HELMHOLTZ RESONATOR FOR REDUCING TIRE CAVITY RESONANCE AND IN-VEHICLE NOISE

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ABSTRACT

Automotive manufacturers expect tire suppliers to investigate alternative approaches of controlling the tire cavity resonance in vehicles other than changing the shape and design of the tire. The intention of this case study is to demonstrate such an approach in eliminating the tire cavity resonance by installing a sound-damping resonator on the wheel assembly. The predicted transmission loss for such a resonator model given in this paper is compared to the experimental result. In terms of quietness, the sound-attenuating resonator controls the cavity resonance and noise. However, this investigation should be extended to include multiple resonator units of different dimensions to attenuate the cavity resonance at a wide range of frequencies.

SOMMAIRE

Les fabricants automoteurs prévoient que les fournisseurs de pneu examinent des approches alternatives de contrôler la résonance de cavité de pneu dans les véhicules changeant autrement que la forme et la conception du pneu. L'intention de cette étude de cas sera obligé à démontrer telle une approche dans éliminer la résonance de cavité de pneu en installant un résonateur de son-étouffe sur l'assemblée de roue. La perte prédite de transmission pour un tel résonateur modèle donné dans ce papier en comparaison du résultat expérimental. Sur le plan de calme, le résonateur de son-modère contrôle la résonance de cavité et le bruit. Cependant, cette investigation devrait être étendue pour inclure les unités de résonateur multiples de dimensions différentes pour modérer la résonance de cavité à une gamme large de fréquences.

1. INTRODUCTION

The noise, especially cavity noise, produced by tires has been a concern in the automotive industry. The cavity resonance of the air column inside the tire is a major contributor to the vehicle's interior and exterior noise. A clear understanding of this phenomenon is required to design a suitable noise control solution in eliminating the tire cavity noise.

One of the main sources of in-vehicle noise is the vibration of the tire carcass, which is caused by the resonance frequencies of the tire construction. Thus, the cavity resonance becomes an issue, which is dependent on tire shape and design. The carcass' vibration causes the sidewalls to radiate sound in phase from both sides. As a result of better impedance matching, the sound level emitted inside the carcass usually approaches peak-level of up to 140 dB. Part of this noise is radiated outside through the sidewall but most of this noise is radiated through the suspension and vehicle components, thus reaching the vehicle interior. Changing the design of the tire alone to control the cavity noise is a challenging and frustrating task. Today automotive manufacturers are looking for an alternative method to changing the tire design, in order to control the cavity noise.

The air cavity of a given tire resonates at a certain frequency or at a multiple of frequencies. This is caused by the Doppler effect, which depends on the rotating speed of the tire. In this work, a model of a rectangular resonator, whose mechanical analogy is a simple oscillator, is investigated as a damper to attenuate the cavity resonance inside the tire cavity.

2. MATHEMATICAL MODEL OF RESONATOR DAMPING

The sound damping-resonator model is based on the Helmholtz resonator principles, which acts as a damper and is proposed in this investigation. The resonator model can be incorporated in the air cavity area of the tire. Such a damper unit should eliminate the cavity resonance and improve the in-vehicle noise quality. The resonator can be designed to match the unique need of each tire type and would be marketable as a supplementary rubber product to control cavity resonance. An advantage to this approach is that a unit of multiple resonators can be incorporated into the tire cavity such that by slightly varying the design parameters of each resonator the concerned range of frequencies due to the Doppler effect can be focused.

The Helmholtz resonator, which is used as an acoustics damper, has a resonant frequency tuned to the tire cavity resonance. The geometry of each resonator, as in figure 1, is determined by the size of the cavity of the resonator and the size of the orifice or the opening through which the energy enters and escapes from the cavity of the tire. In the illustrated resonator models, dimensions are chosen for a particular tire-wheel structure so as to be tuned to the cavity resonance of the tire.

Helmholtz resonators may be compared to a typical mechanical spring-mass system. The equivalent of the spring is the compressibility of the air in the cavity and the equivalent of the mass in the spring-mass system is the effective mass of the air in the orifice. When the resonator is tuned to the tire cavity's resonance, then the acoustic pressure disturbances in the tire cavity causes the resonator to oscillate. Thereby, the resonator acts as a large air source and sink at that frequency to effectively absorb the pressure disturbances from further propagation.

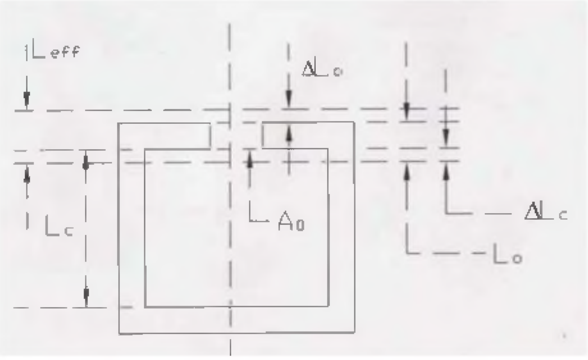

Figure 1 – Helmholtz Resonator

In Figure 1 of the Helmholtz resonator, A_0 is the orifice cross sectional area, A_c is the cavity cross sectional area, L_0 is the length from the opening to the cavity, and V_c is the volume of the cavity. The following mass equation is given as,

$$m = \rho A_0 L_{eff}.$$

The effective length, L_{eff}, is given by,

$$L_{eff} = L_0 + \Delta L_0 + \Delta L_C = 0.96 A_0^{1/2}.$$

For a spring mass system, as in Figure 2, where m is the mass and K is the spring constant, the natural frequency of the system is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{m}}.$$

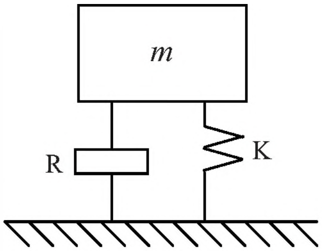

Figure 2 – Mechanical Oscillator

Consequently, at 273 ^{0}K and at the velocity of sound C_0 ($3.31/10^4$ cm/s for air), the resonator frequency is

$$f_n(T) = \frac{C_0}{2\pi}\left(\frac{A_0 T}{273 \times V_C L_{eff}}\right)^{1/2}.$$

The ratio of orifice radius r_0 to cavity volume V_C is approximated using,

$$\frac{r_0}{V_C} = \frac{9.96 \times f^2}{10^8 T}.$$

In the above equation, f is the frequency of the tire cavity resonance. These equations can be used to determine the size of the resonator and to tune the tire cavity resonance.

Figure 3 is a model of a duct with a side branch in which the resonator is attached. This model is often used in industries to attenuate pure noise tones propagating along the duct. A tire cavity may be considered similar to a duct, where the standing wave propagation results in cavity noise.

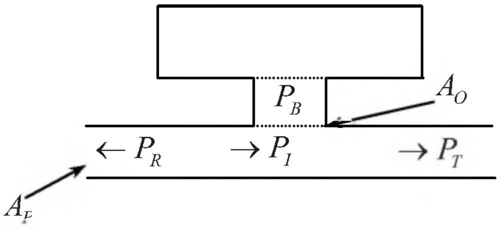

Figure 3 – Transmission loss across the resonator

At resonance frequency, the resonator short-circuits the transmission of acoustic energy so that $\left|\frac{P_R}{P_I}\right|$ approaches unity and $\left|\frac{P_T}{P_I}\right|$ approaches zero.

The resonator effectively simulates a pressure release termination and results in transmission loss which is given by,

$$T_L = -20\log_{10}\frac{P_T}{P_I} = 20\log\left(1+\frac{\rho C A_0^2}{2A_P R_a}\right).$$

In the above equation, the resistance is given by,

$$R_a = \frac{\rho C A_0^{5/2}}{2\pi V_C} \text{ at } f = f_n.$$

The transmission loss at frequencies for $f^2 << f_n^2$ becomes

$$T_L = 10\log_{10}\left[1+\left(\frac{\pi V_C f}{C A_P}\right)^2\right],$$

which tends to zero as $f \to 0$.

At frequencies $f^2 >> f_n^2$, the equation becomes

$$T_L = 10\log\left[1+\left(\frac{C A_0}{4\pi A_P L_{eff} f}\right)^2\right];$$

which tends to zero as $\frac{f}{f_n} \to \infty$.

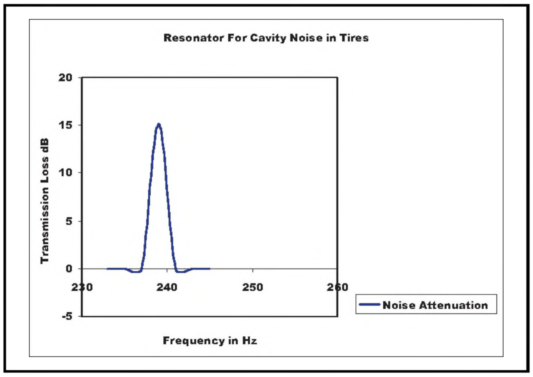

Figure 4. Predicted transmission loss of the propagating sound waves inside the tire cavity

The resonator model predicts a transmission loss that should attenuate the cavity noise up to 14 dB as shown in Figure 4. According to predictions, it is believed that the magnitude of transmission loss reduces to zero as the frequency of the tire cavity resonance moves further away from the frequency of the resonator.

3. EXPERIMENTAL TIRE

An experimental tire was mounted onto a minivan left front wheel and tested on a smooth surface in the laboratory. A tire with customer compliant for cavity resonance was selected for the experimental study. Based on the prediction and test results, the cavity resonance was determined to be around 230 Hz. As mentioned earlier, the Doppler effect and speed variation can cause the cavity resonance to be spread over a small range of frequencies. However, this investigation is limited to only 230 Hz, as the resonance is highly noticeable at the normal highway speed of 55 to 60 mph. In order to address the range of frequencies, a sound-damping unit of multiple resonators with varying dimensions, should be investigated.

Table 1 shows the predicted values of resonance frequency when the speed variation was included in the estimation.

Input Tire size: W = 215 mm; Aspect Ratio = 70%; Rim Diameter = 15 in.				
Input Contact Length = 6.75 in.				
Tire Size: 215/70 x 15; Circumference = 61.36 in.				
Speed, mph	Freq1, Hz	Freq2, Hz	Freq3, Hz	Freq4, Hz
0	215.5	215.5	225.2	225.2
5	214.4	216.5	224.1	226.2
10	213.4	217.5	223.0	227.3
15	212.4	218.6	221.9	228.4
20	211.3	219.6	220.8	229.5
25	210.3	220.6	219.8	230.5
30	209.3	221.7	218.7	231.6
35	208.2	222.7	217.6	232.7
40	207.2	223.7	216.5	233.8
45	206.2	224.7	215.5	234.9
50	205.1	225.8	214.4	235.9
55	204.1	226.8	213.3	237.0
60	203.1	227.8	212.2	238.1
65	202.0	228.9	211.1	239.2
70	201.0	229.9	210.1	240.3
75	200.0	230.9	209.0	241.3

Table 1 – Cavity resonance between 0 to 75 mph.

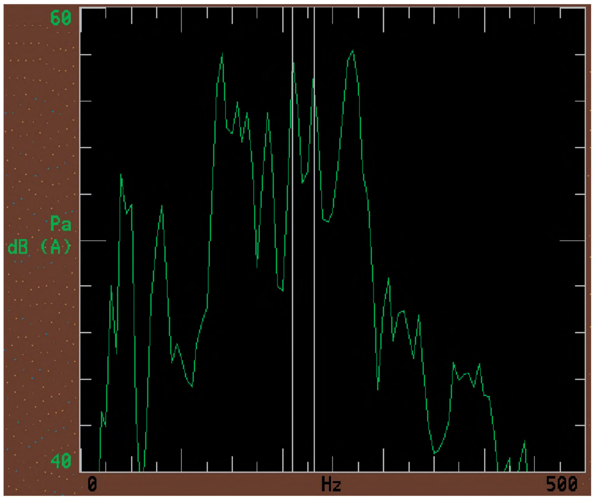

Figure 5 – Peak hold noise spectrum

A coast down test was conducted in the speed range of 70 to 20 mph on a smooth surface. The test result shown in Figure 5, peak hold between 209.9 Hz and 229.8 Hz, confirms the range of the predicted cavity resonance in Table 1.

The dimensions of the resonator were calculated based on the mathematical model shown in Figure 1 to attenuate the tire cavity resonance of 230 Hz between 55 and 60 mph. Figure 6 and Figure 7 show the experimental model that was built and mounted to the wheel.

Figure 6 – Side view of the mounted resonator.

Figure 7. Resonators are wrapped around the dip of the base

4. EXPERIMENTAL VERIFICATION

A 15-inch tire was fitted onto a minivan front wheel and tested in the Goodyear's Acoustic Study Laboratory on a smooth surface. Noise was measured at the interior and exterior of the vehicle along with the acceleration levels at the spindle vertical, F/A and lateral directions.

Measurements were repeated for the same test conditions with a unit of multiple resonators wrapped around the base of the wheel as shown in Figure 7. The parameters of the resonators are identical and tuned to 230 Hz in this investigation.

Figure 8 and Figure 9 show the interior noise measured for a regular wheel and a resonator attached wheel. The effect of the resonator was noticed between 40 to 70 mph, however, the effect was peak at 55 mph. A drop in noise level up to 8 dB is observed at the cavity resonance.

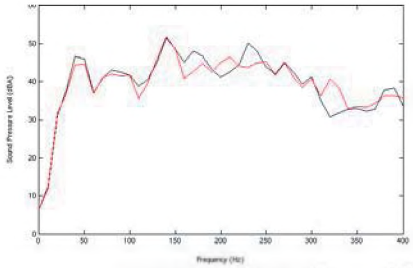

Figure 8. Interior noise attenuation at 60 mph
Dark – without resonator; Light – with resonator.

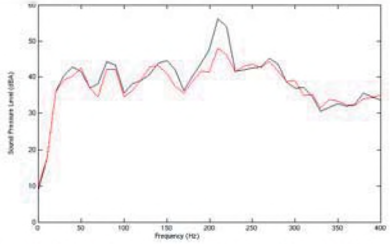

Figure 9. Interior noise attenuation at 55 mph
Dark – without resonator; Light – with resonator.

Similarly Figure 10 through Figure 12 are for the spindle vertical, F/A, and lateral vibration. The spindle vertical, F/A, and lateral vibration have been reduced up to 10 dB in all cases at the cavity resonance frequency.

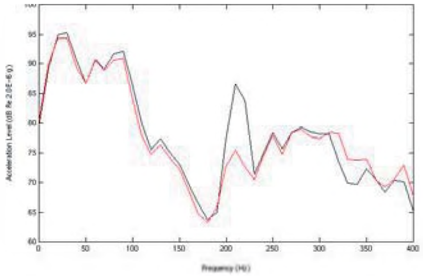

Figure 10. Reduction in Spindle vertical vibration at 55 mph
Dark – without resonator; Light – with resonator.

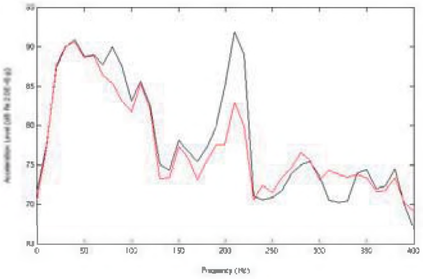

Figure 11. Reduction in Spindle F/A vibration at 55 mph
Dark – without resonator; Light – with resonator.

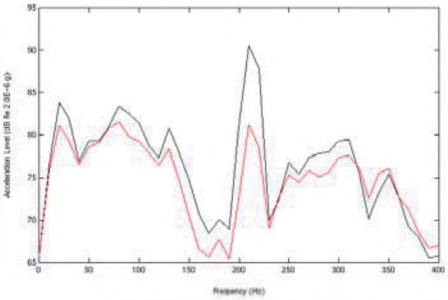

Figure 12. Reduction in Spindle lateral vibration at 55 mph Dark – without resonator; Light – with resonator.

5. CONCLUSIONS/RECOMMENDATIONS

This study shows that the concept resonator works on reducing the cavity noise as expected. It is expected that incorporating resonators of different dimensions into the multiple resonators unit, the cavity noise at a broad frequency range can be controlled. It is recommended that further investigation into multiple resonator units with varying resonator dimensions be conducted. These resonator units may be designed and manufactured in different sizes using hard rubber or plastic to suit specific tire sizes.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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This work was patent disclosed, ID 2001-371, by Goodyear Tire and Rubber Company and cannot be used without the written consent of the Goodyear Tire and Rubber Company for any tire noise related application and development.