Tyre Cavity Coupling Resonance and Countermeasures

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Abstract. This paper aims to investigate the coupling resonance conditions of the tyre, cavity and rim with the attachment of trim layers on the inner surface of tyre to mitigate the resonance effect. In order to validate the mathematical formulation, finite element analysis and experimental modal testing were performed to determine the frequency response function (FRF) for a tyre-wheel assembly with and without the trim layers as well as for separated tyre and rim. It was found that the resonance magnitude has been reduced when the trim layers were added. Couplings of cavity resonance to the tyre and rim were plausible due to the proximity of their resonance frequencies. Trim materials were tested using an impedance tube to suggest the best sound absorbing materials that can be used to mitigate the tyre cavity resonance effect.

Introduction

The elimination of the tyre acoustic cavity resonance is one part of wheel tyre structural design and optimization. Tyre acoustic cavity has a resonant frequency range of 200-250 Hz. Since the first discovery of the phenomenon in 1990 [1], several authors have investigated the causes and effects by theoretical formulation, computer simulation, and experimental works [2]. In addition, the resonance effect of tyre structure coupled to tyre cavity has been discussed in previous work [3].

There were a number of countermeasures proposed by past researches on how to mitigate the effect of the tyre cavity resonance. Most of them were related to the tyre and rim structure modifications, which are difficult to be implemented and maintained in the aspects of cost and reliability. For example, many researchers have tested the foam or other suitable porous materials filled into the tyre cavity which would attenuate inside wave propagation and therefore eliminate the distinct peak at the first cavity resonance mode [1-4]. Haverkamp [4] found that filling the mineral fibres into the tyre cavity could reduce the transmitted energy by more than 20 dB. In contrary, secondary measures such as applying absorbing material inside the tyre would increase cost, thereby puts it in the least of preferences by the vehicle industry. Instead, the industry requires the tyre manufacturers to integrate the solution into the construction of the tyres [5]. This could be made possible by layering the tyre inner surface with some sort of trim layers in the configuration that can be integrated to the primary design of the tyre.

Acoustic Theory. Tyre inner wall can be regarded as a rigid reverberation surface without sound absorption material boundary. It can be shown that the sound field inside the tyre satisfies the wave equation where φ is the acoustic velocity potential.

$$\nabla^2\varphi - \left(\frac{1}{c^2}\right)\frac{\partial^2\varphi}{\partial t^2} = 0 \tag{1}$$

By Fourier transform of Eq.1, it gives Helmholtz equation (2) where $\zeta = \omega/c$, ζ is the wavenumber, c is the speed of sound, and ω is the frequency in radian/second.

$$\nabla^2\varphi - \zeta^2\varphi = 0 \tag{2}$$

In cylindrical polar coordinates (r, θ, x), the Hemholtz equation is written as

$$\frac{\partial^2\varphi}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2} + \frac{\partial^2\varphi}{\partial x^2} + \zeta^2\varphi = 0 \tag{3}$$

As in Fig. 1, r refers to the radial direction, θ is the azimuth direction, and x is the axial direction of the torus.

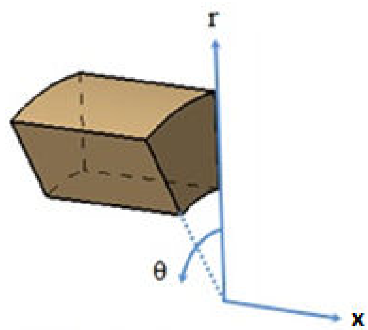

Fig. 1 Cut out of torus representing tyre axis.

Resonance frequency. A simple form of the i-th tyre cavity resonance frequency is given by $f = i \times c/L$ where i is the i-th cavity resonance and L is the circumference of the tyre at its cross-section centre. However, by assuming a factored solution and using separation of variables in Eq. 3, tyre cavity natural frequency can be calculated from the wavenumber k_{mn}.
Let $\varphi(r,\theta,x) = R(r)\Theta(\theta)X(x)$, then

$$\frac{R''}{R} + \frac{R'}{rR} + \frac{\varphi''}{r^2\varphi} + \frac{X''}{X} + \zeta^2 = 0 \tag{4}$$

Equation (3) leads to three differential systems related to axial, radial, and azimuthal direction.
Let $\frac{X''}{X} + \zeta^2 = k^2$ and multiply all terms by r^2, gives $\frac{r^2R''}{R} + \frac{rR'}{R} + \frac{\varphi''}{\varphi} + k^2r^2 = 0$, let $\frac{\varphi''}{\varphi} = -m^2$, it all simplified to the third differential system,

$$r^2R'' + rR' + (k^2r^2 - m^2)R = 0 \tag{5}$$

The general solution for (5) is

$$R(r) = A_m J_m(kr) + B_m Y_m(kr) \tag{6}$$

where J_m and Y_m are respectively the Bessel functions of the first and second kind; both of order m.
Differentiating (6) with respect to r gives

$$R'(r) = A_m J'_m(kr) + B_m Y'_m(kr) \tag{7}$$

Implementing rigid boundary conditions such as $R'(a)=0$ and $R'(b)=0$ and solving the two simultaneous equations gives

$$J'_m(k_{mn}a)Y'_m(k_{mn}b)-J'_m(k_{mn}a)Y'_m(k_{mn}b)=0 \tag{8}$$

where a is the outer tyre radius and b is the inner tyre radius, J_m is the Bessel's function of the first kind, and Y_m the Bessel's function of the second kind. The first four resonance frequencies of the tyre cavity are illustrated in Fig. 2 for the case where a is 0.306 m, b is 0.179 m and the speed of sound c is 343 m/s. *k1, k2, k3,* and *k4* represent Eq. 5 for m=0 and n=1,2,3,4 for which the roots are related to the acoustic natural frequency by $k=\omega/c$ [6].

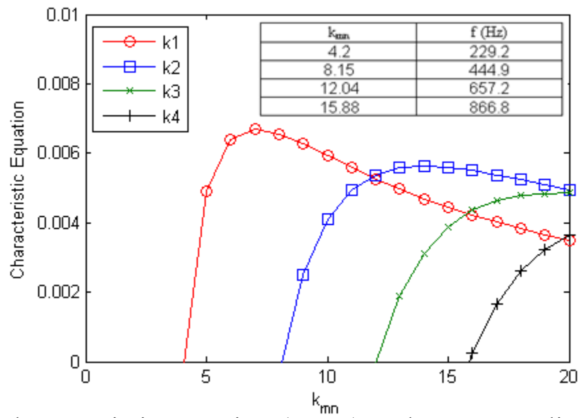

Fig. 2 Roots of the characteristic equation (Eq. 5) and corresponding natural frequencies.

Acoustic Modal Analysis

Finite Element Analysis. Finite element analysis were performed and the results are summarised in Table 1 while the mode shapes for the resonance frequency are depicted in Fig. 3a and Fig. 3b [1, 7]. For the tyre and rim simulation analysis, the rim was fixed at the stud holes and given a surface pressure of 34 psi, while for the tyre, the inside surface was given a surface pressure of 34 psi and fixed at the bead area [7]. For the alloy rim, the impact test result was inferred due to unavailability of CAD data. The tested tyre was a Bridgestone RE92 205/65/R15. The tyre material properties were assumed as isotropic, with the Young Modulus of 480 MPa and Poisson ratio of 0.49 [8].

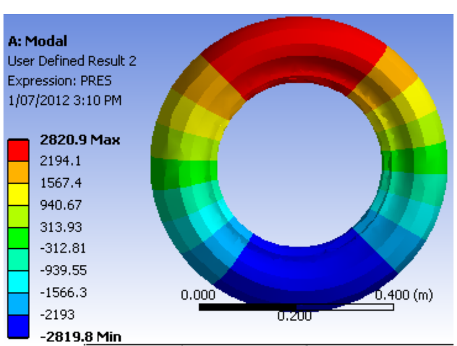

Fig. 3a The vertical tyre cavity resonance mode shape.

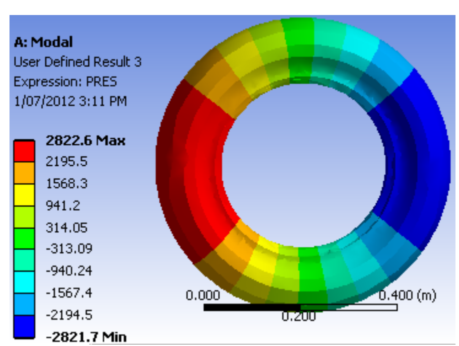

Fig. 3b The front-aft tyre cavity resonance mode shape.

Table 1. Tyre and rim resonance frequencies - fixed support and air pressure 34 psi load.

Component	Resonance Frequency (Hz)						
Tyre (FEM, 200-300 Hz)	238.4	247.1	247.6	257.4	258.1	279.7	295.7
Steel rim (FEM, 170-600 Hz)	177.4	177.6	233.9	236.3	476.8	556.7	-
Tyre cavity (FEM, 200-700 Hz)	227.2	227.5	453.9	454.5	679.2	-	-
Alloy rim (Impact Test, 200-800 Hz)	355	780	-	-	-	-	-

Modal Experiment. To validate the cavity resonant frequencies calculated by Eqs. 4, 5 and finite element modal analysis, modal testing were performed using an impact hammer (with steel cap) mounted with a force transducer (PCB086C03) and a tri-axial accelerometer Bruel & Kjaer 4506B mounted on the tyre thread centre. The tyre was impacted by the hammer three times (as suggested in B&K user manual) at position 90 degrees in azimuthal direction from the accelerometer. The impact and accelerometer position were tested at several points along the tyre thread and the best curve was taken using the Brüel & Kjær Pulse system and software LabShop V12.5. For the rim, the accelerometer was placed at the centre of axial direction and impact was at 90 degrees in azimuthal direction. The modal test was performed for the alloy rim with and without the tyre fitted. The results are illustrated in Fig. 4a, Fig. 4b, Fig. 6, and Fig. 7 where the modal frequencies or the resonant frequencies were recorded at the frequencies of FRF amplitude curve peaks. The results show their good correlations to those using the finite element modal analysis method.

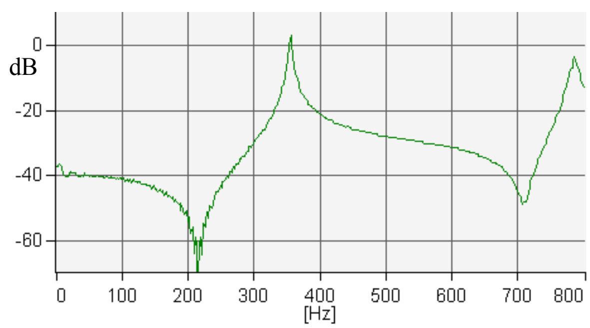

Fig. 4a FRF for alloy rim**.**

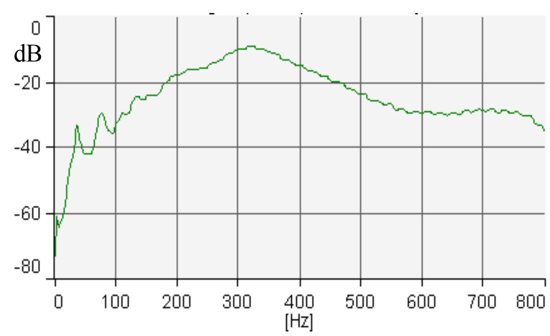

Fig. 4b FRF for tyre.

Resonant Coupling of the Tyre Cavity. Resonant coupling of the tyre cavity to the tyre or the rim or the both can intensify the effect and cause the hub vibration at 200-250 Hz frequency range. It is therefore preferable to change the modal properties of tyre and rim so that they are in safe distance from the cavity resonance frequency. From the modal testing result on the steel and alloy rim, it suggests alloy wheel is better because of its first structure resonance at 355 Hz, far away from the first tyre cavity resonance frequency. This will avoid the resonance coupling between the tyre cavity and rim. Steel rim proved to be a bad choice due to its resonant frequencies close to those of the tyre cavity. On the resonance coupling between the tyre cavity and the tyre structure itself, it proved to be more complicated and hard to determine since the tyre modal density is high. From the simple finite element simulation to the tyre structure, the tyre structure resonance frequency at 238 Hz may couple to the tyre cavity resonance. If alloy rim is used, the rim resonance at 355 Hz could couple with the tyre structure resonance at 348 Hz although this is not in the interest of the tyre cavity resonance effect.

(a) **(b)**

Fig. 5 Damaged trim on rim and another trim fitted inside tyre.

Cavity Resonance Mitigation. The insert of absorbing materials inside tyre air cavity have been tested before [1-4]. The materials were fitted to the rim or filled into the tyre at static condition. As tested by the author, it is difficult to fit a tyre into a rim when the rim is attached with trim or absorbent materials. As shown in Fig. 5(a), the material would easily disintegrate upon fitment. Therefore, putting material at the rim surface is considered unfeasible in comparison to placing it on the tyre inner surface. The placement of absorbent materials into the tyre inner surface was done previously but without any guideline to the attachment method or the parameters of materials [1, 4]. In this experiment, a similar trim material as used in automotive trim components was glued to the tyre inner surface covering the flat area. The material thickness was 20 cm, and the installation is depicted in Fig. 5(b).

Comparison of Resonance when using Trim. Impact tests were performed for the tyre-wheel system for the tyre with and without the trim layer added. The difference of the vibration amplitudes between both cases was observed. When installed with the trim layer, the resonance amplitude gave a lower overall value in comparison to that of the tyre-wheel without trim layer. The vibration suppression is very apparent at 215-230 Hz (Fig. 6).

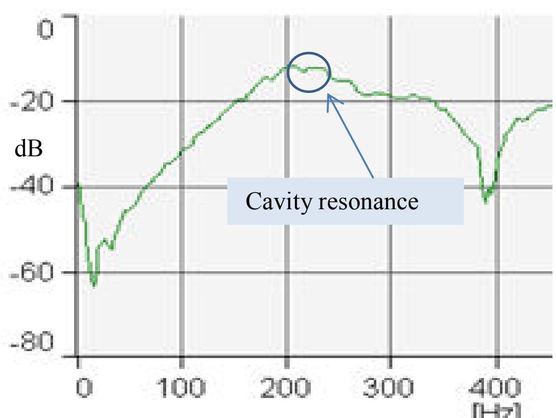

Fig. 7 FRF of the tyre-wheel without the added trim layer.

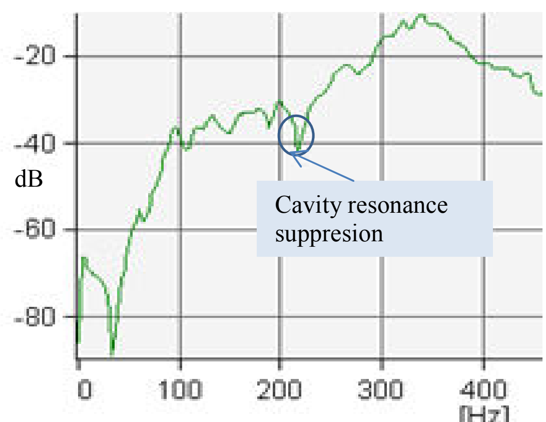

Fig. 6 FRF of the tyre-wheel with the added trim layer.

Trim Sound Absorption. Another test was performed to suggest a possible material to be used inside the tyre as a possible low cost solution to mitigate the tyre cavity resonance effect. In impedance tube test, two trim materials were tested to determine which material has better sound absorption properties. One of the materials was of closed cell polyethylene foam with a thickness of 10 mm and another one was polyfelt (material used in automotive door trim) with a thickness of 25 mm. The sound absorption coefficient for the polyfelt is better than those of the polyethylene foam material for the 200-250 Hz frequency range. It is therefore plausible to use the same trim material as that in the car door panel trim to reduce the tyre cavity resonance effect. The benefit can be a low cost solution for the reason mentioned above.

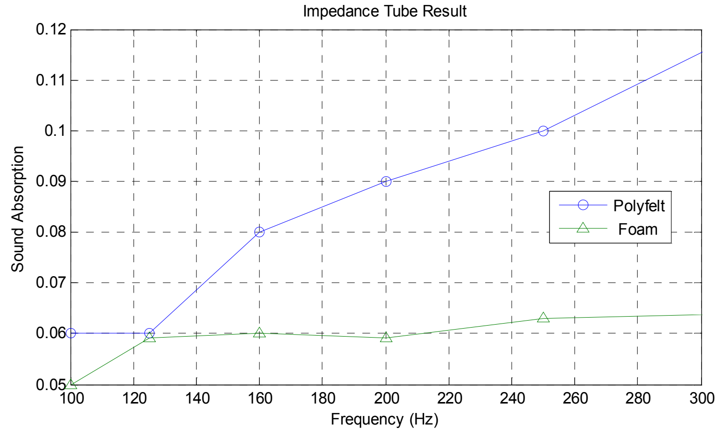

Fig.7 Sound absorption coefficient of polyfelt and polyethylene foam.

Summary

In this study, an analytical formula for calculating the tyre cavity resonance frequencies has been derived and the calculated results have been verified by the finite element method and experimental modal analysis testing. The results correlated well, and the effect of attaching trim layers to the tyre inner surface was found to be effective in suppressing the resonance amplitude at the tyre cavity frequency of 215-250 Hz. The condition of the resonance coupling is that the tyre structure or the rim has the same resonance frequency as the tyre cavity which increases the severity of the tyre cavity resonance. The attachment of a standard trim layer similar to that used in the vehicle door panels was found to be sufficient to reduce the tyre cavity resonance effect. It is thereby suggested that the solution is viable due to its low cost and easy installation. Further work will focus on the sound pressure variation inside the tyre cavity due to the interaction with trim.

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