SESSION B: RAILWAY ENGINEERING

Influence of signal-to-noise ratio on the accuracy of experimental determination of wheel-rail interaction forces

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ABSTRACT

This paper analyzes the influence of the signal-to-noise ratio (SNR) on the accuracy of the experimental determination of wheel-rail interaction parameters – vertical force Q, lateral force Y, and contact point position y_{tk}. The research was conducted on an instrumented wheelset developed from a standard wheelset, with strain gauges optimally positioned and connected into Wheatstone bridges. Experimental tests were carried out on a specialized test stand within the Laboratory for Railway Engineering and Structural Testing at the Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac. The noise level in the electronic components of the measurement system and its influence on the final measurement error were analyzed based on the results of corresponding static and dynamic measurements. Using appropriate statistical analysis, it was determined that the noise level originating from the Wheatstone bridges and associated electronics causes significant dispersion of output signals, especially at lower force intensities. The results show that under lower loads (characteristic of empty vehicles) the SNR is less favorable, leading to an increase in the relative measurement errors of the aforementioned parameters. Conversely, under higher loads and critical values of the Y/Q ratio, which are of interest for assessing vehicle running stability according to relevant international standards, the SNR is significantly more favorable and measurement errors decrease. The obtained results confirm that the SNR is a key factor in the reliability of the measurement system for the experimental determination of wheel-rail interaction parameters. One of the directions for further improvement in measurement accuracy is the application of modern fiber-optic sensors, which have significantly higher resistance to electromagnetic interference and enable a more favorable SNR, thus opening a promising path toward a new generation of instrumented wheelsets with even higher measurement accuracy.

KEYWORDS

Signal-to-noise ratio, SNR, Wheel-rail interaction, Wheel-rail contact forces, Wheel-rail contact point, Instrumented wheelset, Derailment coefficient, Strain gauges.

1. INTRODUCTION

Wheel-rail interaction represents one of the most complex and most studied phenomena in the dynamics of railway vehicles [1, 2]. On an extremely small contact surface, measuring only 1.5 to 5 cm², very intense forces are generated, which have a key influence on running stability, safety, comfort, as well as on the wear and fatigue of railway vehicle and track components. Among the most important parameters for assessing the dynamic behavior of railway vehicles, according to international standards UIC 518 and EN 14363, are: the vertical wheel-rail contact force Q, the lateral wheel-rail contact force Y, their ratio Y/Q, which is a direct indicator of derailment risk, and the position of the wheel-rail contact point y_{tk} [3, 4].

In order to determine these parameters as accurately as possible, the most reliable method is experimental testing using instrumented wheelsets. Modern instrumented wheelset systems, such as the one presented in this paper, are essentially standard commercial wheelsets with monoblock wheels onto which strain gauges are glued. The strain gauges are connected in appropriate Wheatstone bridge configurations and placed at pre-determined optimal radial distances in order to maximize sensitivity to the forces being measured [5–7]. Although continuous efforts are being made to improve the design, calibration and signal processing algorithms, these measurements are still characterized by significant measurement uncertainty, and the study of errors and their causes therefore remains one of the key development directions in this field [8].

From the aspect of measurement accuracy, the signal-to-noise ratio (SNR) has been identified as the dominant influencing parameter, and its increase is directly related to the possibility of increasing measurement accuracy [9]. Recent research has also shown that errors arising from contact point movement and wheel rotation represent a significant source of problems [10–12]. However, the influence of noise on the signal, particularly pronounced under low loads (characteristic of empty wagons), remains one of the greatest challenges.

In accordance with the foregoing, the main objective of this paper is to examine the influence of the SNR on the accuracy of determining the wheel-rail interaction parameters (Q, Y, Y/Q and y_{tk}), based on a detailed analysis of experimental data obtained using an experimental setup consisting of an instrumented wheelset and a test stand. The test results have shown that the experimental setup used enables the determination of the vertical force Q, the lateral force Y and their ratio Y/Q with a relative error of less than 10%, and the contact point position y_{tk} with an error of less than 15%. Of particular importance is the comparative analysis of measurement accuracy under low and high loads, as well as the indication of the practical implications of the obtained results. This quantitative assessment provides the basis for drawing final conclusions with a special emphasis on future research directions in the field of developing instrumented wheelsets.

2. FORCES IN WHEEL-RAIL INTERACTION

When negotiating curves, there is a constant risk of the leading wheel flange climbing onto the outer rail head, i.e., of the railway vehicle derailing from the track. The key indicators of this risk, i.e., the key influencing parameters on which the running stability of railway vehicles in curves depends, are the forces in the wheel-rail interaction. Knowing these forces precisely allows very reliable conclusions to be drawn about the running stability of railway vehicles in curves, based on the results of research into the derailment mechanism.

In practical analyses of the running stability of railway vehicles, the most commonly used parameters are the vertical forces Q and the lateral forces Y, which are derived from the actual wheel-rail interaction forces – the normal forces N and the lateral tangential forces F_η (Fig. 1).

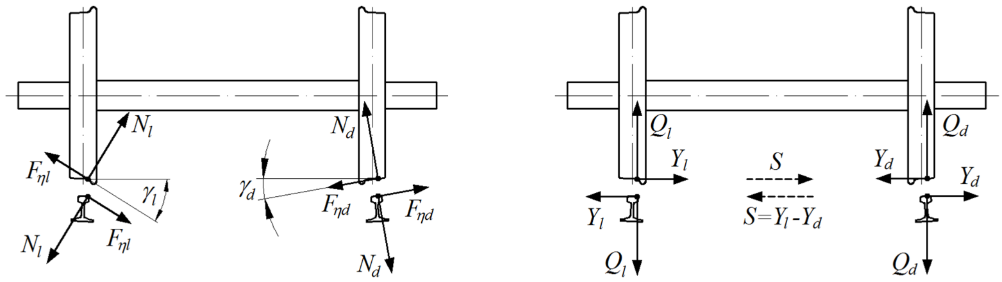

Figure 1: Vertical forces Q and lateral forces Y derived from normal forces N and lateral tangential forces F_η in wheel-rail interaction

The lateral force Y acts parallel to the track plane, while the vertical force Q acts normal to the track plane, so that the values of these forces are obtained by projecting the actual forces onto the said planes. Accordingly, the vertical and lateral forces in the interaction of the left (l) and right (d) wheel and rail are:

$$Q_l = N_l \cos\gamma_l + F_{\eta l} \sin\gamma_l \quad (1)$$

$$Y_l = N_l \sin\gamma_l - F_{\eta l} \cos\gamma_l \quad (2)$$

$$Q_d = N_d \cos\gamma_d - F_{\eta d} \sin\gamma_d \quad (3)$$

$$Y_d = N_d \sin\gamma_d + F_{\eta d} \cos\gamma_d \quad (4)$$

The resulting lateral force S in the wheel-rail interaction is:

$$S = Y_l - Y_d \quad (5)$$

The total vertical force Q in the wheel-rail interaction during motion is variable and consists of static, quasi-static, dynamic, and additional components. The static component is constantly present during motion and practically represents the static load Q_0, which includes the dead weight of the railway vehicle and the weight of the cargo. In determining it, it is assumed that the total weight of the vehicle and cargo is evenly distributed across all wheels. The quasi-static component appears only when railway vehicles negotiate curves, in cases where the running speed differs from the equilibrium speed. In that case, the magnitude of uncompensated lateral acceleration and the height of the vehicle's center of mass dictate the redistribution of the total vertical load between the wheels of the wheelsets. The dynamic component is present to a greater or lesser extent during the motion and arises from numerous disturbances originating from track irregularities and damage, irregularities and damage of wheelsets, running instability, traction, braking, etc. The additional component most often arises from uneven load distribution and asymmetry, i.e., errors in the assembly and adjustment of certain structural elements of railway vehicles (most often suspension elements). The total resulting lateral force S during motion is also variable and consists of quasi-static, dynamic, and additional components. The quasi-static component appears when railway vehicles negotiate curves and depends on the uncompensated lateral acceleration and the distribution of forces between the wheelsets in the bogie. The dynamic and additional components arise due to a large number of disturbances, similarly to the case of the vertical force Q.

The study of the derailment mechanism by flange climbing and the assessment of running stability of railway vehicles in curves are directly related to the ratio of lateral and vertical forces in wheel-rail interaction. To determine the limit values of the Y/Q ratio, the Nadal equation is most commonly used.

Due to the under-radial steering of the wheelset and the existence of a certain angle of attack of the wheel against the outer rail, a lateral tangential force F_η appears, which tends to lift the wheel flange onto the rail head (Fig. 2). In general, this force equals the product of the normal force N acting in the contact surface and the coefficient of friction μ between the wheel and the rail. Therefore, if the wheel flange is pressed more strongly against the rail head (greater normal force N) or if the coefficient of friction μ is higher, the tangential force F_η that tries to raise the wheel flange onto the rail head is also greater.

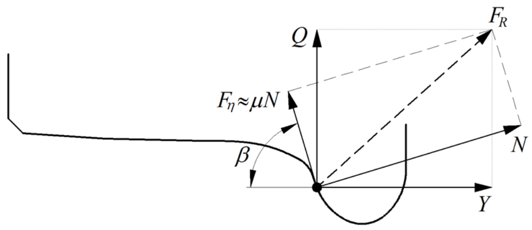

Figure 2: Forces in the initial phase of wheel flange climbing onto the rail head

In analysis of this problem, Nadal assumed that the angle of attack of the wheel against the rail has rather large values ($\psi \geq 0.5°$), so that the contact angle γ is approximately equal to the wheel flange angle β, and the tangential force F_η acts almost vertically. According to Nadal, the wheel flange begins to climb onto the rail head if the vertical component of the normal force N and the tangential force F_η is equal to or greater than the wheel load Q. Based on Fig. 2 and the previous expressions, the lateral and vertical components of the normal force N and the tangential force F_η in the wheel-rail interaction are:

$$Y = N \sin\beta - \mu N \cos\beta \tag{6}$$

$$Q = N \cos\beta + \mu N \sin\beta \tag{7}$$

Based on the previous expressions, the Nadal equation can be defined, which enables the determination of the critical ratio of lateral to vertical force Y/Q at which the process of wheel flange climbing onto the rail head begins, using the known coefficient of friction μ and the wheel flange angle β:

$$\frac{Y}{Q} = \frac{\tan\beta - \mu}{1 + \mu \tan\beta} \tag{8}$$

In the international standards UIC 518 and EN 14363, limits, i.e., limit values of the ratio of vertical and lateral forces in wheel-rail interaction, are defined, which must be satisfied when assessing the dynamic behavior quality of railway vehicles. In this case, the absolute maximum values of the ratio of vertical or lateral force are not relevant for comparison with the defined limit values; rather, following appropriate statistical processing, the 99.85 percentile of the signal filtered with a low-pass filter having a cutoff frequency of 20 Hz is taken into account:

$$\left(\frac{Y}{Q}\right)_{\text{20Hz, 2m, mean, 99.85\%}} \leq \left(\frac{Y}{Q}\right)_{doz} = 0.8 \; - \text{for curves of radius } R_k \geq 250 \;\; m \tag{9}$$

In experimental tests, i.e., prototype testing of railway vehicles, the aforementioned Y/Q ratio is directly recorded using instrumented wheelsets, with one of the greatest problems being its contamination due to the influence of noise.

3. EXPERIMENTAL SETUP

For the tests, an instrumented wheelset was used, based on a standard commercial wheelset intended for freight railway vehicles (Fig. 3). The wheelset has monoblock wheels with an S1002 profile, a nominal rolling diameter of 920 mm, and a static load per wheel of 112.5 kN. The main components of the measurement system are connected to each other via a wireless Ethernet network, which enables communication between them. These components include: the instrumented wheelset equipped with strain gauges placed on both wheels; the electronic-computer unit for receiving and storing measurement signals during experimental testing (housed in the measuring wagon during track tests); and the computer module for processing and displaying experimental results (which can be located outside the measuring wagon during track tests).

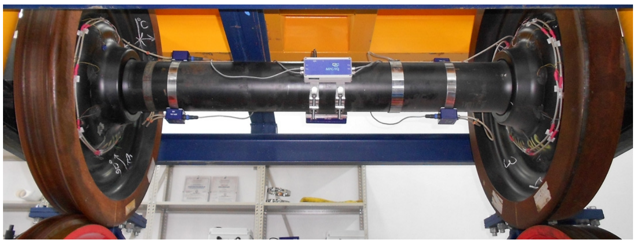

Figure 3: Instrumented wheelset[4,9]

Each wheel of the instrumented wheelset contains glued strain gauges at four radial distances from the wheel center, namely: ρ=360 mm (outer side of the disc) – for measuring the vertical force Q, ρ=168 mm (inner side of the disc) – for measuring the lateral force Y, ρ=262 mm (inner and outer side of the disc) – for measuring the contact point position y_{tk} [6, 9]. At each radial distance, 8 strain gauges are placed, arranged at an angle of 45° and connected in a full Wheatstone bridge configuration. Signals from the measuring bridges are collected in the appropriate computer unit via a telemetry measurement system, while the angular position of the axle Φ_0 is also measured using biaxial accelerometers.

Experimental tests were carried out on a special test stand within the Laboratory for Railway Engineering and Structural Testing at the Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac (Fig. 4). The test stand enables experimental testing and calibration of instrumented wheelsets with a load capacity of 22.5 t for normal track gauge, i.e., independent application of vertical force Q and lateral force Y under laboratory conditions. The main parts of the test stand are: 1–lower wheelset, 2–horizontally movable carrier of the lower wheelset, 3–upper wheelset (wheelset being tested-calibrated), 4–vertically movable carrier of the upper wheelset, 5–supporting structure, 6–hydraulic systems for applying vertical and lateral forces, 7–transducers for recording the applied values of vertical and lateral forces, 8–drive electric motor with gearbox and cardan shaft, 9–safety systems, and 10–control module.

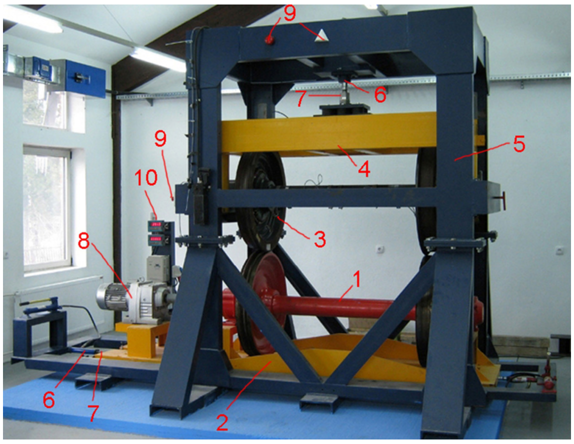

Figure 4: Special test stand for testing and calibration of instrumented wheelsets [4, 9]

The lower wheelset of the test stand has its left wheel machined to simulate the rail head, while the upper wheelset rests on rolling bearings on the right side, ensuring free rotation. The vertical force is applied by a hydraulic cylinder acting on the vertically movable carrier of the upper wheelset. The lateral force is applied by a horizontal hydraulic cylinder acting on the horizontally movable carrier of the lower wheelset. The values of the applied forces are measured by force transducers, with the maximum applicable force values being Q=225 kN and Y=100 kN. The rotational motion of the tested wheelset is achieved indirectly via the lower wheelset, which is driven by an electric motor with a gearbox and a cardan shaft. The drive electric motor has a power of 7.5 kW, and the rotational speed is regulated by a frequency converter located on the control module.

4. SIGNAL-TO-NOISE RATIO AND MEASUREMENT ERROR

In the first phase of experimental tests, static measurements were carried out primarily to verify the linearity of the system. The measurements were performed for three characteristic positions of the contact point between the wheel and the rail simulation, as well as for eight angular positions of the wheel. The formed diagrams of the dependence of the wheel-rail interaction forces applied on the test stand and the signals from the measuring bridges showed a trend of linear dependence between them, thus confirming the linearity of the system. As expected, a certain measurement uncertainty was observed, i.e., a certain degree of dispersion of the measurement results relative to the ideal dependence between the signal and the force, in which all discrete signal values would lie on a single straight line. Typical examples are shown in Figure 5.

The main cause of this problem is noise in the electronic components of the measurement system – in this case, the force transducers and the measuring bridges with strain gauges. It was observed that the influence of signal dispersion is particularly pronounced in cases where the measuring bridges have lower sensitivity to the applied loads, i.e., when the

SNR has lower values. Therefore, it is quite clear that maximizing the SNR represents a key problem in the development of measurement systems for instrumented wheelsets used for the experimental determination of forces in wheel-rail interaction.

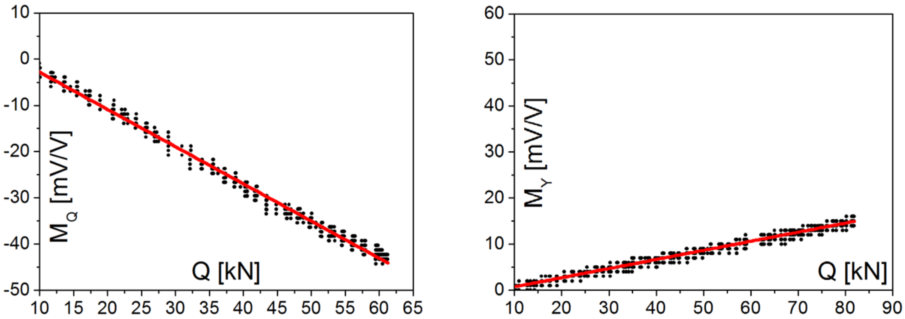

Figure 5: Dispersion of measurement results of signals from the measuring bridges for measuring Q and Y forces

In the next phase, dynamic measurements were carried out with the aim of testing the measurement accuracy of the instrumented wheelset. The accuracy was tested for several different load cases and combinations, i.e., known wheel-rail interaction parameters applied on the test stand, which were to be reconstructed by separating the mixed signals from the instrumented wheelset. Emphasis was placed on two characteristic test cases: in the first, the loads on the test stand approximately corresponded to the wheel loads for an empty freight wagon, and in the second, for a loaded freight wagon. By applying the method for separating mixed signals from the measuring bridges and the corresponding algorithm, the values of the applied parameters in the wheel-rail simulation interaction were reconstructed [4, 9]. Comparative diagrams of the applied and reconstructed values are shown in Figs. 6–8.

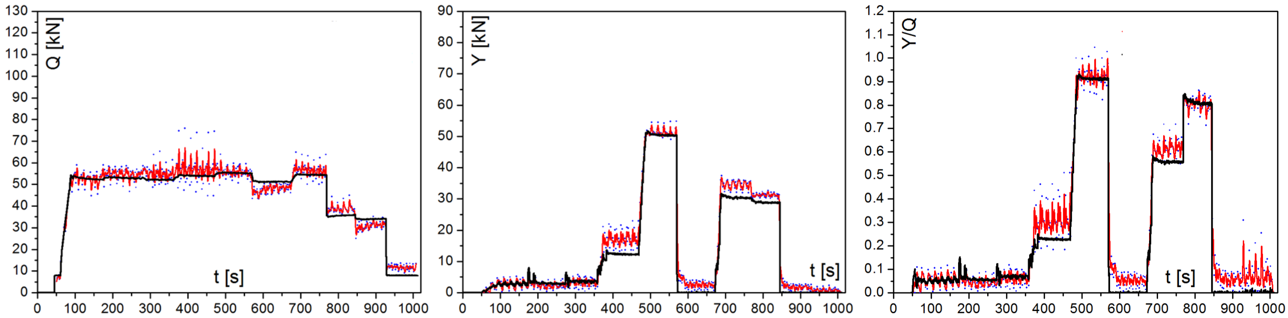

Figure 6: Comparative diagrams of the applied and reconstructed values of Y, Q, and Y/Q for the first test case [9]

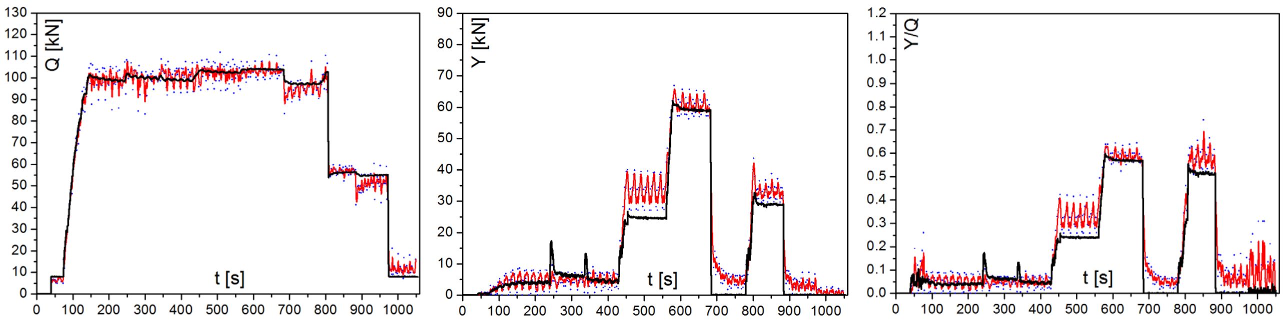

Figure 7: Comparative diagrams of the applied and reconstructed values of Y, Q, and Y/Q for the second test case [9]

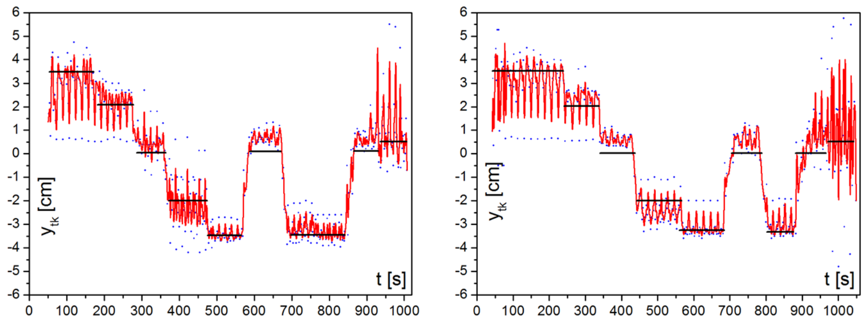

Figure 8: Comparative diagrams of the applied and reconstructed values of y_{tk} for the first test case (left) and the second test case (right) [9]

A very high degree of agreement can be observed between the applied values (black lines in the diagrams) and the reconstructed values (red lines in the diagrams), which confirms the high measurement accuracy of the given instrumented wheelset. The obtained results showed that for angular positions with lower signal values from the measuring bridges, i.e., with a less favorable SNR, a higher degree of dispersion of the wheel-rail interaction parameters obtained by inverse identification, i.e., by reconstruction of the values applied on the test stand, is characteristic (blue points in the diagrams). In angular positions where the sensitivity of the measuring bridges to the applied loads is higher, the degree of dispersion of the reconstructed wheel-rail interaction parameters is significantly smaller. Precisely due to the dispersion caused by the influence of noise, and for easier visualization, the obtained results of the reconstructed wheel-rail interaction parameters are shown using B-splines (red lines in the previous diagrams).

Based on the detailed statistical analyses conducted, it was estimated that the given instrumented wheelset enables the measurement of the vertical force Q, the lateral force Y, and their ratio Y/Q in wheel-rail interaction with errors within limits of less than 10% [4, 9]. Furthermore, it was estimated that the measurement error of the contact point position y_{tk} is within limits of less than 15%. It is particularly important to emphasize that during flange contact (with significant values of the Y/Q ratio or Y force), the previously estimated measurement errors decrease, which is extremely important for the reliability of experimental testing of derailment safety of railway vehicles according to international standards.

For a more detailed analysis of measurement uncertainty, three measurements were performed in static mode with no load, during which output signals from the measuring bridges and signals from the force transducers, i.e., the alpha-numeric displays, were recorded. All three measurements lasted approximately 300 s, thereby sampling a sufficient amount of experimental data for valid statistical analysis. Based on the measurement results, diagrams of the signal changes from the four measuring bridges and of the forces in the wheel-rail simulation interaction were formed as a function of time. In addition, diagrams (histograms) of the statistical distribution of the recorded signals were created, showing the mean values and standard deviations. As an example, the diagram of the signal change from the measuring bridge for measuring the Q force, its statistical distribution, mean value and standard deviation for Measurement 1 are shown in Figure 9.

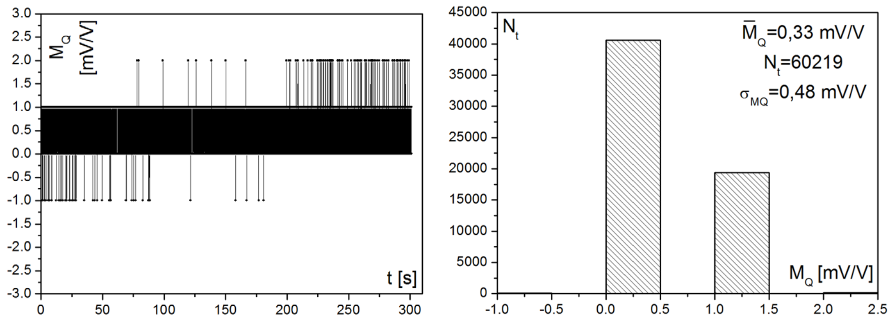

Figure 9: Diagram of the signal from the measuring bridge for measuring the Q force, statistical distribution, mean value and standard deviation for Measurement 1

Analysis of the results obtained from the formed diagrams showed that the degree of dispersion of the recorded force values in the wheel-rail simulation interaction is not large and, in the most unfavorable case, ranges from –2 to 2 mV/V. The recorded values of the vertical force Q scatter within the range of 0–15 N, and the lateral force Y within the range of 0–30 N. Based on this, it can be concluded that noise originating from the force transducers does not have a significant influence on the measurement uncertainty during calibration of the measurement system on the test stand. Therefore, it is evident that the present measurement uncertainty arises exclusively as a consequence of noise in the electronic components related to the operation of the measuring bridges. If the noise level in the electronic components related to the operation of the measuring bridges were reduced, the aforementioned dispersion intervals of the output signals would also decrease. This would consequently result in a significantly lower degree of dispersion of the wheel-rail interaction parameters obtained at the output of the inverse identification algorithm. The ultimate outcome would be a smaller measurement error of the unknown wheel-rail interaction parameters.

It should be noted that the previous analysis was performed on raw signals, without any filtering and statistical processing. In practical applications where filtering and statistical processing would be implemented, the measurement errors are expected to be even smaller than the reported values.

5. CONCLUSION

This paper analyzed the influence of the signal-to-noise ratio (SNR) on the accuracy of determining wheel-rail interaction parameters – vertical force Q, lateral force Y, ratio Y/Q, and contact point position y_{tk} – using an instrumented wheelset based on strain gauges. Static measurements confirmed the linear dependence between the applied forces and the output signals from the measuring bridges, but dispersion was observed due to noise in the electronic components, particularly pronounced at low SNR values (characteristic of empty vehicles). Dynamic measurements for two load levels (empty wagon and loaded wagon) showed that higher forces produce higher output signals, a more favorable SNR, and significantly lower relative measurement errors. Statistical data processing estimated that the given instrumented wheelset enables measurement of the parameters Q, Y and Y/Q with relative errors of less than 10%, and the contact point position y_{tk} with an error of less than 15%. During flange contact (high Y/Q or Y values), the errors are even smaller, which is extremely important for assessing derailment risk according to international standards.

Measurements at zero load confirmed that the dominant noise source originates from the measuring bridges, while the force transducers have a negligible influence. Due to the complexity of the measurement setup and the large number of influencing parameters, absolutely accurate determination of the error is not possible, but the statistical estimate provided in this paper represents a reliable basis. In addition to SNR, measurement accuracy is also influenced by a number of other parameters – the precision of strain gauge application, deviations of their nominal resistance, material inhomogeneity of the wheel, geometric imperfections, etc. Also, the stiffness of the wheel is extremely high, especially in the vertical direction, which results in relatively small output signals from the measuring bridges, even when the aforementioned problems are solved in an optimal manner. Since the SNR cannot be arbitrarily increased by using classical strain gauges, one of the directions for future research should be directed toward the application of fiber-optic sensors, which offer greater resistance to electromagnetic interference and a significantly more favorable SNR, thus enabling a new generation of instrumented wheelsets with even higher measurement accuracy.

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