

Comparative Analysis of Tire Evaluation Methods for an Indirect Tire Pressure Monitoring System (iTPMS)

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ABSTRACT

Starting from the USA and followed by the European Union, legal requirements concerning "Tire Pressure Monitoring Systems" (TPMS) for passenger cars and light trucks will be introduced in China as well and therefore in the third of the three largest automobile markets worldwide.

Changes of pressure dependent physical tire properties such as dynamic roll radius and a certain tire eigenfrequency, which are included in the ESC-wheel speed signals, indicates pressure loss in an indirect manner. Systems with corresponding working principles are called "indirect Tire Pressure Monitoring System" (iTPMS). Since the tire is a structural element with varying characteristics according to the design parameters, the roll radius and frequency behavior due to pressure loss is variable as well. As a consequence, tires have to be evaluated regarding their compatibility to iTPMS during the vehicle development process. In order to firstly reduce the testing effort on the complete vehicle and secondly to perform the evaluation at an earlier stage in the development process, tires shall be tested on external drum test rigs.

This paper researches the systematic differences between the tire evaluation at whole vehicle driving tests on road and at tire test rigs. Based on testing results and simulation models the interaction of tire vibration behavior and suspension influences is analyzed as well as excitation characteristics of roads and cleat crossings.

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INTRODUCTION

The tire inflation pressure has a very large influence on essential vehicle properties such as efficiency and safety. With decreasing tire pressure the rolling resistance coefficient increases. Accordingly, the vehicle efficiency is directly influenced by the tire pressure. In addition to the efficiency under inflation has a potentially negative effect on safety due to a longer braking distance and a higher risk of tire failures while driving.

To avoid especially the safety risk and therefore potential accidents the USA firstly introduced a legal requirement of TPM-systems for passenger cars and light trucks. Starting in 2007 each new vehicle for sale on the US-market needs a TPM-system. Following that the European Union introduced a legal requirement as well with main focus on vehicle efficiency. According to the legislation each new registered car must be equipped with a TPM-system starting in 2014. [1]

To monitor the tire inflation pressure there are two main strategies existing. First one is to detect the pressure and temperature within the tire by using an integrated sensor. Second one is to indicate the tire

pressure indirect based on the ESC-wheel speed signals. If a pressure loss occurs the wheel speed increases at constant driving velocity due to a reduced dynamic rolling radius of the tire. In addition a shift of a certain tire eigenfrequency which appears in a rotational form is observable in the frequency domain of the wheel speed signal. [Figure 1](#) shows the working principle of indirect TPMS using wheel speed analysis and frequency analysis.

According to the working principle of iTPM-systems physical tire properties are evaluated online respectively while driving. As the physical tire properties depend on the constructive design, also the iTPMS relevant tire characteristics vary within a tire program for a specific vehicle platform. [Figure 2](#) illustrates as an example a sensitive and a non-sensitive tire in the frequency domain at 20% pressure loss. Thus the sensitive tire shows a clear shift of the vibration frequency whereas the frequencies of the non-sensitive are nearly pressure independent. In addition to the vibration characteristics also the pressure dependent of roll radius characteristic differs according to tire dimension and design.

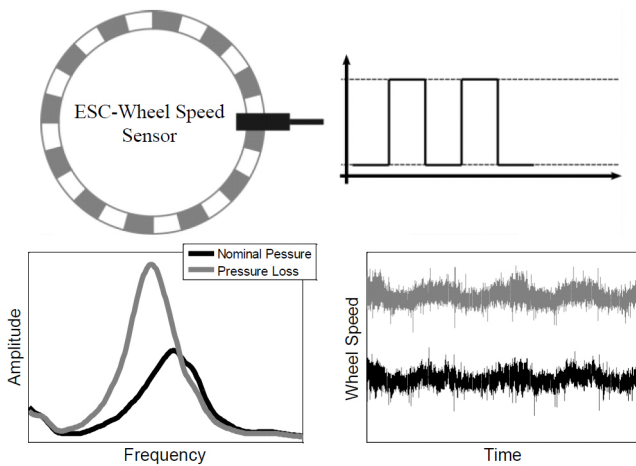


Figure 1. Working principle of indirect tire pressure monitoring system

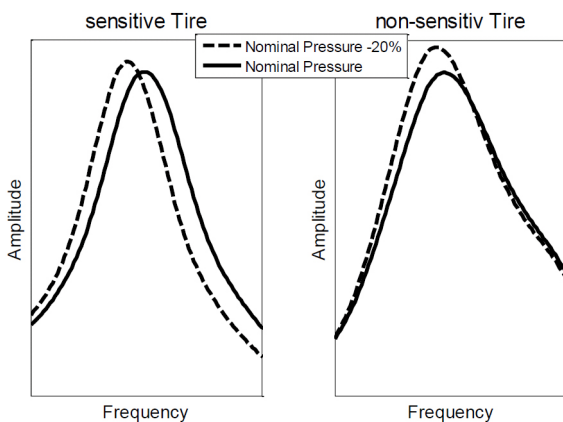


Figure 2. Comparison of a sensitive tire set with a non-sensitive tire set.

As a consequence, tires have been evaluated during the vehicle and tire development process with respect to the sensitivity of the pressure dependent characteristics and therefore to the compatibility to iTPMS. Analyzing tire properties based on vehicle driving tests is one method to check the tire sensitivities. The main disadvantages of driving tests are firstly the necessity of the physical car and therefore an evaluation at a late stage in the development process; and secondly the high effort to perform the tests. In addition to these facts car tests are only representing a check of the whole system performance under certain conditions such as environmental influences or road profile. In order to avoid the disadvantages and to check the tires on a component level at an early stage in the development process with a low testing effort, tires shall be tested on external drum test rigs. [1], [2], [3]

This paper analyzes the systematic differences between tire testing for iTPMS on vehicles and test rigs regarding tire vibration evaluation. After introducing the used tire coordinate system at first a reference is given to present the situation at driving tests. In contrast to the driving tests, at rig tests usually tire forces are detected. Measurements and analyses in this paper consist of both, the wheel speed signal and the tire longitudinal force to investigate the correlation between both measurements.

At test rigs normally cleats mounted on the drum are used as excitation for tire vibrations. The correlation between the pressure dependent longitudinal force and wheel speed is discussed in comparison with driving test results. Tire vibration analyses by cleat excitation on external drum tire test rigs are also presented in [3, 4, 5, 6, 7, 8, 9, 10], [12].

As an intermediate step between tire test rig and whole vehicle tests suspension test rig results are presented to analyze the suspension influences on the tire vibrations in detail. Investigations regarding the interaction between tire vibrations and suspension can also be found in [8], [9], [12].

For interpretation of testing results at vehicle test and rig tests a rigid ring tire model is introduced which enables the consideration of suspension elasto-kinematics. The modal characteristics of the model are calculated and used for testing result interpretation. Rigid ring tire models are a common approach to simulate tire vibrations up to approx. 100Hz. Therefore rigid ring tire models are also presented in [6], [7], [8], [9].

A main difference between driving test and rig test is the vibration excitation. Based on the results of [8] and [12] the speed dependent spectral characteristics of road unevenness excitation as well as cleat excitation at test rigs are calculated and compared to testing results.

TIRE COORDINATE SYSTEM

The measurement and simulation results are illustrated and discussed in a tire coordinate system as shown in figure 3. Accordingly the positive tire longitudinal force is oriented to the positive x-direction in the tire center plane. Also the positive wheel speed corresponds to the positive ϕ -direction.

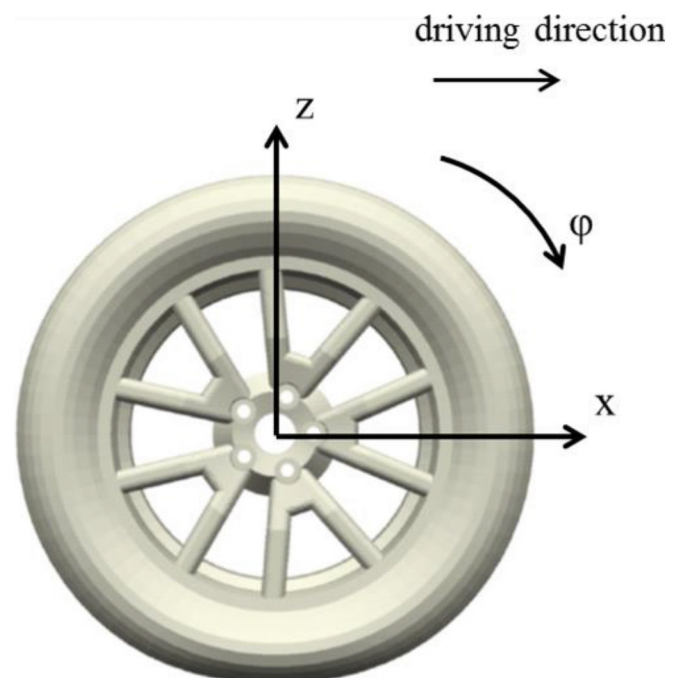


Figure 3. Tire coordinate system

GIVEN SITUATION AT DRIVING TESTS

At first the vibration behavior at driving tests is illustrated as a reference. Figure 4 shows the results at uniform motion (55 kph) and synchronous detection of wheel speed and longitudinal force in the frequency domain. At driving tests on general asphalt surfaces the vibration excitation is realized by the stochastic road profile. It can be seen that a strongly pressure dependent vibration mode occurs at approximately 35-45 Hz. Both the wheel speed as well as the longitudinal force shows the identical behavior when reducing the inflation pressure. The maximum amplitudes are increasing and the peak frequencies are decreasing. In addition, figure 4 shows that the peak frequency of the longitudinal force is around 1 Hz compared to the wheel speed result.

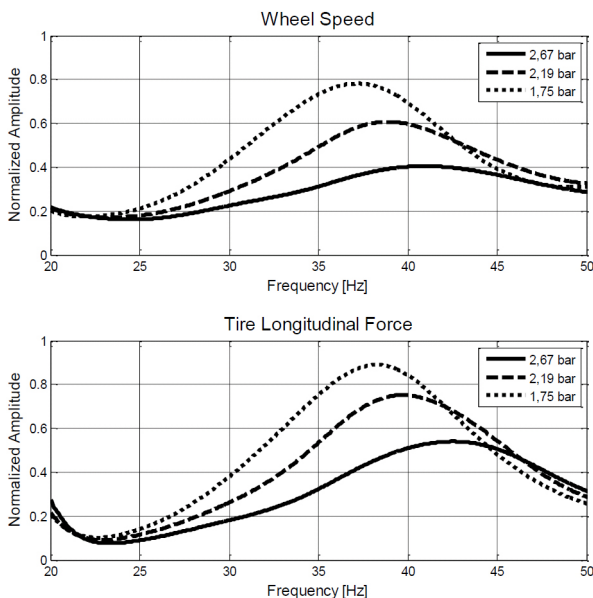


Figure 4. Results of driving tests with tire force and wheel speed measurement in frequency domain at 55 kph.

MEASUREMENTS AT TEST RIGS

Tire Test Rig (Rigid Axle)

At tire test rigs with rigid axle normally cleats mounted on the drum are used as excitation for tire vibrations. The correlation between the pressure dependent longitudinal force and wheel speed will be discussed in comparison with driving test results. Tire vibration analyses by cleat excitation on external drum tire test rigs are also presented in [3, 4, 5, 6, 7, 8, 9, 10], [12]. First the comparison of both parameters in time domain during cleat crossing and following decay process at speed of 30kph is illustrated in figure 5. The results show that there are significant differences at beginning of cleat crossings at around 0,02 seconds due to the dynamics at cleat crossings which are described in [12]. Aside from the fact of a small phase shift looks the behavior of both signals during the decay process very similar. This means that the vibratory tire belt mass performs an oscillatory motion in translational longitudinal x-direction and rotational ϕ -direction.

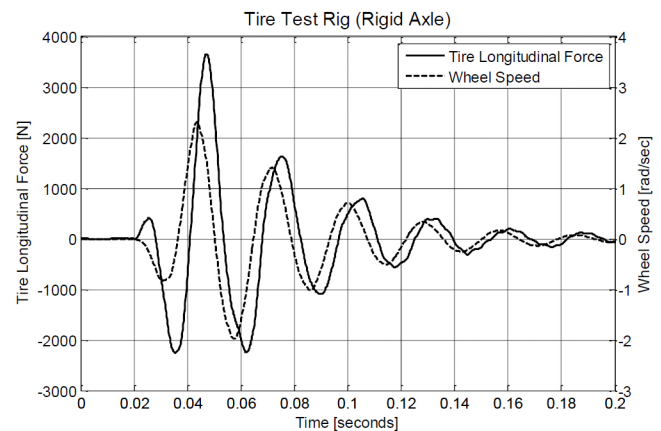


Figure 5. Tire longitudinal force and wheel speed at tire test rig with cleat excitation in time domain at 30 kph

In addition to the time domain analysis, figure 6 shows the pressure dependent comparison in frequency domain. Both parameters show exactly like the driving test increasing amplitudes and decreasing vibration frequencies at a pressure loss. The vibration frequencies seem to be in general on a significant lower level compared to the driving test. The peak frequency values of longitudinal force are again minimal higher.

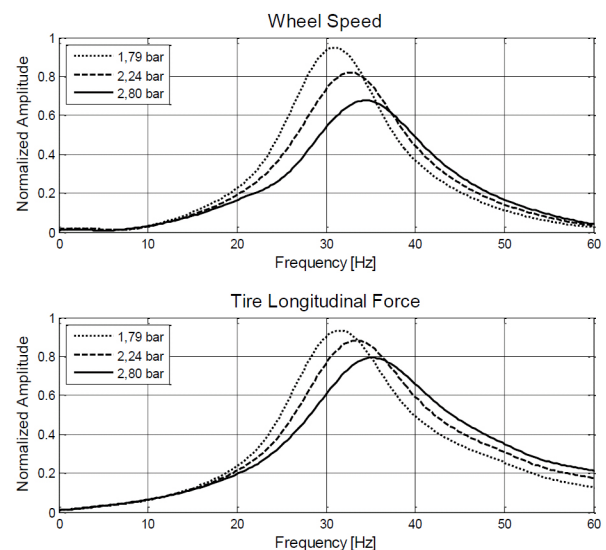


Figure 6. Comparison of wheel angular speed and tire longitudinal force at tire test rig with cleat excitation in frequency domain at 30 kph.

Suspension Test Rig

A suspension test rig represents an intermediate step between a tire test rig with rigid axle and whole vehicle. In contrast to the tire test rig the tire is mounted on a five-link front axle suspension of an upper class car where the construction is representing a quarter-vehicle. Also at the suspension test rig the tire is running on an external drum with identical diameter compared to rigid axle; however, the rim-fixed masses have a degree of freedom in longitudinal direction due to the elasto-kinematics of the suspension.