academicJournals

Vol. 9(12), pp. 591-597, 30 June, 2014
DOI: 10.5897/SRE2014.5956
Article Number: 6BDF5B545703
ISSN 1992-2248 © 2014

http://www.academicjournals.org/SRE

Scientific Research and Essays

Full Length Research Paper

A mechanical approach of overload protection mechanism for a heavy truck wheel force transducer

Lihang Feng[1], Guoyu Lin[1]*, Weigong Zhang[1,2]* and Dai Dong[1]

[1]School of Instrument Science and Engineering, Southeast University, Nanjing, 210096, China.
[2]Suzhou Research Institute, Southeast University, Suzhou 215000, China.

Received 30 April, 2014; Accepted 12 June, 2014

The wheel force transducer (WFT), which measures the force or torque applied to the wheel, is an important instrument in vehicle testing field and has been extremely promoted by researchers. Since the high cost and technical secret of the commercial products may slow down the development of WFT to some extent, Southeast University has devoted to the WFT research with some prototypes. Essentially, the WFT is a multi-axis force sensor (MFS) in which an elastic-body will deform under the applied forces. However, when applying a MFS into vehicle wheel and making it to be a WFT, it may be subjected to forces/moments which exceed the measuring range under the over rated load, especially on a heavy truck WFT under loads of X or Z direction. Plastic deformation and damage may occur on the elastic-body of WFT. This paper presents a mechanical approach of the overload protection mechanism which can prevent the overload damage and guarantee the sensor performance. An intermediate flange, which is elaborately designed using Computer Aided Engineering (CAE) tools, is installed between wheel hub and the elastic body to meet the overload protection. Experiment and prototyping test are conducted on the hydraulic platform. Results show that the proposed overload protection mechanism performs well. In particular, the applied loads over ±120 kN and ±30 kNm are prevented from damage for the heavy truck WFT.

Key words: Wheel force transducer, overload protection mechanism, vehicle wheels/typres, heavy duty trucks.

INTRODUCTION

When the vehicle is moving on the road, three-axial forces of longitudinal force F_x, lateral force F_y, vertical force F_z, and three-axis torques of heeling moment M_x, twist torque M_y, and aligning torque M_z, are applied to the wheel. The interaction between the vehicle and ground is represented by the forces, and therefore, sensing the wheel forces/torques is quite significant in vehicle testing field (Kadhim et al., 2011; Kuchler and Schrupp, 2001; Pavkovic et al., 2009; Pytka et al., 2011). To detect these forces, the famous multi-axis wheel force transducer (WFT) (Weiblen et al., 1999), which offers the capability of acquiring load data at the spindle of a vehicle, has been promoted extremely by researchers and engineers with great interests (Hong and Strumpfer, 2011; Zhang et al., 2011).

Due to the superior qualities of well static and dynamic

*Corresponding author. E-mail: zhangwg@seu.edu.cn, Andrew.Lin@seu.edu.cn Tel: +86 02583794157; +86 13512504727.

Figure 1. The WFTs developed at SEU (The heavy truck WFT consists the overload protection mechanisim in this paper).

performance, on-board testing techniques and flexible, fast and easy installation on different vehicles, the WFTs are made to be necessities of automobile manufactures for vehicles performances verification and product quality improvements. Some world-famous companies including MTS Corp., Michigan Scientific Corp. and Kistler Corp. have already made their products available in market (Lin et al., 2014). The issue is that these WFTs are much expensive and, for business reasons, detailed technical information is not publicly available. It not only impedes the popularization of WFT application but also slows down its further development. Southeast University (SEU, China) has devoted over ten years to developing the instrument. Some prototypes (Figure 1) and published papers are available (Lin et al., 2013, 2014; Wang et al., 2011, 2014).

Generally, as an on-board instrument for wheel forces measurement, the WFT consists of a multi-axis force sensor (MFS) (Song et al., 2007) in which an elastic-body will deform under the applied forces. Measurement of the elastic deformations by appropriate transducers yields electrical signals from which the force components can be derived. However, when applying a common MFS into the vehicle wheel and make it to be a WFT, it may be subjected to forces/moments which exceed the measuring range under the over rated load, plastic deformations and damage may occur on the elastic-body. From the perspective of reliability, since vehicle loads can vary greatly from 100 kg for a motorcycle to more than 10000 kg for a truck, the sensor must bear the whole vehicle weight and have a large measuring range. It implies that performance of force sensitivity, strength and stiffness should be satisfied simultaneously. Moreover, the damage and failure will be much more prone to occur on the WFT of a heavy truck under dynamic loads at X and Z direction. Nevertheless, increasing the force sensitivity always changes the structural dimension so that optimization design and dimensional synthesis need to be processed. It may result in the loss of structural strength and stiffness due to cutting material or using exotic materials. Nowadays, the sensor material covers from normal structure steel to the Aluminum or Titanium alloy which can be learned in some products. Weiblen et al. (1999) has evaluated several different designs of the WFT and the material selection including Titanium alloy versus Carbon fiber composite are compared in detail for two WFT systems. Using the exotic material may not only increase the costs but also increase the processing complexity including quenching, tempering and fatigue tests. If considering road conditions such as rough sandstone, tidal flats and drifting terrain, the reliability and practicability will be more complicated in design.

For the reasons presented above, the problem needs to be tackled with practical considerations. In a broad sense of engineering research, an overload protection mechanism can be made to guarantee the sensor performance and prevent the overload damage. No more exotic material is required and it maintains the merit of economy, practicability and reliability. This paper presents such an overload protection mechanism that a mechanical approach is performed on a heavy truck WFT to meet the requirement. Principle and methodology, design optimization and experimental tests are investigated for the overload protection mechanism of WFT.

PRINCIPLE AND METHODOLOGY

Sensor principle and problem

Essentially, the WFT is a multi-axis force sensor in which an elastic body (Figure 2b) is used to deform under the applied loads and then the wheel force/moment signals are converted by virtue of strain gauges, piezoelectric sensor or other sensing units which are

Figure 2. (a) The assembly diagram of WFT; (b) A typical elastic body of WFT developed at SEU.

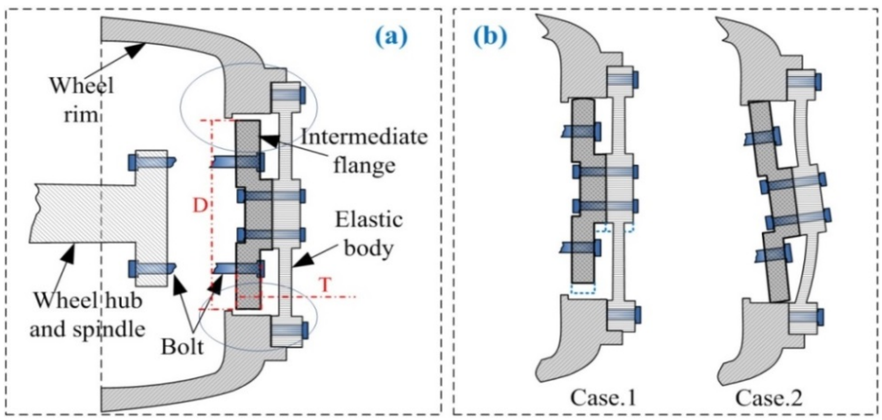

Figure 3. (a) Overload protection mechanism and (b) the intermediate flange deformation.

attached on the sensor body. The most common ways for wheel force detection may be strain gauge measurement technique because of technical accessibility and general applicability (Weiblen et al., 1999). The strain gauge arrangement, Wheatstone bridge and signal amplification and processing circuit are used to convert the force signal into strain, and then into digital voltage outputs. As a mathematical description, the vectors between applied load $\boldsymbol{F}$ (F_x, F_y, F_z, M_x, M_y, M_z) and output signal $\boldsymbol{S}$ (S_{Fx}, S_{Fy}, S_{Fz}, S_{Mx}, S_{My}, S_{Mz}) is related by $\boldsymbol{S}=C\cdot\boldsymbol{F}$. C is the compliance matrix which can be obtained either analytically in structural analysis or experimentally in actual calibration.

According to this basic principle, the sensor body must be installed between the wheel rim and wheel spindle when a multi-axis force sensor (MFS) is made to be a wheel force transducer (WFT). It takes the place of wheel spoke and can be used to sense the forces/moments as a typical installation which is shown in Figure 2a, the elastic body of WFT has such the two-ring structure that an outer ring is connected to wheel rim and an inner ring is connected to the wheel hub. A hub adapter can be used for force transmission between wheel spindle and the elastic body. Apparently, the elastic body is the crucial part of WFT and the damage and failure caused by large vehicle overload at X and Z direction must be avoided.

Overload protection mechanism

Generally, a modified rim and transducer assembly are assembled to the vehicle spindle when using a WFT. Since there is enough space between the wheel hub and wheel rim in a truck wheel, we build the overload protection mechanism by replacing the simple hub adapter with a tailored-designed intermediate flange in the area. As shown in Figure 3, the elastic body connects to the wheel spindle via an intermediate flange. By designing the flange with a proper size, an overload protection mechanism can be built. Two useful cases are illustrated as follows:

Case 1: Overloading force at X or Z direction. If the loading force including the vehicle mass or dynamic load at X or Z direction is too large, the deformation displacement on elastic-body will make the intermediate flange contact with the rim, and then the deflection of elastic-body will be limited to approximately that amount.

Case 2: Overloading moment at X or Z direction. If the overloading moment M_x or M_z is applied, the deformation displacement on elastic-body also makes the flange contact with the rim and it limits the deflection of elastic-body as well. This may occur in such case that the vehicle centre-of-gravity shifts when steering abruptly.

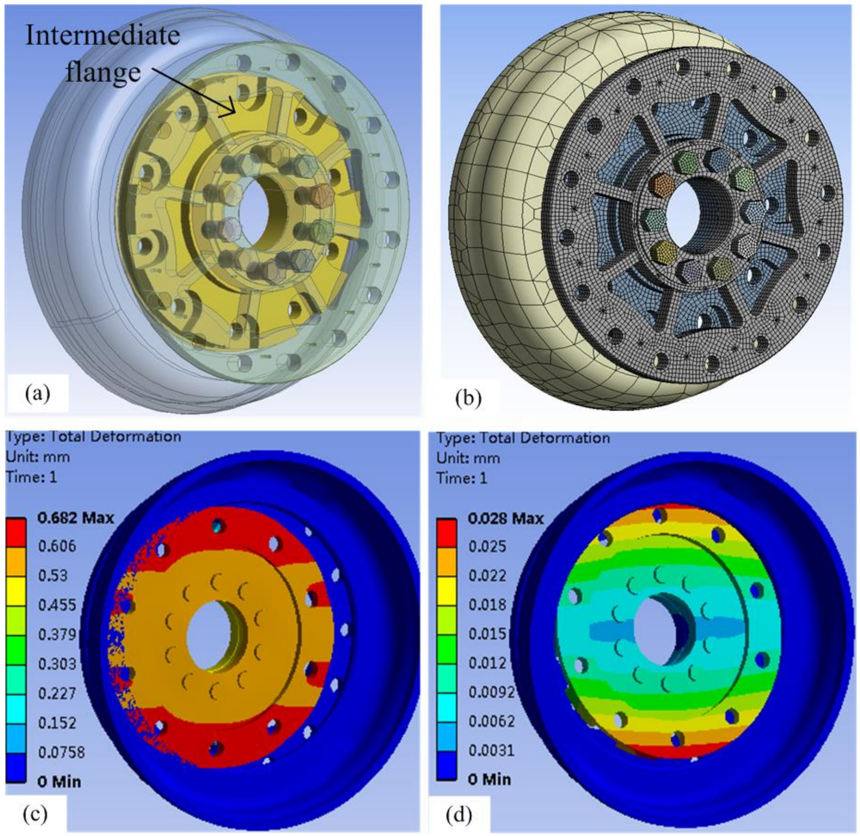

Figure 4. The overload protection using the intermediate flange: (a) the assembly diagram of the intermediate flange; (b) mesh generation (c) the deformation of the intermediate flange under applied force F_x or F_z (d) the deformation of the intermediate flange under applied moment M_x or M_z.

Owning to this mechanism, the boundary dimensions and tolerances of the flange must have the minimum values while the elastic body may have large force sensitivity. Although the monolithic structure of elastic-body makes the sensitivity increase easily, the damage and failure may be prone to occur under loads at X and Z direction. The dimensions of the intermediate flange, which is the key point of the overload protection mechanism, will be designed elaborately and the process may involve practical challenges. Generally, an effort of optimizing the design to meet these often conflicting goals rapidly, and to apply it into the specific vehicle wheels, can be made by using analytical design computer aided design (CAD) and performance prediction tools Computer Aided Engineering (CAE). For the whole mechatronics assembly, the need for physical prototyping is often required to confirm the design and test the mechanism as well.

Design and optimization using finite element method (FEM)

Mechanical design of overload protection

Using the ANSYS workbench, the design and optimization procedure is implemented on the overload protection mechanism (Figure 4). Also the parameters and conditions can be determined. For the purpose of improving the sensor sensitivity of the heavy truck WFT, the elastic body which has the material elastic limit of 980 MPa is designed with a safety factor about 1.5. It is much less than the normal safety factor of allowable stress in engineering mechanics (Gross et al., 2011) where it is larger than 2.0. The sensor has a high sensitivity under the rated loads about 160 kN force and 30 kN.m moment. Considering the two deformation cases, design variables can be identified with the diameter (D) and the thickness (T) of the flange (Figure 3). Since the deformation mainly occurs on the elastic body and the wheel rim is fixed, the aim is to calculate the intermediate flange displacement which can be obtained using Finite Element Method (FEM) analysis under the rated loads. Figure 4 shows the design procedure and optimization result. For better understanding, the connection between wheel rim and the outer ring of elastic body is removed in the Figure. As a result, an outer diameter 385 mm, a thickness 34 mm and a proper gap 0.7 mm can be obtained by Finite Element Method (FEM) simulation. In fact, this design also provides compact assembly to retain the sensor performance, and the non-linearity of response could be reduced to some extent.

Overall design and mechatronics assembly

According to the settled overload protection mechanism of the truck WFT, the overall design including mechanical assembly and electrical system is performed and will be used to test the overload protection. As shown in Figure 5, the intermediate flange and modified rim with its welding flange form the mechanical assembly of the overload protection. The wheel rim is re-formed so that it

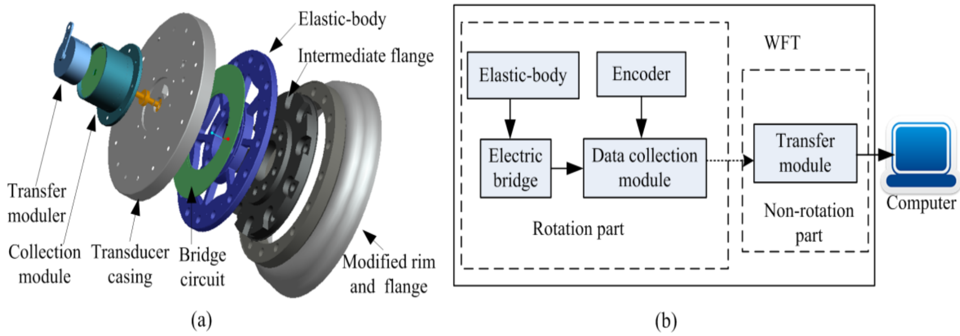

Figure 5. (a) Mechanical assembly of the WFT and (b) the electrical flowchart of WFT system.

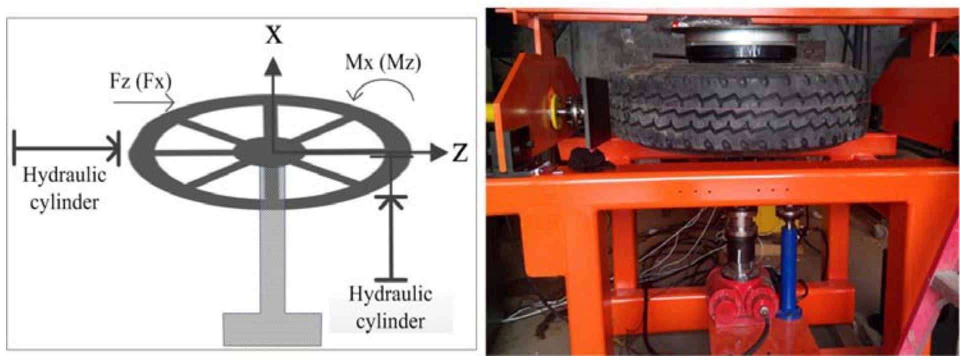

Figure 6. (a) The diagram and (b) physical graph of the overload testing platform.

connects to the outer ring of elastic-body by virtue of its welding flange via bolts. The inner ring of elastic-body connects to the designed intermediate flange and the intermediate flange connects to the wheel hub via bolts as well. This mechanical assembly will support the overload protection mechanism well.

Detailed information of the WFT system can refer to Lin et al. (2014), the overall WFT system consists of transfer module, collection module, transducer casing, elastic-body, intermediate flange, modified rim with its welding flange and some other accessories. The elastic body senses the multi-axis wheel force/moment which can be transfered by the bridge circuit. The collection module, in which an encoder is also placed to detect the rotation angle, is bounded to the transducer casing, and it will rotate with the rolling wheel. The transfer module connects to the collection module by a pair of bearings and does not rotate with the rolling wheel. As a result, the wheel force signals and rotation angle signals will be sampled by the collection module, and then the data is sent to the transfer module by wireless means. The transfer module also receives the data via wireless and transmits it to the upper computer by network bus.

EXPERIMENTAL RESULTS AND DISCUSSION

Experiment and prototyping test

To test the performance of the overload protection mechanism, a specially-made hydraulic controller platform (Figure 6) which is used for calibration can be also used for overload testing. The only difference between the calibration and overload test is that the applied loads in calibration increases to the rated loads of 120 kN or 30 kNm moment but the applied loads for overload test will not stop at the rated loads. To simulate real conditions, the whole truck wheel is bolted on the platform, and the proper tire pressure is inflated with a general value of 9 atmospheres. An analog-digital (AD) converter is used in the collection module to output the circuits signals of the applied force (Lin et al., 2014). Each load is stepwise applied individually and the AD output signals of the four channels can be recorded. The loading and unloading process will be repeated three times with an output of averaging values.

Verification and discussion

Figure 7 shows the WFT response curves under the applied loads. When each load increases in the measurement range individually, the AD output signal of the main channel shows linearity but the rest of that are close to the initial value 3000. Since the vehicle motions on road are complicated, the combined actions may occur. As the built test platform cannot support both compression and tension simultaneously in one uniaxial

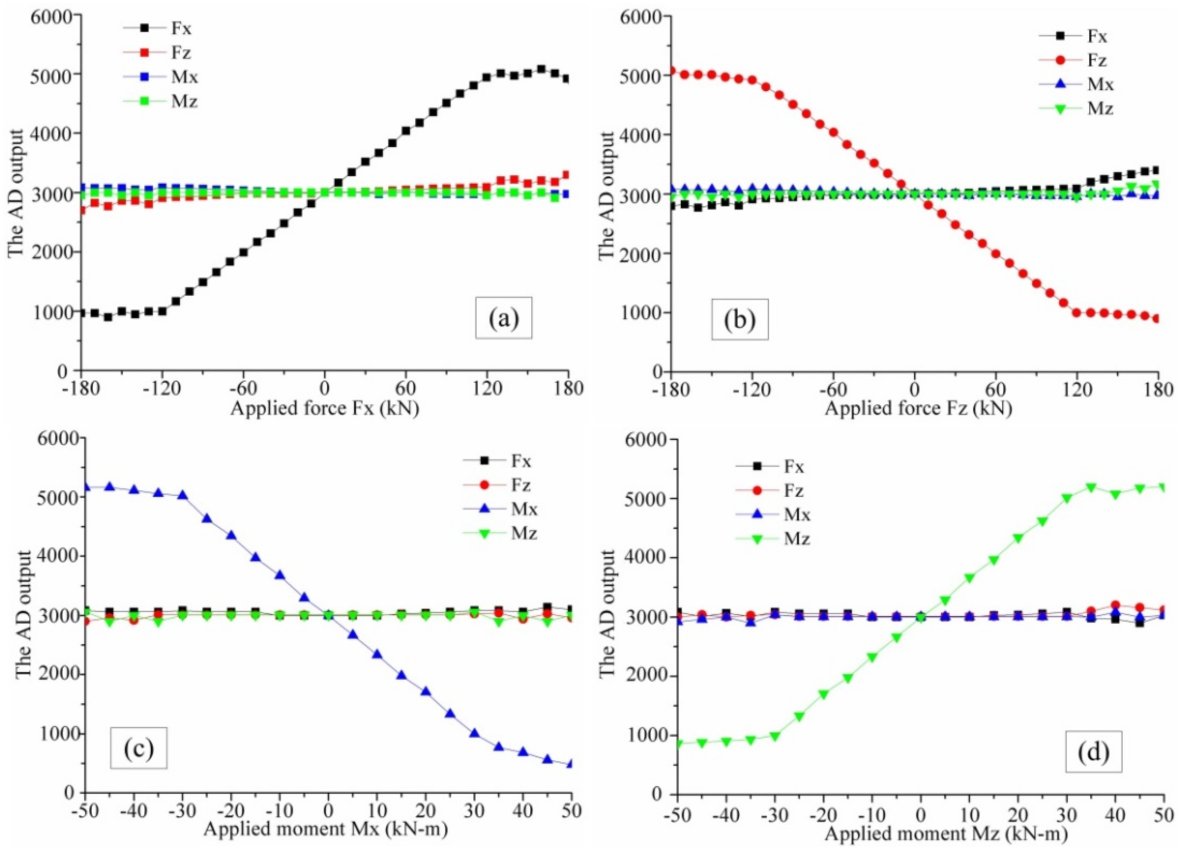

Figure 7. The WFT output curves under each applied load individually.

hydraulic cylinder, two behaviours which combine F_x with M_x and combine F_z with M_z, are tested, respectively. Due to the measuring range difference and unit discrepancy between applied overload force and overload moment, each individual load are depicted separately in Figure 7 for better understanding. Result indicates that the coupling interferences between the multi-dimensions are quite little, and therefore the strain gauge locations are well assigned. However, when the applied loads increase over the rated loads of 120 kN force and 30 kNm moment, the overload protection mechanism starts to take effect. The strain and deformation of the elastic body will be kept and therefore the AD output of the main channel does not increase any more. If considering the safety factor of elastic strength limit of the sensor body, the overloads at ranges of (-180 kN, 180 kN) and (-45 kNm, 45 kNm) are successfully prevented. Since the rest of AD outputs are slightly increasing, it is foreseeable and understandable that the overload protection mechanism makes the intermediate flange contact with the wheel rim and the applied load will be continuously increasing, while the nonlinearity of elastic body deformation may result in the increasing coupling errors. In summary, the overload protection mechanism indeed prevents the overload damage at X and Z direction for the heavy truck WFT and the sensor sensitivity is guaranteed as well. Figure 1 also depicts the WFT with the overload protection which is assembled into a heavy dump truck. Owning to the overload protection, the sensor shows an excellent performance.

CONCLUSIONS AND SUGGESTIONS

In the present work, a mechanical approach of overload protection mechanism for wheel force transducer is introduced and applied to a heavy truck so that the overload at X and Z direction can be avoided. Not only the overload damage is prevented by using a tailor-designed intermediate flange which is installed between wheel hub and the elastic body, but also the WFT sensor performance is guaranteed under the rated measurement range. By using a hydraulic calibration platform, experimental test is conducted and results show that the proposed overload protection mechanism performed well. The linear relations between applied load and WFT output is kept well under the measurement range of (-120 kN, 120 kN) and (30 kNm, 30 kNm). Meanwhile, the overloads of ±180 kN and ±50 kNm applied on the WFT are prevented from damage that the AD output keeps unchanged. It confirmed that the overload protection mechanism is well designed and established for the heavy truck WFT.

Conflict of interest

The author(s) declare that there is no conflict of interest.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers for their useful comments and suggestions. The work was supported Natural Science Foundation of China (No.51305078, 51205413) and Suzhou Science and Technology Project (No. SYG201303).

REFERENCES

Gross D, Hauger W, Schröder J, Wall WA, Bonet J (2011). Engineering Mechanics 2-Mechanics of Materials. Springer.

Hong HJ, Strumpfer SD (2011). Virtual road load data acquisition for twist axle rear suspension. SAE Technical Paper, 2011-01-0026. http://dx.doi.org/10.4271/2011-01-0026

Kadhim NA, Bdullah SA, Ariffin AK (2011). Effect of the fatigue data editing technique associated with finite element analysis on the component fatigue design period. Mater. Des. 32:1020-1030. http://dx.doi.org/10.1016/j.matdes.2010.07.029

Kuchler M, Schrupp R (2001). Multiaxial motorcycle wheel load transducer (in German). VDI Berichte. 1616:249-275.

Lin GY, Pang H, Zhang WG, Wang D, Feng LH (2014). A self-decoupled three-axis force sensor for measuring the wheel force. Proc. IMechE, Part D: J. Automobile Eng. 228:319-334. http://dx.doi.org/10.1177/0954407013508278

Lin GY, Zhang WG, Yang F, Pang H, Wang D (2013). An initial value calibration method for the wheel force transducer based on memetic optimization framework. Math. Probl. Eng. 2013:275060. http://dx.doi.org/10.1155/2013/275060

Pavkovic D, Deur J, Hrovat D, Burgio G (2009). A switching traction control strategy based on tire force feedback. In: IEEE conference on control applications and intelligent control, Saint Petersburg, Russia, 8–10 July 2009, pp. 588-593. New York: IEEE. http://dx.doi.org/10.1109/CCA.2009.5281121

Pytka JA, Tarkowski P, Fijałkowski S, Budzyński P, Dąbrowski J, Kupicz W, Pytka P (2011). An instrumented vehicle for offroad dynamics testing. J. Terramechanics. 48:384-395. http://dx.doi.org/10.1016/j.jterra.2011.06.003

Song AG, Wu J, Qin G (2007). A novel self-decoupled four degree of freedom wrist force/torque sensor. Measurement 40:883-891. http://dx.doi.org/10.1016/j.measurement.2006.11.018

Wang D, Lin GY, Zhang WG, Zhao N, Pang H (2014). The new method of initial calibration with the wheel force transducer. Sensor Review. 34(1): 98-109. http://dx.doi.org/10.1108/SR-12-2012-734

Wang Y, Zhang WG, Wang H (2011). Application of wavelet method with nonlinear threshold control in vehicle wheel force signal denoising. In Proceedings of the 4th International Conference on Intelligent Computation Technology and Automation (ICICTA '11), pp. 957-960, Shenzhen, China, March. http://dx.doi.org/10.1109/ICICTA.2011.525

Weiblen W, Kockelmann H, Burkard H (1999). Evaluation of different designs of wheel force transducers (part II). SAE Technical Paper, 1999-01-1037. http://dx.doi.org/doi:10.4271/1999-01-1037

Zhang LB, Liu HL, Zhang HT, Xu YZ (2011). Component load predication from wheel force transducer measurements. SAE Technical Paper, 2011-01-0737.http://dx.doi.org/10.4271/2011-01-0737