Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

# Tire Surface Vibration and Sound Radiation resulting from the Tire Cavity Mode

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**PACS:** 43.20.MV, 43.20.RZ, 43.20.TB, 43.40.AT, 43.60.GK

## ABSTRACT

It is well-known that acoustical modes exist in tire cavities. Previous research on tire cavity modes has focused on the transmission of structure-borne noise to the vehicle interior due to the force that the tire cavity mode exerts on the wheel hub. In contrast, here the major concern is the identification of the tire surface vibration and the sound radiation from the tire surface that can be attributed to the tire cavity mode. The surface normal vibration of a point-driven tire has been measured over a complete circumference by using a scanning laser Doppler vibrometer. When the space-frequency data is transformed to the wavenumber-frequency domain, a clear feature that can be attributed to the tire cavity mode becomes visible. Although the magnitude of the surface vibration resulting from the tire cavity mode is small, its radiation efficiency is high owing to the high phase speed of the acoustical waves that create the tire cavity mode. It has also been found, that, as expected, tire vibration features associated with the tire cavity mode disappear when the tire is filled with fibrous, sound absorbing material. Finally, measurements of sound radiation from a tire driven by a steady-state-, point-input, and from a tire driven by a uniform impact over the contact patch area are presented, and the features associated with the tire cavity mode are highlighted.

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## INTRODUCTION

The tire acoustical mode, which has long been a factor in cabin interior noise due to the force it exerts on the wheel hub, also affects tire sidewall vibration. This sidewall vibration causes sound radiation from the tire distinct from that resulting from structural wave propagation through the tire carcass. Detection of this acoustic mode could possibly be used to indicate inflation pressure in the tire or the presence of foreign material within the tire cavity.

The measurements and techniques used to detect the effects of the tire acoustical mode on the tire sidewall and on noise radiated from the tire are outlined in this paper. Wavenumber transforms were used to identify the tire acoustical mode from vibration measured along the tire sidwall surface. Further measurements were performed using acoustical detection, allowing for possibility of non-contact detection of the tire acoustical mode in rolling tires.

### Previous Research

Sakata et al. [1] identified the effects of the tire acoustical mode on cabin interior noise. In investigating how force on the tire spindle caused interior cabin noise, they found a noticeable spike at the frequency of the tire acoustical mode. Further experimental testing found that the tire acoustical mode disappeared when the interior of the tire was filled with polyurethane foam that supressed acoustical wave propagation in the tire cavity.

Further analysis of the tire acoustical mode was performed by Thompson [2] and Gunda et al. [3], including analytical models accouting for the periodic boundary condition and splitting of frequency peaks due to deformation in the tire.

Molisani [4] modeled the tire and its acoustical mode using a coupled structural-acoustical finite element method. His model showed significant amplification of the tire sidewall vibration that did not exist when the tire was modelled *in vacuo* without the tire acoustical mode.

Kim et al. [5,6] have explored the vibration of the tire carcass and the resultant coupling with the tire acoustical mode. They developed FEM models for the tire that took into account the sidewall thickness, tread compound, and tread variation around the tire. Their analysis yielded sound radiation from each component of the tire structure, and found that the tire carcass vibration can have significant effects on the acoustical mode amplitude.

Bolton et al. [7] developed a wavenumber decomposition method for analysing waves propagating around the tire belt. Their analysis allowed for clear distinctions between different wavetypes and measurement of properties such as propagation speed and cut-on frequency.

### Background

The tire acoustical mode is caused by propagating waves in the fluid medium enclosed by the tire carcass and the rim. The circular shape of the tire requires that all acoustical modes within the tire cavity have an integer number of wavelengths around the tire circumference. The lowest mode of the tire interior volume will have a frequency equal to $f=c/(\pi d)$, where $c$ is the speed of sound in air (343 m/s at room temperature) and $d$ is the mean tire diameter. For most tires, the first acoustical mode occurs between 200-250 Hz, and higher modes will occur at nearly integer multiples of this first mode. The speed of sound is nearly invariant with pressure; therefore, the tire acoustical mode resonance frequency will remain the same for all interior tire pressures (excluding the effect of the small deformation of the tire due to increased pressures).

Previous research into the tire acoustical mode has shown a sharp peak in axle force at the tire acoustical mode frequency. The sharpness of this peak is due to the small damping provided by air in the tire. Therefore, the peak associated with the acoustical mode is easily detectable in the axle force. It is expected that this force will also cause pressure to be applied to the tire sidewall that will lead to radiation of sound to the exterior at the tire acoustical mode frequency.

## TIRE SIDEWALL VIBRATION MEASUREMENTS

Measurements of a tire were performed to examine the effects of the tire acoustical mode on sidewall vibration. A scanning laser vibrometer was used to measure the vibration of a tire excited by a point force along the belt.

### Methodology

The tires tested were Kelly Safari Signature 235/70R15. These tires were previously provided to the Lab for another project and had small defects; one tire had a small gash along the sidewall rubber and another had small areas of exposed tire belt along the tread. However, because each of these tires with different defects yielded similar test results, it is not thought that these defects affect any of the measurements pertaining to the acoustical mode in the airspace of the tire. The air space in this tire would indicate a tire acoustical mode at 200 Hz without taking into account the size of the tire rim. The rim geometry was not measured precisely; however, it was estimated to be approximately 3-5 cm deep, which would cause an increase of 10-15 Hz of the frequency of the tire acoustical mode. Thus the tire acoustical mode was expected to appear between 210 and 215 Hz.

One of the tires was filled with air, as would be a regular car tire. The second tire was filled with sound-absorbing material typically used as insulation for aircraft cabins. The insertion of the insulation material will reduce propagation of the acoustical mode in the tire and should therefore eliminate any characteristics caused by the acoustical mode. The tire filled with insulation material was still inflated to provide stiffness in the tire equal to that of the air-filled tire.

The tests were performed with tire pressures between 60 pounds per square inch (psi) and 30 psi in increments of 5 psi. Eighty (80) points along the tire sidewall were measured using the scanning laser vibrometer. The tire was mounted to an axle on a rigid stand and was excited using a small shaker attached to the center of the tire tread band through a point stinger. Figure 1 shows a schematic of the tire excitation and scanning path around the tire sidewall.

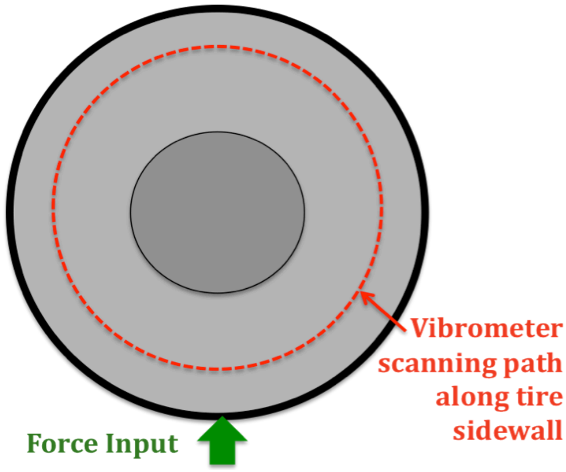


Figure 1: Schematic of tire sidewall vibration measurements.

Each individual measurement point around the tire sidewall produces a frequency spectrum of the vibration normal to the tire surface. The spatial variation of vibration with position on the tire at a single frequency can then be Fourier transformed with respect to position to generate a wavenumber decomposition of tire vibration. The wavenumber is the rate of change of phase with position, and for propagating waves should vary with frequency; the rate of that variation is inversely proportional to wave speed. Thus, a plot of the tire vibration as a function of the wavenumber and frequency can reveal lines that indicate the existence of waves propagating through the tire sidewall and their speed. The tire acoustical mode is a standing wave mode in the tire created by the superposition of two equal strength waves propagating in opposite directions; thus the mode should appear as a single point in the wavenumber-frequency plot.

### Results

A complete wavenumber-frequency plot for an air-filled tire at 55 psi is shown below in Figure 2. The tire vibration is dominated by a slow-moving wave (30 m/s) that cuts on around 100 Hz, with another component cutting on around 250 Hz. This is most probably the tread belt vibration influence on the tire sidewall.

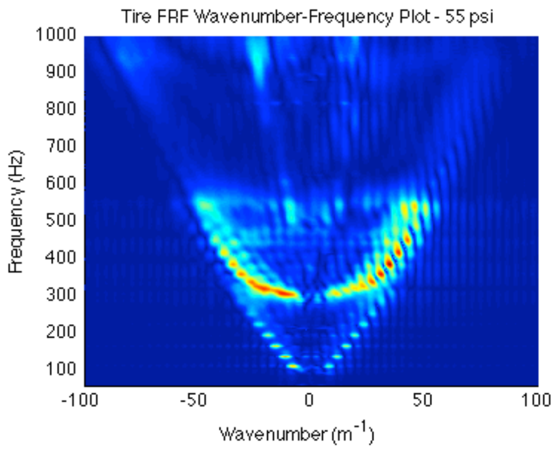


Figure 2: Wavenumber-frequency plot of tire at 55 psi.

Figure 3 and Figure 4 show a detail of the wavenumber-frequency plot close to the expected tire acoustical mode frequency of 212 Hz and wavenumber of $2/d$ (approximately 4 $m^{-1}$ for this tire) for the air-filled and foam-filled tires at 60 psi of inflation pressure, respectively. The presence of a peak there is indicative of the tire acoustical mode.

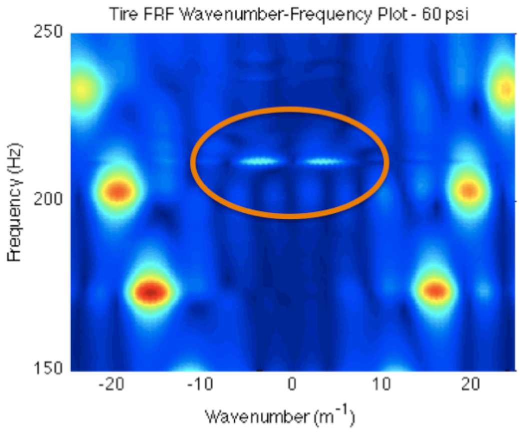


Figure 3: Wavenumber-frequency detail showing tire acoustical mode in air-filled tire.

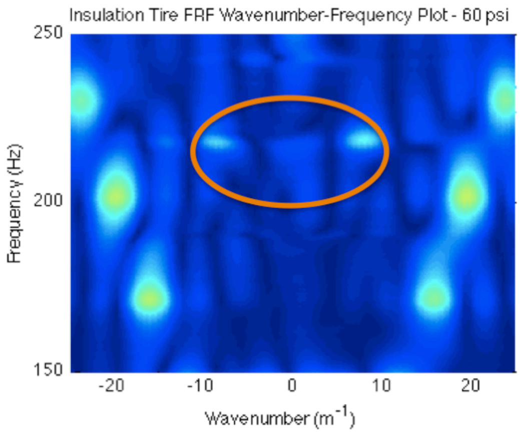


Figure 4: Wavenumber-frequency detail showing lack of tire acoustical mode in insulation-filled tire.

Figure 5 below shows the detailed tire acoustical mode for 30 psi inflation pressure in the tire. While the location of the acoustical mode is the same as in Figure 3, the other features change location with pressure; in particular, a line through the high-amplitude peaks at the edge of the plot reduces in slope with decreasing pressure. This would indicate a reduction in wavespeed of the propagating structure-borne wave along the tire sidewall, which would be consistent with a reduction in the "stiffening" effect of the inflation pressure. Note that these features do not change with the insertion of foam into the tire.

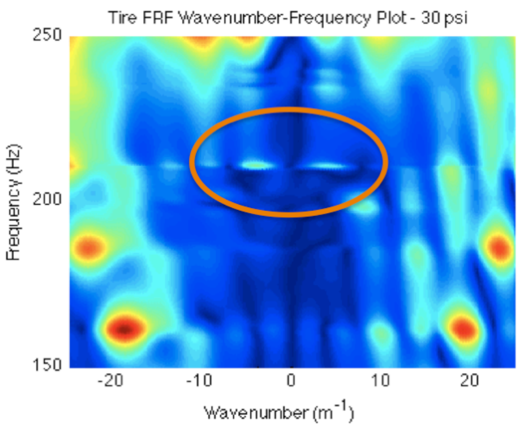


Figure 5: Wavenumber-frequency detail showing tire acoustical mode and surrounding features in air-filled tire at 30 psi.

## ACOUSTICAL MEASUREMENTS

The tire acoustical mode can be seen in tire sidewall vibration; and it has the phase speed of the speed of sound in air; therefore, it can be assumed that the mode would radiate sound effectively into the environment. Acoustical measurements were performed on both the air-filled and insulation-filled tires to gauge whether or not the acoustical mode would produce a detectable tone that could be measured exterior to the tire. In addition to measurements of acoustical radiation similar to the vibration tests, a drop test simulated the effect of excitation over a larger contact patch.

### Steady-State Excitation Methodology

The same two Kelly Safari Signature 235/70R15 tires used in the vibration measurements were used in acoustical measurements. The tire was excited in the same way as the vibration tests. A four-microphone acoustical array was set up adjacent to the tire, with additional measurements of the force input into the tire, the acceleration on the sidewall near the force input, noise from the shaker setup, and acceleration of the axle to which the tire is mounted. Figure 6 shows the experimental setup. Four microphones would not provide enough data for holographic visualization or wavenumber transforms of useful resolution, but do provide some evidence of the nature of the sound radiating from the tire structure. Both the air-filled and insulation-filled tires were tested from 60 to 20 psi in 5 psi increments.

Figure 6: Experimental setup, including microphones around the tire and the shaker mechanism, for experimental measurements.

### Results

Data from the accelerometer located on the axle provides a clear link between previous research on the tire acoustical mode and the present data. The vibration of the axle at 60 and 20 psi is shown below in Figure 7 and Figure 8. The air-filled and insulation-filled tires exhibit significant differences at 145 Hz and 211 Hz, with the air-filled tire displaying a lightly damped spike in axle vibration. It is not known what is causing the difference at 145 Hz, but the 211 Hz spike can clearly be attributed to the tire acoustical mode. At lower pressures, both spikes are reduced in magnitude, which would indicate that the tire acoustical mode is exerting less force on the axle. From these results, it is clear that filling the tire with a foreign material causes the tire acoustical mode to be suppressed.

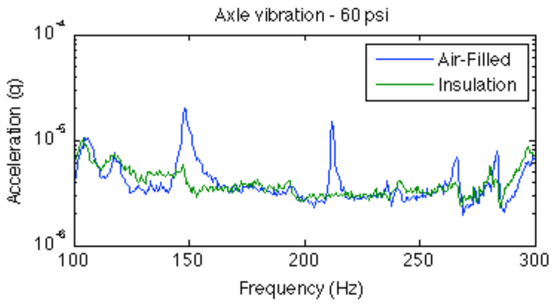


Figure 7: Vibration signature comparison between air- and insulation-filled tires at 60 psi.

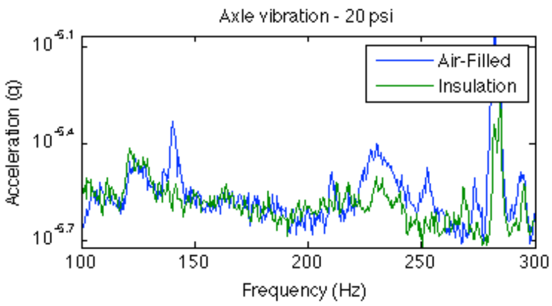


Figure 8: Vibration signature comparison between air- and insulation-filled tires at 20 psi.

A comparison of the acoustical signature of the average radiation recorded by the four microphones is shown below in Figure 9. At 212 Hz, there is a significant difference in the two tires' acoustical radiation signature, with the air-filled tire exhibiting a lightly-damped spike. Otherwise, there is little significant difference in the two tire acoustical signatures. This would indicate that the acoustical mode can be detected with microphones. The 212 Hz peak is much smaller at 40 psi, and at 20 psi the acoustical radiation of the two tires is almost identical. Thus indicating that the radiation of the acoustic mode is affected by inflation pressure.

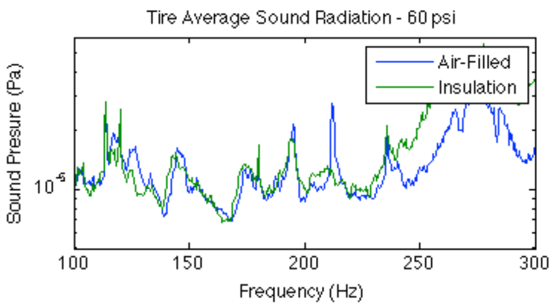


Figure 9: Acoustical signature comparison between air- and insulation-filled tires at 60 psi.

## Drop Test Methodology

During acoustical testing, it was noticed that the two tires exhibited different tonal characteristics when dropped on the floor. Subjectively, those difference were much more significant than those heard during the steady-state, point-force driven acoustical measurements. Drop tests of the tire were recorded to quantify these differences. The tire was dropped from a height of six inches and caught after a single bounce. Two microphones located approximately one foot from the tire were used to record the drop. The time histories of the drops were cropped to an equal length for all tests (regardless of apparent damping of the wave) to provide similar frequency resolution for each test.

## Results

Results from the drop tests are shown below in Figure 10 and Figure 11. The spike at 212 Hz was considerably more prominent during the drop test than in the steady-state, point-force driven acoustical measurements. Further, the spike at 212 Hz is absent when the tire was filled with insulation material. At lower pressures the acoustical signature from the insulation-filled tire begins to look identical to that of the air-filled tire.

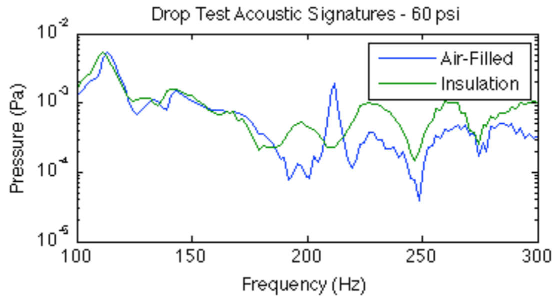


Figure 10: Acoustical radiation from drop tests signature comparison between air- and insulation-filled tires at 60 psi.

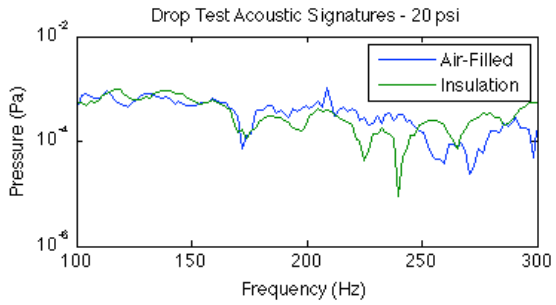


Figure 11: Acoustical radiation from drop tests signature comparison between air- and insulation-filled tires at 20 psi.

The major difference between the two types of tests was in the nature of the force distribution applied to the tire. Since force is applied to the entire contact patch in the drop test, as the tire would experience in normal operation, the results of the drop test were judged to be more representative of operational results. While the vibration excitation used in the steady-state tests was over a very small surface, the drop test impacts the entire contact patch of the tire. The latter excitation will cancel out higher-order vibrational modes propagating in the tire carcass and so will emphasize the lower order acoustical modes.

## CONCLUSIONS

Experimental testing has revealed that the tire acoustical mode can be detected externally. A feature in the wavenumber-frequency plot matches the expected location and characteristics of a standing wave mode at the tire acoustical mode resonance. A similar peak, matching the frequency shown in previous research on the acoustical mode forces on the tire axle, can be found in the acoustical signature of sound radiated from the tire. This distinct peak at the frequency of acoustical mode resonance disappears when the tire is filled with an insulating material that supresses wave propagation.

Further testing will be performed using a wider contact patch for forcing of the tire during steady-state excitation. This should mitigate higher-order modes and further emphasize the acoustical mode in vibration and acoustical measurements. A larger array of microphones will be installed around the tire to allow for visualization of spatial variation in the acoustic mode. An understanding of the spatial variation of the mode could allow for enhanced detection using spatial filtering. Testing will also be performed on a loaded tire to demonstrate the splitting of the acoustical mode seen by Feng and Gu [8] and allow for detection of the acoustical mode in a tire under loaded conditions.

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