by road profile. In this way the tire/road vibration noise can be modeled completely.

Keywords: Radial Tire, Rolling Contact, Rolling Noise, BEM, Mixed Lagrange-Euler Method, Pseudo Excitation Method(PEM)

1 Introduction

Rolling contact noise is attracting an increased amount of attention in automotive and railway engineering. Research has shown that tire noise is a significant part of the total noise of a vehicle [1-8] and that wheel-track noise is the dominant source of railway noise [9-13]. With the development of highways and high-speed railways, more and more attention is being paid to rolling noise.

Both the road and the tire may be the source of noise generation, and the noise can propagate either through the air (airborne noise) or through the structure of the tire and the vehicle (structural borne vibrations). To model the tire vibration-acoustics, one need to model tire vibration response rolling on random road surface.

However, methods of analyzing and simulating rolling noise are far from perfect, and there is currently no reliable method to simulate rolling noise. In the field of tire noise research, no information has been published about the simulation of the rolling noise of a tire with a tread pattern, and the rolling effect of tires has not been considered sufficiently. Previous research has been based on the frequency domain by inputting the road spectrum or a modeled contact force into the tire model [7,14-16]. In the field of wheel-track rolling noise research, only the frequency domain method has been used to predict the rolling noise caused by a vertical excitation [11,13,17,18].

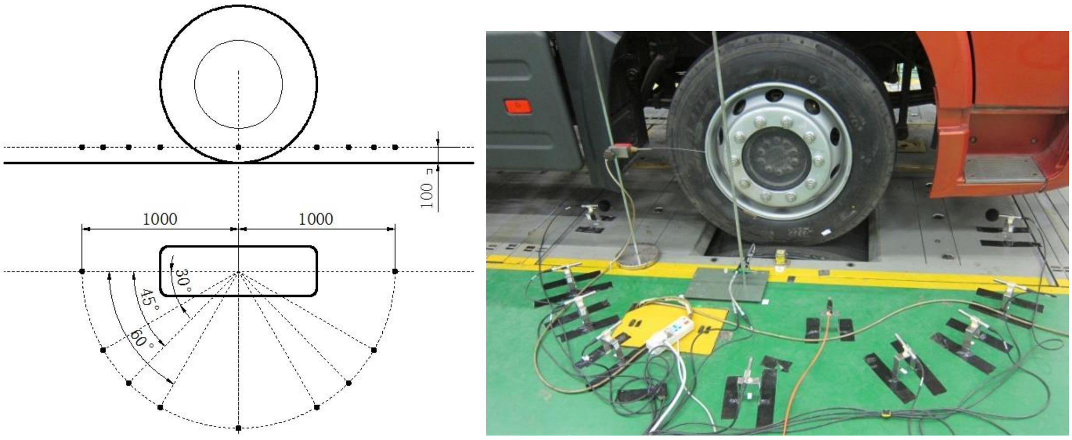
One of the challenge of simulating rolling noise is that the dynamic analysis of the rolling structure must be performed in a Lagrange system, but the acoustic analysis is normally performed in an Euler system, and it is difficult to exchange information between the two systems [19, 20]. This technical difficulty prevents rolling noise analysis from being performed in the time domain. Therefore, all rolling noise analysis is presently performed in the frequency domain. However, frequency domain methods cause two problems. First, a rolling vibration is a gyro system, which is a plural eigenvalue problem; thus, the traditional frequency domain method is not suitable. Second, the impact vibration caused by a tire pattern or tire nonuniformity can only be modeled in the time domain. For these reasons, this paper presents a new time domain method to simulate rolling noise. The method has two core features: mapping the acceleration field in the time domain from a Lagrange mesh to an Euler mesh using the Mixed Lagrange–Euler method and forecasting the vibration noise using the Automatic Matched Layer (AML) method (see section 6).

Another challenge of simulating tire rolling noise is how to model the excitation from random road surface. To solve this problem, we develop a pseudo excitation method (PEM) to represent the excitation from random road surface to tire contact interface. Using this PEM approach, the difficulty to identify road excitation can be circumvented.

Fig. 1 Overall indoor TBR noise test setup

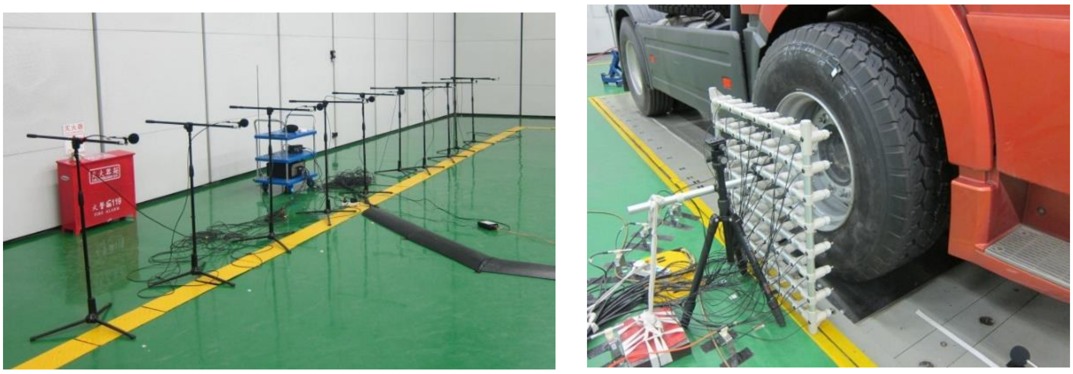
2 Tire noise experimental

To investigate the TBR (Truck and Bus Radial Tyre) noise source, the frequency characteristics and their pass by noise characteristics, a hybrid experimental scheme is developed. As seen in Figure 1, the overall test setup includes drum, test truck, tires and near field test setup, far field test setup as well as holography matrix in semi-anechoic chamber. For near field testing, total 9 microphones have been arranged in a regular angle space, as seen in Figure 2. The near field testing is mainly to characterize the tire noise frequency contents. The far field testing is to model the tire pass by noise, so the distance of the microphone to the tire center is 7.5m, with 1.2m high, total 5 microphone being placed to model the pass by noise, as seen in Figure 3(a).



(a) (b)

Fig. 2 Near Field TBR noise test setup (a) microphone position, (b) test drum/tyre assembly



(a) (b)

Fig. 3 Far field TBR noise test setup; (b) Holography test setup

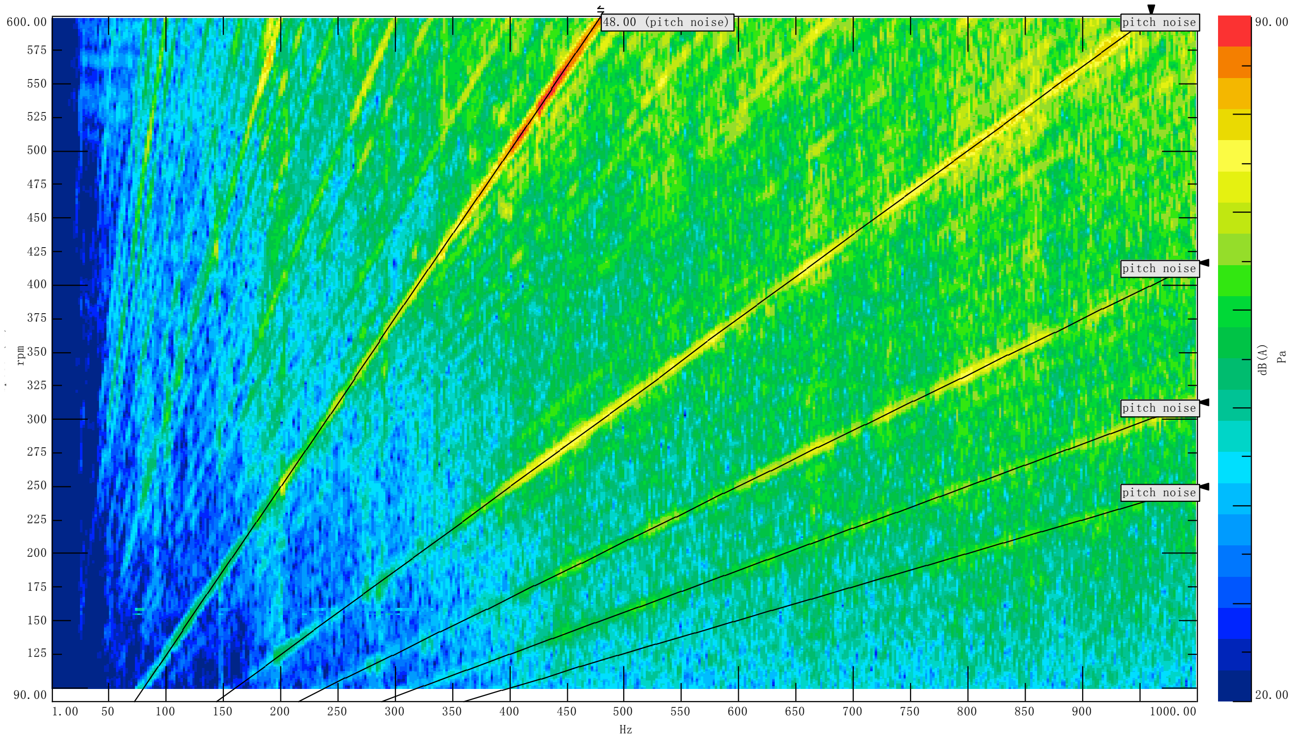


Fig. 4 The noise color map for a 385/65R22.5 TBR

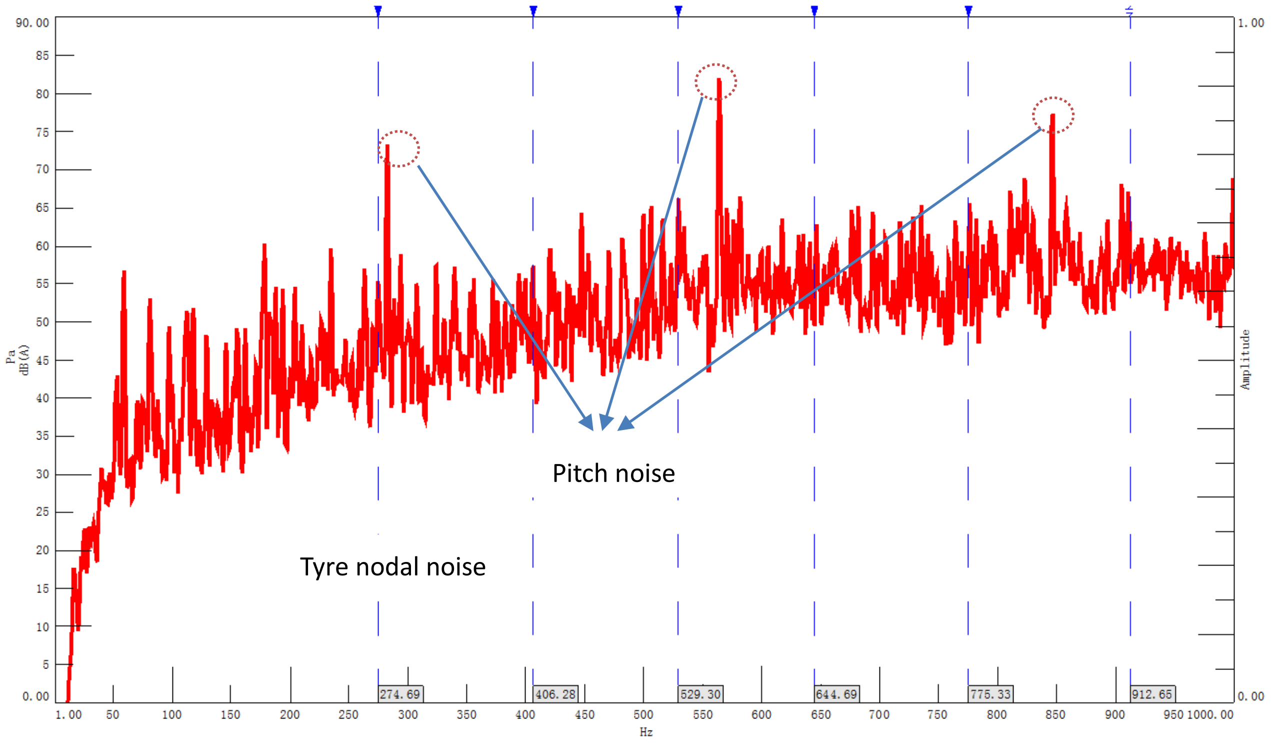


Fig. 5 Noise spectrum of 385/65R22.5 TBR, 0-1000Hz

It is well known that tire speed, width, pattern type, tyre imbalance and non-uniformity have strong influence on tire noise. To investigate the effects of these factors, we selected 6 types of tyres with different width, pattern and non-uniformity grades for the real testing under 4 speed conditions, 50km/h, 70km/h, 90km/h, and 120km/h. Figure 4 shows the noise color map for a 385/65R22.5 TBR, from which one can find that there exist some hot spots in different resonance frequencies.

Another feature in Figure 4 is that there exist acoustic order lines of which the fundamental harmonic equal to the pitch number of tyre patterns. This feature proves that the pattern impact noise mechanism dominates the TBR noise.

The noise spectrum of 385/65R22.5 TBR from 0 to 1000 Hz can be found in Figure 5, from which one can also find the pitch noise peaks and some vibration resonance peaks.

3 Mixed Lagrange–Euler method for rolling analysis

To analyze rolling noise, we want a precise acceleration field. Because the ALE method is not suitable, the explicit Lagrange method is generally used to obtain the changes of the velocity and the acceleration of the material with time. On the other hand, the noise analysis requires the acceleration field on the same stationary mesh as the input signal, which is given by $\mathbf{a}=\mathbf{a}(\chi,t)$ where χ is the reference configuration. This means that the mesh used for the vibration analysis is incompatible with the mesh used for the noise analysis, which hinders the simulation of rolling noise in both the tire field and the wheel-track field. According to the description above, the Mixed Lagrange–Euler method (MLE) method can be used under dynamic conditions. The purpose of the MLE method is also to acquire the velocity and acceleration signals in the reference space, which are given by $\mathbf{v}(\chi,t)$ and $\mathbf{a}(\chi,t)$. The mapping method is used to achieve this goal. First, the explicit FE method is used to analyze the vibration of the rotational structure. The information is then mapped from the Lagrange mesh to the reference Euler mesh by dynamic mapping. Only the information from the skin of the model is required for the vibration simulation. The mapping is performed using Finite Element Interpolation, which ensures the precision and the reliability of the data during the mapping. The Lagrange and Euler meshes are shown in Figure 6.

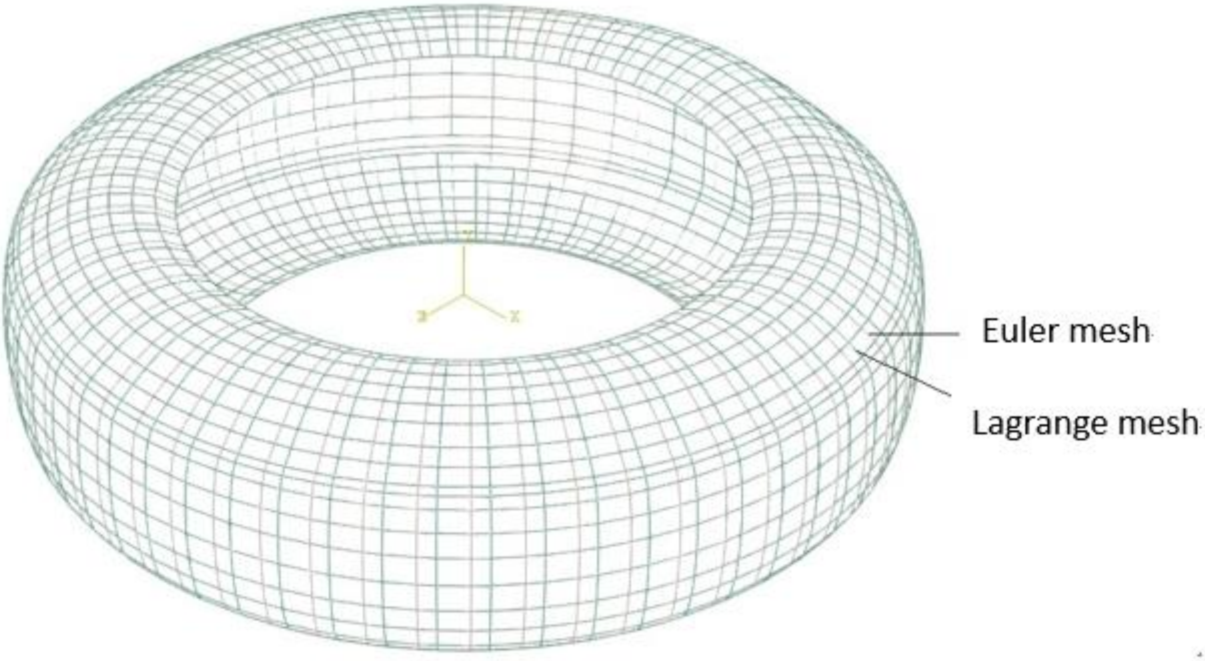


Fig. 6 The relationship between the Lagrange mesh and the Euler mesh.

In the actual analysis of rolling tire noise, the reference mesh (Euler mesh) is the tire mesh and only contains static deformation, including the initial tire configuration and the mesh of the translational displacement. The Lagrange mesh includes complex rotational motion, translational motion and elastic deformation. Therefore, the most important and difficult task is mapping the information between the two meshes using the Finite Element Interpolation method.

As shown in Figure 7, the velocity information of an arbitrary point $P(i,j)$ comes from one of the nodes of the Lagrange element using the numerical interpolation method. Thus, the Lagrange element to which one point in the space belongs should be determined first. In addition, the position of this point in the element, whose coordinate is given by (ξ,η), should be determined. The method is based on the simple principles of plane analytic geometry. Given a point $P(i,j)$ that belongs to element e and its local coordinates (ξ,η), the velocity and acceleration will be acquired from the kinematic information using numerical interpolation

$$(\bullet)_{ij} = \sum_{p=1}^{4} N_p (\bullet)_p \qquad (1)$$

where $(\bullet)$ is the velocity of the contact force, and N_p is the cell shape function given by $N_p = (1+\xi\xi_p)(1+\eta\eta_i)/4$.

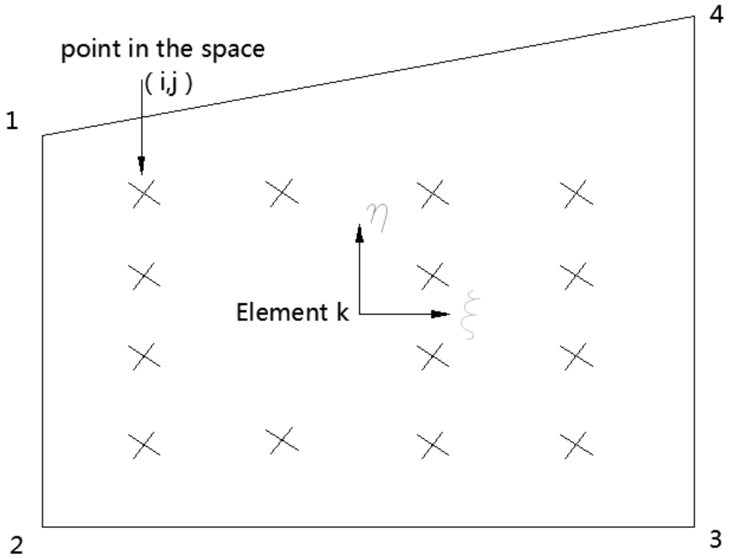


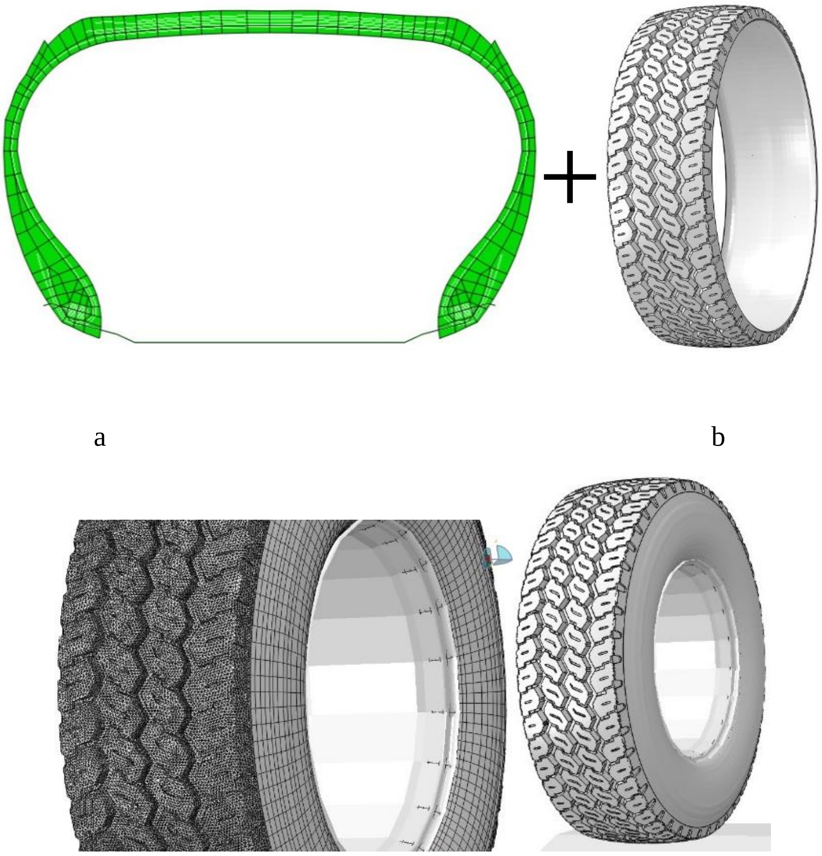
Fig. 7 Mapping the information from the Lagrange element to the Euler node.

The key points of the MLE method are determining the element to which the Euler node belongs and calculating the reference coordinate of the Euler node in the element. Reference [19] describes a method to determine the element. The method is a type of MLE method that can be used to solve the plane problem as well as the contact problem. However, for the problem in this paper, the method described in [19] is not useful because the Euler nodes are located on a curved surface. Therefore, a new method called the Coordinate Transformation Method is used. To determine the relationship between the Euler node and the Lagrange element, the coordinate of the Euler node must be transformed to a plane that is parallel to the Lagrange element, and the relationship between them will be determined using the method shown in [19]. Examples of actual calculations have shown that the method is effective and reliable.

4 The finite element model of a tire with a tread pattern

When a tire rolls, its tread pattern impacts the road surface continuously. The impact between these two surfaces is the main source of the vibration noise. Therefore, the tread pattern model is the most important factor for numerically simulating the vibration noise. To couple the vibration acceleration of the tread pattern with the acoustic boundary elements, the tread pattern rubber and the base rubber should be discretized together. The outer surface of the tread pattern and the outer surface of the grooves can be linked as one surface, and the vibration acceleration data can then be output easily. The following procedures should be used to construct the finite element model of a tire with a tread pattern.

i. Construct the 2D smooth tire model without the tread; see Figure 8(a).
ii. Construct the finite element model of the tread compound (the models of the tread pattern and the base rubber); see Figure 8(b).
iii. Rotate the 2D smooth tire model to form a 3D smooth tire model.
iv. Assemble the 3D smooth tire model and the tread model into one integrated tire model; see Figures 8(c) and 8(d).


a b

c d

Fig. 8 Procedures used to construct a tire model with a tread pattern.

The method used to construct the model of a tire with a tread pattern that is used for the acoustic simulations is different from the ordinary method of constructing a tire model for stress or footprint analysis. If the tire model is used to simulate the stress or footprint under loaded conditions, only the tread pattern is discretized; the base rubber is not discretized with the tread. In this paper, the model is used to simulate the vibration acceleration of the outer surface of the tread compound, so the tread pattern rubber and the base rubber are discretized together. Thus, the outer surface of the tread compound is one continuous surface, so the accelerations of the nodes on the continuous surface can be extracted for the noise simulations.

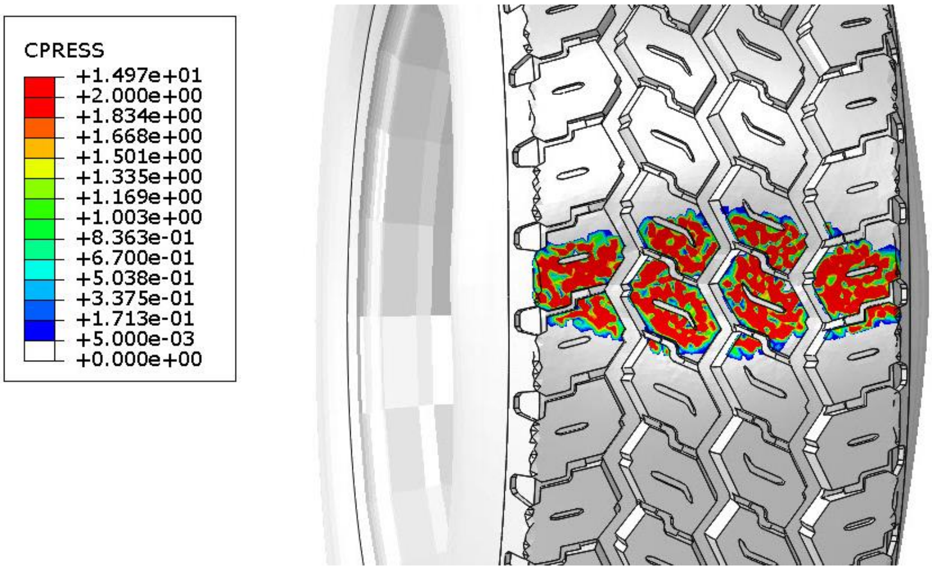


Fig. 9 Footprint and contact pressure distribution at 70% load.

Before the explicit rolling analysis, a footprint analysis with a 70% load was performed (Figure 9). The results show that the maximum contact pressure is 1.5 MPa, which is 2 times the air pressure of the tire. It is well known that the footprint and contact have large influences on the tire noise, so a fine tire model is ideal for the tire footprint and tire noise simulation.

5 The explicit rolling analysis of the tire model

After the footprint analysis, the explicit rolling analysis of the tire model presented above was performed. As was described above, tires with tread patterns are sources of vibration that can emit noise. To obtain steady impact acceleration signals, the tire is accelerated from 0 km/h to 80 km/h in one second; as a result, the tire is rolling at 80 km/h for one second. For the next 0.2 second, the impact accelerations of the outer surface of the tread pattern were output to a file in 400 increments. Figure 6 shows the accelerations of the outer surface of the tire tread at different times. The following conclusions can be summarized from these results:

i. The accelerations in the footprint are unevenly distributed.

ii. The accelerations near the footprint are greater than those in other locations.

iii. The accelerations near the leading edge are greater than those at the trailing edge, but the trailing edge has much a wider distribution of accelerations. This phenomenon was not described in previous tests and theoretical analyses, but it is consistent with the phenomenon that the noise near the trailing edge is greater than that at the leading edge.

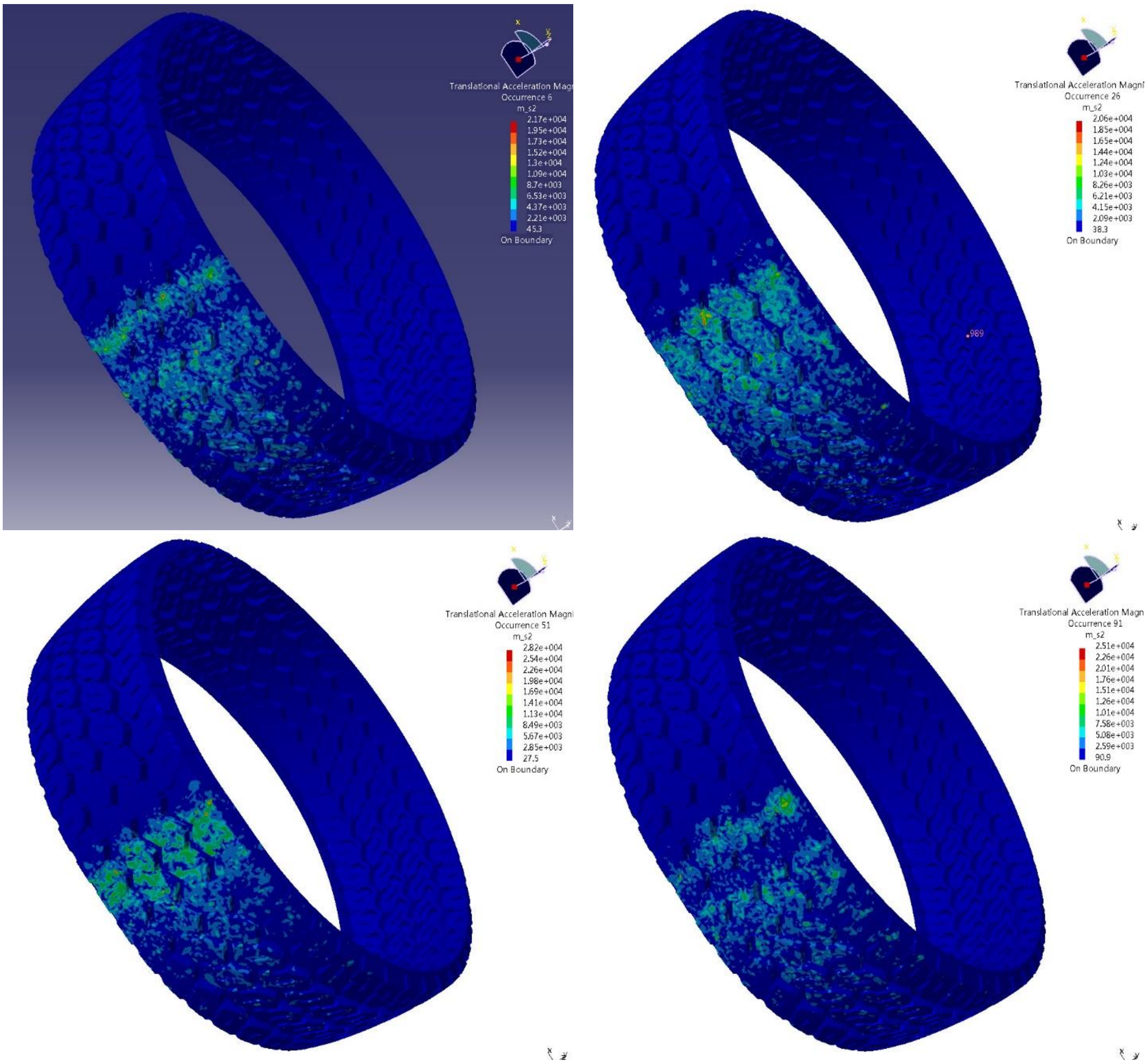


Fig. 10 Accelerations in the footprint at different times.

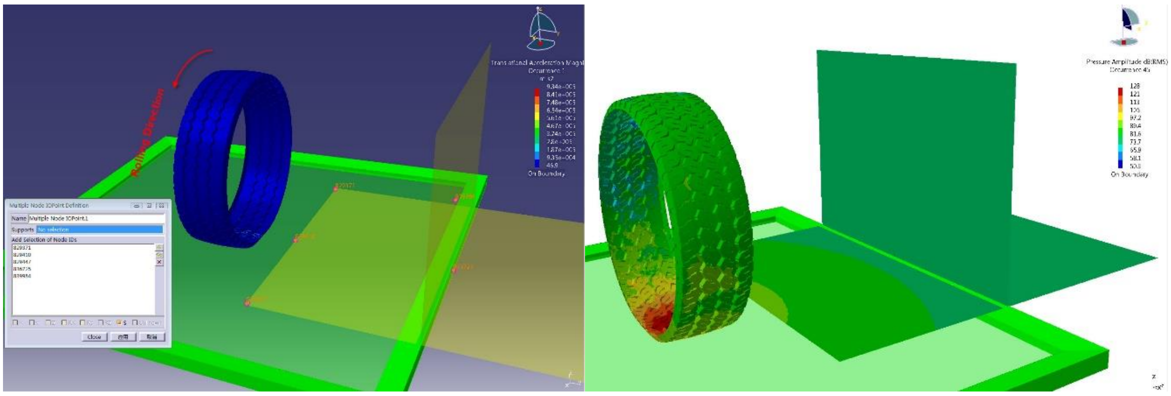


Fig. 11 Noise simulation model, selection of the field points and simulation results.

6 Vibration noise simulation of a rolling tire and comparison with test results

The Boundary Element Method (BEM) is often used to analyze 3D noise propagation and is particularly good for outside noise fields. If the BEM is used, the physical space does not need to be discretized, and the boundary conditions can be satisfied automatically [21]. In the simulation model, the road and the tire act as rigid bodies. The simulation results can be verified by test results, and the main source of noise can be identified from the simulation.

The noise simulation software Virtual LAB V11SL2 is used in this paper. This software uses an advanced technology, the Automatically Matched Layer (AML), to automatically identify the acoustic boundary conditions to transfer the acceleration of the outside surface of the pattern to the acoustic source. Field points are placed around the acoustic source, and the noise pressure can be obtained at the field points after the calculations are performed.

Figure 11 shows the structural mesh of the tread pattern, the acoustic mesh and the field mesh. The red points are the field points that are used to calculate the sound pressure.

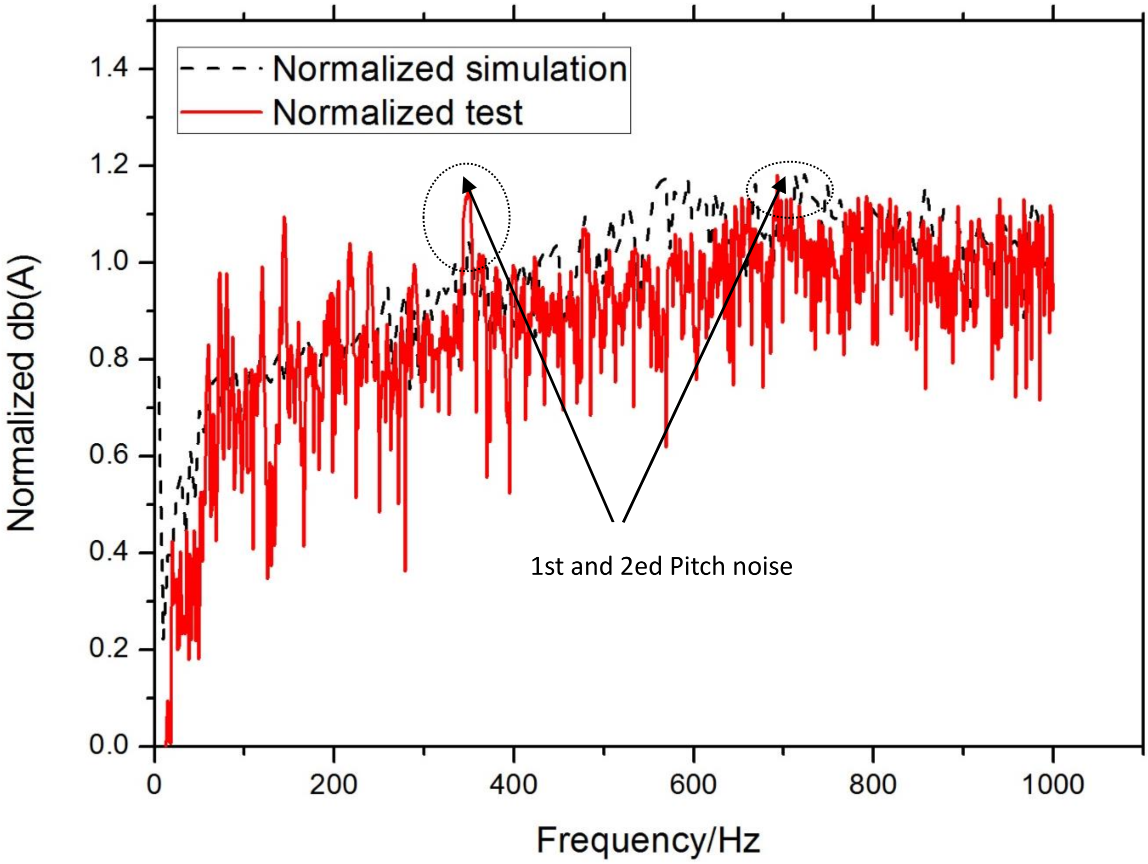


Fig. 12 Normalized noise results of the test and the simulation for a velocity of 80 km/h at the field point at the leading edge.

Figure 12 shows the noise pressure of field point 829,371, which is located in front of the leading edge. The black line represents the test results, and the red line represents the simulation results. These two results are the normalized data from the test and simulation results. The normalization is performed by dividing each dataset by the maximum sound pressure. The following conclusions can be drawn from Figure 8:

i. The normalized data from the simulation and test results agree with each other below 1000 Hz.
ii. The simulation results clearly show the first and second pitch noise peaks, which indicate that the pitch noise peaks come from the pattern impact noise.
iii. The noise below 1000 Hz mainly comes from the pattern impact vibration.

7 Road excited noise

Highway characteristics are essentially random inputs that range from potholes and tar strips to the fine surface texture of the pavement. The pavement's characteristics of interest are changes in the elevation of the pavement as the vehicle traverses the road. The temporal frequency of the vibrations created by a vehicle traveling along the road is given by the following equation.

$$f_t = V/\lambda = Vk \tag{2}$$

where f_t = temporal frequency, V = vehicle velocity, λ = wavelength, k = wave number (cycles/m)

The texture of the highway has a significant influence on the noise generated by a tire. To transfer the road texture power spectrum density (PSD) to excitation on the tire interface, we use the pseudo excitation method (PEM) as following

$$S_{xx} = \sqrt{G_x(f)}e^{j\omega t} \tag{3}$$

where S_{xx} = pseudo excitation force, $G_x(f)$ is the elevation PSD.

Through PEM, one can transfer the tire random vibration analysis on random road surface into a harmonic analysis problem. In this way, one doesn't have to perform stochastic analysis to get the tire response, rather a certain problem.

Like many dynamic systems, the behavior of a tire is dependent on the operating conditions. At low frequency a tire can be approximated by lumped parameters and a single, linear second-order system. Above approximately 20 Hertz, the vibrational modes will be excited by certain pseudo harmonic excitation. Note at lower order and low frequency, the tire impact response can be propagate to whole tire circumference, while at higher order modes, the tire response will be restricted in the contact area, these is due to the high damping of the tire structure in the high frequencies.

The simulated road noise can be found in Figure 13, from which one can find some resonance peaks which are corresponding to the tire structural modal vibration excited by road PSD. These resonance peaks (indicated by blue cycles) agree with the experimental peaks (indicated by blue lines) in Figure 5.

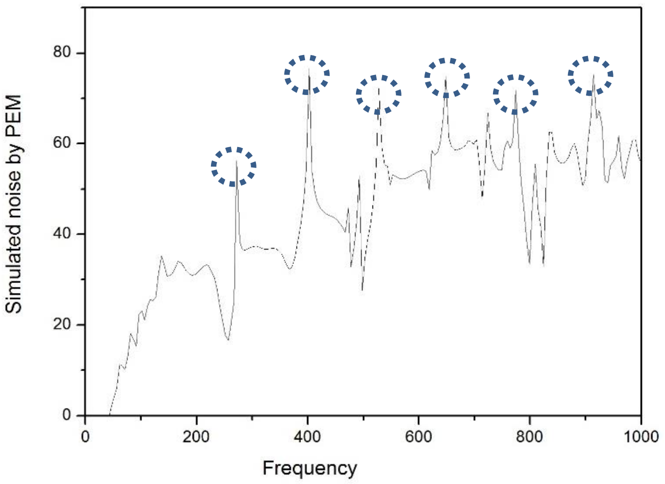


Fig. 13 Road noise excited by road PSD simulated by PEM

8 Conclusion

This paper presents a new methodology of analyzing the rolling noise of a tire and uses the method to simulate rolling tire noise. The new method uses a mixed Lagrange and Euler formulation to simulate the velocity and acceleration fields of a high deformation structure that contacts the road. The dynamic analysis of a rolling tire is performed by transferring the data between the Euler mesh and the Lagrange mesh. The tread pattern rubber and the base rubber are discretized as one component. The accelerations of all of the nodes on the continuous outer surface of the tread pattern are calculated, and these accelerations are used as the source of vibration noise. The vibration noise of the tire is then calculated using the acoustic finite element method. In addition, a Pseudo Excitation Method(PEM) is proposed to simulate effect of road surface profile on the tire noise., which transfers the road elevation power spectral density(PSD) to the sum of harmonic excitation.

A comparison between simulation and test results demonstrates that this method is reliable and practical and shows that the noise below 1000 Hz is mainly impact vibration noise. The method described in this paper is a practical technique for simulating vibration noise and especially vibration noise of a rolling tire. A mixed tread pattern was used in this paper. In the future, a block pattern and a transverse pattern will be studied to verify the method and its applications. This method can also be used to simulate wheel-track noise.

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References

[1] Sandberg, U. and G. Descornet, Road surface influence on tire/road noise. I. Inter-Noise 80. Noise Control for the 80's. Proceedings of the 1980 International Conference on Noise Control Engineering, 1980: p. 259-66 vol.1.

[2] Sandberg, U. and J.A. Ejsmont, 3 BASIC METHODS FOR MEASUREMENT OF TIRE-ROAD NOISE. Noise Control Engineering Journal, 1984. 23(3): p. 98-98.

[3] Oshino, Y. and H. Tachibana, Noise source identification on rolling tires by sound intensity measurement. Journal of the Acoustical Society of Japan (E), 1991. 12(2): p. 87-92.

[4] Sandberg, U., Abatement of traffic, vehicle and tire/road noise - The global perspective. Inter-Noise 99: Proceedings of the 1999 International Congress on Noise Control Engineering, Vols 1-3, ed. J. Cuschieri, S. Glegg, and Y. Yong. 1999. 37-42.

[5] Sandberg, U., Abatement of traffic, vehicle, and tire/road noise - the global perspective. Noise Control Engineering Journal, 2001. 49(4): p. 170-181.

[6] Fujikawa, T., et al., Definition of road roughness parameters for tire vibration noise control. Applied Acoustics, 2005. 66(5): p. 501-512.

[7] Brinkmeler, M., et al., A finite element approach for the simulation of tire rolling noise. Journal of Sound and Vibration, 2008. 309(1-2): p. 20-39.

[8] Berckmans, D., et al., Evaluation of substitution monopole models for tire noise sound synthesis. Mechanical Systems and Signal Processing, 2010. 24(1): p. 240-255.

[9] Nordborg, A., Wheel/rail noise generation due to nonlinear effects and parametric excitation. Journal of the Acoustical Society of America, 2002. 111(4): p. 1772-1781.

[10] Xu, Z., W. Zhai, Prediction and Analysis of Wheel/Rail Noise for High-speed Railway. China Railway Science, 2004. 25(1): p. 20-27.

[11] Zhisheng, X.U., Z. Wanming, Study on Excitation Model for Wheel/Rail Rolling Noise. China Railway Science, 2007. 28(6): p. 75-79.

[12] Fang, J., et al., Effect of Train Speed on Acoustic Radiation Characteristics of High-speed Train Wheel Vibration. Chinese Journal of Mechanical Engineering, 2010. 46(22): p. 96-104.

[13] Yang, X. and W. Zhai, Theoretical Calculation and Control Study on the Wheel/Rail Noises of High Speed Railway. China Railway Science, 2011. 32(1): p. 133-5.

[14] Nackenhorst, U., The ALE-formulation of bodies in rolling contact - Theoretical foundations and finite element approach. Computer Methods in Applied Mechanics and Engineering, 2004. 193(39-41): p. 4299-4322.

[15] Brinkmeier, M. and U. Nackenhorst, An approach for large-scale gyroscopic eigenvalue problems with application to high-frequency response of rolling tires. Computational Mechanics, 2008. 41(4): p. 503-515.

[16] Cesbron, J., et al., Experimental study of tyre/road contact forces in rolling conditions for noise prediction. Journal of Sound and Vibration, 2009. 320(1-2): p. 125-144.

[17] Mazilu, T., Green's functions for analysis of dynamic response of wheel/rail to vertical excitation. Journal of Sound and Vibration, 2007. 306(1-2): p. 31-58.

[18] Delvecchio, S. and J. Antoni, Extraction of angle deterministic signals in the presence of stationary speed fluctuations with cyclostationary blind source separation. Mechanical Systems and Signal Processing, 2012. 27: p. 350-361.

[19] Oertel, C. and Y. Wei, Tyre rolling kinematics and prediction of tyre forces and moments: part I - theory and method. Vehicle System Dynamics, 2012. 50(11): p. 1673-1687.

[20] Wei, Y., C. Oertel, and X. Shen, Tyre rolling kinematics and prediction of tyre forces and moments: part II - simulation and experiment. Vehicle System Dynamics, 2012. 50(11): p. 1689-1706.

[21] O'Boy, D.J. and A.P. Dowling, Tyre/road interaction noise-Numerical noise prediction of a patterned tyre on a rough road surface. Journal of Sound and Vibration, 2009. 323(1-2): p. 270-291.