OPERATIONAL MODAL ANALYSIS OF A TYRE USING A PU PROBE BASED SCANNING TECHNIQUE

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Tyre vibration can be studied with several experimental and simulation techniques. An important goal for a tyre manufacturer is to “tune” the resonant frequency of the tyre subsystem to reduce the structure-borne noise in the car interior. In this paper, a novel measurement technique is applied to determine the operational tyre deflection shapes under different conditions; i.e. free condition, loaded condition, and rolling condition. The vibrational behaviour of a tyre is studied using a PU probe, which comprises a sound pressure and a particle velocity sensor, and a scanning technique. The relative phase information is obtained using a static reference sensor. The experimental data can be used to validate simulated mode-shapes and resonant frequencies.

1. Introduction

As road noise is of increasing concern in urban environments, the development of more silent tyres is pursued. For these investigations it is necessary to characterize the noise radiated. During experimental investigations, vibrations are measured often as they are the origin of sound radiated. Such studies can be rather involved because rubber can behave non-linearly and there can be asymmetrical mode shapes. Moreover, vibration patterns depend on the loading conditions and the way the tyre is excited. Excitation forces exists in normal, lateral, and in front direction, which causes vibrations in axial or in radial direction, see figure 1.

Several methods exist to measure vibrations. For example, accelerometers can measure in three directions. However, they have to be attached to the surface, which can alter the stiffness and damping of the tyre, and tests with rolling tyres are impossible. Alternatively, vibrations can be measured contact-free with Laser Doppler Vibrometers. Disadvantages of this approach are that often the tyre needs to be painted and complicated set-ups with mirrors are required to measure difficult to reach areas. For the investigations described in this paper, the usage of another non-contact method that involves particle velocity sensors is investigated.

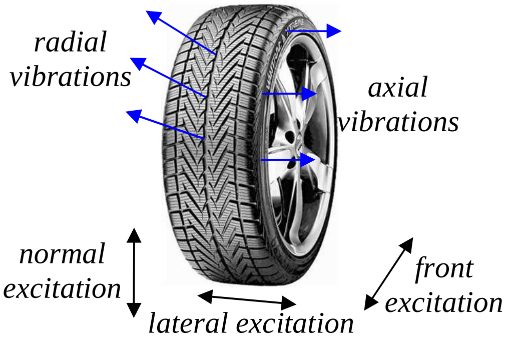


Figure 1. Possible excitation directions and vibration directions.

In the very near field, the normal component of the structural velocity is similar to the normal particle velocity [4]. Therefore, particle velocity sensors can be used to measure structural vibrations in the vicinity of objects. Such vibration tests have a high signal-to-noise ratio because [5]:

- particle velocity levels, due to the vibration of the surface itself, are high due to near field effects.
- particle velocity levels, due to background noise, usually are low because many objects have a high impedance. The incoming and reflected sound waves are nearly equal of strength but opposite in phase, thus they interfere destructively.
- Particle velocity sensors are directional, and can be pointed towards the vibrating surface.

Very near field assumptions apply if two conditions are met; i.e. distance h to the surface should be much smaller its typical size L, and wavelength λ should be much larger than the size of the vibrating surface L; $2\pi \cdot h << L << \lambda$ [4-5]. In this paper, this particle velocity sensor based method is used for three vibration tests:

- a test in unloaded, free conditions,
- a test in loaded conditions where a non-rotating tyre is pressed against a flat surface,
- a test in loaded conditions on a roller-bench.

In the next chapters, these tests are described, and the results are presented and analyzed. During the first two tests, a shaker is used to excite the tyre in normal, lateral, or in front direction. The excitation during the latter test on the roller bench closely resembles the real conditions on the road.

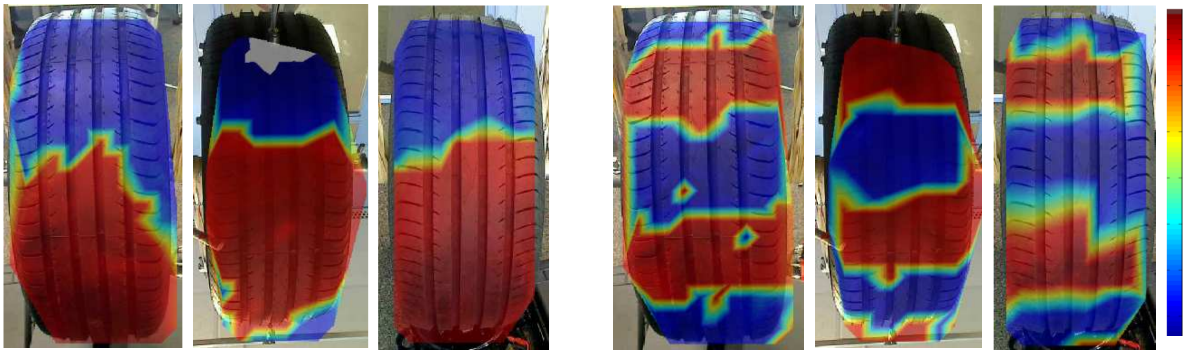
Usually, vibration measurements require many measurement points. Here, a method called Scan&Paint is used to map sound fields quickly and with high resolution [6-7]. It involves a probe that is swept across a surface while a video of the measurement set-up is captured. The probe position is obtained from the video with dedicated software. The tracking procedure is automated, which speeds up the post-process procedure.

2. Tyre measurements under free conditions

In the first test, the operational deflection shape is measured of a tyre in unloaded conditions. The tyre is suspended in elastics, and a stinger is glued to the surface and attached to a shaker that excites the tyre in normal or in lateral direction. An accelerometer is used on a fixed position as phase reference during this measurement. The tyre vibration is measured with a probe containing a particle velocity sensor that is swept across the surface of the tyre. The position of the probe is determined by tracking a colour marker on the probe with a video camera, which is positioned at a distance from the set-up. The path of the probe during the measurement is shown in figure 2 left.

There are many modes, and only a few of them are shown. Figure 2 and 3 show examples of the measured operational deflection shapes (ODS) for several frequencies. The complexity of the modes increases with frequency. The numbers of the colour scales have been removed for confidentiality reasons. Red areas are surfaces with a high velocity level and a positive phase. Green areas indicate surfaces with low levels. Blue areas indicate a high levels, but with a negative phase.

Figure 2. Side view. Left: Scanned path of the probe. Middle: ODS at 53 Hz. Right: ODS at 199 Hz.



top rear view *bottom front view* *top front view* *top rear view* *bottom front view* *top front view*

Figure 3. Operational deflection shapes for three views for 88 Hz (left) and three view for 281 Hz (right).

3. Tyre measurements under loaded conditions

In the second test, the axle of tyre is loaded. Again a stinger was used to excite the tyre in normal direction. For lateral and front excitation the arrangement shown in figure 4 is used, which enables a similar excitation as in reality. The shaker is connected to the tyre's supporting plate, which is suspended freely on bearing balls. Vibration measurements were performed for all excitation directions with the same procedure as described in the previous chapter.

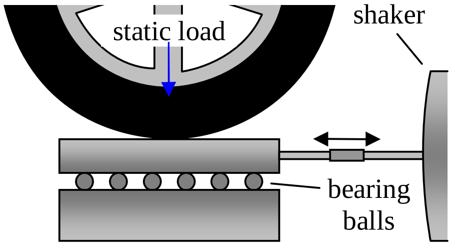


Figure 4. Measurement arrangement to excite in lateral or front direction.

Only during some tests an additional vibration sensor was used as a phase reference, which allows calculation of the operational deflection shapes. For the other measurements it was only possible to calculate the velocity levels (only an absolute level, no sign). In addition, the load on the tyre could only be controlled accurately on one of the two set-ups used.

Figure 5 shows examples of vibration patterns captured with a 4000 N load and front excitation. The absolute particle velocity levels are shown (no directional information). Red areas are surfaces with high velocity levels, blue areas vibrate little. Figure 6 shows operational deflection shapes with normal excitation and a load of approximately 3000 N. In this figure, blue areas do have a high velocity, but a negative phase. Red areas are surfaces with a high velocity level and positive phase, green areas vibrate little. In both figures intricate mode shapes can be identified. Compared to the free suspension case, the shape and frequency of the modes is altered due to the load applied.

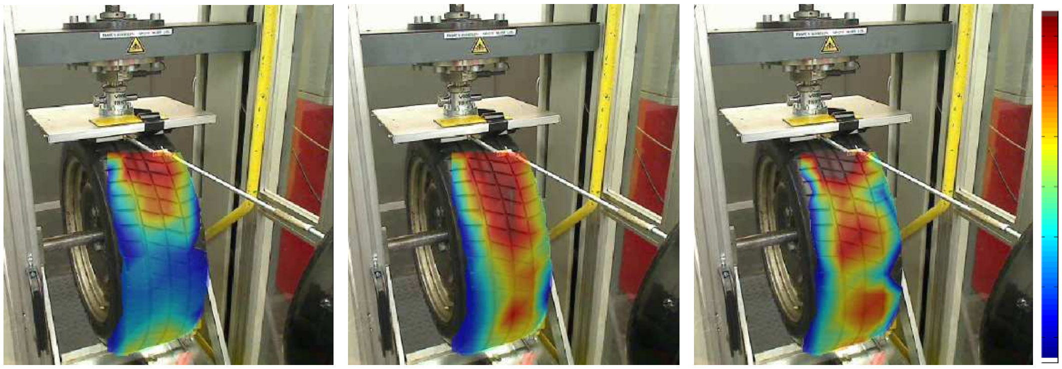
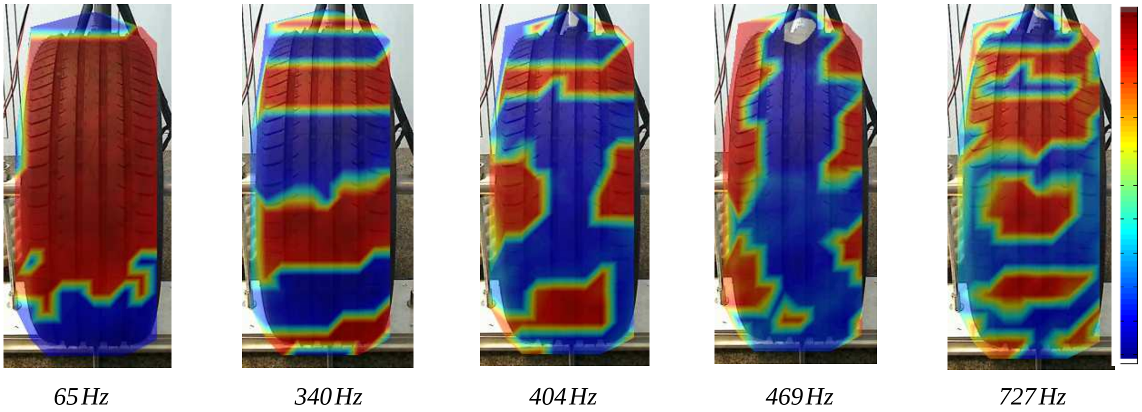


Figure 5. Velocity levels for a 4000 N load and front excitation. Left: 59 Hz. Middle: 94 Hz. Right: 211 Hz.



65 Hz *340 Hz* *404 Hz* *469 Hz* *727 Hz*

Figure 6. ODS examples for a load of approximately 3000 N and normal excitation.

4. Tyre measurements under rolling conditions

In the third test, the tyre was installed on a roller bench where the loading and excitation conditions are similar to the real conditions on a car. As mentioned before, particle velocity probes are affected little by background noise if they are placed in the vicinity of the test object. Consequently, no anechoic room is required to perform the test. Compared to laser based tests, not only the vibration is measured, but also the sound radiated. In [1] a procedure was described to calculate the sound pressure for different angles using different transfer paths. Such an approach might be supplementary to, or even partly replace past-by-noise tests. The advantage of roller bench tests are that conditions can be controlled well (temperature control, no rain, and there is no influence of a test vehicle).

Airflows near a rolling tyre can affect the particle velocity sensor. In 2009, similar vibration tests were performed [1]. However, at that time the development of wind caps was still in an early phase. Tests could not be performed close to the tyre because the airflow was too high. Meanwhile, better wind caps have become available. Here, a commercially available wind screen was used consisting of an open cell foam covered by cloth and loose fibres. No sensor overloads were experienced with this wind cap, which allows measurements near the tyre. A distance of ~50 mm was chosen between the centre of the particle velocity probe and the tyre to keep a safe distance from the rotating tyre because the wind cap already has a radius of 30 mm. As the distance decreases, a higher spatial resolution is achieved and the influence of background noise reduces. Measurements with two tyre types were performed at 45 km/h and 60 km/h. The tyre load was 4000 N. An extension pole for the sensor was used for the safety of the test engineer, see figure 7.

Figure 8 and 9 show examples of vibration patterns measured. Red areas show high velocity levels, blue areas show low levels. At most frequencies the sound radiated around the tyre-pavement interface exceeds the velocity levels of the side wall. However, for some modes the level of side wall vibrations of the tyre are substantial, see e.g. figure 8 left and middle. Especially such frequencies are of interest when optimizing the dynamic stiffness of the tyre.

Figure 7. Tyre on the roller bench. The surface is scanned using an extension pole.

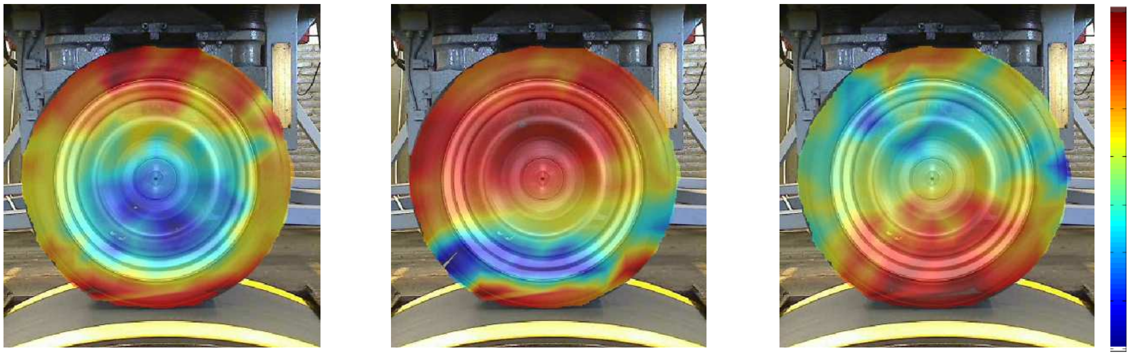


Figure 8. Measured vibration pattern for tyre 1 at 45 km/h. Left: 80 Hz. Middle: 375 Hz. Right: 425 Hz.

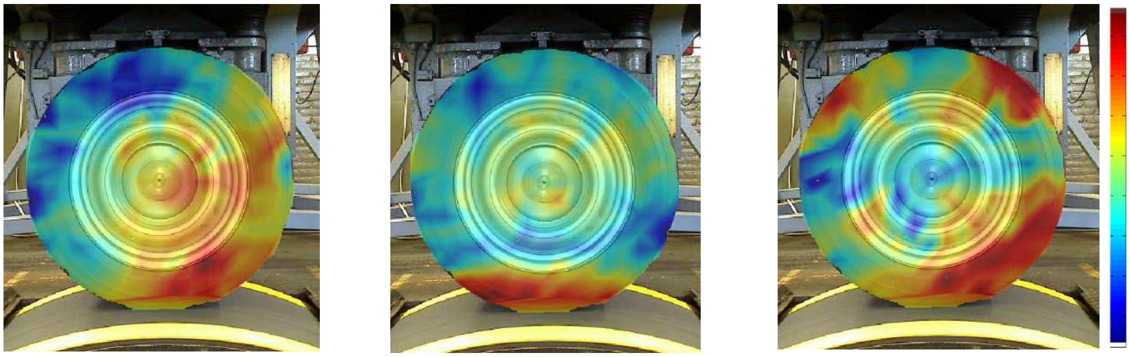


Figure 9. Measured vibration pattern for tyre 2 at 60 km/h. Left: 475 Hz. Middle: 530 Hz. Right: 750 Hz.

The preliminary tests demonstrate the feasibility of measuring tyre vibrations on a roller bench without overloading the particle velocity sensor. However, there are some recommendations for future measurements. The maximum speed during these tests was 60 km/h, as this is the limit of the substrate mounted on the rollers. Different substrates might be used to evaluate higher speeds. Furthermore, no cleat was used (i.e. a strip mounted on the roll to impact the tyre). With such a cleat, the tyre would have been excited even more, and the modes might have been visible more clearly. In addition, no additional sensor was used as phase reference. With this sensor not only the velocity levels can be computed, but also the operational deflection shapes.

5. Conclusions

A methodology to measure vibrations based on particle velocity sensors has been investigated. Advantages of this method are that vibrations can be measured easily without touching the tyre. Three conditions have been tested, i.e. a tyre in unloaded conditions, a tyre in loaded conditions, and a tyre on a roller bench. Whereas test results of the first two conditions can provide useful information about the dynamic response of the tyre and can be used to validate simulations, the roller bench test is a better representation of the actual conditions. Compared to other investigations, tests could be performed close to the tyre because the latest windscreen model has been used, which can cope with higher airflow speeds. For small distances to the vibrating object, the influence of background noise is low and a high spatial resolution can be achieved. No sensor overloads due to airflow were experienced, even though the tyre-sensor distance was only 5 cm.

Intricate mode shapes could be identified in all test conditions. For some tests the velocity levels were calculated. For others, also the operational defection shapes (velocity level times the sign of the phase) could be calculated when an additional sensor was used as a phase reference.

In future investigations, more tyre types might be evaluated and results of different loading conditions might be compared. On the roller bench, the maximum speed was only 60 km/h because this was the maximum of the equipment installed at that time. Higher speeds might be tested in the future. Furthermore, a cleat might be used to excite the tyre stronger, to increase vibration levels.

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