# Influence of Fiber-Reinforced Composite Wheel Resonance on tire cavity noise

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**Summary**
Tire cavity noise is a kind of tonal noise with a frequency spectrum close to 220Hz, and it can be heard clearly inside the vehicle compartment, which is a phenomenon generated by resonance of the acoustic cavity inside the tire-wheel assembly due to the excitation of tire/road. There are lots of factors related to tire cavity noise, such as the dimension and structure of the tire and the wheel etc. As the critical component of transmitting the pressure of tire cavity resonance, the wheel has a very important influence on tire cavity noise by the coupling with cavity resonance. This study just focuses on the effects of fiber-reinforced composite wheel resonance on the tire cavity noise, and a numerical model of the tire-wheel assembly is established by finite element method to simulate this issue. In addition, effects of both fiber-reinforced composite wheel and metal wheel on tire cavity noise are investigated, and the results show that the wheel made of fiber-reinforced composites contributes less to the cavity noise than that of the metal wheel.

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## 1. Introduction

As is known to all, tire acoustic cavity noise inside the passenger compartment with frequency typically in the range of 190-250 Hz caused by the tire cavity resonance is very annoying and disturbing, which is an important source of interior noise for passenger car. The current methods to solve this problem still have some defects, such as, high cost and very difficult to maintain [1-16].

And, as the critical component of transmitting the pressure of tire cavity resonance, the wheel has a very important influence on tire cavity noise, however, there is not enough literature focused on the wheel, especially for the wheel made of fiber reinforced polymer with excellent properties. This paper focuses on this issue with finite element method, also some valuable conclusions have been obtained.

## 2. Finite element model

Since the material data of rubber passenger car tire is not possessed, a 315/60R22.5 smooth truck tire is modeled and analyzed as the research object.

In this paper, the tire-wheel assembly is modeled by Abaqus. The tire-wheel model with acoustic cavity and without acoustic cavity are both established in order to calculate the cavity resonance frequency conveniently. The acoustic cavity is modeled by acoustic medium elements, and the properties of which are estimated by the equation of state of ideal gas based on the data of tire pressure and air density under normal atmospheric pressure. The density of air inside the tire cavity is $\rho_{air} = 10.23\text{kg}/m^3$ and the bulk modulus is $E_{air} = 1.2\ Mpa$. Besides, the air speed of sound is $\text{C} = 343\ \text{m}/s$. In order to simulate the actual conditions of tire-wheel assembly, the tire is inflated first, and the surface of wheel is also applied responding inflation pressure. Then the reference point of rigid road contacting with tire bottom is applied concentrate force as the tire load. The finite element models of tire-wheel assembly is illustrated as Fig. 1.

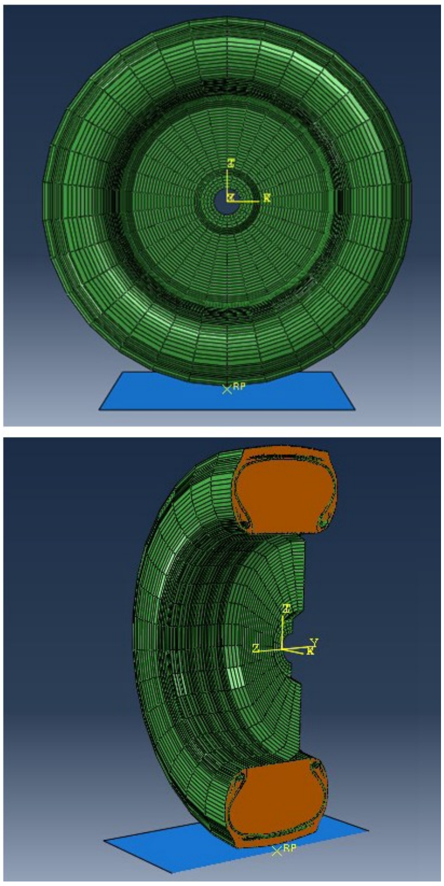


Figure 1. The finite element model of tire-wheel assembly

Furthermore, in order to reflect the advantage of the wheel made of FRP, a wheel made of steel and a wheel made of carbon fiber reinforced polymer (CFRP) are both modeled. The data of material properties used for wheels are shown in table I. The thickness of the steel wheel is 8 mm, but the thickness of the other one made of CFRP laminate $(0/90/\pm45)_{12s}$ is 19.2 mm, taking the requirements of stiffness and strength into consideration.

Table I. The material properties of steel and FRP

| *Steel* | *CFRP(T300/4211)* |
|---|---|
| $\rho$=7.9x10$^3$kg/$m^3$ | $\rho$=1.5x10$^3$kg/m$^3$ |
| $E$=210Gpa | $E_1$=126GPa<br>$E_2$=8GPa<br>$E_3$=8Gpa<br>$G_{12}$=3.7GPa<br>$G_{13}$=3.7GPa<br>$G_{23}$=2.6GPa |
| $\mu = 0.3$ | $\mu_{12}$=0.308 |

## 3. Finite element simulation

In this section, the finite element models established above are used to analyze the two kinds of wheels in terms of minimizing the tire acoustic cavity noise.

### 3.1. The frequency of tire cavity resonance

In the first place, the frequency of tire acoustic cavity resonance should be calculated. Referring relevant literature [2], the frequency response function (FRF) measurements are simulated to identify the resonant frequency of tire acoustic cavity. The simulation is operated by impacting the bottom of the tire through rigid road and measuring acceleration response on the center of wheel.

After the tire being inflated and loaded, a narrow band exciting force is applied to the bottom of the tire through rigid road. But, in order to determine the frequency of the exciting force, the resonance frequency of tire acoustic cavity should be approximated using Equation 1 [2].

$$f = C/L \quad (1)$$

Where:

f= Frequency of the first order tire acoustic cavity resonance

C= Speed of sound in the acoustic medium

L= Circumference of the toroid at the centroid of the cross-section

Based on the approximation, the frequency band of the exciting force should be determined from 145-180 Hz.

Results of the simulation are shown in Fig.2 and Fig.3. As shown in the pictures, the two tire acoustic cavity resonance for the two kinds of models are evident at 164.3 Hz and 166.2 Hz respectively.

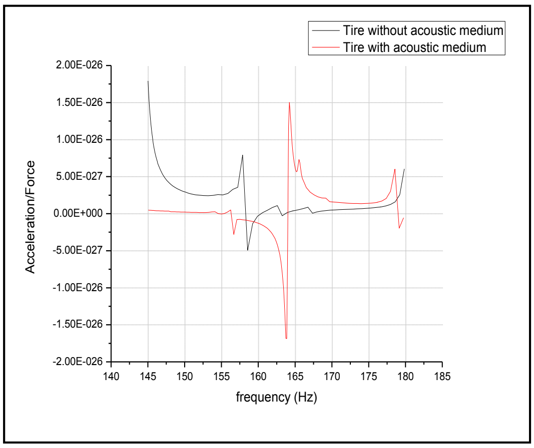



Figure 2. Comparison of tire model with steel wheel in two cases: with acoustic medium and without acoustic medium

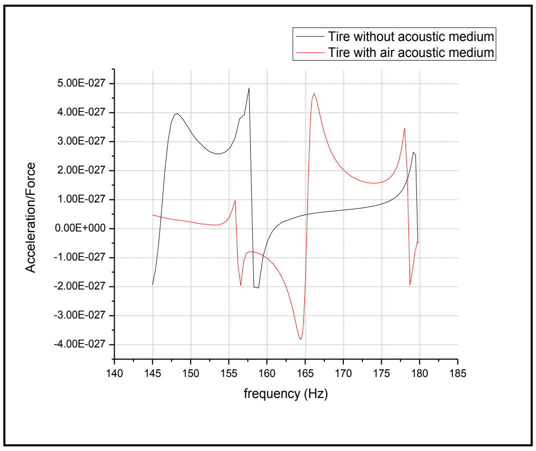



Figure 3. Comparison of tire model with CFRP wheel in two cases: with acoustic medium and without acoustic medium

As illustrated in the figures above, although the two wheels made of different material (steel versus CFRP) are used for the tire models, as expected [2], the material of wheel has little influence on the frequency of tire acoustic cavity resonance. And, the first order vertical acoustic modes of the two models are demonstrated in Fig. 4 and Fig.5.

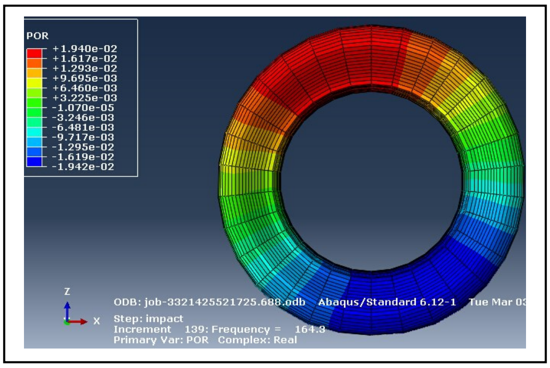



Figure 4. Vertical mode of the tire acoustic cavity resonance with steel wheel

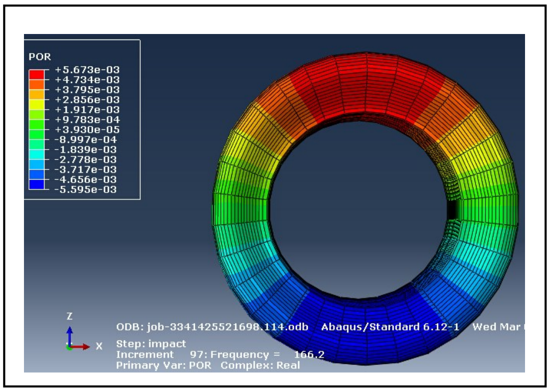



Figure 5. Vertical mode of the tire acoustic cavity resonance with CFRP wheel

### 3.2. Effects of noise reduction

After the simulation in section 3.1, the frequency of the first order tire acoustic cavity resonance has been calculated as shown in Fig.2 and Fig.3. If the two pictures (Fig.2 & Fig.3) are redrawn， as illustrated in Fig.6, different effects of two wheels on tire acoustic cavity resonance become evident.

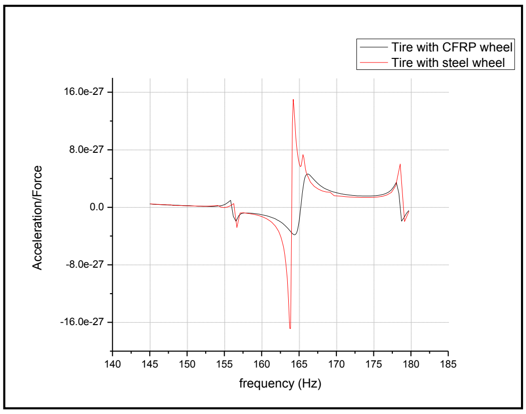



Figure 6. Comparison of tire model with steel wheel and CFRP wheel

In Fig.6, it should be noted that, there are obviously differences between the FRF of two models with different wheels under the same excitation, and the response obtained at center of the tire model with steel wheel is greater than that obtained at center of the tire model with CFRP wheel. It can be concluded that the wheel made of CFRP has better effect on eliminating the tire acoustic cavity noise than that of the wheel made of steel.

In addition to that, as previously described, the surface of wheels is also applied responding inflation pressure based on the real situation, which is different with the general cases. If the surface of wheel is not applied inflation pressure, there will be errors that cannot be ignored for the results especially for the model with steel wheel, which can be found evidently comparing the Fig.7 with Fig.6.

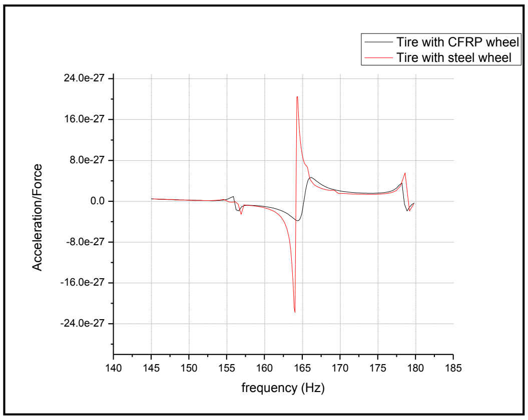



Figure 7. Comparison of tire model with steel wheel and CFRP wheel (no pressure is applied on the surface of the two wheels)

## 4. Analysis of mechanism

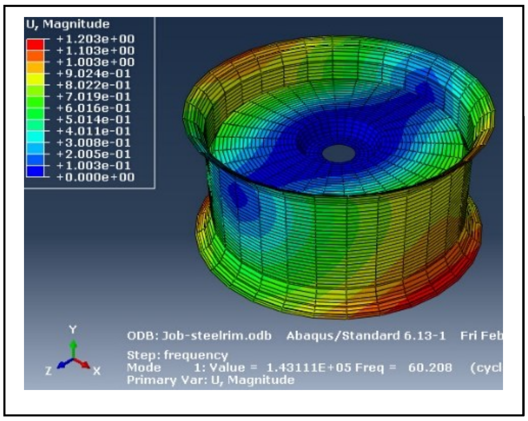
As discussed in the previous references [2, 3, 13], one of the viable solutions for eliminating tire acoustic cavity noise is to de-tune the transmission path from the tire to the passenger compartment. And, the wheel, as an important component of the transmission path, if the structural resonance of the wheel couples with the tire acoustic cavity resonance, the response will be amplified and the noise levels also will be greater. So, if the natural frequency of the wheel is shifted to make the structural resonance of wheel decouple with the tire acoustic cavity resonance, the tire acoustic cavity noise will be minimized remarkably. Besides, if damping of the wheel is higher, which may damp out part of the vibrational energy caused by tire acoustic cavity resonance, so that the tire cavity noise can be minimized to some extent.

As for CFRP, which has even higher specific stiffness than that of steel or other conventional materials (as shown in Table II), as a result of that, the wheel made of CFRP also has higher frequency of structural resonance so as to avoid the coupling with the tire acoustic cavity resonance more likely.

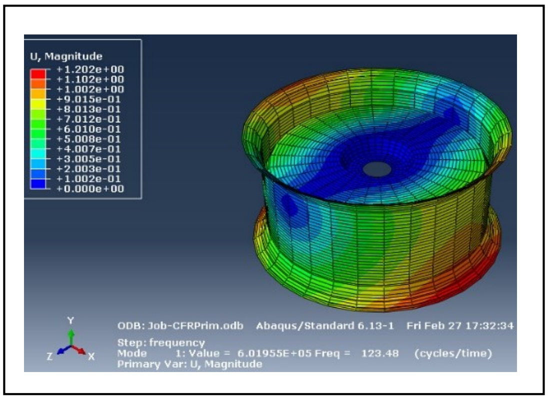
Table II. The natural frequency of the two wheels

| *Mode* | *Frequency (Steel Wheel)/ Hz* | *Frequency (CFRP Wheel)/Hz* |
|---|---|---|
| 1 | 60.208 | 123.48 |
| 2 | 60.208 | 123.48 |
| 3 | 102.08 | **211.95** |
| 4 | **175.07** | 315.01 |
| 5 | 175.07 | 315.01 |

And, the vibration modes of the two wheels are illustrated in Fig. 8.




(1) Vibration modes of the wheel made of steel




(2) Vibration modes of the wheel made of CFRP

Figure 8. The vibration modes of the two wheels

In addition to the advantage of higher frequency of structural resonance, because of the high loss factor of CFRP [17, 18], the wheel made of CFRP also has greater damping than that of the wheel made of steel. As a result of the higher damping, much more vibration energy generated by resonance will be damped out by the wheel so that the tire acoustic cavity noise can be reduced. Take the simulation in this paper as an example, based on the data in the references [19,20] and the resonance frequencies of the two wheels (Steel wheels versus CFRP wheels), the Rayleigh damping coefficients of the two wheels can be approximated roughly, for steel wheel, $\alpha = 0.47, \beta = 1.97\mathrm{E}-006$ , for CFRP wheel, $\alpha = 19.6, \beta = 1.9\mathrm{E}-5$.

## 5. Conclusions

To sum up, the wheel made of CFRP has better effect on minimizing tire acoustic cavity noise than that of steel wheel after detailed finite element calculations. Because of the higher specific stiffness and greater loss factor of CFRP, the structural resonance of wheel made of CFRP is more likely to decouple with the tire acoustic resonance and also can damp out more vibration energy than that of the wheel made of steel.

## References

[1] T. Sakata, H. Morimura, H. Ide: Effects of tire cavity resonance on vehicle road noise. Tire science and technology 2 (1990) 68-79.

[2] R. W. Scavuzzo, L. T. Charek, P. M. Sandy, and G. D. Shteinhauz: Influence of wheel resonance on tire acoustic cavity noise. SAE Technical Paper, 940533.

[3] T. Hayashi: Experimental analysis of acoustic coupling vibration of wheel and suspension vibration on tire cavity resonance. SAE Technical Paper, 2007-01-2345.

[4] Z. C. Feng, P. Gu, Y. Chen, and Z. Li: Modeling and experimental investigation of tire cavity noise generation mechanisms for a rolling tire. SAE Technical Paper, 2009-01-2104.

[5] A. S. Waisanen, J. R. Blough: Road noise TPA simplification for improving vehicle sensitivity to tire cavity resonance using helium gas. SAE Technical Paper, 2009-01-2092.

[6] S. Kim, K. Sung, D. Lee, S. C. Huh: Cavity noise sensitivity analysis of tire contour design factors and application of contour optimization methodology. Journal of Central South University 19 (2012) 2386-2393.

[7] J. K. Thompson: Plane Wave Resonance in the Tire Air Cavity as a Vehicle Interior Noise Source. Tire Science and Technology 23 (1995) 2-10.

[8] M. Zamri, L. Egab, X. Wang: Tyre Cavity Coupling Resonance and Countermeasures. Applied Mechanics and Materials 2014, 471: 3-8.

[9]R. Gunda, S. Gau, and C. Dohrmann：Analytical Model of Tire Cavity Resonance and Coupled Tire/Cavity Modal Model. Tire Science and Technology 28 (2000) 33-49.

[10]L. R. Molisani, R. A. Burdisso, D. Tsihlas: A coupled tire structure/acoustic cavity model. International journal of solids and structures 40 (2003) 5125-5138.

[11]Leonardo Molisani: A coupled tire structure-Acoustic cavity model. Doctoral thesis. Virginia.2004.

[12]Z.C. Feng. Perry Gu: Modeling and experimental verification of vibration and noise caused by the cavity modes of a rolling tire under static loading. SAE International, 2011-01-1581.

[13]Z. Mohamed, X. Wang: A study of tyre cavity resonance and noise reduction using inner trim. Mechanical Systems and Signal Processing 50 (2015) 498-509.

[14]W. B. Clayton, R. Saint-Cyr: Incorporation of the tire air cavity resonance into the modal tire model .Society for Experimental Mechanics, Inc, 16 th International Modal Analysis Conference. 1998, 1: 50-56.

[15]Z. Mohamed, X. Wang, R. Jazar: A survey of wheel tyre cavity resonance noise. International Journal of Vehicle Noise and Vibration 2013, 276-293.

[16]Y. Kamiyama: Development of a New On-Wheel Resonator for Tire Cavity Noise. SAE Technical Paper, 2014-01-0022.

[17]D. A. Saravanos, D. Varelis, T. S. Plagianakos, N. Chrysochoidis: A shear beam finite element for the damping analysis of tubular laminated composite beams. Journal of Sound and Vibration 291 (2006) 802-823

[18]D. X. Lin, R. G. Ni, R. D. Adams: Prediction and measurement of the vibrational damping parameters of carbon and glass fibre-reinforced plastics plates. Journal of composite materials 18 (1984) 132-152.

[19]Chang Shiwei, Zhang Weigang: A simulation analysis on the impact test of composite wheel. Automotive Engineering 32 (2010) 65-68.

[20]Luo Zhong, Yang Kun, Mei Zhiyuan. The analysis of the dynamic natural characteristics and damping of the GFRP laminate composites. Materials Review 27.1 (2013) 126-129.