Research on the Model of Load Acting on the Rim Arising from Tire Acoustic Cavity Resonance

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ABSTRACT

To study the energy transferring characteristics and further attenuate the transferring, the noise load acting on the rim needs to be clarified at first.

In this paper, the finite element model of a tire coupling with acoustic medium in the tire cavity is constructed. The sound field arising from the tire cavity resonance excited by road roughness is simulated, and the sound load acting on the rim is investigated. On this basis, the load model of the sound field is established. Experiments of the sound field inside the tire-wheel assembly are carried out to verify the model of load acting on the rim.

The load model can be used to conveniently simulate the transferring characteristics of the cavity resonance energy to the wheel and suspension system, and is helpful to research the control methods of the noise arising from tire cavity resonance.

Keywords: Tire acoustic cavity resonance, Load model, Experiments, Simulation

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1. INTRODUCTION

Tire cavity resonance noise directly influences the vehicle riding comfort and has obvious peak value on the road test spectrum. At present, almost all automobile tires are filled with air in the cavity between carcass and rim, and the first-order modal frequency of the cavity is generally 200 to 300 Hz [1-3]. As it is within the vibration frequency range of the tire, the cavity may resonate during the movement of the automobile.

Sakata et al. [1] studied the mechanism of the influence of the wheel axle force on the noise in the car. And proved that the tire cavity resonance noise has a significant impact on the passenger ear noise. It has also been found that the first-order modal frequency noise is especially annoying and has a sharp peak with frequency typically in the range of 190-260Hz[4,5]

Tire cavity resonance noise has attracted people's attention, and in recent years has become a hot topic in the field of international tire research. Mohamed et al. [3] studied the acoustic cavity resonance and tire coupling phenomenon and proposed different methods for noise of different frequency ranges. Kim et al. [6] established a finite element model of the tire considering the coupling of the acoustic cavity, and based on this, studied the influence of the structural parameters of the tire on the resonant frequency of the acoustic cavity.

The energy of the acoustic cavity resonance noise is transmitted to the vehicle body through the rim, spoke, hub, suspension system from tire cavity, and then stimulates the sound field inside the vehicle. To study the energy transferring characteristics and further attenuate the transferring, the noise load acting on the rim needs to be researched at first.

Feng [7] studied the vibration noise simulation of truck radial tires, and calculated the sound pressure, tire natural frequency and damping ratio under the rolling condition of the tire by finite element method. Tanaka et al. [8] applied a wide-frequency excitation on static tires to simulate the effects of road surface roughness using a multi-microphone test system. Based on this, the sound pressure distribution in the acoustic cavity and the frequency of the acoustic cavity resonance were tested. Sobhanie [9] established a finite element model of the tire considering the effect of road roughness on the tires and suspension, body system. Masino et al [10] developed a novel method and an exploitation model to predict different types of road surfaces based on tire cavity sound acquired under normal vehicle operation. Though achievements have been made on the issue, no load model has been put forward to describe the sound field distribution. It is of importance to build such a load model so that further investigation of the transferring characteristics and control methods of the resonance noise can be made.

In this paper, the finite element model of a tire coupling with acoustic medium in the tire cavity is constructed. The sound field arising from the tire cavity resonance excited by road roughness is simulated, and the sound load acting on the rim is investigated. On this basis, the load model of the sound field is established. Experiments of the sound field inside the tire-wheel assembly are carried out to verify the model of load acting on the rim.

The load model can be used to conveniently simulate the transferring characteristics of the cavity resonance energy to the wheel and suspension system, and is helpful to research the control methods of t he noise arising from tire cavity resonance.

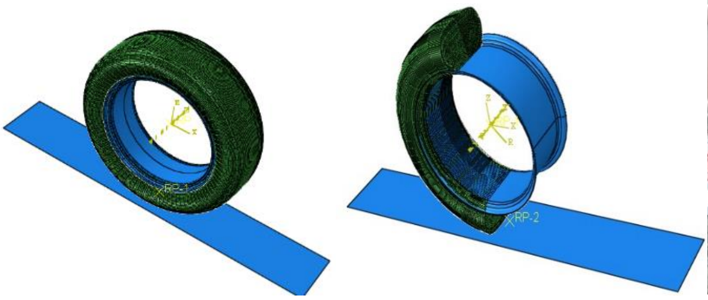
2. SIMULATION MODEL OF TIRE CAVITY ACOUSTIC RESONANCE

To study the acoustic cavity resonance energy acting on the rim, the finite element model of a tire coupling with acoustic medium in the tire cavity is constructed firstly. Take the tire tread vibration as the excitation source of the acoustic cavity, the acoustic-solid coupling system dynamic equation is described as follows[11]:.

$$\begin{bmatrix} [M_s] & [0] \\ \rho[s]^T & [M_f] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{p}\} \end{Bmatrix} + \begin{bmatrix} [K_s] & -[s] \\ [0] & [K_f] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{p\} \end{Bmatrix} = \begin{Bmatrix} \{f_s\} \\ \{0\} \end{Bmatrix} \tag{1}$$

The size of the tire model used here is 185/60 R15, same as the tire used in later experiments. Material properties data of the tire is obtained from the tire manufacturer. In dynamic simulation process, the wheel and ground are considered as rigid bodies as their stiffness is much larger than the tire. The tread pattern features are ignored while the cross-section characteristics of the tire are retained.

The tire model with belt, apex, bead ring, and rubber is constructed as Fig.1(a). Inner acoustic medium is modeled fitting tire's inner surfaces as shown in Fig.1 (b).



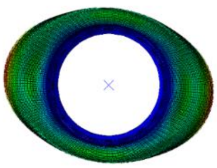
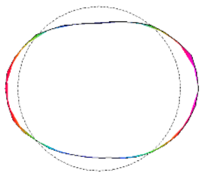
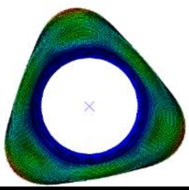
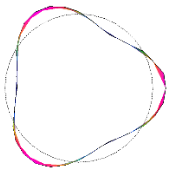
(a) tire model (b) tire model coupling with acoustic medium

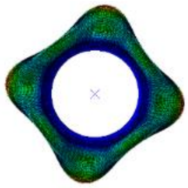
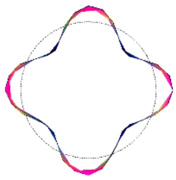
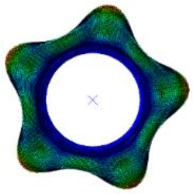
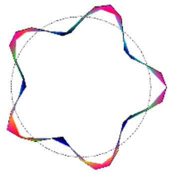
Fig. 1 Tire model

Fig.2 Tested tire

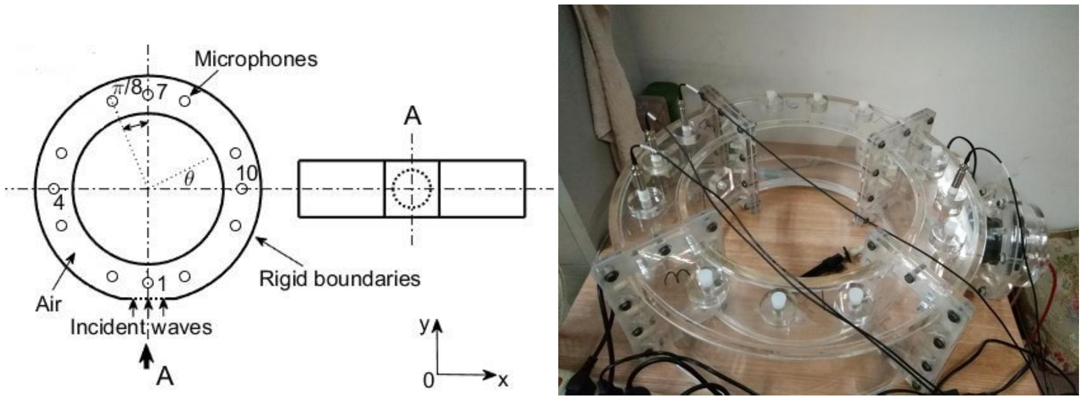
Then tire structure modal tests are carried out to verify the acoustic-solid coupling model. The tire-wheel assembly used for the structure modal tests are shown in Fig. 2. The results comparison is shown as table 1.

Table 1 Comparisons of tire radial vibration mode shapes

Order	Simulation results	Test results
2		
3		

4		
5		

Then acoustic modal tests are carried out by sweep-frequency speed excitation. The frequency of the sound pressure peak from the simulation is about 221Hz, and the peak value is around 24.44Pa, while the peak frequency from the test is about 216.5Hz, and the peak value is around 23.97Pa. The corresponding results from the test and simulation show good consistency. The test equipment is shown as Fig.3.



(a) schematic diagram of test device   (b) test device

Fig. 3. Diagrams of the tire cavity sound pressure experimental system

Now the acoustic-solid coupling model is valid enough for the further simulations.

3. MODEL OF LOAD ACTING ON THE RIM BASED ON SIMULATION RESULTS

3.1 Sound Pressure Distribution in Tire Cavity under Road Roughness Excitation

To study the influence of road load and tire inflation pressure on tire cavity resonance energy, 28 sets of different data are chosen as shown in table.3. Considering ordinary working conditions, the road load is set as 3000N, 3500N, 4000N and 4500N, while tire inflation pressure varies from 2.5bar to 1.9 bar.

Table 2 Sets of simulation states

Inflation pressure/bar	Load/N	Sound pressure Amplitude/Pa
2.5	2990	96.3

2.5	3487	108
2.5	4010	124
2.5	4556	145.9
2.4	2986	83.2
2.4	3467	92.1
2.4	3973	107.7
2.4	4496	118.3
2.3	2997	75
2.3	3478	80.6
2.3	3986	90.9
2.3	4504	100.9
2.2	3054	68.2
2.2	3566	74.6
2.2	4108	80.4
2.2	4665	90.1
2.1	3010	59
2.1	3471	64.3
2.1	3999	68.5
2.1	4487	75.2
2.0	3008	48.5
2.0	3496	54.2
2.0	4003	56.9
2.0	4525	62.7
1.9	3007	35.6
1.9	3499	39.3
1.9	4008	42.5
1.9	4528	46.8

The sound pressure distribution is shown as Fig.4(a). Then the sound pressure of nodes at the center section of the rim is taken out to form Fig.4(b).

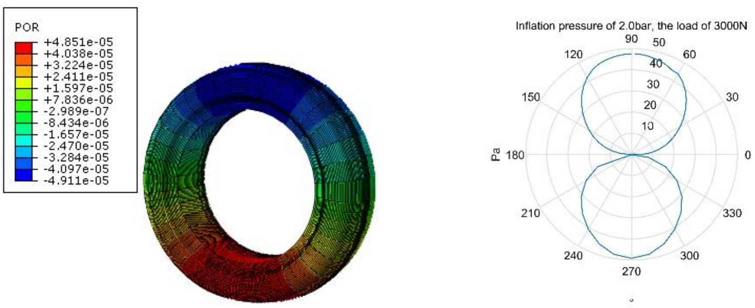


Fig. 4 Sound pressure distribution in 2.0 bar state

3.2 Load Model of the Sound Field Based on Simulation Results

As can be seen from Fig.4 , the sound pressure peaks at two opposite locations and then decreases to 0 after 90° ,which agrees well with the cosine function. Then the load model is defined as

$$P_{sp} = A_{pf} cos\theta \tag{2}$$

where P_{sp} represents the sound pressure of the node at θ, A indicates the amplitude of the sound field during the simulation process, and θ is the angle of the node apart from the peak node.

The comparison of load model and simulation results is shown as Fig.7. As Fig.7 shows, the results are of good consistency, thus the cosine function can well describe the load acting on the rim resulting from cavity resonance.

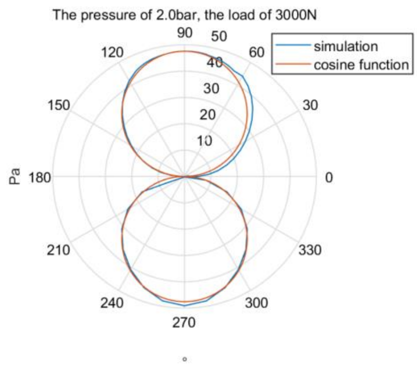


Fig. 7 Sound pressure distribution

To further determine how the road load and tire inflation influence the sound field amplitude, the regression analysis method is used here. It's a statistical analysis method that determines the quantitative relationship between two or more variables. The regression model of the above 28 sets of simulation results is

$$A_{pf} = 265 + 0.000002122x_1^2 + 33x_2^2 - 0.0874x_1 - 172.5x_2 + 0.0398x_1x_2 \tag{3}$$

where A_{pf} represents the amplitude of the sound field during the simulation process, x_1 indicates road load and x_2 means tire inflation pressure. The results are shown as Fig.8.

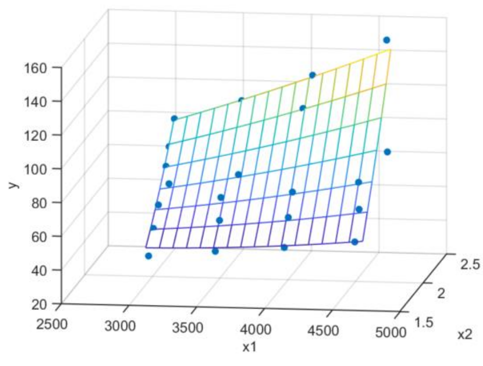


Fig. 8 Regression model

Then the correlation analysis is done, four parameters are used to determine the validation of the load model. $R^2 = 0.99$, and R^2 represents the coefficient of determination of the equation, indicating the degree of interpretation of the variables in the equation. The value of R^2 is between 0 and 1, the closer to 1, the stronger the interpretation. $F = 500$, and F tests the significant level of the equation. If it's larger than 0.05, then the test passes. $p < 0.001$, and p is a significant probability, and the model is considered valid when p<0.001. $s^2 = 7.9, and\ s^2$ shows the estimated error variance. As the results show, the equation can well represents the influence of the road load and tire inflation pressure on the sound field amplitude.

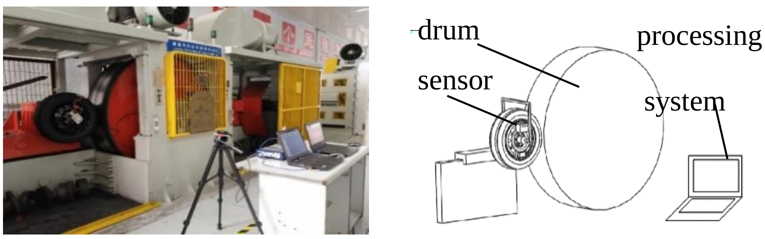
4. EXPERIMENTS OF TIRE CAVITY ACOUSTIC RESONANCE

To verify the load model, experiments of the sound field inside the tire-wheel assembly considering the influence of road load and tire inflation pressure are performed.

4.1 Experiments on the Sound Field of the Tire Resonance

Tire bench test is carried out to investigate the sound pressure amplitude in the cavity resulted from the acoustic cavity resonance. A pressure-tolerable microphone is fixed inside the cavity. It then transfers the sound pressure signal through a wireless telemetry instrument to the signal acquisition and processing system while rotating with the tire. The time history data of the wheel angle sensor is used to determine the angular position of the sound pressure sensor.

The test equipment is shown as Fig.9. In this paper, the assembly of 15-inch wheel and 185/60R15 tire, same as in the simulation model used in section 3.1, is used to test the sound pressure in the tire cavity.



(a) *sound pressure test equipment (b) sound pressure test equipment sketch*

Fig. 9 Sound pressure test equipment

12 sets of different data are chosen as shown in table.3. The road load is varies from 3000N, 3500N, 4000N to 4500N, while tire inflation pressure is set as 2.5bar 2.3bar and 1.9 bar.

Table 3 Sets of experiment states

Inflation pressure/bar	Load/N	Sound pressure Amplitude/Pa
2.5	3000	91
2.5	3500	103
2.5	4000	122
2.5	4500	147
2.2	3000	67
2.2	3500	74

2.2	4000	82
2.2	4500	91
1.9	3000	37
1.9	3500	42
1.9	4000	49
1.9	4500	58

With both the pressure data and angular position data, the sound cavity pressure distribution can be processed as Fig.10.

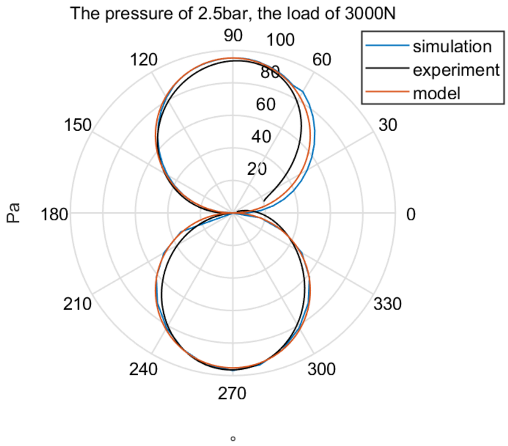


Fig. 10 Sound pressure distribution

As can be seen in Fig.10, the experiment result agrees well with both the simulation result and cosine function. It's safe to conclude that the distribution of sound pressure under the excitation of cavity resonance well fits the distribution of cosine function. The load model raised in section 3.2 is by now proved valid.

4.2 Comparison of Experiments and Simulation Results

Then the experiments results are compared with the load model based on simulation results. As can be seen in Fig.11, where blue dots represent simulation results and red dots show experiment results, the results are in good consistency.

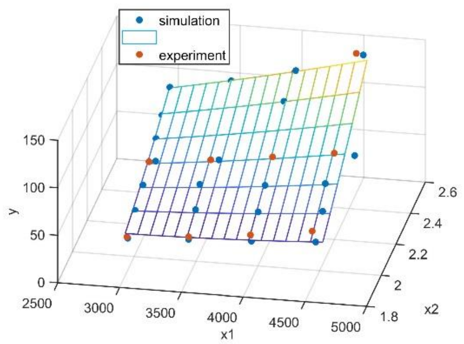


Fig. 11 Experiment results and load model comparison

Then residual analysis is carried out to examine rationality of the model hypothesis and the reliability of the data. The dots in Fig.12 here represent the difference between the experiment value and the estimated value in mathematical statistics. They float up and down at 0, and the straight line indicates its 95% reliable zone. As the line pass through 0, the load model is estimated as valid.

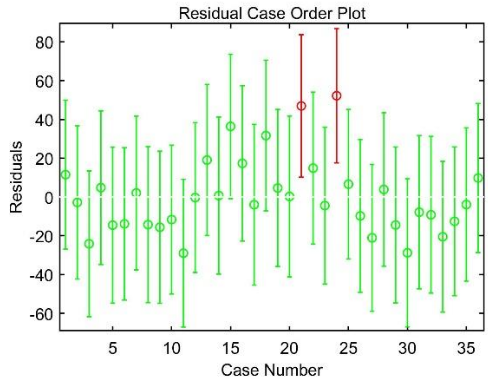


Fig. 12 experiment data residual plot

The load model can be used to conveniently simulate the transferring characteristics of the cavity resonance energy to the wheel and suspension system, and is helpful to research the control methods of the noise arising from tire cavity resonance.

5. CONCLUSIONS

In this paper, a load model of the sound field considering tire inflation pressure and road load is established based on simulation results, and experiments are carried out to verify the load model. The following conclusions may be reached:

1 The distribution of the sound field arising from tire cavity resonance agrees well with cosine function distribution. And the amplitude of the field is the peak sound pressure at the resonance frequency. Both simulation and experiment results have proved it valid.

2 A load model considering tire inflation pressure and road load is put forward to describe the sound pressure amplitude of the cavity resonance.

3 The load model can be used to conveniently simulate the transferring characteristics of the cavity resonance energy to the wheel and suspension system, and is helpful to research the control methods of the noise arising from tire cavity resonance.

6. ACKNOWLEDGEMENTS

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