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Basics of experimental determination of wheel-rail contact forces by using instrumented wheelsets

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The wheel-rail contact forces are the main influential parameters and indicators of quality of dynamic behaviour of railway vehicles. Their exact determination has a great practical importance in development and testing of railway vehicles. Past experiences have shown that the best way for determination of these forces is experimental testing or measurement that can be stationary (track side systems) and continuous (vehicle side systems). When it comes to the vehicle side systems, which are obligatory in many cases of certification of railway vehicles according to the international standards, there is no universally and prescribed technical solution. Consequently, today there are number of solutions of these measuring systems which are mainly based on using of instrumented wheelsets. The aim of this paper is to analyze the most relevant methods and to define basics of measurement of wheel-rail contact forces and contact point position using instrumented wheelsets. Results of the paper can be an important source of information for scientists and engineers, considering the deficiency of literature and scientific publications in this field.

Keywords: Wheel-rail contact forces, Instrumented wheelset, Experimental testing, Railway vehicles.

0. INTRODUCTION

The derailment mechanism is closely connected with wheel-rail contact forces which cause vibrations, wear, thermal effects, noise, fatigue, failure, and other adverse effects in exploitation of railway vehicles. Of utmost importance are vertical force Q and lateral force Y whose relation Y/Q is crucial for assessment the safety against derailment (Fig. 1).

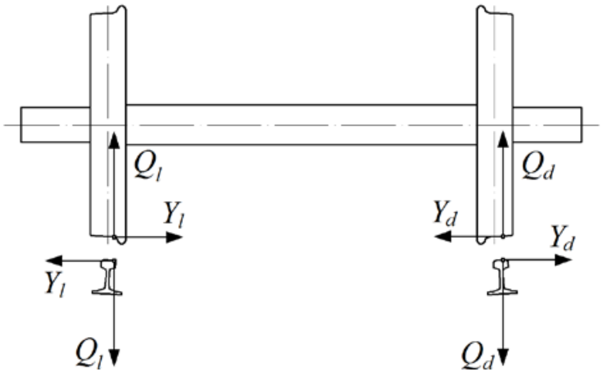

Fig. 1: Wheel-rail contact forces

Finding ways for more accurately and reliably analytical and experimental determination of these forces is one of the most important tasks in railway vehicle dynamics [1–4]. The analytical approach is based on appropriate models of wheel-rail contact and numerical solution of formed equations [5]. However, the most reliable approach implies the experimental testing or measurement which can be realized from the track-side and from the vehicle-side. The track-side measuring systems are usually based on measurement of strains of the rail [6, 7]. On the other hand, the vehicle-side measuring systems (instrumented wheelsets) are usually based on measurement of strains of the wheel [8]. Instrumented wheelsets are equipped with sensors, usually strain gauges, and can be placed on the railway vehicles to be tested (Fig. 2). Their application is obligatory in many cases of the certification of railway vehicles according to the international standards UIC 518 and EN14363 [9, 10].

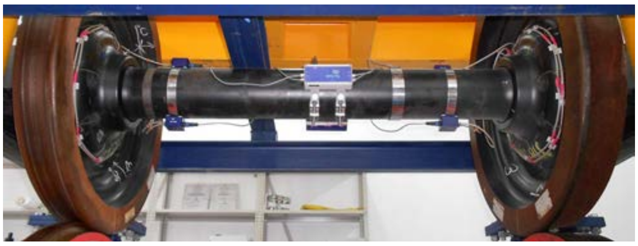

Fig. 2: Instrumented wheelset

The main objective in the development of instrumented wheelsets is to achieve high measurement accuracy. The degree of fulfilment of this goal depends on the success of solving of more mutually coupled problems related to the strain gauges locations, inverse identification method, way of calibration, etc. [11–14]. Over the years, many researchers are dealt with solving of these problems, which are still in trend in scientific and professional public. It is important to note that today there is no universal method for measurement of wheel-rail contact forces using the instrumented wheelset. Although the mentioned international standards prescribe using the instrumented wheelsets in certain phases of certification of railway vehicles, they do not define the technical solution and the required accuracy of measurement system. That is why there are many different approaches and methods, while each of them has certain advantages and disadvantages compared to the other [15]. In this sense, the main objective of this paper is to analyze the most relevant methods and to define basics of measurement of wheel-rail contact forces and contact point position using the instrumented wheelsets.

1. METHODS OF MEASUREMENT OF WHEEL-RAIL CONTACT FORCES

All methods of experimental determination of wheel-rail contact forces are based on two approaches: measurement from the track side and measurement from

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the vehicle side. These approaches are stemmed from the impossibility to measure these forces directly in place of their existence – wheel-rail contact. The problem solving lies in the fact that forces causing certain deformations of structures in its vicinity during the running. By measurement deformations of these structures (elements of track or vehicle), forces in wheel-rail contact can be determined in an indirect way.

The track-side measurement is usually based on checkpoints placed at certain points along the track. They are equipped with sensors (usually strain gauges) placed on the track elements (usually rails), which measure strains during the train passing. First steps in introduction of track-side measurement have been made by ORE (Office for Research and Experiments) – later ERRI (European Rail Research Institute). In report published 1970. ORE has identified the key problems and gave general guidelines for their solution, but without defining of unique measurement method [16]. Since then, different technical solutions of such measurement systems are developed. The most of them are based on measurement of rail strains using the strain gauges [6, 7]. Determination of strain gauges positions is usually based on the FEM (Finite element method) analysis of rail strains. The key problem is to find locations with the highest sensitivity on Q and Y forces, as well as minimal crosstalk. Calibration of measurement system can be based on the FEM results or can be done using special tools and equipment in near-real conditions. The main advantage of track-side method is that measurement is performed for each wheelset of any train that passes through the checkpoint. The main disadvantage of this method is that it does not allow continuous measurement during the train running. Measurements are carried out only at discrete points on the line which are estimated as critical from the point of quality of dynamic behaviour of railway vehicles. However, the process of certification of railway vehicles in accordance with mentioned international standards involves the continuous measurement of parameters of dynamic behaviour along the certain track sections. Therefore, application of track-side measurements is limited on the field of monitoring of vehicles that are already in exploitation.

The vehicle-side measurements of wheel-rail contact forces are usually based on instrumented wheelsets. They are equipped with sensors (usually strain gauges) which measure certain strains during the running of tested vehicle, on the basis of which wheel-rail contact forces can be determined in an indirect way. Generally, all technical solutions of instrumented wheelsets are based on two approaches: measurement over the axle and measurement over the wheel. First solutions of measurement over the axle appeared in early seventies of the 20th century. Although they are in the meantime significantly improved, their main characteristic is based on measurement of bending and torsion moments in certain sections of the axle [17–19]. The solution in the Fig. 3 is based on measurement of bending and torsion moments in six different sections of the axle. In this way it is possible to determine the approximate values of the six wheel-rail contact forces. Moments are measured using the strain gauges connected in the proper configurations of Wheatstone bridges. Advantages of these solutions are based in relative simple measurement system and in possibility for changing wheels of instrumented wheelset. The more important are their disadvantages which are primarily reflected in the impossibility to compensate measurement error due to changing the contact point position. Measurement over the axle was used a long time in German Railways. Because the mentioned disadvantages, this method is replaced with the modern solutions.

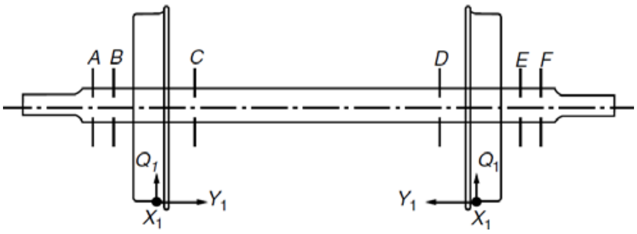

Fig. 3: Instrumented wheelset based on measurement over the axle [19]

First concrete solutions of measurement over the wheel of instrumented wheelset emerged in the fifties of the 20th century when method of Olson and Johnsson is appeared [20]. From that time until today, the large number of technical solutions of measurement over the wheel of instrumented wheelset is developed [21]. All solutions are based on two approaches: measurement over the wheel with spokes and measurement over the standard monoblock wheel. The largest contribution to the development of instrumented wheelsets with spoked wheels gave the British Railways during the seventies and eighties of the 20th century [22–24]. The solution is based on measurement of strains using the strain gauges placed on the certain sensitive locations of spokes (Fig. 4). The strain gauges are in certain configurations connected into the Wheatstone bridges in order to obtain high sensitivity and measurement accuracy. The advantage of this method is in better sensitivity on the effects of Q force due to the higher elasticity in the vertical direction. The main drawback is a very complex and expensive machining of spokes that require high precision. This method is rarely used today, although it has long been in use in the UK and Switzerland.

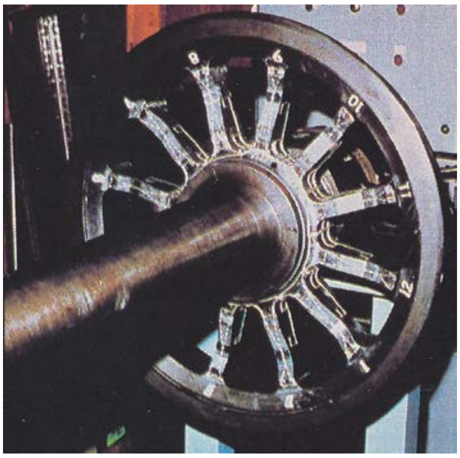

Fig. 4: Instrumented wheelset based on wheels with spokes [23]

Instrumented wheelsets with measurement over the standard monoblock wheels appeared in the fifties of the 20th century. After the occurrence of method of Olson and

Johnsson, the development of such instrumented wheelsets flowed upward with the increasing of sensitivity and accuracy of measurement [25–27]. In the eighties of the 20th century in this area a significant step forward is made in region of former Yugoslavia. At that time, Jovanovic and colleagues developed instrumented wheelset based on the application of strain gauges placed on the standard monoblock wheels [28]. Measurement of wheel-rail contact forces using the instrumented wheelsets based on the standard monoblock wheels is today most common method that is widely used [29–34].

The key advantage of vehicle-side measurement is that it allows continuous measurement. The main disadvantage is that the measuring system is connected with one wheelset. Since the design of wheelsets for different types of railway vehicles can vary significantly, the instrumented wheelsets must be adapted to the specific types of vehicles or bogies. This causes the high costs of their development and production.

2. FORMULATION OF PROBLEM OF CONTINUOUS MEASUREMENT OF WHEEL-RAIL CONTACT FORCES AND CONTACT POINT POSITION

The basic problem in measuring of wheel-rail contact forces consists in the fact that these forces cannot be measured directly in the contact surface between wheel and rail. Consequently, these forces are determined indirectly based on measurement of strains of structures which are located in the vicinity of the contact surface. In the measuring systems from the vehicle side, measurement is usually carried out through the wheel as an element of railway vehicles that is exposed to the greatest loads due to the effect of given forces. Measurement of wheel strains using strain gauges enables indirectly determination of wheel-rail contact forces using an algorithm. The main problem of all indirect methods comes from the fact that the wheel strains are not arise only as a result of actions of lateral and vertical forces to be measured, but they are at the same time affected by the various other parameters. Taking into account and the proper understanding of the effects of these parameters is a key prerequisite for development of high-quality method for experimental determination of wheel-rail contact forces and achieving a high measurement accuracy.

The wheel strains during running are caused by the following forces in the wheel-rail contact: vertical force Q, lateral force Y and longitudinal force X. In addition, these strains are affected with: contact point position y_{cp}, wear of wheel profile w, angular velocity of the wheel ω and temperature field T. The dependence of wheel strain in point j from the mentioned parameters can be expressed as follows [8]:

$$\varepsilon_j = f\left(Q, Y, X, y_{cp}, w, \omega, T\right) \tag{1}$$

Thus, on the basis of wheel strains or signals from Wheatstone bridges, which are mixed due to the influence of all mentioned parameters, it is necessary to determine indirectly the values of unknown parameters Q, Y and y_{cp}. This problem belongs to the group of inverse identification problems and it can be schematically represented as shown in Fig. 5.

Due to the high stiffness of the wheel, strains which are registered by strain gauges have very low values, particularly at the effect of Q force. There is very important problem how to obtain the highest possible values of the signals from Wheatstone bridges and increase signal-to-noise ratio. Bearing in mind that strains are changeable along the wheel body, it is extremely important to determine locations or radial distances with highest sensitivity to the effects of parameters to be measured. Placing the strain gauges on such locations provides greater sensitivity of the measuring system or higher values of output signals from Wheatstone bridges. If the strain gauges are placed at locations with insufficient sensitivity, small values of the output signals will be obtained, which will lead to the great signal-to-noise ratio and large measurement error. In addition, very important problem is determination of optimal layout, number and way of connection of strain gauges, also in order to obtain the highest possible values of output signals, or with the aim of compensating of influence of the certain parameters from expression (1). So, the main prerequisite for obtaining the high measurement accuracy is interactive and quality solving of defined problems as well as the problem of development of inverse identification algorithm.

3. PRINCIPLES FOR SOLVING OF FORMULATED PROBLEM

The basis for solving of formulated problems should be the FEM model of the wheel of wheelset which is selected as platform for development of the instrumented wheelset. A key task of the model is to provide accurate determination of the stress-strain state of the wheel at actions of given parameters defined in expression (1). This allows the identification of influence of given parameters on the wheel strains or signals from Wheatstone bridges, which is of crucial importance for quality solution of the problem and obtaining high

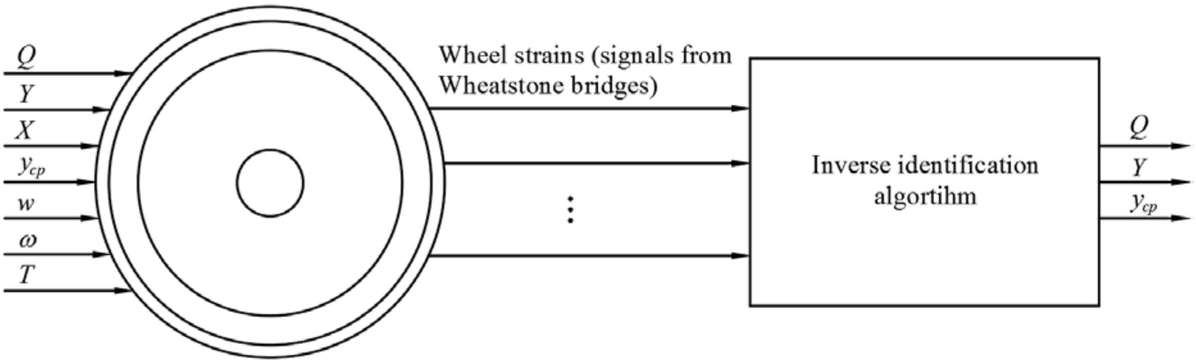

Figure 5: Inverse identification problem in measurement of wheel-rail contact forces and contact point position

measurement accuracy. The model should enable accurate identification of optimal locations of strain gauges, as well as their optimal layout, number and way of connection. In addition, it should enable testing and verification of developed algorithm of inverse identification. In this way, the costs of development of instrumented wheelset are significantly reduced. An example of stress-strain state of the wheel obtained with the FEM calculation is shown in Fig. 6.

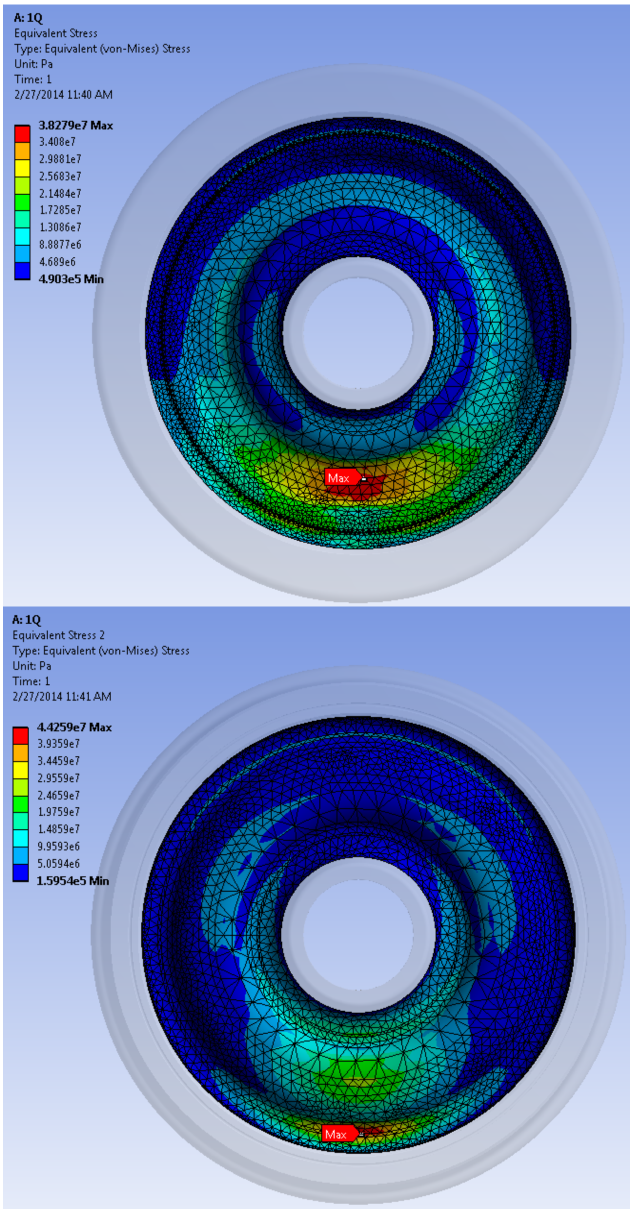

Fig. 6: Example of stress-strain state of the wheel obtained with the FEM calculation [8]

Of all parameters in expression (1), only the influence of longitudinal force X can be neglected. The reasons lie in the facts that instrumented wheelsets are primarily intended for testing of hauled vehicles in which this force has no significant values, and that measurement of this force is not prescribed in the certification process according to the mentioned international standards. It is significant to point out that standards do not require measurement of the contact point position in certification process of railway vehicles. However, this parameter has a certain influence on wheel strains and must be taken into account in order to achieve high measurement accuracy of Q and Y forces. The influence of parameter w is manifested by changing of wheel profile during a certain period of exploitation of instrumented wheelset. In order to achieve a high measurement accuracy, influence of this parameter should be taken into account in inverse identification algorithm [8]. Finally, influences of parameters ω and T on output signals from Wheatstone bridges should be compensated via appropriate way of connection of strain gauges [8]. In this way, the signal from Wheatstone bridge which is placed at certain radial distance becomes the following function:

$$S_m = f\left(Q, Y, y_{cp}\right) \tag{2}$$

Therefore, based on output signals from Wheatstone bridges, three unknown parameters Q, Y and y_{cp} should be determined. Bearing in mind that each strain gauge registers the relative strain ε, and the fact that the wheel is in zone of elasticity, according to the Hooke's law there will be a linear relationship between stress or wheel-rail contact force and the registered strain. The same is true for Wheatstone bridge that is composed of multiple strain gauges. Since the relationship between registered strain of every individual strain gauge and applied force is linear, correlation between the signal from Wheatstone bridge and applied wheel-rail contact force will be also linear. On this basis, the dependence of signal S_m from Q force and Y force is linear in expression (2). However, the key problem arise from the fact that, due to the complex non-linear geometry of the wheel profile, the dependence of the signal S_m from the contact point position y_{cp} is nonlinear. This non-linear relationship can be transformed into linear by introduction of moment M of Q and Y forces with respect to the nominal contact point (Fig. 7).

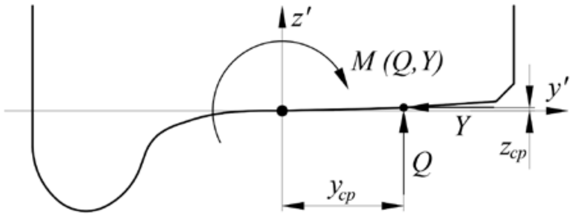

Fig. 7: The moment M of Q and Y forces with respect to the nominal contact point position

Moment M is in fact a non-linear function of parameters Q, Y and y_{cp} [8]:

$$M = -Q \cdot y_{cp} - Y \cdot z_{cp} \tag{3}$$

For development of FEM model and stress-strain analysis of the wheel, of crucial importance is that mentioned linear relationships allow that, for arbitrary chosen contact point position, the total strain can be expressed as sum of individual strains caused by the individual actions of Q and Y forces. Mathematically, this can be expressed as follows:

$$\varepsilon_t = \varepsilon_t\left(Q, Y\right) = \varepsilon_t\left(Q, 0\right) + \varepsilon_t\left(0, Y\right) \tag{4}$$

Thus, in formed FEM model, stresses and strains of the wheel can be analysed at individual actions of Q and Y forces in different contact point positions (Fig. 8).

The primary objective of stress-strain analysis is to determine locations with the greatest sensitivity to the individual actions of parameters to be measured (vertical force Q, lateral force Y and contact point position y_{cp}), where there is no mixing of their influences in the values of the wheel strains or output signals from Wheatstone bridges. Placing the strain gauges on radial distances with high sensitivity and without mixing of influence provide the establishment of a very simple mathematical dependence between the output measuring signal and unknown force that caused it. This dependence is determined by the calibration of the measuring system which can be realized on special test stand or by using the results obtained with the FEM model of the wheel. In this case, the inverse identification algorithm is relatively simple. Based on the value of a measuring signal from radial distance that is the most sensitive to the effect of given force, its value is determined. However, if for a given wheel geometry there are no such locations, or if the output signal obtained from the Wheatstone bridge (placed on the radial distance with the greatest sensitivity to the certain parameter) is mixed due to the influence of other parameters to be measured, troubleshooting is significantly complicated. It is very important to emphasize that if this problem is not identified, measurement will be carried out with a large error.

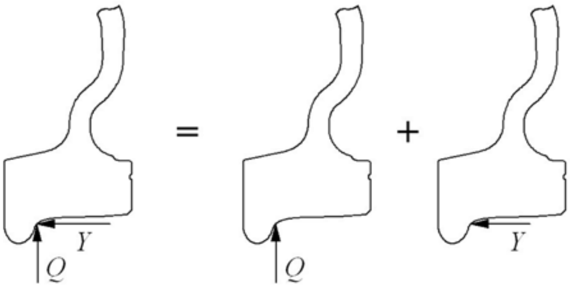

Fig. 8: The consequence of linear relationships between wheel strains and forces Q and Y

In order to achieve high measurement accuracy, one of the solutions is compensation or neutralization the influence of mixing with the appropriate way of connecting of strain gauges into Wheatstone bridges. Thereby, it should bear in mind that mixing can never be completely neutralized. The second approach involves using some of the methods that allow determination of individual influences of parameters to be measured, based on the values of mixed output signals from Wheatstone bridges. In this case, the radial distances with the highest sensitivity should be selected, regardless of the degree of mixing of the influence of parameters to be measured.

So, the way of solution of all these problems depends on the results of stress-strain analysis obtained from the model of specific type of wheel of standard wheelset which is chosen as a platform for development of instrumented wheelset. The results of the stress-strain analysis and FEM model should be verified with the experimental tests on real object, or wheel of the selected wheelset.

4. CONCLUSION

The experimental testing is the most reliable way to determine the parameters of dynamic behaviour of railway vehicles, especially those most important – wheel-rail contact forces. There is no universal method or technical solution for measurement of these forces. Also, there is no universal technical solution of instrumented wheelset which can be characterized as the best. Every method and technical solution, depending on a purpose and technical characteristics, have certain advantages and disadvantages compared to the others. In that sense, the aim of this paper was to define the basics for solution of problem of measurement of wheel-rail contact forces and contact point position using instrumented wheelsets. The key problems in development of instrumented wheelsets are identified. They are related to the determination of optimal layout, number and way of connection of strain gauges, as well as the development of inverse identification algorithm. The special attention is dedicated to the importance of development of the FEM model of the wheel, which is basis for solving all these problems. The results of this paper give very important guidelines for optimal solving of formulated problems, which is main prerequisite for development of instrumented wheelsets of high accuracy.

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