RESEARCH OF DYNAMIC MEASUREMENT CHARACTERISTICS OF WHEEL FORCE SENSOR

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Abstract – This paper deals with the dynamic measurement characteristics of wheel force sensor. Tests on servo-hydraulic shaker test bench and on four post test bench have shown the influences of tyre and suspension and defined the limitation of this measurement. With three simulation models of different level of detail, the dynamic measurement characteristics are explained by simulation in comparison with the test results. A compensation method is examined according to the acquired understanding of this system. The limiting of WFS in dynamic measurement can be extended to higher frequency range.

1 INTRODUCTION

Driving test, bench test in laboratory, and numerical calculation in dynamic simulation are widely undertaken in the vehicle development for improving ride comfort, drive safety and handling of the vehicle. Driving test and bench test can represent the system dynamic behaviour in reality or in a controlled environment. But it is more efficiently to study the influence factor for a better understanding of its interdependencies in simulation. The problem is, that the quality of the simulation is strongly dependent on the knowledge and experience of the user. Only a correct application in simulation can produce usable results. Because of the complexity in vehicle dynamic test, the information deficit between test and simulation may exist. Therefore the demand of using advanced measurement technology to help analyzing and correctly modelling the corresponding dynamic simulation models is constantly increasing thanks to the advancement in electronics and sensor technology.

Tyre is the only interface between road and ground vehicle that transfers all forces and moments coming from the ground. The measurement of tyre forces and moments is important for in vehicle and tyre development, vehicle dynamic control and many other related areas like fuel consumption optimization and so on. To measure the forces and moments in three space directions as close as possible to the tyre contact area, the original hub can be replaced by the tyre test instrument wheel force sensor(WFS) or so called measuring rim. Nowadays wheel force sensor can achieve a very high accuracy and resolution by using a combination of multiple sensing elements in delicate designed structure and by implementing other innovative measurement technologies.

Despite the fact of the high accuracy the wheel force sensor itself can reach today, in some circumstances the measured forces and moments can still not be easily regarded as the tyre forces at the road contact area. For instance because the sensor is mounted between the hub carrier and the rim, the dynamic part of the tyre vertical load can be missing during the measurement with the vertical acceleration of the most part of the wheel[1][2]. Besides that the measured forces also have to be transferred under the complex influences of the tyre. Due to lack of understanding of its measurement dynamics, the difference between forces and moments at tyre contact area and the measured values from wheel force sensor may become so great, that the accurate sensor can't be able to give out accurate measurement result anymore. In the research of the tyre and suspension model for vehicle vertical dynamics, it is observed in Figure 1 that the amplitude and phase difference between the vertical forces from the wheel force sensor and from the tyre contact area already start to alter after the car body eigenfrequency. The observed difference has increased to a level of about 60 % in amplitude and about 30 degree in phase. There are also some clear changes above 15 Hz, what interestingly corresponds to the wheel eigenfrequency. This dynamic behaviour varies with the change of suspension damping rate as well [3][4].

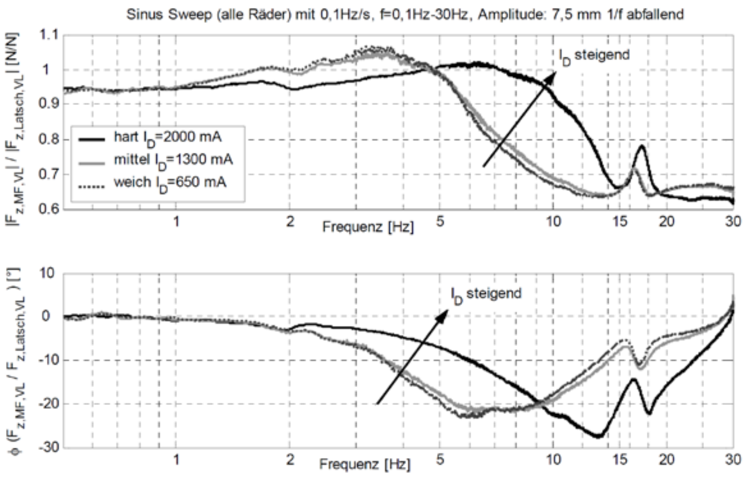


Figure 1: Transfer function between wheel load from wheel force sensor(rim) and vertical force at tyre contact area(post force) dependent on different passive damper setting[4].

This phenomenon indicates that the tyre and suspension system can both have a great influence on the dynamic measurement characteristics of the wheel force sensor. Therefore this research was motivated in order to get a physical understanding of this system and to find a solution to further increase the accuracy of the measurement.

2 TEST METHODS AND TOOLS

2.1 Methodology

Within the context of this paper presented, the research of dynamic measurement characteristics of WFS in vertical tyre load transfer was conducted. Three analytical models of the suspension considering the wheel force sensor were introduced by using the combination of mass, linear spring and linear damper elements with different level of detail. The more detailed analytical models for simulation have taken the tire belt mass and tire structure into consideration after the discussion of various forms of force transfer in this measurement system. Furthermore the transfer functions of each model were calculated by solving the state space formulation. To validate the validity of these simulation models, two dynamic tests were performed. Focusing upon the tyre, the WFS and the wheel alone were installed onto a servo-hydraulic shaker test bench for analyzing the influence of tyre structure on the dynamic measurement characteristics of WFS. Afterwards test for the whole tyre-vehicle-suspension system was performed on a four post test bench as well. The results were analyzed by comparing the simulation outcome with the test results. Based on the acquired knowledge, a compensation method was discussed.

2.2 Wheel force sensor

In this research the wheel force sensor from A&D Europe GmbH is used to measure the force on the wheel hub. As shown in Figure 2, the sensor can be adapted with a hub adapter and an adapting rim to a variety of wheel dimensions. With a sensor mass of 3.82 kg, the total wheel weight with adaption and WFS was increased from 27 kg to 29 kg in this work, which means an additional 7.4 % of original weight. For the application in real driving situation or on a test bench with rotating wheel, the measured values have to be transferred from the rotating coordinate system of the sensor to the non-rotating coordinate system of the wheel with the help of the signals from a rotary transmitter. The output values of WFS are forces and moments in all three space directions, wheel rotating speed and angle. In appendices the specifications of WFS are listed in table 1 [5].

Because of the kinematic and elastic characteristics of the suspension system during driving and steering, the coordinate system of the wheel will keep moving relative to the ground or to the car body. If a additional correction of the coordinate system is needed, it is also possible by integrating the WFS with wheel position sensor (WPS) and laser ground sensor (LGS) to get most of the state information during dynamic driving test. WPS uses several parallel rod systems with five individual angular position sensor to calculate the wheel displacement in all three directions and the three wheel rotation angles relative to the car body. LGS can determine the camber angle of the wheel, the pitch angle of the body and tyre radius relative to the ground by using three laser distance sensors. With another two laser Doppler sensors, the velocity at the wheel over ground in longitudinal and lateral directions can also be measured [6][7].

Figure 2: left: WFS with rotary transmitter, rim- and hub adaption; right: WFS integrated with LGS and WPS on test vehicle (Pictures from A&D Europe GmbH)

With carefully positioned sensing elements made by strain gauge and a special designed sensor structure, the signals from each sensing elements can be re-composed based on a verified calibration model on real-time DSP platform. That means, each sensing element does not measure one force or moment component directly. On the other hand, the measurement is realised through the calculation of multiple sensor signals with a calibration model. In this way, the generally unavoidable crosstalk effect can be significantly reduced. In the design of every single sensing element, the temperature influence on the measurement is also considered and minimized. To increase the signal quality even further, a A/D conversion happens directly in the sensor at 10 kHz. This early digitalization of measured signal can contribute to a better noise performance and the measurement can be recorded with a sampling rate of 1 kHz. A high precision A/D conversion also assures, that the mechanical structure of the sensor can be built as stiff as possible for having a better sensitivity and dynamic performance at the same time. According to the test from the manufacturer shown in Figure 3, the sensor was fixed to a very stiff metal foundation, a hammer strike was applied to the sensor to start a free vibrating process. The test result recorded with a sampling rate of 10 kHz can indicate that the eigenfrequency of the system is even over 2 kHz, which is far over the normal application range in vehicle and tyre dynamics. By taking the peak frequency together with the measurement result in time domain and the known mass of the sensor, a approximation to the stiffness and damping ratio of the sensor can be obtained for the later simulation.

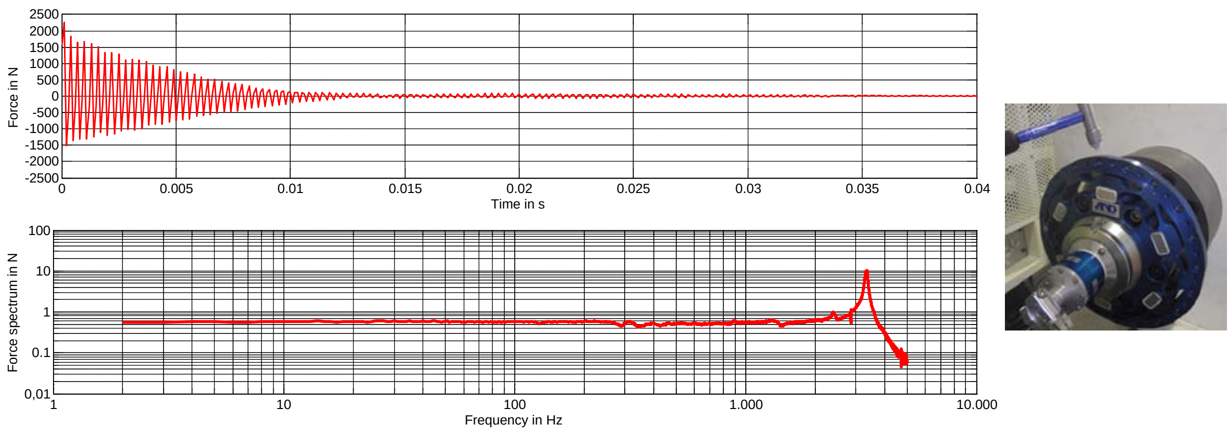


Figure 3: Measurement of force in time and frequency domain from WFS in hammer test (Data from A&D Europe GmbH)

2.3 Servo-hydraulic shaker test bench

Servo-hydraulic shaker test bench was used to analyze the dynamic measurement characteristics of

WFS under the influence of tire structure and to identify the suggested tyre simulation models. During the test, the wheel with WFS was fixed to a solid basis at the centre and the shake was controlled by hydraulic system to stimulate the tyre at the contact area with a amplitude of 1, 2 and 5 mm in a frequency range from 0.5 to 70 Hz. Moreover the tyre was tested with three various tyre pressures of 1.5, 2.5 and 3.5 bar. Here two forces from the shaker and from the WFS were measured respectively together with the movement signal from the test bench. In order to obtain the force at the contact area accurately, a free test without wheel was also conducted from 1 to 100 Hz. In this way the mass between contact area and the sensing element was identified by the dynamic force F_{dyn} and the movement of the shaker z_{shaker} by

$$m_{comp} = \frac{F_{dyn}}{-\omega^2 \cdot Z_{\mathrm{shaker}}}.$$

Afterwards the force at tyre contact area for the tyre test was corrected by

$$F_{\mathrm{contact}} = F_{\mathrm{shaker}} + m_{\mathrm{comp}} \cdot \omega^2 \cdot Z_{\mathrm{shaker}},$$

where F_{shaker} is the measured force from test bench.

Figure 4: Tyre test on a servo-hydraulic shaker test bench with WFS

2.4 Four post test bench

Dynamic measurement on four post test bench is aimed to study the characteristics of WFS similar to real driving situation under the complex influence of the suspension system. It is like an extension of the test on servo-hydraulic shaker test bench, but with a complete vehicle standing on four hydraulic controlled shaker. Here all four wheels were stimulated with the same excitation signal, and the test result can be compared with a simplified one-fourth vertical vehicle dynamic simulation model, although the coupling effect between different wheels may still exist to a certain level. During the test, the tyre contact force was also measured from the test bench after the same mass correction method by servo-hydraulic shaker test bench. Besides that, the force from WFS, the shaker movement from the test bench and the vertical acceleration at wheel hub from mass-production sensor were also recorded during the test with a linear sine sweep signal from 0.1 to 30 Hz, while the eigenfrequency of the car body and the wheel are all included within this range. It is to mention that the quality of the recorded acceleration signal may be limited by the specification of the mass-production sensor. And the test vehicle has a firm spring and middle firm (I_D= 900 mA) damper setting.

3 MODELLING

In order to understand the dynamic measurement characteristics of the WFS, three analytical models were built in this work. At this step, it was aimed to find the possible influence factors in tyre and suspension on the dynamic measurement. Therefore all elements in simulation models were built with mass, linear spring and linear damper as shown in Figure 5. The test results were used afterwards to identify the parameters with a strong simplification. For the servo-hydraulic shaker test bench, the centre of the wheel was fixed to a solid basis which can be illustrated by the dash line, the tyre and the WFS were located between road excitation and the fix point. The simulation models for 1/4 vehicle vertical dynamic model are demonstrated with body mass, spring and damping element of the suspension.

3.1 Modelling of tyre and WFS

Model 1 (wheel)

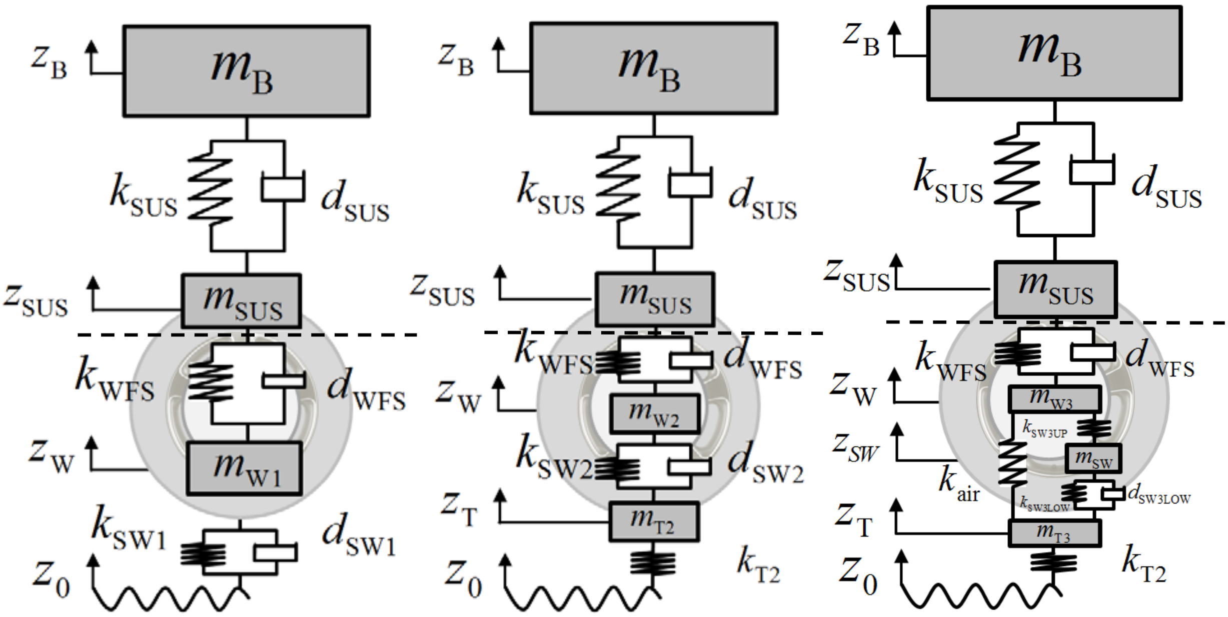
Under the assumption that the dynamic part of the tyre load can be missing because part of the wheel mass including tyre, rim, and part of the WFS are moving between road and the WFS, this part of wheel can be considered as one concentrated mass element with tyre spring and damping in Model 1. This part of mass m_{W1} weights 29kg. Although the dynamic tyre stiffness and damping can change with different amplitude and frequency of excitation under the complex influences of rubber friction and air compression in a certain range. To simplify the analytical simulation at this step, tyre stiffness k_{WFS} was estimated with the test result on servo-hydraulic shaker test bench to be 250 kN/m by 1.5 bar, 390 kN/m by 2.5 bar and 420 kN/m by 3.5 bar and damping d_{WFS} was estimated to be 80 Ns/m. Because of the high eigenfrequency of WFS, the stiffness k_{WFS} and damping d_{WFS} of WFS are not sensitive to the result in this study.

Model 2 (wheel+tread)

If part of the tyre like tread and side wall can be considered as one independent mass, in model 2 the mass m_{W1} will be divided into m_{T2} and m_{W2}. According to the measured force transfer behaviour shown in the next chapter, the mass m_{T2} can be estimated by the peak frequency of the force transfer with the known tyre stiffness $k_{\mathrm{SW2}} = k_{\mathrm{SW1}}$ to be 6 kg and m_{W2} 23 kg accordingly. The tyre damping d_{SW2} can regulate the amplitude at the peak frequency, therefore it can also be determined by the test result to be 80 Ns/m. For this simulation, the tread stiffness k_{T2} do not play any role in the dynamic force transfer in interested frequency range.

Model 3 (wheel+tread+sidewall)

The third model assumption is that the force transfer of the tyre can be realized through tyre side wall and air pressure. Therefore a spring element k_{air} was used to simulate the effect of the air pressure, and the tread mass m_{T3} and mass of sidewall m_{SW} were meant to simulate the local dynamic movement in the tyre. For the dynamic force transfer behaviour on the servo-hydraulic shaker test bench, the tread mass m_{T3} can be estimated in the same way as by model 2 to be 6 kg, the tyre stiffness caused by air pressure k_{air} is the same as the other two models and the side wall damping d_{SW3UP} to be 80 Ns/m. Other parameters like side wall mass m_{SW}, side wall stiffness $k_{\mathrm{SW3UP}}, k_{\mathrm{SW3LOW}}$ cannot be easily estimated in this test because of their low sensitivity in test results. But the result from four post test bench in next chapter has shown, that the local movement of sidewall mass can possibly affect the difference between tyre load at contact area and the measured vertical force from WFS. The author estimates, that an extended measurement of acceleration at different location of the tyre on four post test bench can contribute to an improvement of the parameter identification of this model.



(a) Model 1(wheel) *(b) Model 2(wheel +tread)* *(c) Model 3(wheel +tread +side wall+air)*

Figure 5: Schematic of simulation models

3.2 Modelling of 1/4 vehicle model

Combine the above described tyre and WFS models with the remaining unsprung mass from suspension m_{SUS}, the shared vehicle body mass m_B, the suspension stiffness k_{SUS} and damping d_{SUS}, simplified one-fourth vertical vehicle dynamic simulation models were built. Because of the strong simplification of the non-linear suspension system, the target of this work is firstly to see whether the suspension characteristics can influence the dynamic measurement of WFS. If the influences exist, the causes and in which direction the influences can be should be explained. When the working operating range of one simulation model is validated, the model can be further applied in simulation environment to predict the measurement of WFS in dynamic test and to help compensating the measurement result.

4 RESULTS

4.1 Servo-hydraulic shaker test bench

The test results from servo-hydraulic shaker test bench and the simulation results of three models are shown in Figure 6. It can be seen from the test results, that the transfer function between force from WFS and force at tyre contact area starts to go up rapidly in amplitude start from about 10Hz. At 30 to 50 Hz it can reach a maximum of about 20 times with a phase change of about 180°. The peak of this transfer behaviour can be affected by the change in tyre stiffness caused by different tyre pressures. Afterwards the difference in force transfer drops to less than 100 % quite rapidly. Due to the fact that these tests were performed at several constant frequencies, the accuracy of the transfer function at the frequencies in between cannot be completely assured, especially when there is a steep gradient. Even so, it can be seen that the results of different amplitude of excitation still match perfectly at most of the frequencies with each other. The change of their maximum can be explained by the excitation dependent relative damping affected by the rubber friction and a shift of eigenfrequency caused by the frequency dependent dynamic tyre stiffness.

The simulation results with the three above mentioned models have shown, model 1 without further description of the tyre structure cannot simulate the observed dynamic transfer behaviour. With the help of WFS, it is proved that the tyre thread mass can influence the force transfer in this test. Model 2 and model 3 are able to simulate this characteristic with a satisfactory accuracy until about 60 Hz. Another fact to mention is that for different tyre pressure only the tyre stiffness k_{SW2} in model 2 and the stiffness

k_{air} caused by air pressure in model 3 are needed to be adjusted according to measured value. The deviation in amplitude at high frequency and in phase is supposed to be affected by the non-linearity of the tyre stiffness and damping. By using a validated tyre model with description of the non-linear effect, the quality of the simulation is supposed to be further improved.

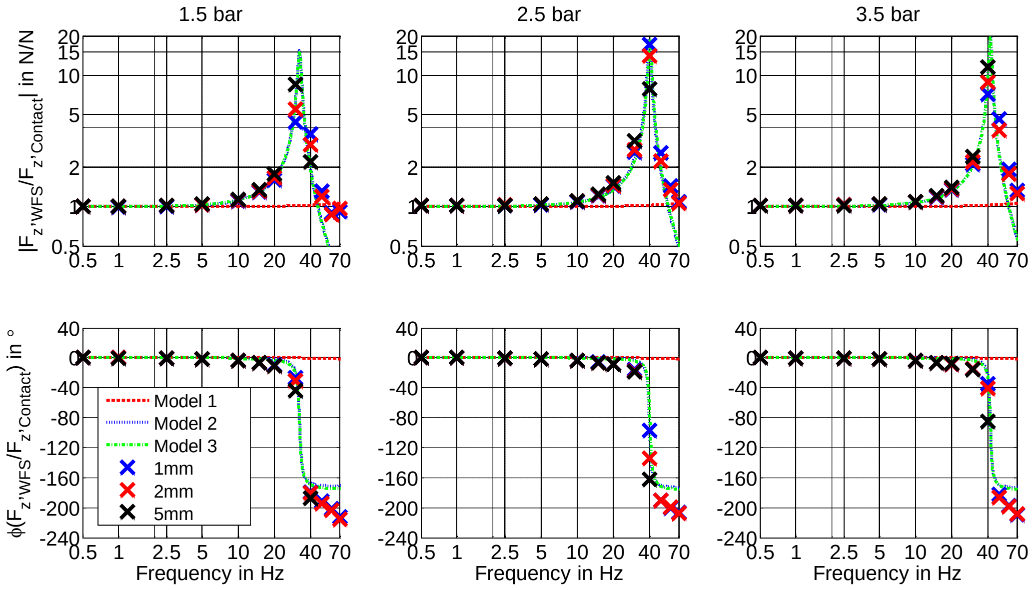


Figure 6: Transfer function between force from wheel force sensor(rim) and force at tyre contact area(shaker force) with tyre pressure of 1.5, 2.5 and 3.5 bar, and deflection amplitudes 1, 2 and 5 mm

4.2 Four post test bench

The results from four post test bench are shown in Figure 7. It is clear to see, that the measured vertical force from WFS varies with the excitation frequency. The simulation results have shown, that with a strong simplification of the vertical dynamic model, the amplitude and frequency relevant stiffness and damping in suspension system make it impossible to reproduced the test result at any frequencies. A complete identification and modelling of the whole system still require more efforts, but with the already identified parameter and by comparison with the test results, the linear simulation model can still explain some of the important influence factors.

At low frequency range the vertical force from WFS can represent the tyre load at contact area with small phase difference until about 4 Hz. The difference in amplitude of force in the range of car body eigenfrequency (1 Hz to 4 Hz) can be explained by the missing mass between WFS and the ground. If the non-linearity of the suspension is considered, all three models are supposed to simulate this system till the range of car body eigenfrequency.

In the range of 4 Hz to 15 Hz between car body eigenfrequency and wheel eigenfrequency it can be seen, that the damped vibration of the car body works like a relative solid basis, which lead to 20 % increase of measured force. It can also be explained with the help of three simulation models that this increase in difference of force measurement is dependent on the unsprung mass, body mass and is very sensitive to the suspension stiffness and damping. After the range of body frequency the body and wheel starts to move in an opposite phase with a increasing of wheel acceleration.

Above the wheel eigenfrequency of about 15 Hz, it is observed that the difference in tyre load measurement drops dramatically to just about 50% with a phase change of about 50 degree. The simulations have shown, that it is caused by the stable phase difference between body and wheel with a descending of wheel acceleration after wheel eigenfrequency. The 50% corresponds to the mass distribution of the unsprung mass over WFS and under it. From this point, model 1 can no longer describe the phase change of the force difference. At high frequency, the tyre structure dominates the dynamic measurement characteristics of WFS, independent mass of tyre tread or side wall is needed. An locally amplitude and phase change in the dynamic measurement is also found at about 16 Hz. Here model 2 without fine description of tyre side wall mass will not be able to simulate this change, at even higher frequency, the difference in amplitude also cannot be explained by model 2. The assumption of linear model 3 can qualitatively describe all observed dynamic changes in the measurement. The identification of the non-linearity of the system is supposed to further improve the quality of the simulation. Without a detailed simulation model, additional sensor information is still needed for the estimation of dynamic wheel load .

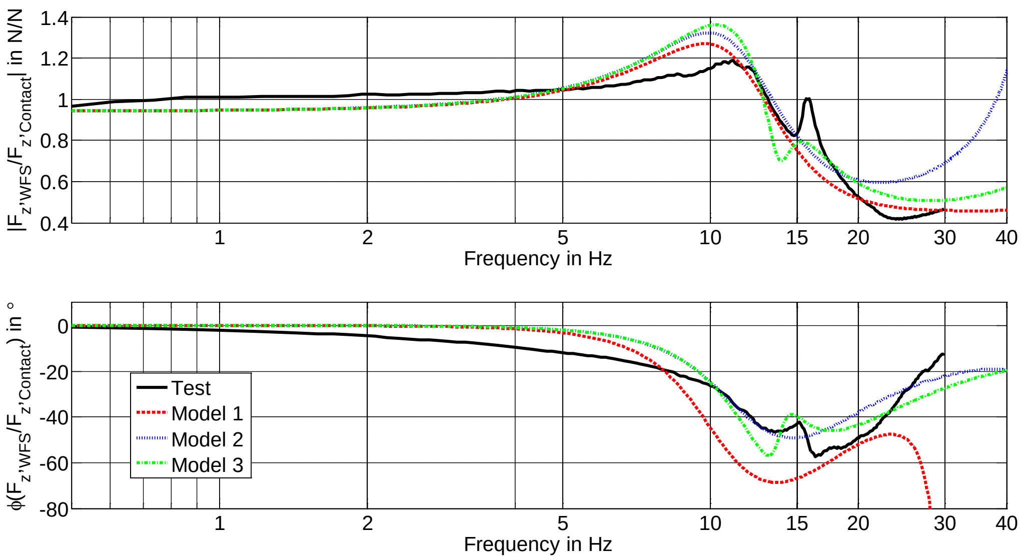


Figure x: Transfer function between wheel load from wheel force sensor(rim) and vertical force at tyre contact area(post force), I_D=900mA(middle), tyre pressure 2.55bar

5 COMPENSATION

According to the acquired knowledge from test and simulation, the missing part of the measurement in dynamic load at tyre contact area can be compensated with additional acceleration signals in an inverse model. Even the identification of the tyre structure is not always a easy task, a compensation of measurement from WFS F_{Z_WFS} is still possible with $\ddot{Z}_{hub}$ from an acceleration sensor at the wheel hub and the mass m_{Wheel} between WFS and the ground by

$$F_{\text{Z\_contact\_compensated}} = F_{Z\_WFS} + m_{\text{Wheel}} \cdot \ddot{Z}_{hub} .$$

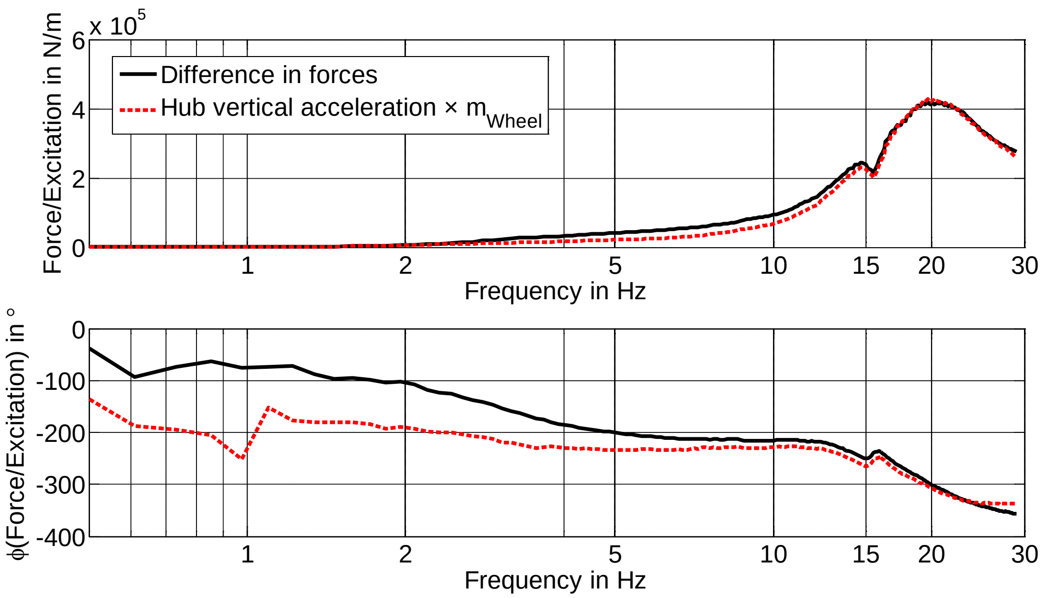


Figure 8: Comparison between difference in forces (WFS and wheel load at tyre contact area) and the product of vertical acceleration at wheel hub and part of wheel mass, I_D=900mA(middle), tyre pressure 2.55bar

Figure 8 has shown, that the difference in forces is comparable to the product of wheel hub acceleration and the mass between WFS and the ground. Because of the limited accuracy of the mass-production sensor, the lack of low-frequency information with linear sine sweep input and possible error in phase of each signal, the value to be compensated still cannot completely match the acceleration signal.

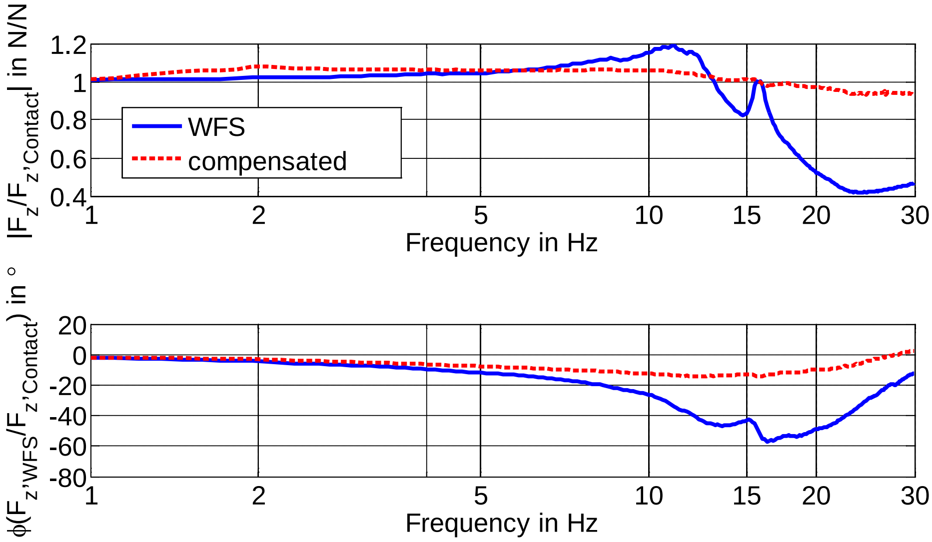


Figure 9: Transfer function between wheel load compensated with hub acceleration and vertical force at tyre contact area(post force), I_D=900mA(middle), tyre pressure 2.55bar

Even so the result of this compensation method is demonstrated in Figure 9. With the help of an additional acceleration sensor, most of the difference in dynamic measurement of WFS can be compensated in amplitude as well as in phase. The limiting of WFS in dynamic measurement can be extended from about 5 Hz to over about 15 Hz.

6 CONCLUSION AND OUTLOOK

The research have shown that both tyre and suspension can influence the measurement characteristics of WFS during the application and the developed model of different level of detail with linear elements corresponds to the measured phenomenon to certain frequency range. Understanding of the non-linearity of the system is supposed to improve the quality of the simulation. Moreover the wheel force sensor model can be used to predict the measurement result and its inverse model is able to compensate most of the measurement error in validity range. With this correction method the limiting of the tyre force measurement can be extended.

The future works in this topic are:

- Consideration of the complex non-linearity in tyre like friction, dynamic stiffness and relative damping
- Consideration of the complex non-linearity in stiffness and damping of suspension system
- Extension of the research into measurement of forces and moments in different directions
- Extension of the research into measurement with rotating wheel
- Prediction of the quality of dynamic measurement of WFS in driving test
- Development the parameter identification method

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APPENDICES

Table 1: Specifications of wheel force sensor

Items	Specifications	Items	Specifications
Fx	±24kN	Crosstalk	±0.5% (at the maximum load)
Fy	±15kN	Angular resolution	1024/360°
Fz	±24kN	Temperature guarantee range	-20 to +80℃
Nominal load	±8kN	Operating temperature range	-40 to +100℃
Mx	±4.5kNm	Zero temperature effect	0.005%/℃ (at the maximum load)
My	±7.2kNm	Span temperature effect	0.005%/℃
Mz	±4.5kNm	Total error	±0.1% (Including non-linearity and hysteresis at the maximum load)
Weight	3.82kg	Resolution	1/4000