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One solution for measurement of wheel-rail contact forces

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Abstract

This paper presents one solution for measurement of wheel-rail contact forces by using instrumented wheelset developed at the Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia. In addition to measurement of wheel-rail contact forces which is necessary for assessment of safety against derailment in accordance to the standards UIC 518 and EN 14363, the developed solution enables measurement of location of wheel-rail contact point. The optimal ways for solution of key problems in development of instrumented wheelsets are proposed. Identification of parameters to be measured is based on the method of blind signal separation (BSS) using independent component analysis (ICA). The developed solution is validated by experimental testing of prototype of instrumented wheelset on specially designed test stand. It was concluded that developed solution enables reliable testing of safety against derailment of railway vehicles, while measurement error of derailment coefficient is less than 10%, that corresponding to the latest world solutions.

Keywords: measurement, wheel-rail contact forces, derailment coefficient, contact point position, instrumented wheelset.

Nomenclature

Q	Vertical force in wheel-rail contact
Y	Lateral force in wheel-rail contact
Y/Q	Derailment coefficient
y_{cp}	Coordinate of contact point
U_A/U_E	Output signal from Wheatstone bridge
ε	Strain
A	Matrix of mixing
W	Matrix of separation
P	Matrix of values of parameters in wheel-rail contact applied on the test stand in calibration process
S	Matrix of values of signals recorded at the actions of applied loads in calibration process
M	Moment M of forces Q and Y in relation to the nominal contact point
z_{cp}	Vertical coordinate of contact point
$\tilde{Q}$	Estimated value of Q force at the exit from inverse identification algorithm
$\tilde{Y}$	Estimated value of Y force at the exit from inverse identification algorithm
$\tilde{M}$	Estimated value of moment M at the exit from inverse identification algorithm
$\tilde{y}_{cp}$	Estimated value of y_{cp} at the exit from inverse identification algorithm

1. Introduction

The most reliable way for determination of lateral and vertical wheel-rail contact forces Y and Q is experimental testing or measurement which is prescribed by the international standards UIC 518 and EN14363 [1, 2]. The measurement is based on the instrumented wheelsets which are equipped with appropriate sensors (usually strain gauges) and which are mounted on the tested vehicle. During the running, instrumented wheelset provides measuring signal Y/Q which is the basis for assessment of derailment risk of the tested vehicle. The mentioned standards do not define the technical details and the required accuracy, so there are a number of different measurement methods and technical solutions of instrumented wheelsets [3]. There are many significant differences related to the solution of the most important problems such as locations, layout, number and way of connection of strain gauges, inverse identification, way of calibration, etc. Today's solutions are mainly based on standard wheelsets with monoblock wheels equipped with strain gauges, and without any subsequent machining [4]. The strain gauges can be placed on the inner and the outer side of the wheel at specific radial distances from the center point. The determination of optimal radial distances is usually based on the FEM calculations of wheel strains, which is one of the main problems in development of instrumented wheelset [5]. Furthermore, there are very significant problems related to the determination of optimal layout, number and way of connection of strain gauges into Wheatstone bridges, solving the way of calibration, development of inverse identification algorithm, signal transmission, power supply, etc. [6, 7]. The main aim in solving all these problems in development of instrumented wheelset is to reduce the measurement error which at modern instrumented wheelsets is less than 10% [8, 9]. With such motivation, authors of this paper are developed a unique and universal solution for measurement of wheel-rail contact forces by using instrumented wheelset whose prototype is located at the Faculty of Mechanical and Civil Engineering in Kraljevo, Serbia [3, 10]. The aim of this paper is to present this solution in order to contribute the overall development of experimental testing of safety against derailment of railway vehicles.

2. Locations of strain gauges

In first phase of development of instrumented wheelset, the wheel model is formed. Standard wheelset made of Bonatrans Group for freight vehicles and normal track gauge (1435 mm) is used as a platform. The model is created in ANSYS software package and consists of 194516 finite elements and 323535 nodes. The key fact in stress-strain analysis is that for an arbitrary contact point position on the wheel, overall strain can be expressed as linear combination of strains caused by the individual action of forces Q and Y. Thus, it allows that wheel stresses and strains can be analyzed for individual actions of forces Q and Y, in different contact point positions. The stress-strain analysis should lead to the determination of locations on the wheel disc with highest sensitivity to the individual actions of three parameters to be measured (vertical force Q, lateral force Y and contact point position y_{cp}). For stress-strain analysis, three representative locations of wheel-rail contact point are selected (Fig. 1). The wheel calculation is performed for six different load cases as given in table 1.

Table 1. Load cases for wheel calculation

Load case	Q [kN]	Y [kN]	y_{cp} [cm]	
1Q	100	0	CP1	0
1Y	0	50	CP1	0
2Q	100	0	CP2	3,5
2Y	0	50	CP2	3,5
3Q	100	0	CP3	-3,5
3Y	0	50	CP3	-3,5

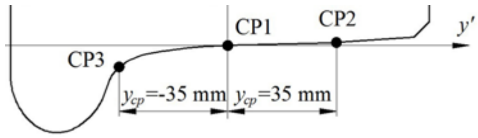


Fig. 1 Locations of wheel-rail contact point for stress-strain analysis

On the basis of the FEM results, the comparative diagrams of equivalent strain ε_e on the inner and the outer side of the disc in function of distance from the wheel center z, are formed (Fig. 2). The analysis is performed for vertical plane which contains center of the wheel and contact point position.

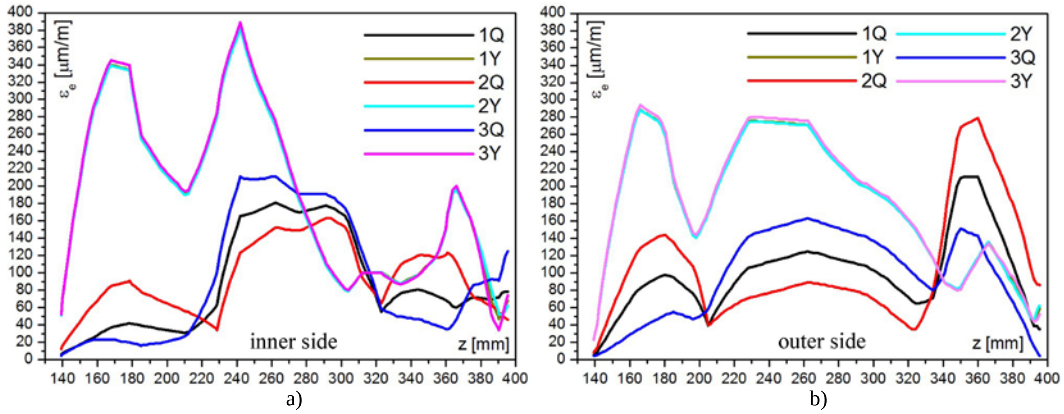


Fig. 2 Comparative diagrams of equivalent strain on inner (a) and outer side of the disc (b)

Besides what they enabled exact detection of places with highest sensitivity to individual actions of parameters to be measured, formed diagrams has shown that influence of contact point position on the disc strains caused by Y force can be neglected. It was found that for accurate determination of values of parameters Q, Y and y_{cp}, minimum of four independent measuring signals or four Wheatstone bridges are necessary. Also, the diagrams has shown very important fact that at all radial distances on the disc there will be significant degree of mixing of influence of given parameters in output measurement signals. Therefore, individual influences of parameters being measured should be determined on the basis of mixed output signals from four independent Wheatstone bridges. For this purpose, the authors chose the application of the method of Blind Source Separation (BSS) using Independent Component Analysis (ICA). Therefore, optimal radial distances are chosen according to the criteria of maximum disc sensitivity to the effects of parameters to be measured (Fig. 3). It is important to note that formed FEM model of the wheel and results of stress-strain analysis are verified by experimental tests on real object [3, 10].

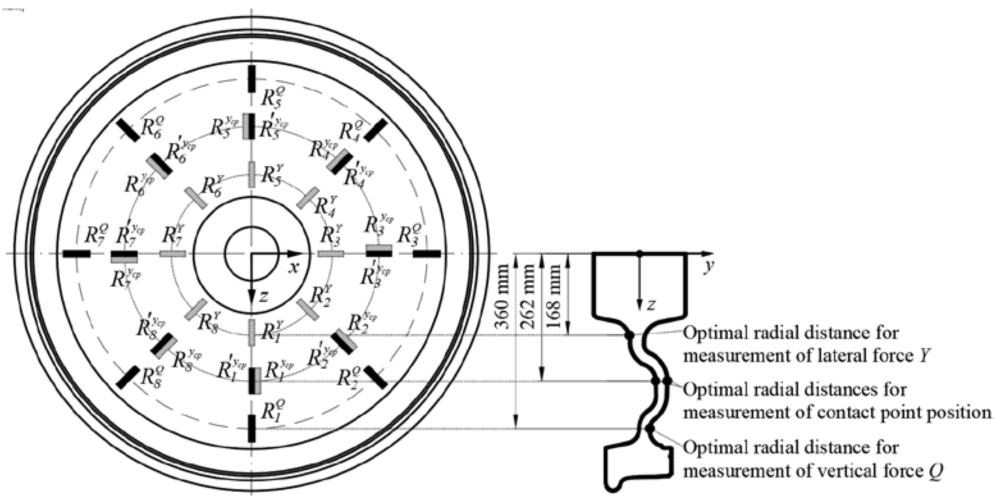


Fig. 3 Optimal radial distances, layout and number of strain gauges

3. Layout, number and way of connection of strain gauges

In order to obtain optimal solution, different variants of layout, number and way of connections of strain gauges are analyzed. More precisely, variants with 1, 2, 4, 8, 12 and 16 strain gauges on each of previously determined four optimal radial distances, for three different running speeds of 50, 100 and 150 km/h, are analyzed. For each variant, following parameters are analyzed: time that elapses between two neighboring representative values of signal, distance traveled between two neighboring representative values of signal and frequency of transit of the strain gauges above wheel-rail contact point. A special attention is devoted to determining whether a given variants provide compensations of influences of centrifugal acceleration and temperature. The results of analysis has shown that optimal variant is those with 8 strain gauges per one radial distance [3, 10]. It provides sufficient reliability of the measurement and is not much expensive and complex for technical realization of the measurement system. Optimal layout and number of strain gauges are shown in Fig. 3.
The main objective in selection of optimal way of connection of strain gauges is to obtain the highest possible values of the output signals from Wheatstone bridges in moments of their crossings above the contact point. In this aim, values of strains on locations of the strain gauges, obtained using the FEM model, are analyzed. The analysis of the output signals has shown that the best solution is that all eight strain gauges on the one radial distance are connected in the one full Wheatstone bridge. Largest values of the output signals for different load combinations are obtained when two neighboring strain gauges on a given radial distance are connected in series in the same bridge circuit. In case of constant values of wheel-rail contact forces, this ensures that Wheatstone bridge shows identical discrete values of the measuring signal in the moments when strain gauges passing above the contact point. In addition, it provides the compensations of influences of centrifugal acceleration and temperature. Optimal way of connection of strain gauges is shown in Fig. 4.

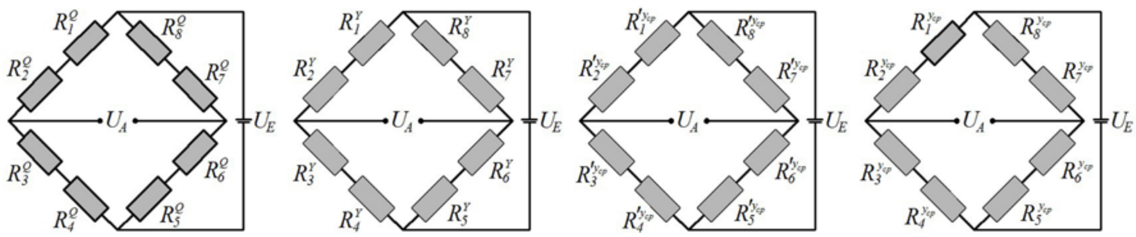


Fig. 4 Optimal way of connection of strain gauges

In general case, the output signals can be determined using the following expression:

$$\left(\frac{U_A}{U_E}\right) = \frac{k}{4}\left(\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4 + \varepsilon_5 + \varepsilon_6 - \varepsilon_7 - \varepsilon_8\right) \tag{1}$$

It is important to note that expression (1) and FEM results provide reconstruction of output signals for specific load cases.

4. Inverse identification

Since the condition of application of the method of BSS using ICA is that number of sensors (in this case Wheatstone bridges) is equal to number of original input signals to be measured, beside parameters Q, Y and y_{cp}, the fourth – fictive parameter Q+Y is introduced [3, 10]. The processes of mixing and separation of signals in developed algorithm are represented with block diagrams in Fig. 5.
The mixing process can be mathematically defined as follows:

$$\mathbf{s}(t) = \mathbf{A} \cdot \mathbf{p}(t) \tag{2}$$

where:
$\mathbf{s}(t)$ – vector of output mixed signals from Wheatstone bridges, which has the following form:

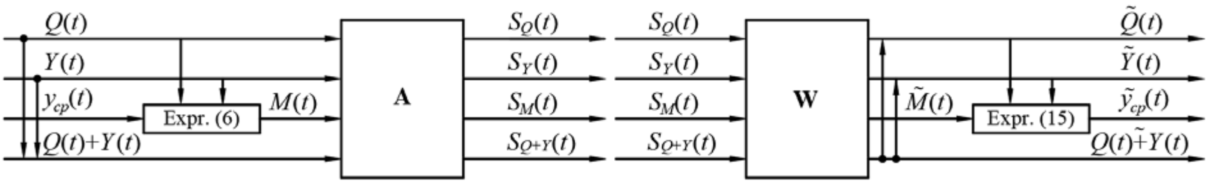
$$\mathbf{s}(t)=\begin{bmatrix} S_Q(t) & S_Y(t) & S_M(t) & S_{Q+Y}(t) \end{bmatrix}^T \tag{3}$$

A – unknown square mixing matrix, which has the following form:

$$\mathbf{A}=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \tag{4}$$

p(t) – vector of original source signals of unknown parameters in wheel-rail contact to be measured, which has the following form:

$$\mathbf{p}(t)=\begin{bmatrix} Q(t) & Y(t) & M(t) & Q(t)+Y(t) \end{bmatrix}^T \tag{5}$$



a) b)

Fig. 5 Block diagrams of signals mixing (a) and signals separation (b)

The moment M is introduced in order to solve the problem of non-linearity of the model that is caused by the nonlinear wheel profile. Its determination is performed in accordance with Fig. 6 and from the following expression:

$$M=-Q\cdot y_{cp}-Y\cdot z_{cp} \tag{6}$$

Since the moment M is parameter of wheel load, its relationship with wheel strains (output signals) will have a linear character. Hence, mixed signals from Wheatstone bridges in the general case can be expressed as follows:

$$S_m=f\left(Q,Y,M\right)=f\left(Q,0,0\right)+f\left(0,Y,0\right)+f\left(0,0,M\right) \tag{7}$$

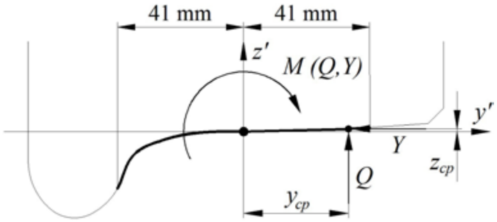


Fig. 6 Moment M of forces Q and Y in relation to the nominal contact point (y_{cp}=0)

The signals separation process and estimation of parameters being measured can be defined as follows:

$$\tilde{\mathbf{p}}(t)=\mathbf{W}\cdot\mathbf{s}(t) \tag{8}$$

where:
$\tilde{\mathbf{p}}(t)$ – vector of estimated original source signals of parameters being measured, obtained from inverse identification algorithm, which has the following form:

$$\tilde{\mathbf{p}}(t)=\left[\tilde{Q}(t) \quad \tilde{Y}(t) \quad \tilde{M}(t) \quad Q(t)\tilde{+}Y(t)\right]^T \tag{9}$$

W – unknown square separation matrix which is inverse mixing matrix $\mathbf{W}=\mathbf{A}^{-1}$, or:

$$\mathbf{W}=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}^{-1} \tag{10}$$

$\mathbf{s}(t)$ – vector of output mixed signals from the four Wheatstone bridges which has a form (3)
Based on the results of the calibration, unknown separation matrix **W** is determined by the following expression:

$$\mathbf{W}=\mathbf{P}\cdot\mathbf{S}^{-1} \tag{11}$$

where:
P – matrix of values of parameters in wheel-rail contact applied on the test stand in calibration process (or in model if calibration is realized using FEM results),
S – matrix of values of signals from Wheatstone bridges recorded at the actions of applied loads in calibration process (or calculated if calibration is performed using FEM results).
The forming of square matrixes **P** and **S** is based on the four different measurements which should include representative cases of the wheel loads. Based on that, the matrix **P** has the following form:

$$\mathbf{P}=\begin{bmatrix} Q_1 & Q_2 & Q_3 & Q_4 \\ Y_1 & Y_2 & Y_3 & Y_4 \\ M_1 & M_2 & M_3 & M_4 \\ Q_1+Y_1 & Q_2+Y_2 & Q_3+Y_3 & Q_4+Y_4 \end{bmatrix} \tag{12}$$

For such defined matrix P, the following matrix S is:

$$\mathbf{S}=\begin{bmatrix} S_{Q1} & S_{Q2} & S_{Q3} & S_{Q4} \\ S_{Y1} & S_{Y2} & S_{Y3} & S_{Y4} \\ S_{M1} & S_{M2} & S_{M3} & S_{M4} \\ S_{Q_1+Y_1} & S_{Q_2+Y_2} & S_{Q_3+Y_3} & S_{Q_4+Y_4} \end{bmatrix} \tag{13}$$

After signals separation and determination of parameters at the output of inverse identification algorithm, coordinate y_{cp} should be determined, while simultaneously coordinate z_{cp} is unknown. For a given wheel profile UIC ERRI-S1002, the best analytical description of relation between y_{cp} and z_{cp} is following:

$$\begin{aligned} z_{cp} &= 0,00221+0,00443y_{cp}+0,01305y_{cp}^2+0,01106y_{cp}^3-0,00874y_{cp}^4-1,91369\cdot10^{-4}y_{cp}^5+ \\ &+9,20203\cdot10^{-4}y_{cp}^6-5,61175\cdot10^{-5}y_{cp}^7-3,7586\cdot10^{-5}y_{cp}^8+4,72959\cdot10^{-6}y_{cp}^9 \end{aligned} \tag{14}$$

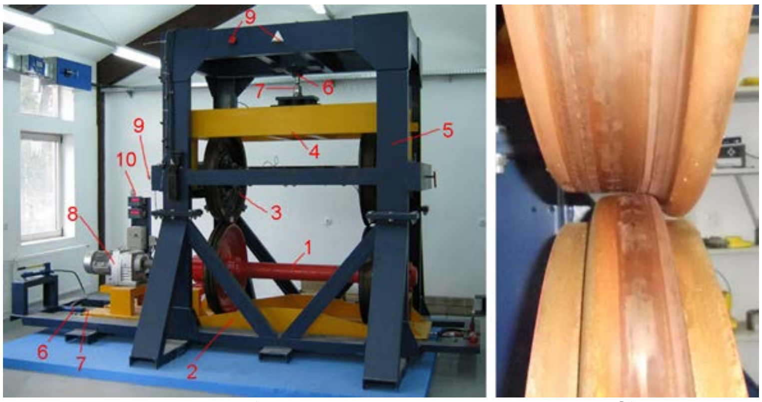
Combining the expressions (14) and (6) and additional arranging gives the mathematical relation which, based on the signals $\tilde{Q}$, $\tilde{Y}$ and $\tilde{M}$, determines the coordinate of contact point $\tilde{y}_{cp}$:

$$\begin{aligned} &\tilde{M}+0,00221\cdot\tilde{Y}+\left(\tilde{Q}+0,00443\cdot\tilde{Y}\right)\cdot\tilde{y}_{cp}+0,01305\cdot\tilde{Y}\cdot\tilde{y}_{cp}^2+0,01106\cdot\tilde{Y}\cdot\tilde{y}_{cp}^3- \\ &-0,00874\cdot\tilde{Y}\cdot\tilde{y}_{cp}^4-1,91369\cdot10^{-4}\cdot\tilde{Y}\cdot\tilde{y}_{cp}^5+9,20203\cdot10^{-4}\cdot\tilde{Y}\cdot\tilde{y}_{cp}^6- \\ &-5,61175\cdot10^{-5}\cdot\tilde{Y}\cdot\tilde{y}_{cp}^7-3,7586\cdot10^{-5}\cdot\tilde{Y}\cdot\tilde{y}_{cp}^8+4,72959\cdot10^{-6}\cdot\tilde{Y}\cdot\tilde{y}_{cp}^9=0 \end{aligned} \tag{15}$$

Since the wheels profiles of instrumented wheelset are changed under the influence of wear, it is important to perform the periodically recording the actual profile and, if necessary, correcting the coefficients in given equations. Before production of prototype of instrumented wheelset, the developed algorithm of inverse identification is tested by using the results of FEM model. Obtained results for various load cases have confirmed its extremely high accuracy and applicability in the process of measurement of wheel-rail contact forces and contact point position by using the instrumented wheelset [3, 10].

5. Experimental results and discussion

Based on the previous results, the prototype of instrumented wheelset is developed and tested. It is composed of following electronic devices: 8 full Wheatstone bridges with 8 strain gauges, 4 units for excitation and data acquisition, unit for wireless radio connection with electronic unit for receiving and storing of measuring signals; and battery unit. The measurement and determination of angular position is based on two two-axis accelerometers, one for rotational speeds less than 5 rpm/sec, and second for rotational speeds greater than 5 rpm/sec. The tests were carried out in laboratory on a special test stand (Fig. 7a) which provides simulation of wheel-rail contact and independent application of forces Q and Y, as well as the changing the contact point position (Fig. 7b) [11]. Application of Q and Y forces is realized using the hydraulic cylinders (6) which are operated by a hand pumps, while registering the values of applied forces is performed using the force converters (7).



1- lower wheelset
2- horizontally movable carrier of lower wheelset
3- upper wheelset (instrumented wheelset)
4- vertically movable carrier of upper wheelset
5- supporting structure
6- hydraulic systems for application of the vertical and lateral forces
7- converters for registering the values of vertical and lateral forces
8- electric motor with gear unit and Cardan coupling
9- safety systems
10- control unit

a) b)

Fig. 7 Overall view of the test stand (a) and a close look at the contact point position (b)

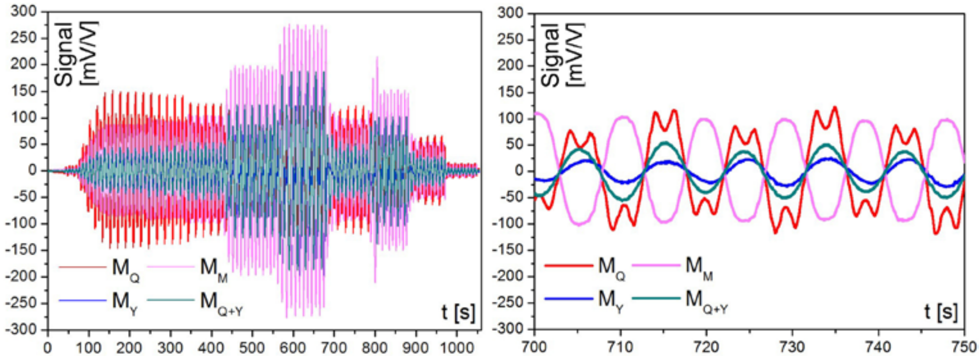
In the first phase of experimental tests, the static tests are performed [3, 10]. The tests have confirmed linearity between output signals and applied wheel-rail contact forces. At the same time, they have shown that there is a certain measurement uncertainty which is manifested by a certain degree of dissipation of measurement results in relation to the ideal relationship between the signal and force. The measurement uncertainty comes from the noise in the electronic components of the measuring system. Consequently, signal to noise ratio has a key influence of the measurement accuracy.

In the next phase, the calibration is performed. Since the system is linear, for formation of separation matrices it is necessary and sufficient to carry out the four characteristic measurements during the calibration. During these measurements, the values of introduced parameters in wheel-rail contact and output signals are registered. On this basis, according to the expression (9) the separation matrices for eight angular positions are obtained.

Finally, accuracy of signals separation at the real object, for different load cases and combinations of parameters in wheel-rail contact applied on the test stand, is tested [3, 10]. Among other load cases (which cannot be presented because of limited space), prototype of instrumented wheelset is subjected to the loads on the test stand, which corresponding to the loads of wheel for loaded 4-axles freight wagon. The output signals from Wheatstone bridges and results of inverse identification for this test case are shown in Figs. 8-10.

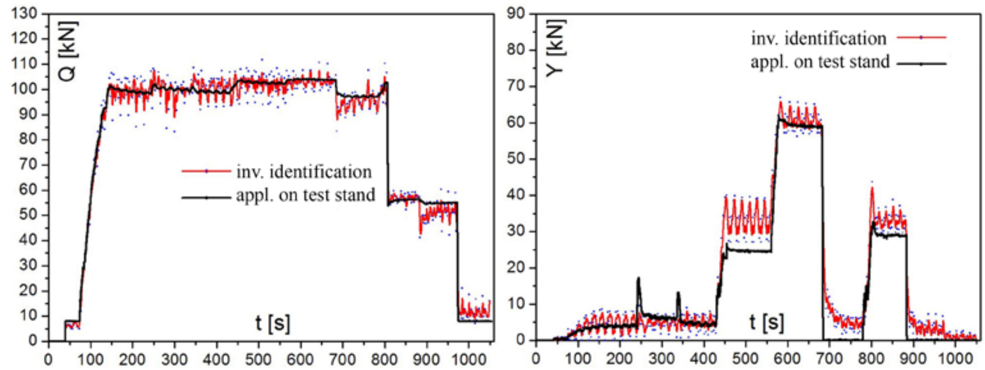
The obtained results have shown a high degree of correlation between the parameters of wheel-rail contact applied on the test stand and obtained with inverse identification. It is obvious that the main influential parameter on the measurement accuracy is signal to noise ratio, which primarily depends on the sensitivity of Wheatstone bridges on a certain loads or their combinations. In angular positions with lower values of output signals or smaller signal to noise ratio, there are a higher degree of dissipation of results of parameters in wheel-rail contact obtained with inverse identification (Figs. 9 and 10).

In the final stage of the research, the measurement uncertainty and measurement error are analyzed [3, 10]. The obtained results have shown that measurement uncertainty is occurs solely as a result of noise in electronic components related to the Wheatstone bridges. Also, results of analysis have shown that measurement errors can be caused by numerous influential parameters and imperfections. In this research the measurement error is estimated on the basis of detail statistical analysis. It was obtained that measurement error of vertical and lateral forces *Q* and *Y* and their ratio *Y*/*Q* is less than 10%, while the estimated error of measurement of contact point position is less than 15% [3, 10].



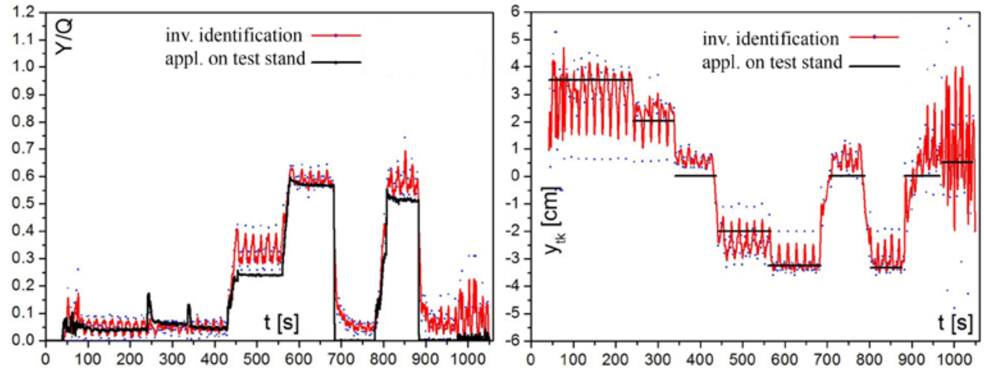
a) b)

Fig. 8 Overall output signals from Whetstone bridges (a) and their parts in interval 700÷750 sec (b)



a) b)

Fig. 9 Comparative diagrams of vertical force *Q* (a) and lateral force *Y* (b) applied on test stand and obtained by inverse identification



a) b)

Fig. 10 Comparative diagrams of derailment coefficient *Y*/*Q* (a) and contact point position y_{cp} (b) applied on test stand and obtained by inverse identification

6. Conclusion

This paper presents one solution for measurement of wheel-rail contact forces in order to testing of safety against derailment of railway vehicles. The key problems in development of instrumented wheelsets are analyzed. The solutions for their resolving are proposed. Experimental tests on the prototype have shown that key influential parameter on the accuracy of instrumented wheelsets is signal to noise ratio. In accordance with developed inverse identification algorithm, the testing of separation of mixed signals on given prototype is performed. Obtained results and detailed statistical analysis of measurement errors have shown that measurement error of vertical and lateral forces *Q* and *Y* and their ratio *Y*/*Q* is less than 10%, while the estimated error of measurement of contact point position is less than 15%. It can be concluded that proposed solution enables very reliable experimental determination of parameters in wheel-rail contact with the measurement accuracy which is on level of the most contemporary world solutions. In this sense, the developed solution has a huge potential in experimental testing of safety against derailment of railway vehicles.

Acknowledgment

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