Determination of optimal layout, number and way of connection of strain gauges on instrumented railway wheelsets

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The instrumented wheelsets are unavoidable measurement equipment in experimental testing of derailment risk of the railway vehicles in accordance to the international regulations. There is no universal technical solution of instrumented wheelsets. There are a lot of different approaches when it comes to the solution of the problems of the determination of locations for placement of strain gauges, as well as their layout, number and way of connection into Wheatstone bridges. The main aim in solving these problems and the design of instrumented wheelsets is achieving the highest possible sensitivity and measurement accuracy. As a continuation of the previous author's researches, this paper analyses mentioned problems and proposes one methodology for their optimal solution. The content of the paper may be useful for all those who are dealing with the problems of development or usage of instrumented railway wheelsets or similar measurement equipment.

Keywords: Instrumented wheelset, Strain gauges, Wheel-rail contact forces, Derailment risk.

1. INTRODUCTION

In the processes of certification of newly-designed or modified railway vehicles the international regulations, in a large number of cases, prescribing the usage of the instrumented wheelsets [1, 2]. They are primarily used for continuous indirect measurement of vertical force *Q* and lateral force *Y* in wheel-rail contact (Fig. 1). The ratio of these two forces *Y*/*Q* is the main parameter for assessment of the derailment risk of tested railway vehicle [3].

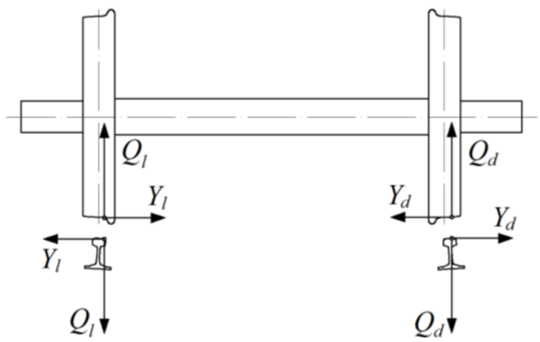

Figure 1: Wheel-rail contact forces

Although they define obligatory usage of instrumented wheelsets, international regulations don't provide more details related to their design and technical solution, measurement accuracy, sensitivity, etc. As a consequence, there are a lot of different approaches and technical solutions of instrumented wheelsets from one test centre or manufacturer to another. The approaches significantly varies when it comes to the solution of the problems of the determination of locations for placement of strain gauges, as well as their layout, number and way of connection into Wheatstone bridges [4]. Success in solving all these problems directly affects the accomplishment of the main aim in development of instrumented wheelsets - high measurement accuracy.

As a continuation of the previous author's researches in this field, this paper, in a gradual and systematic way, analyses the problems of determination of optimal layout, number and way of connection of strain gauges in the phase of design of instrumented wheelsets. Given in mind the lack of literature and publication with this thematic, the content of the paper may be very useful for all those who are dealing with the problems of development or usage of instrumented railway wheelsets or similar measurement equipment.

2. PRINCIPLE OF OPERATION OF STRAIN GAUGE AND WHEATSTONE BRIDGE

Knowledge of the principle of operation of strain gauge and Wheatstone bridge is the basis for solving the problem of experimental determination of unknown parameters in wheel-rail contact and determining the optimal layout, number and way of connection of strain gauges on the wheel of instrumented wheelset, with the aim of achieving high measurement accuracy. The strain gauges in their present form were found and patented in the middle of the last century in USA. From then, strain gauges have been using as one of the most common transducers in experimental tests of mechanical and other structures. Their primary purpose is measurement of strains, but they can also be indirectly used to measure stresses, forces, moments, as well as other quantities that can be related to the strains.

The principle of operation of strain gauge is based on the resistance effect, i.e., on the change of the electrical resistance of the wire during its loading. In general, each strain gauge consists of two flat insulating strips between which a thin conductive wire is placed which is bent several times in order to increase its length (Fig. 2).

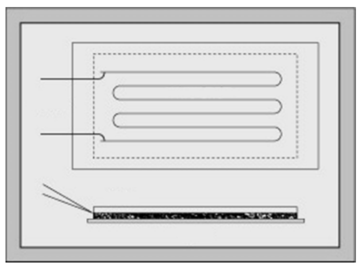

Figure 2: Construction of strain gauge

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The strain gauge is glued to the surface of the tested object, and when the object is deformed, it simultaneously deforms and changes electrical resistance of the strain gauge. In the general case, there is the following mathematical connection between the change in the electrical resistance of the strain gauge and the measured strain of the object:

$$\frac{\Delta R}{R} = k\varepsilon \tag{1}$$

where: ε – measured strain of the object, R – nominal resistance of strain gauge, ΔR – change of resistance of strain gauge, k – strain gauge factor.

Bearing in mind that the values of strains ε measured during testing of structures are very small, it can be concluded that the change in resistance ΔR also will be very small. Precisely for that reason, direct resistance measurements are not performed in the practise, but Wheatstone bridges are used.

Wheatstone Bridge is defined as an electrical circuit designed to accurately and precisely measure of electrical resistance. It consists of 4 resistors (in this case the resistors are strain gauges of nominal resistances R_i, i=1÷4), power supply and measuring instrument (Fig. 3). The electrical voltage U_E is supplied to one diagonal of the bridge, while the measuring instrument measures the output electrical voltage U_A that occurs between the ends of the other diagonal of the bridge.

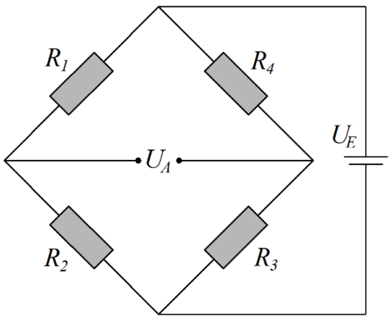

Figure 3: Wheatstone bridge

The output voltage of the Wheatstone bridge U_A can be calculated according to the following expression:

$$U_A = U_E \frac{R_1R_3 - R_2R_4}{(R_1+R_3)(R_2+R_4)} \tag{2}$$

If the bridge is composed of 4 strain gauges of identical resistances and is in equilibrium, the change of resistance of each strain gauge ΔR_i (i=1÷4) leads to the occurrence of bridge imbalance, where the output voltage U_A can be determined according to the following expression:

$$U_A = U_E \frac{\frac{\Delta R_1}{R} + \frac{\Delta R_3}{R} - \frac{\Delta R_2}{R} - \frac{\Delta R_4}{R}}{4} \tag{3}$$

By replacing expression (1) into the previous expression, a connection is established between the strains registered by each of the four strain gauges ε_i (i=1÷4) and the output voltage of the Wheatstone bridge U_A:

$$U_A = U_E \frac{k(\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4)}{4} \tag{4}$$

By combining active strain gauges (glued to the tested object), passive strain gauges (not glued to the test object) and resistors that are an integral part of the measuring instrument, in the general case, it is possible to realize three types of configurations of Wheatstone bridges: full-bridge configuration, half-bridge configuration and quarter-bridge configuration.

Given in mind that the output voltage of the Wheatstone bridge U_A is proportional to the supply voltage U_E, the influence of changes in resistance or strains of strain gauges on the output voltage of the bridge is usually described by U_A/U_E ratio which is dimensionless, and according to expression (4) can be defined as:

$$\frac{U_A}{U_E} = \frac{k}{4}(\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4) \tag{5}$$

Since at a supply voltage of several [V], the output voltage is usually of the order of several [mV], then the U_A/U_E ratio, i.e., signal from measuring – Wheatstone bridge is usually expressed in [mV/V] units.

3. SIGNALS FROM MEASURING BRIDGES AT MEASUREMENT OF PARAMETERS IN WHEEL-RAIL CONTACT

In experimental determination of unknown parameters in wheel-rail contact using an instrumented wheelset, only those discrete values of mixed signals from measuring bridges that appear at the moments when each strain gauge passes above the contact point between wheel and rail, are relevant (Fig. 4).

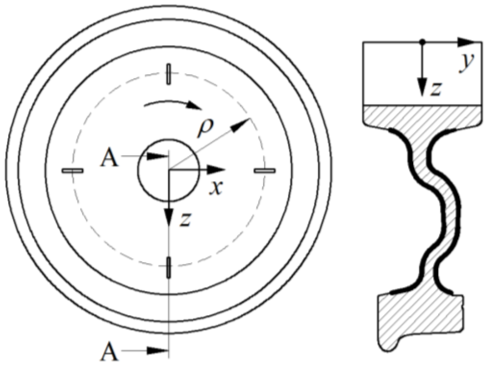

Figure 4: Section A-A relevant for determination of unknown parameters in wheel-rail contact

In order to analyse the signals in more detail, one specific case is considered. It implies that at each optimal radial distance on the wheel there is one full measuring bridge which is formed by connecting of 4 strain gauges, arranged at angles of 90° (Fig. 5).

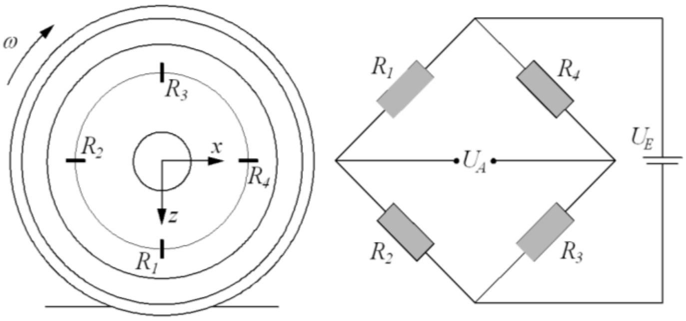

Figure 5: Full measuring bridge at wheel formed by connecting of 4 strain gauges arranged at 90°

During wheel rotation, a measuring signal is obtained from each bridge, which changes as a function of the change of parameters in the wheel-rail contact, speed of movement and angular position of the wheel. The maximum values of the measuring signals appear at the moments when the strain gauges pass above the contact point, i.e., 4 times during one rotation of the wheel (Fig. 6). The intensity of these maximum values depends on the intensity of wheel-rail contact forces and the position of contact point, while the time between their occurrence t_p depends on the running speed of the tested vehicle. Therefore, when there are 4 strain gauges at a given optimal radial distance, the discrete values of the measurement signals relevant for determining the unknown parameters in the wheel-rail contact are obtained at each 1/4 of the wheel circumference. All other values of measuring signals, in periods when strain gauges are not above the contact point, have no significance for measuring. Thus, in the inverse identification algorithm, during one wheel revolution, maximum discrete values of each of the measuring signals are introduced, which arise as a consequence of mixing the influence of the parameters to be measured. By solving the inverse identification problem and determining individual influences based on the values of the mixed input signals, output signals of the unknown parameters are obtained (Fig. 7) [3, 5]. These output signals represent discrete values whose intensity changes during the time, i.e., movement along the track, where the time t_p depends on the running speed of the tested railway vehicle.

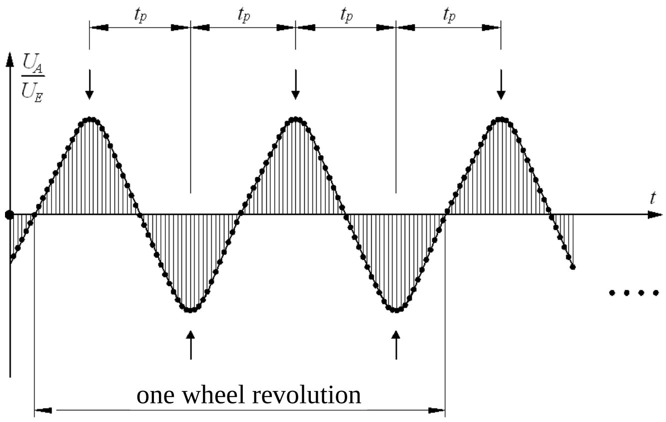

Figure 6: Appearance of measuring mixed input signals obtained during one wheel revolution

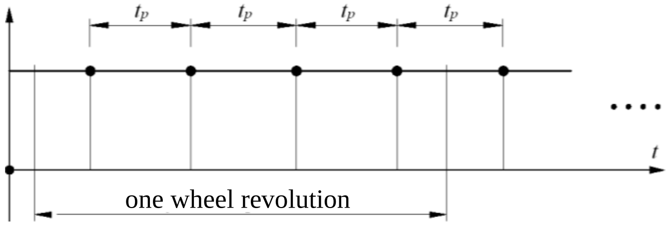

Figure 7: Appearance of the output signal of parameters in the wheel-rail contact

4. DIFFERENT SOLUTIONS OF LAYOUT, NUMBER AND WAY OF CONNECTION OF STRAIN GAUGES

In accordance with the previous considerations, different variants of layout, number and way of connection of strain gauges are analysed in this chapter, which should lead to the definition of the optimal solution. For each solution, the following characteristics are determined, which are extremely important for the analysis of its acceptability as well as assessment of measurement quality: time elapsed between two adjacent representative values of the measuring signal (t_{rv}); distance travelled between two adjacent representative values of the measuring signal (s_{rv}); frequency of strain gauges crossing above the wheel-rail contact point (f).

A special attention is paid to the analysis of whether the given solution enables compensation of the influence of centrifugal acceleration due to wheel rotation, as well as the influence of ambient temperature and temperature due to braking. All solutions were analysed for three different running speeds of 50, 100 and 150 km/h. The basic parameters related to the wheel running with specified speeds are given in Table 1.

Table 1: Parameters of wheel running with speeds of 50, 100 and 150 km/h

Parameters of wheel running		Running speed v [km/h]		
		50	100	150
Angular speed of wheel	ω_o [rad/s]	30.19	60.39	90.58
Number of revolutions per sec	n_o [o/s]	4.81	9.62	14.42
Duration of one revolution	t_o [s]	0.21	0.10	0.07
Distance traveled during one revolution	s_o [m]	2.89	2.89	2.89

4.1. One strain gauge

If at a certain radial distance there is one strain gauge connected in quarter-bridge (Fig. 8), only one representative discrete value of measuring signal relevant for determining unknown parameters in wheel-rail contact is obtained during one wheel rotation. The basic characteristics of solution with one strain gauge are given in Table 2.

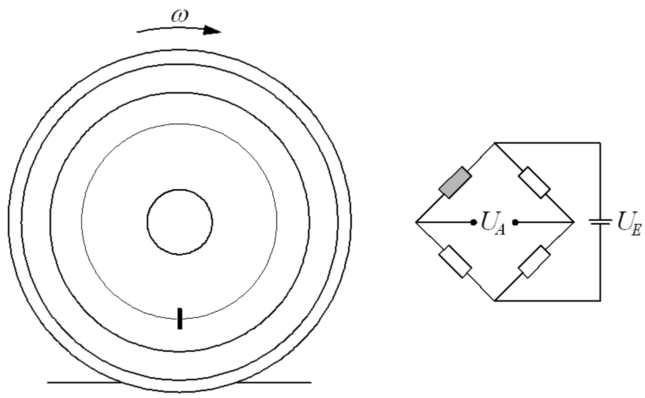

Figure 8: One strain gauge connected in quarter-bridge

Table 2: Characteristics of solution with one strain gauge

Characteristics	Running speed v [km/h]		
	50	100	150
t_{rv} [ms]	210	100	70
s_{rv} [m]	2.89	2.89	2.89
f [Hz]	4.76	10	14.28

It can be seen that, regardless of the speed v, the distance travelled between two adjacent representative discrete values of the measuring signal s_{rv} is 2.89 m. Given that international standards require the measurement of forces in the wheel-rail contact and the *Y*/*Q* ratio per 2 m of distance travelled, it can be concluded that a solution with one strain gauge is unacceptable. In addition, the quarter-bridge solution does not provide the necessary compensation for the effects of centrifugal acceleration due to wheel rotation and the effects of ambient temperature and temperature due to braking.

4.2. 2 strain gauges at 180°

If at a certain radial distance there are 2 strain gauges arranged at 180° and connected in half-bridge (Fig. 9a), two representative discrete values of measuring signal relevant for determining unknown parameters in wheel-rail contact are obtained during one wheel rotation. The basic characteristics of this solution are given in Table 3.

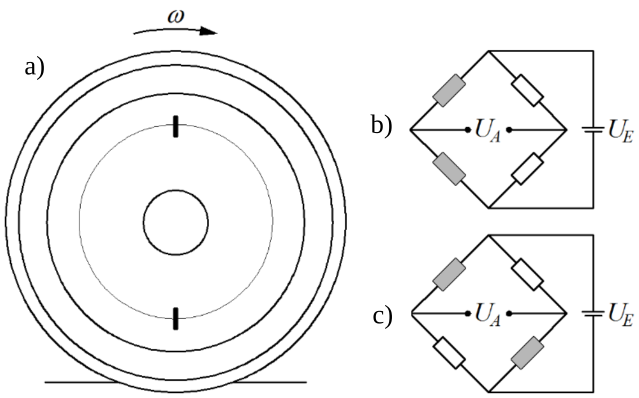

Figure 9: 2 strain gauges arranged at 180°

Table 3: Characteristics of solution with 2 strain gauges

Characteristics	Running speed *v* [km/h]		
	50	100	150
t_{rv} [ms]	105	50	35
s_{rv} [m]	1.445	1.445	1.445
f [Hz]	9.52	20	28.57

In this solution, the distance travelled between two adjacent representative values of the measuring signal is 1.445 m, i.e., it is twice smaller in relation to the solution with one strain gauge. Discrete values of signal relevant for determining the parameters in the wheel-rail contact would be obtained for every 1.445 m of distance travelled, which is insufficient from the aspect of measurement reliability. Solution with 2 strain gauges connected in a half-bridge configuration enables compensation of the influence of centrifugal acceleration and temperature, if strain gauges are connected in adjacent branches of the bridge (Fig. 9b). If strain gauges are connected in opposite branches of the bridge (Fig. 9c), the mentioned undesirable influences are duplicated.

4.3. 4 strain gauges at 90°

If at a certain radial distance there are 4 strain gauges arranged at 90° and connected in full-bridge (Fig. 5), four representative discrete values of measuring signal relevant for determining unknown parameters in wheel-rail contact are obtained during one wheel rotation. The basic characteristics of this solution are given in Table 4.

In this solution, the distance travelled between two adjacent representative values of the measuring signal is 0.7225 m. Discrete values of signal relevant for determining the parameters in the wheel-rail contact would be obtained for every 0.72 m of distance travelled, which is on the very edge of acceptability from the aspect of measurement reliability and quality. Solution with 4 strain gauges connected in a full-bridge enables compensation of the influence of centrifugal acceleration and temperature.

Table 4: Characteristics of solution with 4 strain gauges

Characteristics	Running speed *v* [km/h]		
	50	100	150
t_{rv} [ms]	52.5	25	17.5
s_{rv} [m]	0.7225	0.7225	0.7225
f [Hz]	19.05	40	57.14

4.4. 8 strain gauges at 45°

If at a certain radial distance there are 8 strain gauges arranged at 45° and connected in full-bridge (Fig. 10a), 8 representative discrete values of measuring signal relevant for determining unknown parameters in wheel-rail contact are obtained during one wheel rotation. The basic characteristics of this solution are given in Table 5.

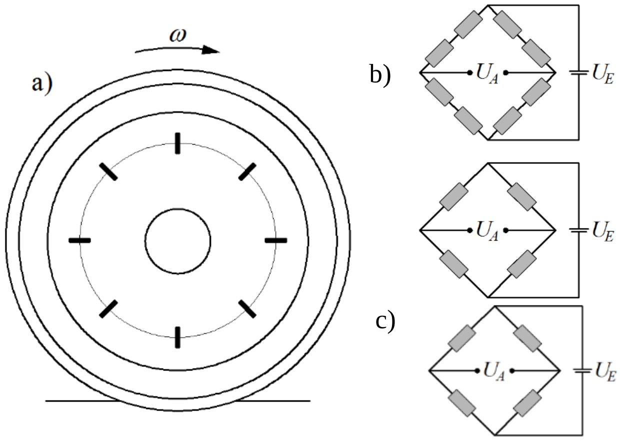

Figure 10: 8 strain gauges arranged at 45°

Table 5: Characteristics of solution with 8 strain gauges

Characteristics	Running speed *v* [km/h]		
	50	100	150
t_{rv} [ms]	26.25	12.5	8.75
s_{rv} [m]	0.36125	0.36125	0.36125
f [Hz]	38.09	80	114.28

With this solution of layout and number of strain gauges, the discrete values of the measuring signal relevant for determining the parameters in the wheel-rail contact would be obtained approximately every 36 cm of distance travelled, which is two times larger than the solution with 4 strain gauges. The strain gauges can be connected in one full-bridge (Fig. 10b), or in two independent full-bridges (Fig. 10c). Both ways enable compensation of the influence of centrifugal acceleration and temperature.

4.5. 12 strain gauges at 30°

If at a certain radial distance there are 12 strain gauges arranged at angles of 30° (Fig. 11a), which are connected in one or three full-bridges (Fig. 10b,c), 12 representative discrete values of measuring signal are obtained during one wheel rotation. The basic characteristics of this solution are given in Table 6.

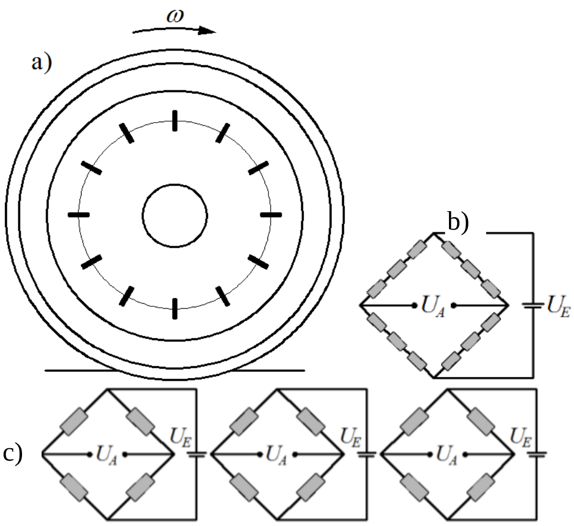

Figure 11: 12 strain gauges arranged at 30°

Table 6: Characteristics of solution with 12 strain gauges

Characteristics	Running speed *v* [km/h]		
	50	100	150
t_{rv} [ms]	17.5	8.33	5.83
s_{rv} [m]	0.24083	0.24083	0.24083
f [Hz]	57.14	120.05	171.53

With this solution of layout and number of strain gauges, the discrete values of the measuring signal relevant for determining the parameters in the wheel-rail contact would be obtained approximately every 24 cm of distance travelled. The strain gauges can be connected in one full-bridge (Fig. 11b), or in 3 independent full-bridges (Fig. 11c). Both ways enable compensation of the influence of centrifugal acceleration and temperature.

4.6. 16 strain gauges at 22.5°

If at a certain radial distance there are 16 strain gauges arranged at angles of 22.5° (Fig. 12a), which are connected in 1, 2 or 4 full-bridges (Fig. 12b,c,d), 16 representative discrete values of measuring signal are obtained during one wheel rotation.

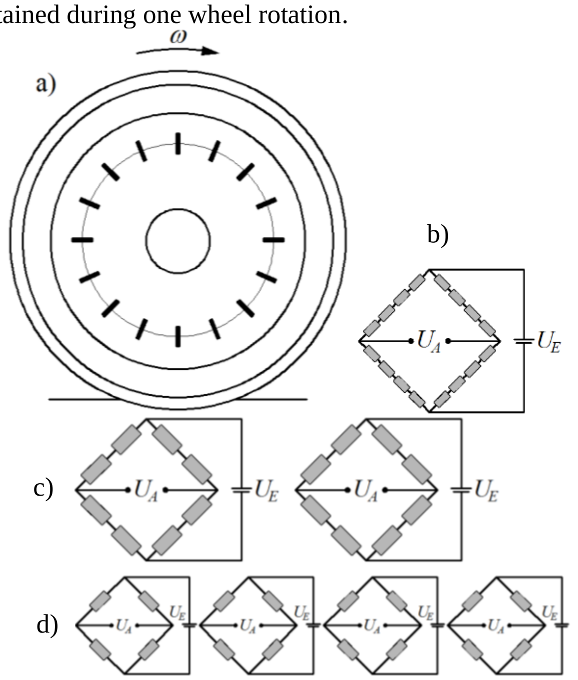

Figure 12: 16 strain gauges arranged at 22.5°

The basic characteristics of the solution with 16 strain gauges are given in Table 7. With this solution, the discrete values of the measuring signal relevant for determining the parameters in the wheel-rail contact would be obtained approximately every 18 cm of distance travelled. The strain gauges can be connected in one full-bridge (Fig. 12b), 2 independent full-bridges (Fig. 12c) or 4 independent full-bridges (Fig. 12d). All three ways enable compensation of the influence of centrifugal acceleration and temperature.

Table 7: Characteristics of solution with 16 strain gauges

Characteristics	Running speed *v* [km/h]		
	50	100	150
t_{rv} [ms]	13.125	6.25	4.375
s_{rv} [m]	0.180625	0.180625	0.180625
f [Hz]	76.19	160	228.57

5. SELECTION OF OPTIMAL LAYOUT AND NUMBER OF STRAIN GAUGES

When choosing the optimal layout and number of strain gauges, several mutually contradict criteria should be taken into account. First of all, the criterion of reliability of measurements must be taken into account. It should be taken into account that international standards prescribe determination of wheel-rail contact forces at 2 m of the distance travelled. Thus, the first criterion that should be taken into account is the distance travelled between two adjacent representative discrete values of the measurement signal s_{rv}, authoritative for determination of the unknown parameters in the wheel-rail contact. If the choice of layout and number of strain gauges were made according to this criterion, then the optimal solution would involve a large number of strain gauges. However, such solutions are unacceptable from the aspect of the possibility of technical realization of the measuring system and its cost price. Therefore, when choosing the optimal solution, the criteria of the number of strain gauges at one wheel n_{sgw} and the number of strain gauges on the instrumented wheelset n_{ws}, must also be taken into account. In order to select the optimal solution, Table 8 is formed, which gives a comparative overview of the values of previously defined parameters relevant for the selection of the optimal layout and number of strain gauges.

Table 8: Comparative overview of parameters relevant for the selection of the optimal solution

Criterion	Number of strain gauges at one radial distance					
	1	2	4	8	12	16
s_{rv}	289 cm	144 cm	72 cm	36 cm	24 cm	18 cm
n_{sgw}	4	8	16	32	48	64
n_{ws}	8	16	32	64	96	128

It can be seen that according to the criterion of the distance travelled between two adjacent representative values of the measuring signal, the most favourable solution is with 16 strain gauges. However, that means that one wheel would be equipped with 64, and one instrumented wheelsets with 128 strain gauges. In addition to the high production costs, such a solution would be extremely difficult for technical implementation due to the presence of a large number of strain gauges, cables and other equipment in a very limited space. Somewhat smaller, but similar problems exist with the solution with 12 strain gauges, which is also not favourable. On the other hand, solutions with one and two strain gauges are not acceptable from the aspect of measurement reliability, and the solution with 4 measuring tapes is at the very limit of acceptability. Based on all this, it can be concluded that the optimal solution is with 8 strain gauges that provides sufficient reliability of measurement, and at the same time it is acceptable from the aspect of technical realization and cost price of the measuring system. The finally determined optimal layout and number of strain gauges per wheel is shown in Fig. 13.

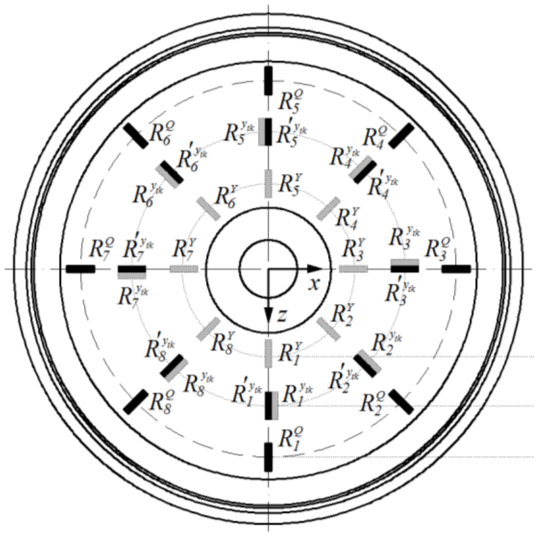

Figure 13: Finally determined optimal layout and number of strain gauges per wheel [5]

6. SELECTION OF OPTIMAL WAY OF CONNECTION OF STRAIN GAUGES

By analysing the output signals from the measuring bridges U_A/U_E, and based on the values of strains obtained from the wheel FEM model [3], it was concluded that the most favorable solution is to connect all eight strain gauges at one radial distance into one full measuring bridge. The highest values of the output signals U_A/U_E for different load combinations are obtained when two adjacent strain gauges at a given radial distance are connected in series, in the same branch of the measuring bridge. This solution ensures that, in the case of constant values of the wheel-rail contact forces, the given bridge shows identical discrete values of the measuring signal at passing the strain gauges over the contact point. The defined optimal way of connection of strain gauges at four optimal radial distances according to Fig. 13, is shown in Fig. 14.

It is very important to emphasize that the defined way of connection of strain gauges enables compensation of the influence of centrifugal acceleration due to wheel rotation, as well as the influence of ambient temperature and temperature due to braking. In the general case, the output signals from the measuring bridges shown in Fig. 13 can be determined based on the following expression:

$$\left(\frac{U_A}{U_E}\right)=\frac{k}{4}\left(\varepsilon_1+\varepsilon_2-\varepsilon_3-\varepsilon_4+\varepsilon_5+\varepsilon_6-\varepsilon_7-\varepsilon_8\right) \qquad (6)$$

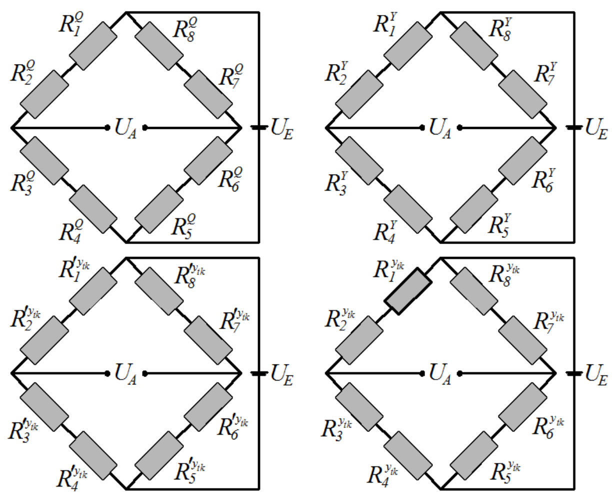

Figure 14: Defined optimal way of connection of strain gauges at four optimal radial distances

7. CONCLUSION

Obtained optimal solutions of layout, number and way of connection of strain gauges, with determination of their optimal locations - radial distances, provide good basis for development of instrumented wheelsets of high performance and measurement accuracy. These results have a high practical significance, bearing in mind that the instrumented wheelsets will certainly be used for a long time for testing the dynamic behaviour of railway vehicles. Further researches in this field should be directed toward the testing of eventual convenience of usage of fibber-optic sensors instead the strain gauges.

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