Determination of linear and angular displacements of steered wheel of a car

K Wach

1 Institute of Automobiles and Internal Combustion Engines, Faculty of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Cracow, Poland

krzysztof.wach@mech.pk.edu.pl

Abstract. The paper describes a test bench measurements of linear and angular displacements of steered wheel of a car. The measurements were conducted using a functional model of prototype measuring instrument. The theoretical principles of the measurement are discussed and the analysis of the results is performed.

1. Introduction

The Modern cars are being constantly developed. The automotive industries, as well as the research and development centres, conduct their researches to improve safety, reduce fuel consumption and minimize harmful effects on the environment. On the other hand, the development of diagnostic methods is ongoing [1-5].

If it comes to safety, a special emphasis is put on an improvement of vehicles chassis, especially suspension and steering systems.

In addition to numerical analyses [6-10], test bench experiments [11,12] and road tests are also carried out [13-15]. The results of these tests allow for example for the optimization of the suspension structure or for the determination of the car handling characteristics [16,17]. During this type of tests, the vehicle is instrumented with a number of measuring sensors that record its speed, acceleration acting on it, etc. An important element of research on the development of suspension systems is the measurement of linear and angular displacements of the wheels relative to the vehicle body. The aim of these tests is to improve the handling properties of cars and ensure the best stability and driveability.

2. Theoretical basis of the measurement

The presented work deals with the measurement of displacements of steered wheel in relation to the body of a vehicle. The measurement was realized using a functional model of a prototype measuring instrument. Figure 1 shows a schematic diagram of the mechanism of the instrument.
Figure 1. The scheme of the mechanism of a functional model of the measuring instrument.
1– External plate attached to a body, 2– Internal plate fixed to a wheel, 3– Bearing hub, 4– Wheel rotation axis. Detailed notation described in text

The mechanism consists of external and internal plate, connected with nine links $d_i$, $i=1–9$ with linear displacement sensors $s_i$, $i=1–9$ built in. The inner plate is connected to the axis of rotation of a wheel using bearing hub. The external plate is fixed to the vehicle body. The instrument’s links are connected to the external plate using ball joins named $H_i$, $i=1–9$ and to the internal plate using special construction ball joints $D_j$, $j=1–3$. The measurement is based on logging the changes of the lengths of instrument’s links $s_i$, $i=1–9$. Knowing this changes, it is possible to determine the coordinates of the centres of the ball joints $D_j$, $j=1–3$ according to systems of equations (1) to (3) [18-20].

\[
\overrightarrow{r}_{D_1H_i}^T \overrightarrow{r}_{D_1H_i} = (l_{D_1H_i} + s_i)^2, \quad \text{where } \begin{cases} i = 1, \\ i = 4, \\ i = 5, \end{cases}
\]

(1)

\[
\overrightarrow{r}_{D_2H_i}^T \overrightarrow{r}_{D_2H_i} = (l_{D_2H_i} + s_i)^2, \quad \text{where } \begin{cases} i = 2, \\ i = 6, \\ i = 7, \end{cases}
\]

(2)

\[
\overrightarrow{r}_{D_3H_i}^T \overrightarrow{r}_{D_3H_i} = (l_{D_3H_i} + s_i)^2, \quad \text{where } \begin{cases} i = 3, \\ i = 8, \\ i = 9, \end{cases}
\]

(3)

Having them, the coordinates of two points $D_n$, $n=4,5$ defining the axis of rotation of a wheel can be calculated using equation (4).

\[
\overrightarrow{r}_{D_jD_n}^T \overrightarrow{r}_{D_jD_n} = (l_{D_jD_n})^2, \quad \text{where } j = 1–3, n = 4,5
\]

(4)

Now it is possible to determine a unit vector $e_k$, lying on the wheel rotation axis, needed to calculate steering $\delta$ and camber $\gamma$ angles and linear displacements of steered wheel $\Delta K_y$. (See equations (5) and (6)).
\[ \delta = -\arctg \left( \frac{e_{kx}}{e_{ky}} \right), \]  
\[ \gamma = -\arcsin(e_{kz}). \]  

A detailed description of the theoretical basis of measurement has been presented in works [19-23].

3. Measurement of the displacements of steered wheel

The changes of linear and angular positions of steered wheel were measured on a test bench shown in figure 2.

The tests were performed on the fifth generation Volkswagen Passat Variant, equipped with an independent multi-link suspension in a front axle and a twist-beam suspension in a rear axle. The measurements consisted of the registration of changes of the lengths of the prototype instrument’s links during turning the wheels at three different suspension deflections \( q \): neutral position, 57 mm rebound and 43 mm compression position. The data registration was performed at approximately every 2\(^\circ\) of steering angle. Those lengths were used for calculation of rotation and translation of the front left wheel of the car, according to the section 2 of this article. Additionally, a displacement of steering rack \( u_p \) was measured with an optical linear displacements sensor.

Figure 2. An overview of the test bench. The tested car, the functional model of the measuring instrument, a battery, an analogue-to-digital converter and a computer for data registration are visible.

Figure 3 shows the scheme of measuring configuration. All data went to an analogue-to-digital converter and then were registered on a hard drive of a computer.

Regardless of the measurements with the prototype instrument, a reference measurements, consisted of measuring the steering angle using a universal protractor with a vernier scale of 0\(^\circ\)05’, were performed simultaneously.
4. The sample results

4.1. The elongations of links of the instrument
The determination of lateral and linear displacements of steered wheel was based on the measurements of changes of the prototype instrument’s links elongations. Figure 4 shows the sample elongations of the two links $s_1$ and $s_7$ against the steering rack displacement $u_p$ and suspension deflection $q$.

![Figure 4](image)

(a) (b)

Figure 4. The sample changes of lengths of the prototype instrument’s links against the steering rack displacement $u_p$ and suspension deflection $q$.

4.2. The suspension characteristics
The changes of instrument’s links lengths $s_i$, for $i=1–9$, were used to determine the dependencies of steering angle $\delta$, camber angle $\gamma$ and the lateral displacements of steered wheel $\Delta K_y$ against steering rack displacement $u_p$ and suspension deflection $q$. The sample dependencies are presented in the Figure 5.

![Figure 5](image)

(a) (b) (c)
Figure 5. The sample dependencies of steering angle $\delta$ (a), camber angle $\gamma$ (b) and lateral displacements of steered wheel $\Delta K_y$ (c) against steering rack displacement $u_p$ and suspension deflection $q$.

The results obtained using the functional model of prototype instrument were compared with the results of reference measurements conducted using an universal protractor, the results of this comparison are presented in figure 6.

Figure 6. The comparison between the results of measurements with a prototype instrument and the reference measurements with an universal protractor. The dependencies of steering angle $\delta$ against the steering rack displacement $u_p$ for three different suspension deflections $q$: (a) - neutral position of suspension, (b) - 57 mm rebound, (c) - 43 mm compression.
5. Summary
The task of presented preliminary measurements was the evaluation of the proposed method of determination of linear and angular displacements of steered wheel. The method is based on the measurement of changes of lengths of instrument’s links $s_i$. The values of these changes are then inserted into the system of nine equations, whose solution gives the coordinates of three points $D_i$ lying on the plane of the wheel. Knowing these coordinates it is possible to determine the steering angle $\delta$ and camber angle $\gamma$, as well as the lateral displacements of steered wheel $\Delta K_y$ against the steering rack displacement $u_p$ and suspension deflection $q$.

Simultaneously, the reference measurements of steering angle $\delta$ were conducted. The comparison between the obtained results shows good accuracy of proposed measurement method. The qualitative and quantitative similarities between the results of both steering angle measurements are visible.

Although the method seems to be accurate enough for stationary measurements, it would be quite difficult to use such measuring instrument for a dynamic road tests. That’s why, the presented instrument is only a functional model of a real device. The results of presented work and drawn conclusions will be used for the further development of presented method of measurement.

References
[1] Gajek A and Strzępek P 2016 The analysis of the accuracy of the wheel alignment inspection method on the side-slip plate stand IOP Conf. Ser.: Mater. Sci. Eng. 148 012037
[2] Maniowski M, Para S and Knapczyk M 2016 Modernisation of a test rig for determination of vehicle shock absorber characteristics by considering vehicle suspension elements and unsprung masses IOP Conf. Ser.: Mater. Sci. Eng. 148 012020
[3] Seling M, Shi Z, Ball A and Schmidt K 2012 A modern diagnostic approach for automobile system condition monitoring J. Phys.: Conf. Ser. 364 012013
[4] Szczyżynski-Sala W and Dobaj K The analysis of diagnostics possibilities of the Dual-Drive electric power steering system using diagnostics scanner and computer method IOP Conf. Ser.: Mater. Sci. Eng. 148 012054
[5] Janczur R Proposal to use vibration analysis steering components and car body to monitor, for example, the state of unbalance wheel IOP Conf. Ser.: Mater. Sci. Eng. 148 012009
[6] Jonnson J 1991 Simulation of dynamical behaviour of a front wheel suspension Vehicle System Dynamics 20 269-81
[7] Ammon D, Gisper M, Rauh J and Wimmer J 1997 High performance system dynamics simulation of the entire system tire-suspension-steering-vehicle Vehicle System Dynamics 27 435-55
[8] Bauman E A, McPhee J J and Calami P H 1998 Application of genetic algorithms to the design optimization of an active vehicle suspension system Computer Methods in Applied Mechanics and Engineering 163 87-94
[9] Kowalski M S 2016 Kinematic analysis of four-link suspension of steering wheel by means of equation sets of geometrical constraints with various structure IOP Conf. Ser.: Mater. Sci. Eng. 148 012013
[10] Korzeniowski D and Ślaski G 2016 Method of planning a reference trajectory of a single lane change manoeuvre with Bezier curve IOP Conf. Ser.: Mater. Sci. Eng. 148 012012
[11] Ślaski G and Pikosz H 2011 The influence of damping changes on vertical dynamic loads of wheel - Experimental investigations Archives of Transport 23 239-47
[12] Wach K 2018 Measurements of the angular and linear displacements of steered wheel Technical Transactions M 115 219–27
[13] Lozia Z 1992 An analysis of vehicle behaviour during lane-change manoeuvre on an uneven road surface Vehicle System Dynamics 20 417-31
[14] Szczyrzyński-Sala W and Lubas J 2016 Evaluation the course of the vehicle braking process in case of hydraulic circuit malfunction IOP Conf. Ser.: Mater. Sci. Eng. 148 012055
[15] Żębala J, Wach W, Ciępka P and Janczur R 2016 Determination of critical speed, slip angle and longitudinal wheel slip based on yaw marks left by a wheel with zero tire pressure SAE
[16] Shim T and Velasumy P C 2011 Improvement of vehicle roll stability by varying suspension properties *Vehicle System Dynamics* 49 129-52

[17] Mántaras D A and Luque P 2012 Virtual test rig to improve the design and optimisation process of the vehicle steering and suspension systems *Vehicle System Dynamics* 50 1563-84

[18] Grzyb A 1992 On a perturbation method for the analysis of the kinematics of mechanisms *Z. Angew. Math. Mech.* 72 615-18

[19] Struski J and Wach K 2012 Theoretical basis of determining the translation and rotation of steering wheel stub axle *Engineering Transactions* 60 41–54

[20] Struski J and Wach K 2015 Theoretical basis of determination of the linear and angular displacements of steered wheel *Logistyka* 4 5840–49

[21] Struski J and Wach K 2012 Analysis of the measuring instrument's mechanism for determination of translation and rotation of steered wheel *Technical Transactions* M 3 87–100

[22] Wach K 2016 The theoretical analysis of an instrument for linear and angular displacements of the steered wheel measuring *IOP Conf. Ser.: Mater. Sci. Eng.* 148 012029

[23] Wach K and Kupiec R 2017 Determination of initial configuration of mechanism of an instrument for measuring the translation and rotation of a steered wheel *Technical Transactions* M 6 197–207