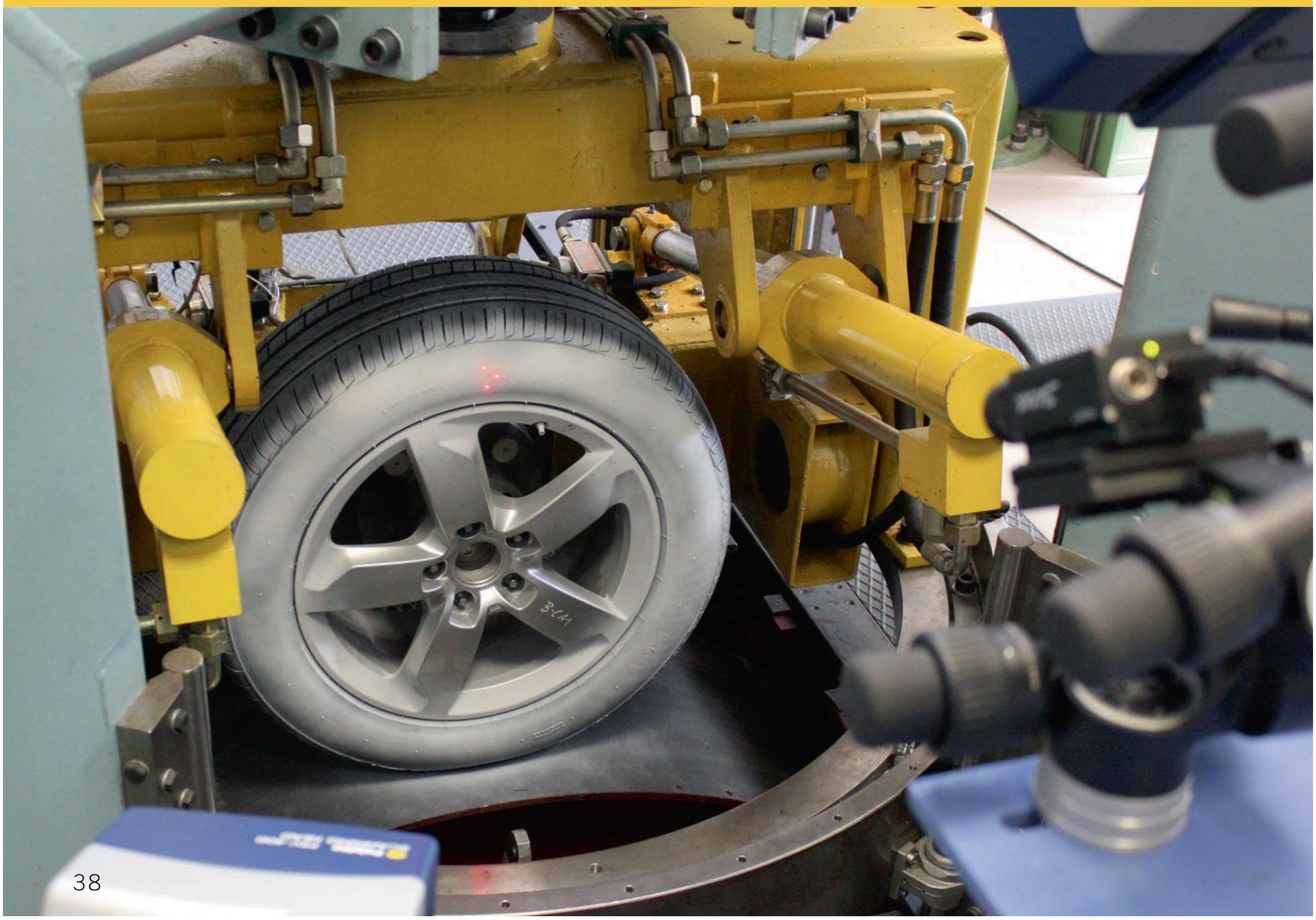
MONITORING 3-D VIBRATIONS OF CAR TYRES

The tyre is the most important connection between driver, vehicle and road. For reasons of comfort optimisation and tyre pressure monitoring, it is important to know the exact vibration behaviour of tyre faces. Fraunhofer IWU and Dresden University of Technology have conducted measurements with a 3-D laser scanner and other test stands to determine the excitations from the road/tyre contact. Contrary to conventional test methods the advantages of the vibrometer like non-contact measurement and a large number of measurement points is consequently utilised.



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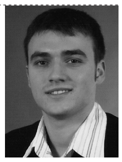

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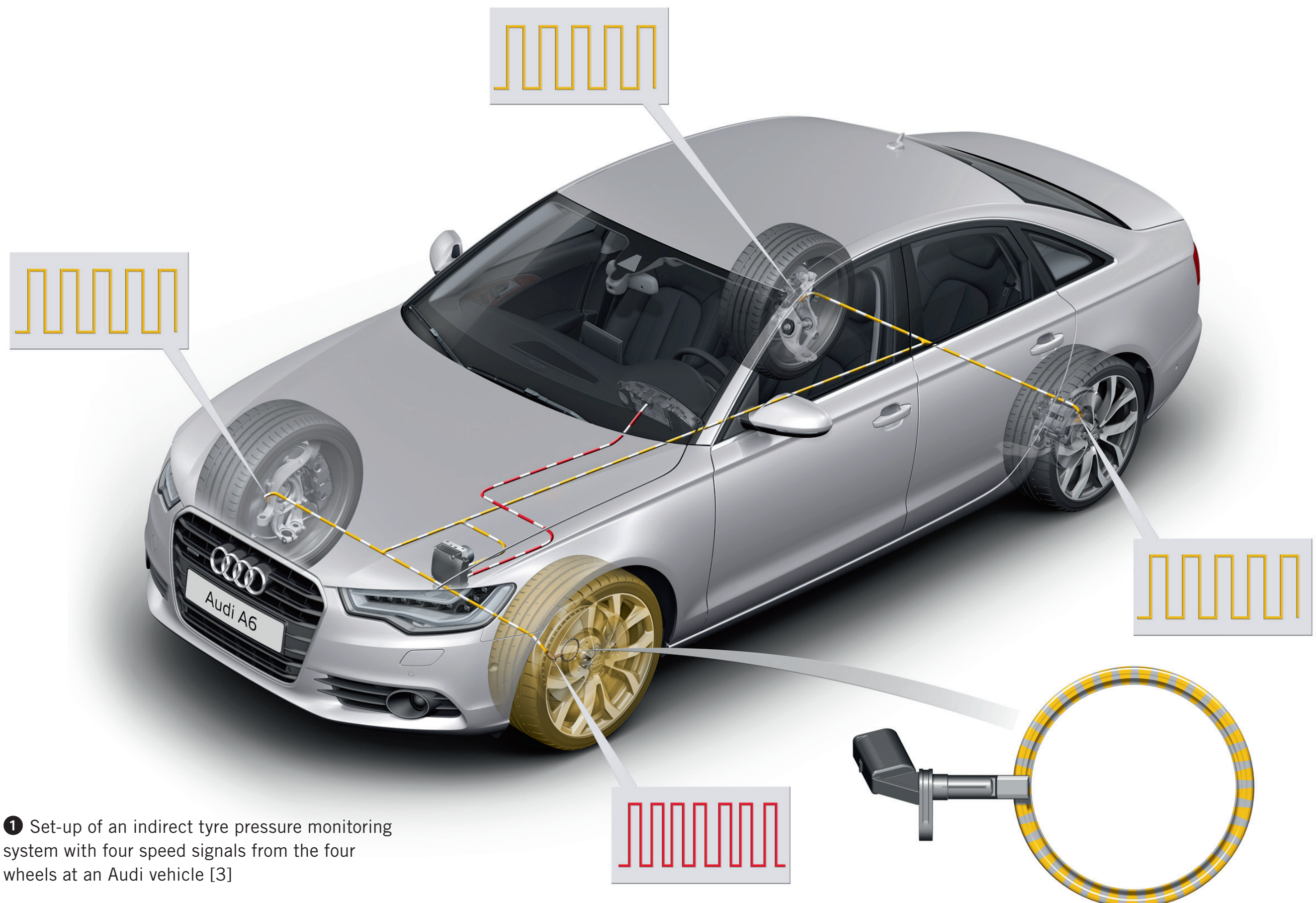
TYRES AS SAFETY ITEM

Vibrations of tyre passenger cars are highly important in terms of overall vehicle characteristics such as safety, comfort and efficiency. A deep understanding of the physical connections creates the basis for integrating reliable, cost- and time-efficient methods of analysing tyre vibration behaviour into the vehicle development process.

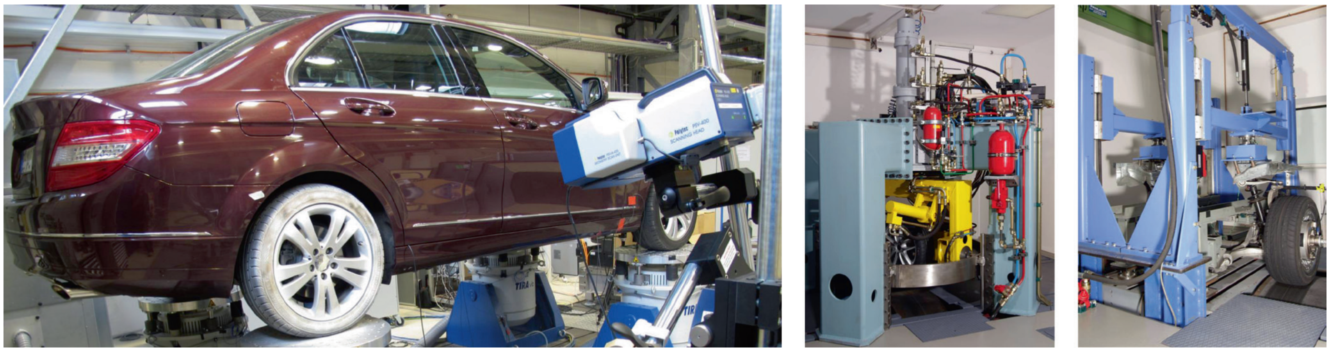
At the Institut für Automobiltechnik Dresden (IAD, Dresden Institute for Automobile Technology) at the Dresden University of Technology, as well as the Fraunhofer Institute for Machine Tools and Forming Technology (IWU), Group for Vehicle Technology and Acoustics, there are a variety of options using both experimentation and simulation for the analysis of relevant tyre vibration patterns as a response to particular road surface excitation patterns. This article focuses in particular on the comparison of tyre face vibrations using a contactless 3-D laser scanner (vibrometer) for measurements.

SIGNIFICANCE OF TYRE VIBRATIONS

According to [1], comfort while travelling in a vehicle is described as "the total of all mechanical and acoustic vibrations



❶ Set-up of an indirect tyre pressure monitoring system with four speed signals from the four wheels at an Audi vehicle [3]



❷ Overview of the tyre testing environment at the Dresden research centre – vibration test stand at the Fraunhofer IWU (left), external drum test stand at the IAD (centre) and wheel suspension test stand at the IAD (right)

affecting the passenger". A decrease in comfort can lead to effects such as increased mental and physical pressures on the driver, which in turn increases the risk of accidents. This means that the comfort of a vehicle is of great importance at a whole-vehicle level, in terms of both safety and quality. The transmission behaviour of the tyres affects the way vibrations from the roadway and wheels are transferred via the chassis to the interior of the vehicle. Research projects such as [1 and 2] are concerned with the objectification of the tyre vibration behaviour affecting comfort, and the correlation to subjective analyses.

Tyre vibration behaviour also has a major impact on indirect tyre pressure monitoring. This system warns the driver if the inner tyre pressure is becoming too low and is included as a part of driver assistance systems. Indirect systems use an analysis of the wheel rotation speed signal, ❶, to identify any loss of tyre pressure. As well as a change in the dynamic wheel radius, the rotation speed signal will also show a pressure-related frequency shift in characteristic tyre vibration shapes. The ESP control unit carries out the analysis of the sensor signals. During driving, the system compares the current system variables with the specified figures.

This shows that tyre vibration behaviour has an important physical effect on general vehicle characteristics such as comfort and safety and efficiency related driver assistance systems. The following paragraphs describe the tools for an experimental investigation into tyre vibration behaviour at the Fraunhofer IWU and the IAD.

OPTIONS FOR TYRE TESTING

Here, three test stands, ❷, shall be presented more in detail which can be used for tyre pressure monitoring. The vibration test stand at the Fraunhofer IWU, ② (left), can be used to analyse the tyres while standing and loaded. During testing, the vehicle is positioned so that each of the four vibrators supports one wheel. The test stand can also be used to replicate chassis noises on the whole vehicle and for dynamic strength tests.

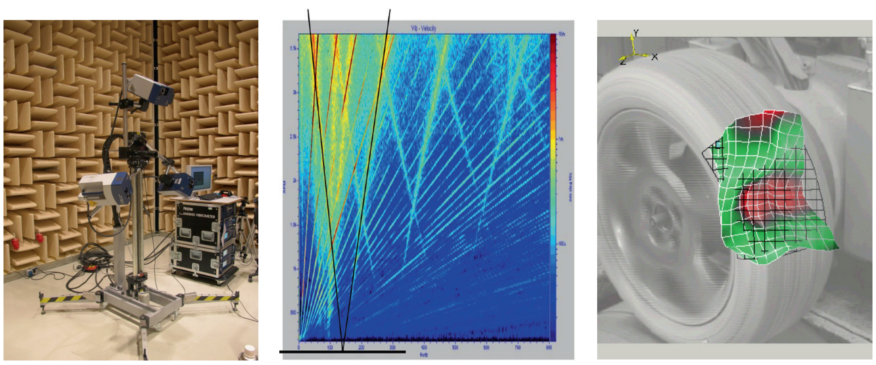
A second common method for analysing the vibration behaviour of a rotating, loaded tyre is driving over a bump bar on an external drum test stand. This tyre test stand at the IAD, ② (centre), allows this method to be used to analyse tyre characteristics in isolation from the influence of the chassis. It is also possible to carry out bump bar measurements on the wheel suspension test stand at the IAD, ② (right), to investigate tyres under the influence of wheel suspension.

TEST STAND INVESTIGATIONS

The reasoning behind using a 3-D laser vibrometer, ❸ (left), is that it enables contactless measuring and the ability to use a large number of measuring points. Likewise, a classic modal analysis on rotating tyres with affixed sensors and hammer excitation is not viable. Now, using laser measuring technology allows for detecting specific areas of the tyre face with a high degree of resolution, ③ (right).

However, it must be ensured that the excitation is kept constant across all measuring points for the entire measurement period. Due to the calculation of averages and the high resolution, respectively a large number of measuring points, it can take several hours for a complete scan of each operational state, depending on the respective number of measuring points.

The vibration behaviour of a loaded, standing tyre has already been successfully analysed at the Fraunhofer IWU site in Dresden [4]. During the first test



❸ Test stand investigations – measurements with a 3-D laser vibrometer with three scanning heads (left), fixed and rotating vibration patterns in a (Campbell) frequency diagram (centre), and detecting specific areas of the tyre face (right) measurements on the external drum test stand at the IAD, it became clear that the test and measurement system configurations, and the manner in which the tests were carried out, all required improvement to ensure that the dynamic vibration behaviour of a rotating, loaded tyre could be measured with a (from the company Polytec) 3-D laser vibrometer.

To keep the amount of time required on the tyre test stand low, the vibrometer was installed on a miniature tyre test stand, which contained a 1:10 scale model of the IAD tyre test stand [5]. Alongside the scanning head positioning, this also allowed for a comparison of the video images with the laser beams and for a clear decision to be made regarding the position and location of all scanning heads in the room. An additional laser for distance measurement was brought in to create a phase reference in the reference system. The positioning of the scanning heads within the 3-D system plays a particularly important role when measuring rotating objects as the maximum peripheral speed cannot exceed the maximum allowable velocity components in the direction of the beam. Alternatively, the scan angle must be reduced, for example by increasing the working distance between the laser and the object being measured.

A further challenge when taking measurements on a rotating surface are speckle noises, which show as reply signals when increasing the rotation frequency. The “Speckle Training” option is implemented within the Polytec software to minimise the associated signal noises.

When presenting the results regarding vibrations on rotating surfaces, it should be noted that there are both fixed and rotating vibration patterns. ③ centre, marked in black, shows the division of a vibration pattern with an increasing rotation speed. The lines intersect at zero rotations where their eigenfrequency is at a standstill. With increasing rotation speed, there are almost linear increases in deviation from the eigenfrequency between the two modes. This essential behaviour can also be observed in rotating tyres, but in combination with other effects that occur due to the tyre construction and materials.

Due to the flattening of the loaded tyre and the associated disruption of the symmetry in the tread area, the two eigenmodes of the unloaded tyre already at a standstill are split into two separate eigenmodes with individual eigenfrequencies. In general, the majority of eigenmodes appear with increasing rolling speed at low natural frequencies. This deviation becomes greater the higher the order of the mode (number of vibration nodes) is. This is why only small deviations appear with eigenfrequencies of the eigenmodes are of a lower order, such as the fixed belt vertical mode. This is why the frequency order of the eigenmodes is no larger than a still wheel at high speeds. On a rotating wheel, the eigenmode pairs that are split by flattening and rotation have complex vibration patterns which rotate in opposite directions [6].

VALIDATING THE MEASUREMENT RESULTS

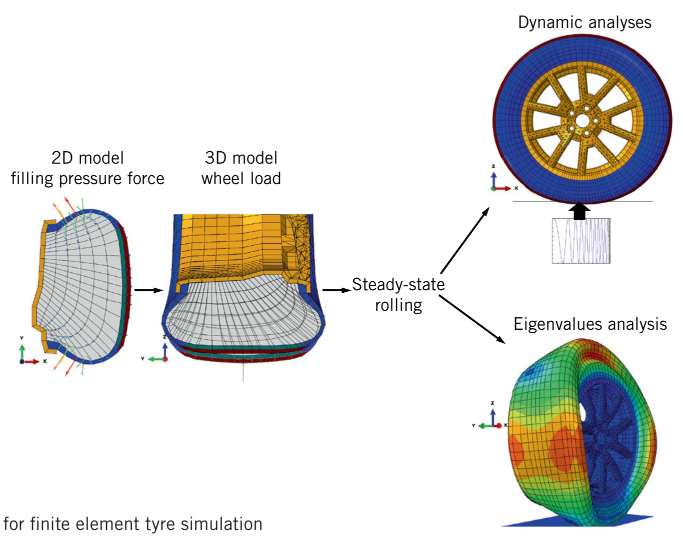
Following completion of the preparatory investigations on the miniature tyre test stand, measurements were taken on the external drum test stand at the IAD with a 235/60 R18 tyre. These were carried out with a constant wheel load and air pressure at speeds of 20 and 30 km/h (12.4 and 18.6 mph). Measurements were taken both while rolling along a flat steel drum, as well as with excitation caused by bump bar mounted on the drum.

In order to detect the vibration movements on the tyre face, the 3-D laser vibrometer was placed side-on to the rotating wheel and programmed with a network of measuring points. For each scan point, an average was calculated from at least 40 individual measurements over a single measurement period of 800 ms.

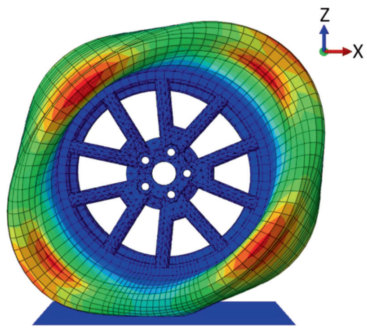
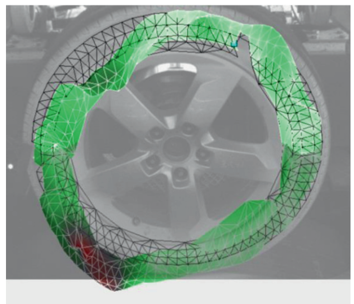
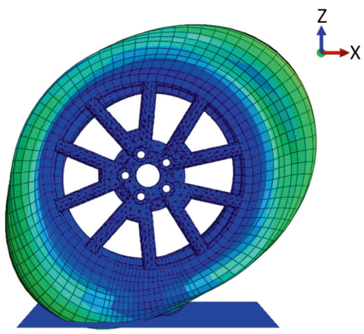
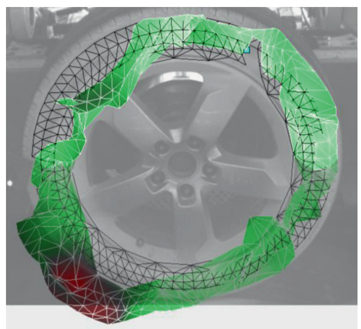
To balance the results gained from the IAD external drum test stand, the vibration patterns are compared with the vibration patterns of the FEM tyre model introduced by Bahnert in [7] in order to ensure that the vibration behaviour of a rotating wheel in the frequency range of up to approximately 250 Hz can be depicted with sufficient accuracy. Depending on the task required, the modular model construction makes it possible to supplement the tyre model with a flexible rim structure and a mesh for the air column. The tyre cross-section is split into the side wall, tread and belt, as the rubber components have different material characteristics depending on their function. Investigations carried out by Kindt [6] have shown that up to 500 Hz, the tyre rotations are not noticeably affected by the profile design. This is why the tread is depicted as slick in the model.

The simulation process, ❹, in Abaqus begins with the application of equivalent forces for the filling pressure on the two dimensional model. After transferring the results to a three dimensional model, the wheel load is added by adjusting a fixed, level plate relative to the tyre and the boundary conditions for steady-state rolling. Finally, the transfer functions for dynamic analyses and the eigenvalues of the tyres are programmed in accordance with the boundary conditions.

❺ shows an example of a comparison between the FE simulation and measure-



❹ Simulation process for finite element tyre simulation

FE simulation results from Abaqus	**Measurement results from the 3-D laser vibrometer**
Turning mode 2: 93.9 Hz	Turning mode 2: 91.3 Hz
	
Radial mode 2: 85.7 Hz	Radial mode 2: 83.3 Hz
	

⑤ Good conformity at the comparison of simulation and measurement for the vibration patterns

ment results of two different vibration patterns on the x-z plane. The comparison is between a simulation and a measurement on the flat steel drum at a speed of 30 km/h (18.6 mph). The FE-calculated eigenvibration patterns on the left column of ⑤ are contrasted with the vibration patterns identified by the measurements at close to identical frequencies. The movement of the tyres in a particular vibration pattern are not as clearly identifiable in the measurements as in the simulations, however basic similarities in the vibration patterns can be identified.

It should be noted that the scanner head position was not optimal due to the inaccessibility of the test stand construction. The FE calculation of the vibration patterns was not made on the basis of a concrete excitation, whereas the real measurements displayed a type of operational vibration analysis due to the drum and tyre surfaces. A further reason for discrepancies in the validation is the curved surface of the test stand drum as opposed to the flat surface in the model.

CONCLUSION AND OUTLOOK

Using a 3-D laser vibrometer on an external drum test stand to identify tyre vibration patterns presents a substantial challenge. Following extensive preliminary considerations and preparatory measurements on a miniature tyre test stand, operational vibrations were successfully identified in a passenger car tyre. The comparison with eigenvibration patterns using an FEM tyre model shows good conformity of certain vibration patterns, meaning that a correlation between measurement and simulation can be achieved and used.

Once comparable tyre vibration patterns can be identified both in measurements and simulations, it becomes possible to derive a mechanical replacement model based on validated tyre vibration patterns. The objective of this would be to increase understanding of the working mechanisms behind tyre vibration behaviour on the vehicle and the test stand in order to develop efficient methods for ensuring the correct functioning of for example indirect tyre pressure monitoring systems.

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