MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Characteristics of sound pressure in the tire cavity arising from acoustic cavity resonance excited by the curvature change of tread

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ABSTRACT

Under the conditions of the low-noise powertrain design, the noise in car cabin from the tire cavity resonance is often remarkable. One of the excitations for the tire cavity is the effects of tire's rolling. In this paper, theoretical analysis of the cyclic curvature change of the tread is carried out, and the corresponding simplification and equivalent methods are investigated. The excitation process is analyzed by simulation method, and then the results are compared with the theoretical results. Finally, the simulation analysis of the tire-cavity coupling model under above excitation is carried out to analyze the sound pressure distribution inside tire cavity. The laws of sound pressure distribution and the generation conditions for tire cavity resonance under the excitation of tread curvature change are analyzed.

Keywords: Tire acoustic cavity resonance; Tire rolling; Curve change
I-INCE Classification of Subject Number: 76

1 INTRODUCTION

The noise in car cabin has a direct influence on the passengers' riding comfort, and it is an important parameter of vehicle quality as well. With steady advancement in engine and the noise & vibration reduction technology of the drive system [1, 2], the noise of tire stands out from the others, thus how to reduce tire noise becomes one of the major tasks of improving the automotive noise vibration and harshness(NVH) properties. Noise generated by a rolling tire is mainly emitted from the tread blocks.

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However, it has been reported that smooth tire also generates noise[3]. Sakata et al.[4] studied the mechanism of axle force's effects on noise inside the car and the results showed an obvious peak in frequency spectrum. It has been found that the noise associated with the first acoustic mode of the cavity is especially annoying since this noise has sharp peaks with frequencies typically in the range of 190-260Hz[5,6] under 70-80 km/h cruising conditions, which means the acoustic cavity resonance of tire has a remarkable effect on noise inside the car.

The acoustic cavity resonance of tire is a kind of sound pressure distribution of the cavity sound field. Generally, the excitations for the cavity sound field include the road roughness, the tread pattern, unbalance force and the curvature change of tread. When the acoustic cavity resonance of tire takes place, the first acoustic mode of the cavity exists in the standing wave, and its energy can be transferred into the car efficiently, discomforting the passengers. Simulation of sound pressure distribution inside tire cavity deserves attentions to suppress acoustics resonance and ameliorate noise environment inside car.

Some researchers focused on experimental analysis. Many researchers[7,8] found two resonance peaks inside the car cabin. Hayashi[9] adopted an approach of input a random noise into the tire directly to study the coupling mechanism. Some researchers established theoretical models to analyse tire cavity resonance. Feng et al.[10], Mohamed and Wang[11] developed dynamic equations for the first cavity modes of a rotating tire under the static load condition. The transmitted forces along the fore/aft direction and the vertical direction showed two peaks at frequencies that were independent both on the tire static load and vehicle speed. Most finite element models to describe tire cavity were constructed according to the effective linear length travelled by the acoustic waves along the annular conduit[4,11,12], while some others preferred to use the exact cavity shape in modelling progress[11,13,14]. Tanaka[15] proposed a method for measuring the resonance sound pressure of a tire cavity. Wang et al.[16] focused on the effects of coupling of tyre, cavity and rim on the resonance induces noise. These works lay a good foundation of tire cavity resonance studies, but they focused more on acoustic performance in the car cabin or oversimplified the finite element model, and few investigated the sound pressure amplitude in the tire cavity from the cavity resonance and its affection. However these are essential to investigate the noise transfer feature from the tire cavity to the car cabin and explore the noise control method.

When the tire is rolling on the road, the road roughness, the tread pattern, unbalanced force and the curvature change of tread jointly excite the tire acoustic cavity. Yi et al.[17] researched the characteristics of sound pressure in the tire cavity arising from acoustic cavity resonance excited only by road roughness. However, the curvature change of tread when the tire contact with ground with road load was not considered. In this paper, the excitation arising from curvature change of tread is only taken into consideration to clarify its effects on the acoustic cavity resonance of tire. Firstly, a tire model coupling with acoustic medium is constructed. Then, the excitation caused by the curvature change of tread is analyzed theoretically, and the corresponding simplification and equivalent methods are investigated. The excitation process is analyzed by simulation method, and then the results are compared with the theoretical results. Finally, the simulation analysis of the tire-cavity coupling model under above excitation is carried out to analyze the sound pressure distribution inside tire cavity, and the generation conditions for tire cavity resonance under the excitation of tread curvature change are analyzed. These works may lay a foundation for gaining an insight into the mechanism and control method of the tire acoustic resonance.

2 COUPLING MODEL OF TIRE AND ACOUSTIC CAVITY

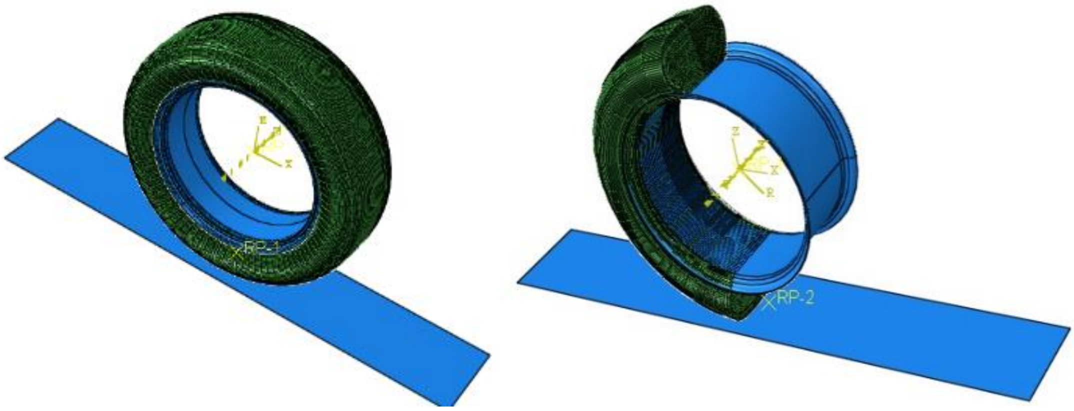
For subsequent simulation of sound pressure distribution in the tire arising from the excitation of tread curvature change, the finite element model of tire coupling with acoustic medium is constructed firstly.

Realistic size of the tire model adopted here is 185/60 R15. For simplification, the tire material is assumed to be homogenous, and is described by Neo-Hookean model

$$\sigma = 2C_{10}[(1+\varepsilon)-(1+\varepsilon)^{-2}] \tag{1}$$

where σ and ε are stress and strain respectively, and C_{10} is the coefficient of Neo-Hookean model. According to the experimental result of tire tread material, C_{10} is defined as 12.

Since the stiffness of the tire is much smaller than those of the wheel and ground, the wheel and ground are set as rigid bodies in the dynamic simulation. In the modeling process, the cross-section characteristics of a certain type of tire are retained, and the features of the tread pattern are ignored. Fig.1 shows the tire model and the inner acoustic medium model in ABAQUS.



(a) tire model *(b) tire model coupling with acoustic medium*

Fig. 1 Tire model

The acoustic-solid coupling model is validated by the modal test of the tire structure as well as the acoustic mode test of the acoustic cavity similar to reference [17].

3 ANALYSIS OF THE TIRE CAVITY NOISE EXCITED BY THE PERIODICAL CHANGE OF TREAD CURVATURE

3.1 Theoretical Model and Analysis of the Excitation Caused by the Periodical Change of Tread Curvature

The simplified process of the periodical change of tread curvature is shown in Fig. 2, in which the periodical part represents the outer contour of the central section of the tire and the horizontal line represents the ground. Point A is the centre point of the tire. Line AB is perpendicular to the ground. In the right triangle ABC, $AC = R,$ in which R is the radius of the tire, $AB = R_s$ and $BC = L$. The length of line BC can be presented as follows:

$$BC = L = \sqrt{AC^2 - AB^2} = \sqrt{R^2 - {R_S}^2} \tag{2}$$

As shown in Fig.2, point C is set as the initial moment and point D is set as time t. Point E is the intersection point of line AD and the outer contour of the central section of the tire. The speed of the car is V_0. Only the normal velocity of the tread can excite the vibration of the tire cavity in the process of the periodical change of tread curvature caused by tire rolling. Therefore, only the normal velocity of the tread is calculated. The length of DE and its vertical component can be described as follows:

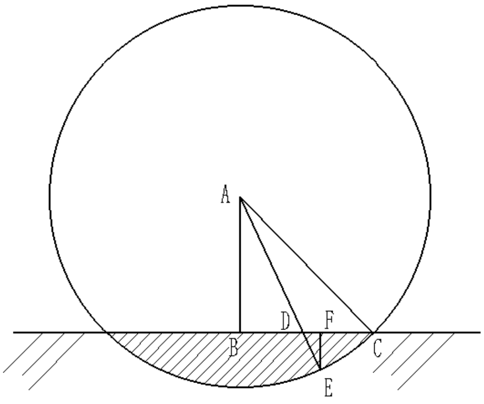


Fig. 2 Tire rolling model

$$DE = AE - AD = R - \sqrt{{R_S}^2 + (L - CD)^2} = R - \sqrt{{R_S}^2 + (L - v_0 t)^2} \tag{3}$$

$$EF = DE \cdot \cos\theta = \left(R - \sqrt{{R_S}^2 + (L - v_0 t)^2}\right) \cdot \frac{R_S}{\sqrt{{R_S}^2 + (L - v_0 t)^2}} \tag{4}$$

Then with the differentiation of Eq.(4), we can get the vertical velocity of point D, which is corresponding to the angle θ.

$$v_D = \frac{d(EF)}{dt} \tag{5}$$

The patch contacts with ground can be divided into N independent points. Their vertical velocity can be calculated by Eq.(2)-(4). To simplify the calculation, these different velocity excitations at different positions can be approximated as a sinusoidal excitation with the same energy input per unit time. The sinusoidal excitation can be presented as follows:

$$v = V_a \sin(\omega t) \tag{6}$$

where ω is determined by the speed of the tire and the length of the patch contact with ground.

$$\omega = 2\pi f = 2\pi \frac{1}{T} = 2\pi \frac{1}{2L/v_0} \tag{7}$$

To calculate the magnitude of the velocity, we need to get the RMS of velocity according to Eq.(8). The amplitude of the sinusoidal excitation can be calculated by Eq.(8).

$$v_{rms} = \sqrt{\frac{\sum_{i=1}^{N} v_{Di}^{2} \Delta s_i}{S}} \tag{8}$$

$$V_a = \sqrt{2} v_{rms} \tag{9}$$

where S is the area of the patch contact with ground, Δs_i is the finite area of an element.

When tire pressure is 2.5bar and load is 4000N, the data of the outer contour of the tire central section can be obtained by simulation as follows: R=285mm, Rs=278mm, v_0=72 km/h, L=62.8mm. The length of EF can be calculated by Eq. (10). Also ω and V_a can be calculated by Eq. (11) and Eq. (12).

$$EF = \frac{79230 - 278\sqrt{81227 - 2.512 \cdot 10^6 t + 4 \cdot 10^8 t^2}}{\sqrt{3943.84 - 2.512 \cdot 10^6 t + 4 \cdot 10^8 t^2}} \tag{10}$$

$$\omega = 2\pi(1/\frac{2L}{v}) = 2\pi \times (1/(2 \times 0.003138)) = 1000.63 \text{rad/s} \tag{11}$$

$$V_a = \sqrt{2} v_{rms} = 3438 \times \sqrt{2} = 4861.33 \text{mm/s} \tag{12}$$

According to the motion equation of sound wave, the sound pressure is about 5043.6Pa when V_a is 4861.33mm/s and tire pressure is 2.5bar. But it is apparently different with the result of bench testing, which is about a few hundred. After analysis, we know that in the model of Fig. 2, only the geometric change of the part on tire which contact with ground is considered. While the geometric change of the part which do not contact with ground is ignored.

Apparently, the abrupt change of geometry and the faster vertical velocity on point C in Fig. 2 are unreasonable. So, the normal velocity of the entire deformed area of the tire surface should be considered.

3.2 Simulation analysis of the periodical change of tread curvature caused by tire rolling

To consider the geometric change of the part which do not contact with ground, we make the simulation when tire pressure is 2.5bar and load is 4000N. To concentrate the effect into the ground contact part, the shape of contact patch is obtained, shown in Fig. 3. According to the result, the distances between finite element joints on tire outer surface and centre point of tire (hereinafter called '$\mathcal{R}$') in the range of θ from 0^0 to 25^0 are shown in Fig. 4. For simplicity, in the subsequent calculation, it was simplified to a circle with a radius of 50mm. The amplitude and frequency of sinusoidal excitation can be calculated by Eqs. (7)-(8) as follows: $v_{rms} = 877.9mm/s$, $f = v_0/l = 80Hz$.

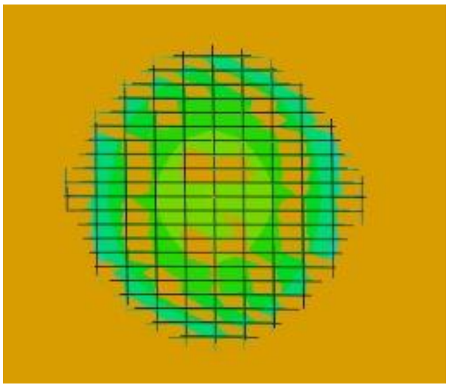


Fig. 3 Contact patch

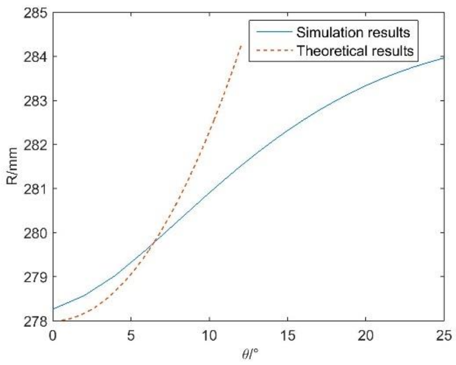


Fig. 4 Comparison of $\mathcal{R}$

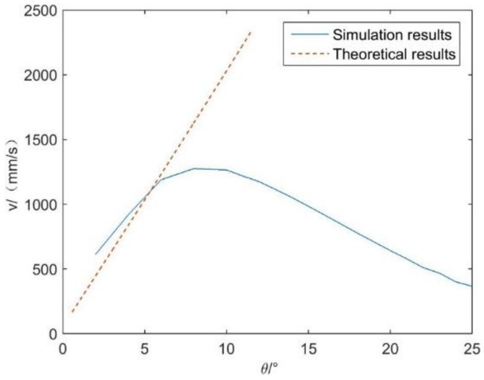


Fig. 5 Comparison of tire surface velocity

From the above, we can see that the amplitude of velocity is Significantly lower than the theoretical analysis data. Because, when tire is rolling on the ground, the deformation area includes not only the ground contact part, but also the area that is about to touch the ground and the area that has just left the ground.

The $\mathcal{R}$ in the theoretical analysis is shown in the dotted line in Fig. 4. In fact, the deformation area is larger than the ground contact area during tire rolling. The $\mathcal{R}$ in the simulation is shown in the solid line in Fig. 4. We can know from Fig. 4, the maximum of θ in theoretical analysis is only 12.7254°, while it is about 25° in the result of simulation. The gradient of $\mathcal{R}$ with respect to θ in theoretical analysis is greater, so the corresponding velocity excitation is greater. The comparison of tire surface velocity obtained by the two methods is shown in Fig. 5. It can be seen that the velocity in theoretical analysis is greater, which has differences with actual situation. Therefore, the velocity excitation obtained in the simulation is adopted in the subsequent analysis.

This simplified method is close to the reality of the tire rolling process. However, to be simple, when we replace the curvature variation of the whole tread area with the variation of $\mathcal{R}$ in the central section of tire, there is an approximation. There is also an approximation when we choose the selected rectangular part instead of the entire deformation area.

4 THE SOUND PRESSURE DISTRIBUTION IN THE TIRE CAVITY CAUSED BY THE PERIODICAL CHANGE OF TREAD CURVATURE CAUSED BY TIRE ROLLING

Firstly, for each of the seven cases in Table 1, we can get the data of the tire tread curve by simulation. Then the amplitudes and frequencies of excitation are obtained by further calculation.

Table 1– Simulation analysis result

Group	Tire pressure (bar)	Load (N)	Speed (km/h)	excitation frequency (Hz)
1	2.5	4000	72	80
2	2.5	4000	120	133
3	2.5	3000	72	100
4	2.5	3000	120	166
5	3	3000	72	125
6	3	3000	120	208
7	3	3000	144	250

In the “Steady-state dynamics, Modal” step of ABAQUS, acoustic response of the tire cavity is obtained. The joint of air finite element in the bottom center of the tire cavity shown in Fig. 6 is chosen to be the reference point. The spectrum characteristic of refence point represents the acoustic response of tire cavity. In the first six cases, the excitations all fail to generate any response within the range of 210~260Hz. However, the sinusoidal excitation frequency of the seventh group was 250Hz, the excitation frequency is set to be 249~251Hz to simulate single frequency excitation. Because the excitation frequency is within the cavity resonance frequency range, the sound pressure at reference point reaches 2000Pa. Fig. 7 shows the distribution of sound pressure in tire cavity.

Fig. 6 Position of refence point in tire cavity

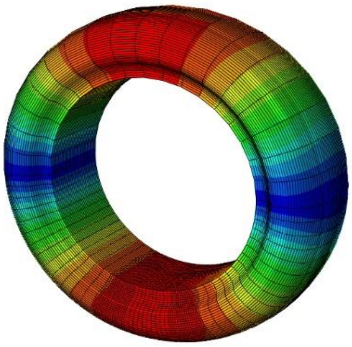


Fig. 7 Sound pressure distribution of group 7

As we can see, tread curve due to tire rolling has harsh conditions to excite tire cavity resonance. It requires a certain combination of tire pressure, load and velocity to make sinusoidal excitation frequency close to the natural frequency of tire cavity resonance.

5 CONCLUTIONS

In this paper, the acoustic response of tire cavity under excitation is analyzed in detail from the angle of the tread bending during tire rolling. The following conclusions may be reached:

1 Theoretical model of tread bending during tire rolling is built. The expression of the vertical velocity component of points at any position on ground contact part is analysed.

2 A method that simplify different velocity excitations at different positions into a sinusoidal excitation with the same energy input per unit time is founded. Through finite element simulation analysis, the shape of contact patch under the load of road is obtained, and then vertical velocity of the part which do not contact with ground is calculated. Finally, the excitation is concentrated from the entire deformation area into contact patch.

3 As we can see from the spectrum characteristics of refence point in different combinations of tire pressure, load and velocity, tread curve due to tire rolling has harsh conditions to excite tire cavity resonance. It is different from broadband road roughness excitation, which can easily excite tire cavity resonance in 200~260Hz. It requires a certain combination of contact patch length and speed to excite tire cavity resonance. And if the excitation frequency covers natural frequency of tire cavity resonance, tread curve due to tire rolling will excite tire cavity resonance to a great peak sound pressure.

ACKNOWLEDGEMENT

The authors would like to thank the financial support provided by the Natural Science Foundation of China (Grant No.51675021).

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