DETERMINATION OF OPTIMAL LOCATIONS OF STRAIN GAUGES ON INSTRUMENTED WHEELSETS

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Abstract *– This paper presents one universal method for determination of optimal locations of strain gauges on instrumented wheelsets for measurement of wheel-rail contact forces and contact point position. The method is based on development of wheel model and systematically analysis of results of FEM calculation. The procedure is shown on standard 22.5 t wheelset for freight wagons. For analysed wheel, 4 optimal radial distances for measurement of 3 parameters (vertical force Q, lateral force Y and location of contact point position* y_{cp}*) are determined. Placing strain gauges on optimal locations is one of the main preconditions for high measurement accuracy of instrumented wheelset. The proposed method is verified with the experimental tests on real object.*

Keywords – Strain gauges locations; Instrumented wheelset; Wheel-rail contact forces; Contact point position.

1. INTRODUCTION

The instrumented wheelsets have very important role in testing of running safety of rail vehicles [1, 2]. One of the key problems in their development is determination of the most suitable locations of strain gauges. For different wheel types, optimal locations are different and their determination is one of the main prerequisite for obtaining a high measurement accuracy [3]. The way of determination of optimal locations of strain gauges is generally unavailable for most people who are dealing with development of instrumented wheelsets. With motivation to contribute to this area, this paper propose one universal method for determination of strain gauges locations. The content of the paper can be helpful for people involved in research and development of instrumented wheelsets, as well as those who deal with the design of wheelsets and problem of wheel-rail contact.

2. TROUBLESHOOTING

The wheel strains which should be measured are consequence of influence of various parameters. There are vertical, lateral and longitudinal wheel-rail contact forces (Q, Y, X), contact point position (y_{cp}), wheel wear (w), wheel angular velocity (ω) and wheel temperature field (T). Therefore, unknown values of Q, Y and y_{cp} must be determined on the basis of the mixed signals from Wheatstone bridges located on the wheel. In design of instrumented wheelset, the primary aim is getting the highest possible values of signals (increase signal-to-noise ratio) and thus provide greater measurement accuracy. In this sense, it is necessary to identify locations (radial distances) in which the wheel is the most sensitive to the effects of parameters to be measured. In this approach, the whole problem of design of instrumented wheelset is based on the wheel model and appropriate analysis of results of FEM calculation. In the model, the influence of X force should be neglected while influences of ω and T should be neutralized in later phases through intelligent layout and way of connection of strain gauges into Wheatstone bridges [4, 5]. Since the wheel is in zone of elasticity, there is a linear correlation between given force in wheel-rail contact and strains (signals from Wheatstone bridges) caused by that force. So, for arbitrary contact point position, overall strain in any point of the wheel can be expressed as a sum of individual strains caused by individual actions of forces Q and Y. This provide that wheel strains can be analysed for individual actions of forces Q and Y in different contact points.

3. WHEEL MODEL AND FEM CALCULATION

The standard 22.5 t wheelset (made of Bonatrans) is used for demonstration of the method in this paper.

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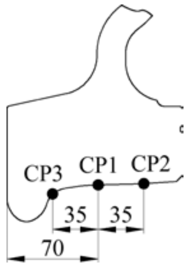
The model consists of 193495 finite elements and 322197 nodes. The calculation is performed in ANSYS for 3 contact point positions y_{cp} and 6 load cases, as shown in Fig. 1.



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. The contact point positions and load cases taken into account in FEM calculation

The calculation results are confirmed that wheel has a great safety factor for all loads cases, while disc is the most sensitive part and it is further analysed. The reference coordinate system for strain analysis on disc surface is shown in Fig. 2.

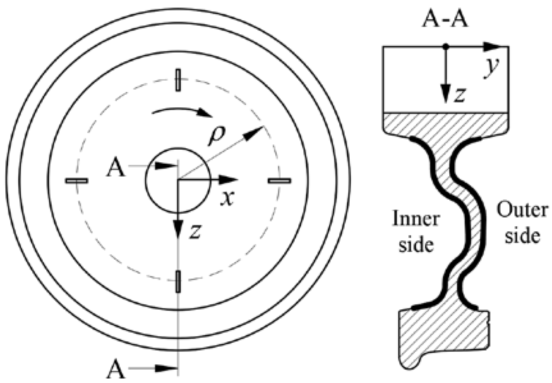


Fig. 2. The reference coordinate system for strain analysis on disc surface

An example of obtained results of relative equivalent strain ε_e is shown in Fig. 3.

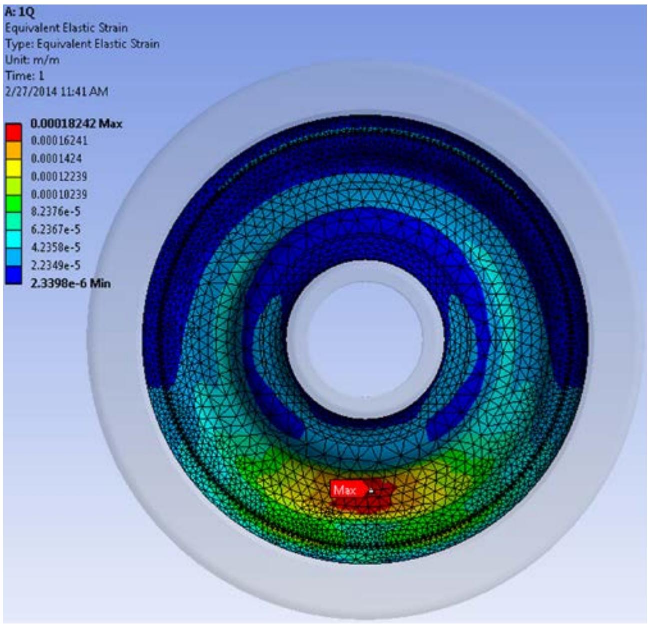


Fig. 3. The equivalent strain at inner side of disc (1Q)

In the next step, 24 diagrams of change of ε_e in function of coordinate z at inner and outer side of disc are formed for section A-A. These diagrams are combined in two comparative diagrams shown in Figs. 4 and 5.

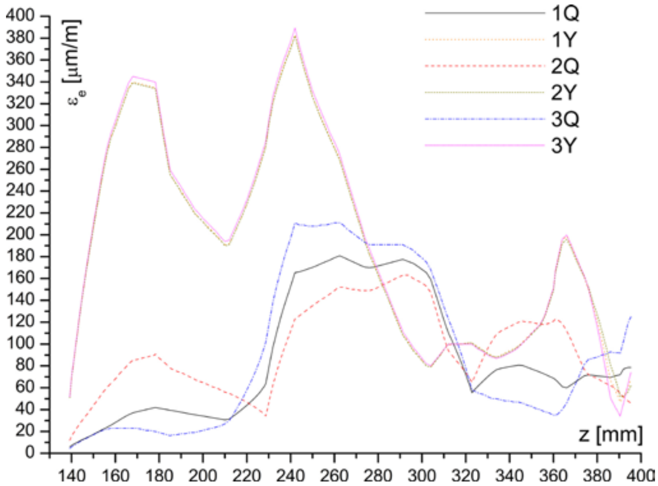


Fig. 4. The comparative diagram of change of equivalent strain on inner side of disc

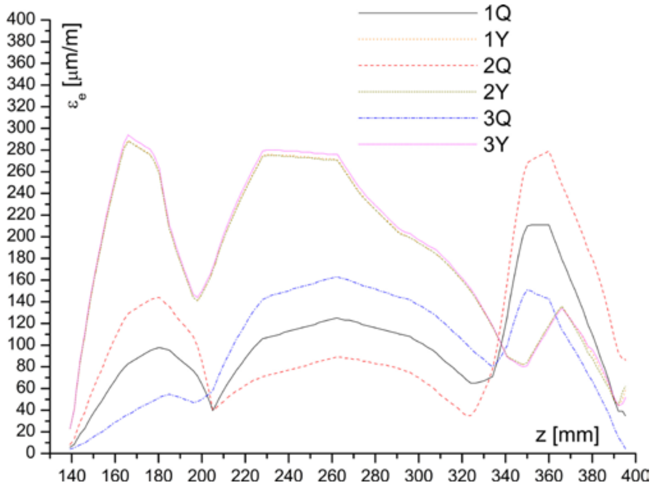


Fig. 5. The comparative diagram of change of equivalent strain on outer side of disc

4. DETERMINATION OF OPTIMAL LOCATIONS OF STRAIN GAUGES

The maximum sensitivity of disc on Q force is at radial distance ρ=262 mm on inner side and ρ=360 mm on outer side (Figs. 4 and 5). At this stage, it can be concluded that these radial distances are the most suitable for placing strain gauges for measurement of Q force. Simultaneously, there is a question whether the output signal from this Wheatstone bridge is influenced with parameters Y and y_{cp}.

The maximum sensitivity on Y force is at ρ=168 mm and ρ=242 mm on inner side, as well as ρ=166 mm and ρ=236 mm on outer side of disc (Figs. 4 and 5). These distances are the most suitable for placing strain gauges for measurement of Y force. Also, there is a question whether the output signal from this bridge is influenced with parameters Q and y_{cp}.

The results have shown that strains on inner and outer side of disc are independent of change of contact point position of *Y* force (Figs. 4 and 5). Accordingly, this influence is neglected. On the other side, the location of *Q* force significantly affects the strains. There are only few radial distances in which this influence is small and they are the most suitable for placing strain gauges of Wheatstone bridge for measurement of *Q* force, if aim is to compensate the error due to the change of contact point position. However, there are important issues related to a low disc sensitivity on *Q* force in given distances, as well as possibility of mixing with influence of *Y* force. Since aim is measurement of contact point position, of special importance is finding distances with the largest influence of this parameter. There are following: ρ=180 mm, ρ=262 mm and ρ=354 mm on inner side, as well as ρ=180 mm, ρ=262 mm and ρ=360 mm on outer side. They are the most suitable for Wheatstone bridge for measurement of parameter y_{cp}. From given six, three distances (ρ=262 mm on inner as well as ρ=262 mm and ρ=360 mm on outer side) are in correlation with distances with the highest sensitivity on *Q* force. Since y_{cp} is determined on the basis of strains caused by *Q* force, there is a question whether the output signal is affected by influence of *Y* force.

The obtained results have shown that in all radial distances on inner and outer side there is crosstalk or mixing of influences of parameters to be measured. For analysed wheel there are no distances which are in the same time sensitive to *Q* force and insensitive to *Y* force, and vice versa. Consequently, it is not possible to establish a simple relations between output signals and parameters to be measured. So, the method which enables determination of individual influences of parameters to be measured based on mixed output signals from Wheatstone bridges should be applied. One of the most suitable is method of Blind Source Separation (BSS) using Independent Component Analysis (ICA). In this case, final selection of optimal radial distances should be performed according to the criteria of maximum sensitivity to the effects of parameters being measured, regardless to crosstalk or degree of mixing of their influence in output signals from Wheatstone bridges [5].

On the basis of previous results it can be concluded that mixed strains on inner and outer side of disc depend from lateral force *Y* (regardless of contact point position) and whether vertical force *Q* acting in tread zone near nominal running circle (environment of CP1), tread zone near outer side of wheel (environment of CP2) or flange zone (environment of CP3). Accordingly, for accurate determination of values of unknown parameters *Q*, *Y* and y_{cp} minimum 4 independent measuring signals or 4 Wheatstone bridges are necessary.

The values of equivalent strains on determined radial distances with highest sensitivity are given in Table 1. Optimal distances are those with maximum sensitivity or with largest strains at the effects of parameters to be measured. The finally selected optimal radial distances are shaded in the Table 1.

Table 1. The values of equivalent strains on radial distances with highest sensitivity and finally selected optimal radial distances

Parameter	ρ [mm]	Disc side	ε_e [μm/m]		
			CP1	CP2	CP3
Q	262	inner	181	152	211
	360	outer	211	279	143
Y	166	outer	289	288	294
	168	inner	340	339	345
	236	outer	275	275	280
	242	inner	383	382	389
y_{cp}	180	inner	87	41	19
	180	outer	144	98	51
	262	inner	181	152	211
	262	outer	125	89	163
	354	inner	118	74	40
	360	outer	211	279	143

5. EXPERIMENTAL TESTS

The experimental tests were carried out in laboratory for testing of railway vehicles at the Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia. The experiment is realized with 3 independent Wheatstone half-bridges placed on the previously determined optimal radial distances. There are the following measuring points (Fig. 6): MP-1 (on outer side of disc at radial distance *z*=360 mm for measurement of *Q* force), MP-2 (on inner side at distance *z*=168 mm for measurement of *Y* force) and MP-3 (on inner side at distance *z*=262 mm for measurement of y_{cp}).

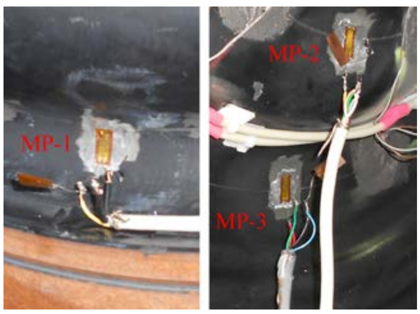


Fig. 6. Strain gauges at three measuring points

At measuring points, strain gages are placed in one vertical plane containing the wheel-rail contact point. This corresponds with cross section A-A in Fig. 2, so numerical and experimental results can be compared. Each of 3 strain gauges is connected into a half-bridge configuration using one additional strain gauge for temperature compensation. The 120 ohms strain gauges of HBM's production are used. The relative strains in vertical direction ε_z are measured and compared with the same obtained by the FEM. For a given radial distances, strains ε_z are almost identical to relative equivalent strains ε_e. Strains ε_z are measured for 3 different contact points that correspond to those from numerical calculation (Fig. 7).

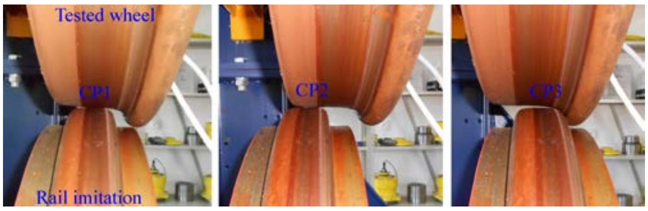


Fig. 7. The three contact points in experimental tests

The experiment is performed on special stand for testing and calibration of instrumented wheelsets [4] (Fig. 8). Data acquisition is carried out by using 8-channel universal amplifier QuantumX MX840A by HBM.

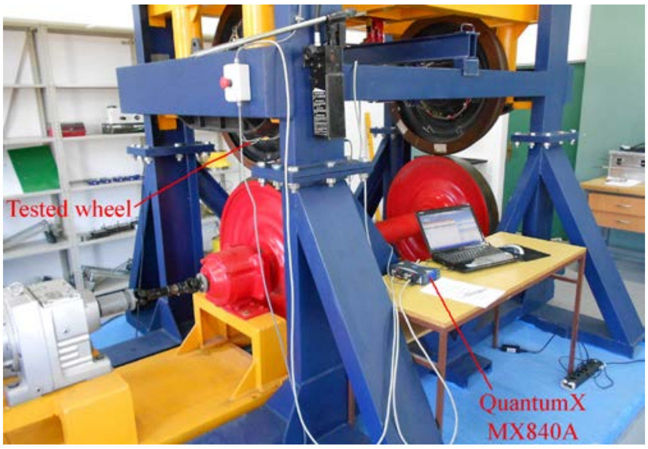


Fig. 8. The detail from experiment on the test stand

The results of experimental tests for different loads cases and their comparison with FEM results are given in Table 2.

Table 2. The comparison of experiment and FEM

Load case	Source	Strain ε_z [μm/m]		
		Measuring point		
		MP-1	MP-2	MP-3
Q=40 kN,	Exp.	–83	10	–65
Y=0, CP1	FEM	–85	12	–73
Q=60 kN,	Exp.	–123	14	–95
Y=0, CP1	FEM	–127	18	–109
Q=40 kN,	Exp.	–102	23	–58
Y=0, CP2	FEM	–114	31	–61
Q=40 kN,	Exp.	–147	34	–86
Y=0, CP2	FEM	–171	47	–92
Q=0,	Exp.	–47	–101	–76
Y=15 kN, CP3	FEM	–36	–100	–79
Q=0,	Exp.	–101	–233	–162
Y=35 kN, CP3	FEM	–84	–232	–185
Q=40 kN,	Exp.	–109	–141	–163
Y=20 kN, CP3	FEM	–103	–140	–190
Q=60 kN,	Exp.	–197	–276	–302
Y=40 kN, CP3	FEM	–179	–277	–338

It can be seen that results obtained by experimental tests are very similar to results obtained by the FEM. Generally, it can be concluded that deviations between numerical and experimental results are about 10÷15%. It can be concluded that experimental results confirm the validity of wheel model and numerical results.

6. CONCLUSION

This paper presents a method for accurate identification of optimal locations of strain gauges on instrumented wheelsets for measurement of wheel-rail contact forces Q and Y, as well as contact point position. The method is applied on standard wheelset with 22.5 t axle load and normal track gauge, intended for freight wagons. Problem solution is based on development of wheel model and systematically analysis of strains distribution on wheel disc for individual action of vertical and lateral forces in different contact point positions. Four optimal radial distances for placing the strain gauges for measurement of three parameters are identified. The validity of model is confirmed with experimental tests performed on special stand for testing and calibration of instrumented wheelsets. Proposed method is universal and can be successfully applied to any wheelset which is selected to be instrumented.

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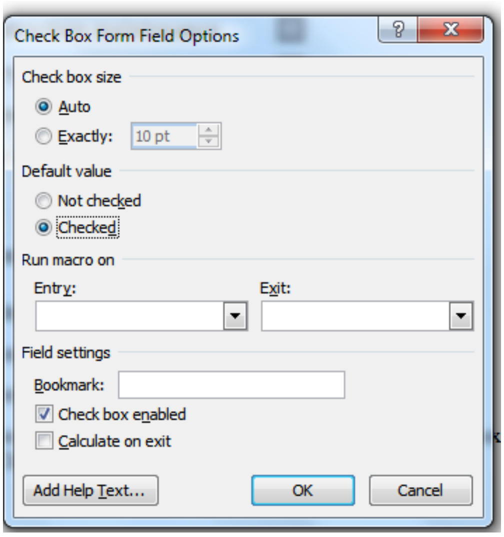

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