Contributions to a better understanding of tire cavity noise

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Introduction

The air cavity as a source of tire/road noise was discovered in the beginning of the 1990s, when the vehicle industry gave the suspension a more sportive condition and when it became popular to use tires with lower aspect ratios. As efficient solutions to lower the transmission of that sound into the vehicle interior, mainly secondary measures like absorbing materials in the tire were proposed by tire manufacturers. Unfortunately the vehicle industry rejected the use of those solutions for cost reasons and asked the tire manufactures to integrate primary measures directly in the tire construction which requires a good understanding of the relevant mechanisms. Furthermore direct measures on cavity vibration within the tire construction may influence other tire performance criteria.

Cavity influence on interior noise

When a tire is rolling on a road, the tire surface is excited to vibration but also the air inside the tire is vibrating. The amplitude of the vibration is high, if the air column vibrates in one mode and is transmitted via the rim into the suspension of the vehicle as structure-borne noise. The natural frequencies of push rod, tie-rod etc. can further amplify the vibration, and there are several transfer paths through the vehicle body into the cabin.

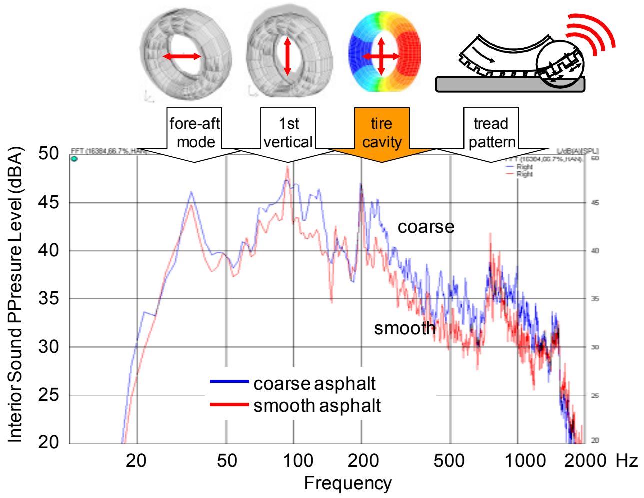

Figure 1: Interior noise sources

If the noise spectrum inside a vehicle cabin is measured, the spectrum of the interior sound pressure shows clearly defined frequency ranges which can be assigned to the tire vibration modes, the tire cavity mode and the excitation of the road (Figure 1). The cavity mode has higher amplitudes if the road surface is rougher and can be very disturbing if the cavity vibration excites the air inside the cabin with the first cavity mode.

Stationary tire

The first cavity mode occurs for an unloaded non-rolling tire if the average tire circumference equals one wavelength λ (2 π R = λ). The frequency f of this cavity mode for an unloaded non-rolling tire is calculated from:

$$f = \frac{c}{\lambda} \quad \text{[Hz]} \qquad (1)$$

With a speed of the sound c of 340 m/s and an average effective circumference of 1.5m (arithmetic mean of rim and tire) the frequency of the first cavity mode is 227 Hz. Depending on the tire size and on the higher sound speed of a warm tire this frequency can vary between 180 Hz and 270 Hz. Basically the cavity frequency only depends on the geometry of the rim and of the inflated tire and is independent of the tire construction.

As a function of the rising deflection the cross-section over the footprint decreases which leads to a split into two frequencies: The lower one acts in the fore-aft, the higher in the vertical direction (Figure2).

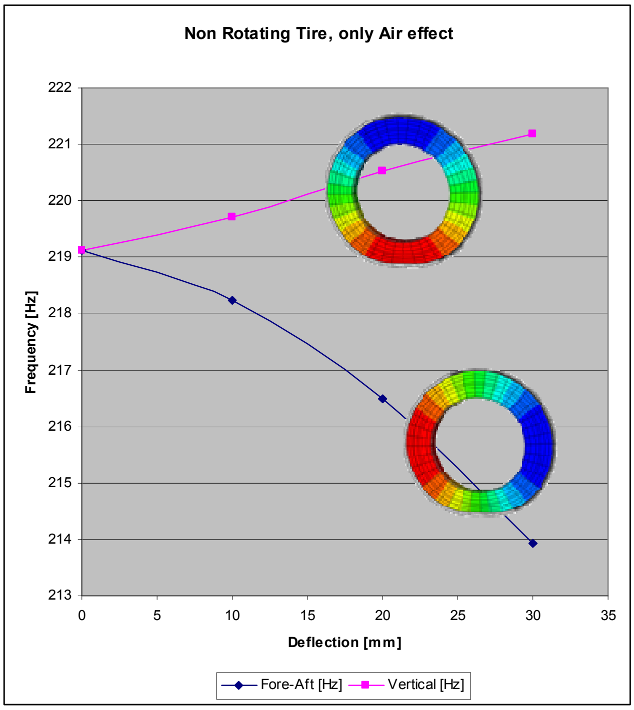

Figure 2: The split into two cavity frequencies as a function of deflection.

A finite element simulation against a rigid spindle was carried out to simulate the coupling of the cavity to the tire (Figure 3). Viscoelastic material laws for the different rubber components and acoustic elements for the air were used in an ABAQUS simulation. For a good correlation between the simulation and the test results the damping properties of the compounds - the only damping terms in the simulation - are fundamental. A precise dynamic measurement is needed to determine the complex modulus as a function of frequency and stress/strain history, esp. for the calculation of rotating tires. The procedure used is described in [1].

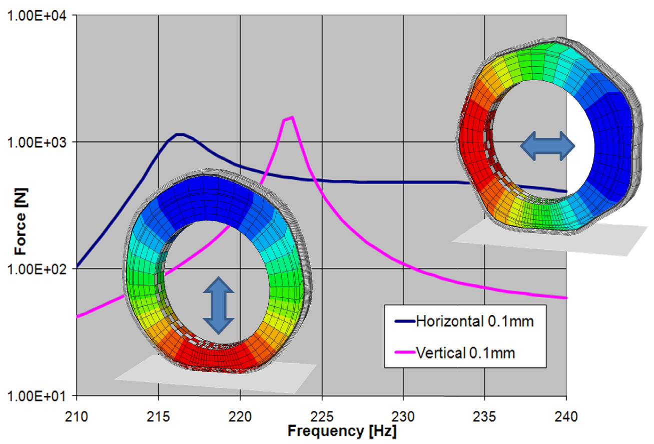

Figure 3: Stationary, coupled FEM simulation of the horizontal and vertical 1st cavity mode

The shape of the horizontal cavity-mode is equal to the fore-aft mode, which appears at approx. 30 Hz. The shape of the vertical mode looks like the 1st vertical tire mode, which is present at approx. 90 Hz. This shows the strong coupling of the tire to the air. The dominant sub-system is the cavity: The shift of the cavity frequency by coupling with the tire is below 1 Hz.

The speed dependence of cavity mode in rolling tires

The stationary situation as described can be evaluated very well by shaker testing, but it is of no real interest under driving conditions. It is known for a rotating tire that the air inside the cavity rotates at the same speed as the tire. Therefore one wave is traveling with, the other against the rotation. The cavity frequency splits up into two frequencies, as shown in Eq. 2..

$$f_{Cavity} = i\, {}^{c}\!/\!_{\lambda} \pm (s * i + \Delta f), \qquad \text{[Hz]} \qquad (2)$$

$$i = 1, n$$

$$\Delta f \approx 0.5 \qquad \text{[Hz]} \qquad (3)$$

The frequency shift is proportional to the number of revolutions per second, *s*. The shift factor , which can be identified by simulation as well as by measurement, is caused by the coupling of the cavity mode to the tire. This again shows the minor influence of the tire to the frequency in the coupled system.

It is expected that both, the stationary horizontal and vertical mode, split up in two frequencies due to the Doppler-effect, but Eq. 2 shows only two frequencies at one speed (beside the harmonics). To analyze the behavior due to rotation, an FEM simulation of a rotating tire was performed. The modes were excited by a vertical vibration of the whole footprint, like on a flat track. The horizontal and vertical forces at a rigid spindle are shown in Figure 4. The vertical mode splits up into two as expected. But beside the vertical forces, horizontal forces of the same level occur. This indicates two single waves, traveling with and against the rotation of the tire. Theses modes are independent of the excitation direction: For horizontal excitation the frequency will not change. In the rotating system of the tire, only one mode exists. The split into vertical mode and fore-aft mode of the stationary system disappears.

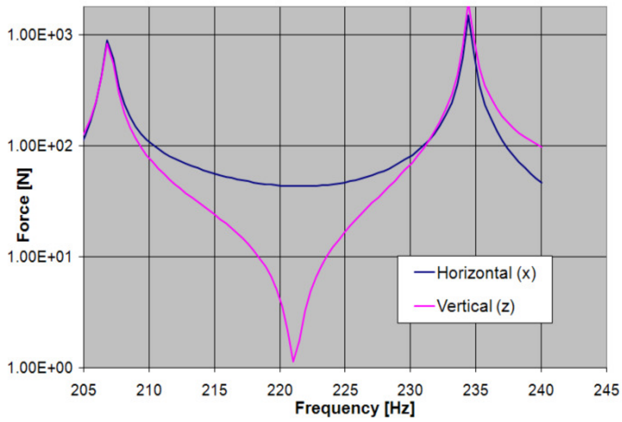

Figure 4: Rotating, coupled FEM simulation of the 1st cavity mode, vertical excitation (0.2mm), 100km/h

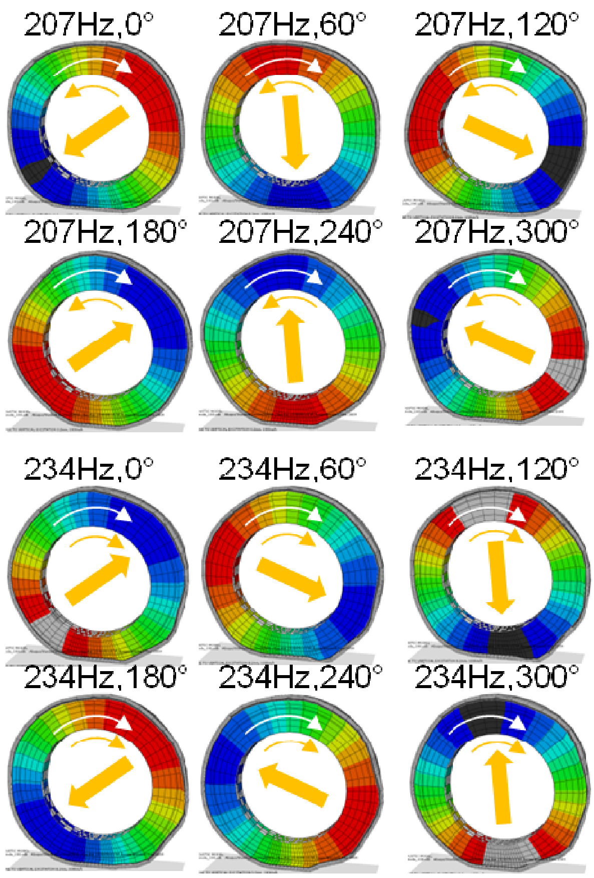

Figure 5: Anticlockwise and clockwise rotation of the cavity. High pressure red, low pressure blue. Tire rotates clockwise, 100km/h

The rotating pressure distribution acts on the rims surface like a rotating force vector, shown in Figure 5 as a straight arrow. At 207 Hz, the wave travels anticlockwise and against the rotation of the tire. At 234 Hz, the wave travels clockwise with the tire's rotation and will therefore be quicker at the same speed relative to the tire.

The rotating force is of high importance to the design of the suspension system: Independent of the direction of the excitation of the tire the suspension system is always excited by a rotating vector in the x-z plane.

Beside the 1st cavity mode also the harmonics are present (Eq. 2). Simulation and measurement show the same level of cavity pressure for the higher modes as for the 1st mode. At the spindle, only the 1st cavity mode is relevant (Figure 6). The integral of the pressure acting at the rim is very small due to the symmetric distribution at higher modes.

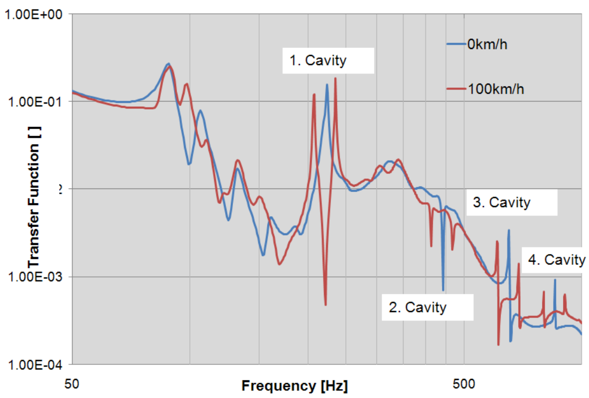

Figure 6: FEM simulation of the transfer function footprint/flexible spindle, vertical, stationary and at 100 km/h

Cavity Noise Measurements

As the cavity vibrations are transmitted as structure-borne noise into the vehicle a common way to measure the cavity frequencies and amplitudes is to measure the forces at a measuring hub in horizontal and vertical direction. The signals were analyzed with FFT in the frequency range of 0-3200 Hz with 6400 lines by spectrum averaging with 66.6 % overlap and 10 exponential averages.

To distinguish the eigenfrequencies and the speed-dependent components in the signal a rundown of the tire on a drum test stand from 100 km/h to 20 km/h was performed and a spectrum was measured each 2 km/h. All results were combined in a contour plot. The interpretation of the measurement result is not easy as the amplitudes of the cavity modes are overlaid by the amplitudes of the order excitation from the tread in the force signals. So it is difficult to estimate the influence of the cavity modes only.

Therefore a measurement method to measure the sound pressure from the cavity modes only was developed. The force measurement was supplemented by a microphone measurement inside the tire. The usage of a normal measuring microphone is critical for this application as due to the inflation pressure the sound pressure inside a tire is higher than 140 dB which is the upper limit of the dynamic range with less than 3 % distortion for many ½′′ microphones. The bigger problems, however, are the vibration sensitivity of condenser microphones and the fact that these microphones are not constructed to work in a rotating system with high gravity forces.

Figure 7: Rim with hydrophone for measuring sound pressure inside the tire

As an alternative for this application a mini hydrophone was used, but we had to learn the hard way that normal hydrophones, too, are not constructed for such an application. So an acoustically open load-carrying system was constructed around the hydrophone (Figure 7). The tire was fixed to a loading device with measuring hub, which controls a constant loading and constant inflation pressure. The hydrophone signal was transmitted out of the tire via a slip-ring assembly (Figure 8).

Figure 8: Signal transfer for sound pressure measurement inside the tire

With such a measuring set-up it is possible to measure the forces at the hub and the sound pressure inside a tire up to high frequencies.

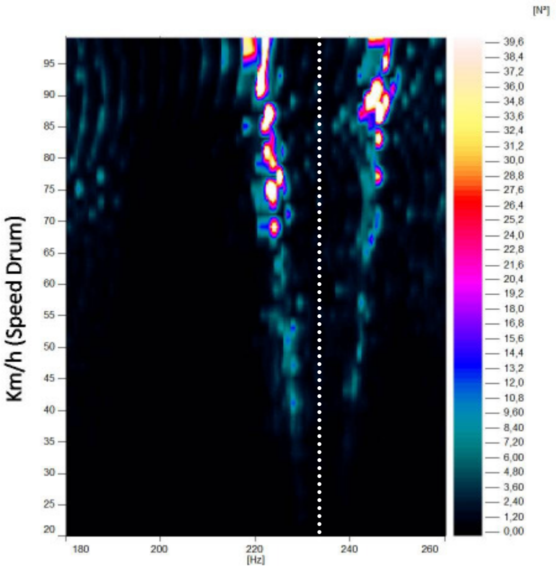

Figure 9: Measurement of the horizontal forces at the hub during a run-down from 100 km/h to 20 km/h

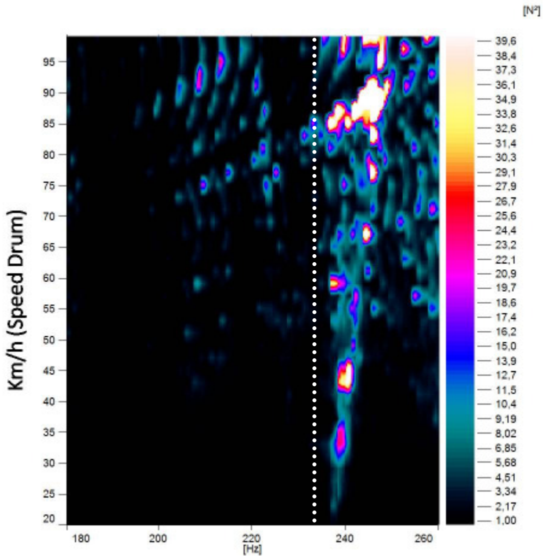

Figure 10: Measurement of the vertical forces at the hub during a run-down from 100 km/h to 20 km/h

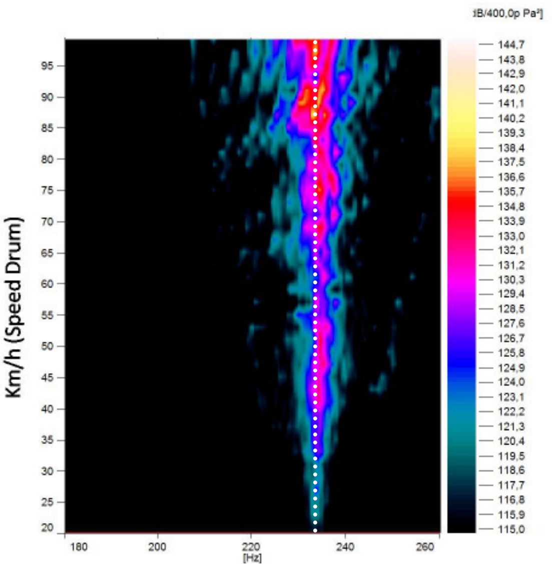

Figure 11: Sound pressure measurement inside a tire during a run-down from 100 km/h to 20 km/h

With these measurements the simulation results could be verified. For the first cavity mode the results are displayed in Figure 9 to 11. The sound pressure measurement inside the tire (Figure 11) results in only one speed-independent frequency as expected, and due to the Doppler Effect the cavity frequency in the force measurement at the hub splits symmetrically into two frequencies. For better comparison a dotted line marks the position of the cavity frequency. In the horizontal forces (Figure 9) the left branch has higher amplitudes and in the vertical forces (Figure 10) the right branch has higher amplitudes. This general behavior has been approved in several measurements with combined excitation both in vertical and horizontal, like on a real road.

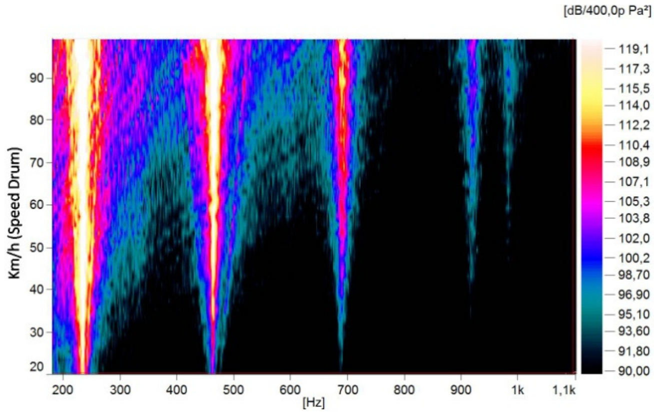

Figure 12: Sound pressure measurement inside a tire during a run-down from 100 km/h to 20 km/h

Besides the first cavity frequency (one full wavelength around the rim) three more harmonics occur in the sound measurement inside the tire (Figure 12) as well as in the simulation (Figure 6). At higher speeds and around 1000 Hz an additional frequency was measured which may be the first cross mode of the cavity vibration.

Conclusions

The paper presents current FEM simulation results based on real tire constructions to understand the problem. Additional sound measurements in the tire were carried out with a hydrophone to validate the simulations and to contribute to a better understanding of the sound generating mechanisms. The new simulation and measurement procedures presented in this paper lead to a better understanding of tire-cavity noise and are the basis for innovative countermeasures – at the tire and at the suspension system.

The dominant sub-system cavity-air vibration is strongly coupled to the tire vibration.

The rotating force generated by the cavity vibration is of high importance to the design of the suspension system: Independent of the direction of the excitation of the tire, the suspension system is always excited by a rotating vector in the x-z plane.

References

[1] Haertel, V., Wrana, C.:Dynamic mechanical analysis of filled elastomers. Kautschuk, Gummi, Kunst., 10 (2008), 647-655