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Estimation of the wheel-rail lateral contact force through the analysis of the rail web bending strains

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ABSTRACT

Vertical overloads and imbalances in the composition of a railway vehicle can result in damage to the track and in a non-conformity regarding safety of operation. On the other hand, wheel-rail lateral contact forces are more directly involved in the running safety and deserve a special focus. In this paper, an experimental approach to estimate lateral forces applied by rolling stock to the track is presented. The method is based on the analysis of bending strains in the cross plane of the rail web. This approach allows the decoupling of effects of the lateral force from those of the vertical one with a simple combination of bending stresses measured on the rail web. The research uses finite element simulations and laboratory tests. The numerical and experimental results have identified an independent coefficient from the applied loads by which it is possible estimate the magnitude of the lateral force.

1. Introduction

The monitoring and verification of contact forces, applied by rolling stock to the track, is a fundamental topic of study for Railway Administrations and Research Institutions. Vertical overloads and imbalances in the composition of a railway vehicle can result in damage to the track and in a non-conformity regarding safety of operation. On the other hand, wheel-rail lateral contact forces are more directly involved in the running safety and deserve a special focus. Particular conditions like curves at low speed, twisted track and a high friction coefficient are the principal reasons for derailments, which normally occur in stations, depots and marshalling yards. The European Standard EN 14363 [1] prescribes the limit of contact forces between wheel and rail and regulates static and dynamic tests for the approval of rolling stock. It is well known that the distribution of wheel-rail contact forces, vertical (Q) and lateral (Y), depends on the load position, on their magnitude and on the characteristics of the vehicle suspension system.

The methods developed to measure wheel-rail contact forces can be divided in two main categories: on-board and wayside methods. On-board measurement devices are installed on the wheels and/or wheelset, while wayside devices are directly installed on the track. Wayside measuring devices are more economically sustainable and allow monitoring of the running safety behaviour (Y/Q derailment ratio) for all vehicles on a specific site with a given track geometry. Although estimation of wheel-rail vertical loads is a well-developed field [2,3], measurement of both lateral and vertical forces is rather uncommon. In the past, several authors had dealt with these subjects, as Ahlbeck-Harrison [4–6] and Moreau [7]. The main difficulty with this type of measurement is the hard decoupling of the effects of the vertical force from those of the lateral one. In fact, vertical and lateral forces produce, at the same time, a bending moment on the rail web that makes it difficult to estimate distinct effects.

However, in the last decades, some researchers have tried to overcome this limitation. Milković et al. [8] proposed a method based on Blind Signal Separation (BSS) using independent component analysis (ICA). The process attempts to minimize the correlation and increases the statistical independence of mixed signals. The experimental setup consists of a set of strain gauges on the rail web and another set on the rail foot. The strain gauges installed on the rail web measure vertical forces, while the strain gauges installed on the rail foot measure the lateral ones. The main limitation of this method is the non-linear dependence between the coordinates of the wheel-rail contact point and the geometry of the railhead profile. The dependence is a known function for new railhead profiles and can be determined measuring the worn profile, but it changes during the train regular service and it is

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different for the left and the right railhead. This fact also suggests a periodical repetition of the calibration process, in order to avoid a decrease of system accuracy. Delprete et al. [9] have developed a simple transducer called MPQY for measuring, at the same time, vertical and lateral forces through a sensor in a hole made in the rail web. According to the authors the only position that allows a separation of the effects of vertical forces from those of lateral forces is the shear–torsion centre. As it is known, the coordinates of this point depend on the geometry of the rail section, which makes this method closely related to the type of adopted rail. In the same way, Molatefi et al. [10] have studied a method for the measurement of vertical forces in the barycentre of the rail web, where lateral forces have less effect on measurements. The research compares a conventional method, that uses strain gauges on the rail web surface, with the MPQY approach. The work demonstrates that the magnitude of vertical strains is nearly the same for the MPQY transducer and for the conventional method, but the magnitude of lateral strains in the cross section of the rail is lower than those measured on the lateral surface. This result makes the measurements in cross section less sensitive and therefore less suitable for lateral forces evaluation. Even Bracciali et al. [11–13] propose a rail web sensor which is able to measure at the same time the vertical and the lateral forces applied by the wheels on the rails. In this case, the development of the sensor is motivated by the consideration that the rail web is located where the neutral planes of the bending cross identify the neutral axis. Putting the sensor in a drilled hole in the location of the horizontal neutral plane makes available a region where each force component can be measured separately. The main disadvantages of such location of the sensor are: the lower measurement sensitivity for lateral loads (as shown in the first sensor concept), the considerable ability of the production of the transducer because of the little space to glue the strain gauges, the problems related to the forced installation into the rail web hole in order to ensure the reliability of the measurements over the time and, finally, the hard procedure of calibration that has to be performed directly on the track. Recently still Bracciali et al. [14] examined other measurement techniques for the evaluation of lateral loads. They investigated the simultaneous application of three available methods in literature which intrinsically provide different results. The paper describes an iterative procedure to reconstruct the wheel-rail contact point location giving an estimation of vertical and lateral contact forces. However, the research shows a considerable lack of accuracy of the finite element simulations compared to the experimental test (about 30%). The authors attribute this lack of accuracy to a different experimental setup compared to the simulations. Moreover, the experimental results regarding the measurement of lateral forces, are not compared with any other reference value as made for the vertical ones. The authors validated the lateral force measurements only keeping in consideration the results obtained from similar cases. In conclusion, Yifan et al. [15] proposed a conventional method based on the rail bending moment. This method regards the rail profile as a cantilever beam and measures the bending moment difference of the rail web section of different height, but they do not provide a detailed technical description.

Most of these works are based on the development of new sensors (which alter the structural integrity of the rail with holes on the rail web) and on new methods wherein the decoupling of vertical and lateral forces depends on demanding calculations, on the coordinates of the wheel-rail contact point, on wheel–rail wear and on hard calibration process. Moreover, the sensitivity of lateral forces measurement is not yet comparable to that of vertical ones.

The methodology proposed in this paper is inspired by the work of Moreau [7] and it is able to overcome previous disadvantages: for example, it is able to process the acquired data with a simple computing algorithm. The proposed method has also a good measurement sensitivity, it is independent from the wheel-rail contact point and from other boundary conditions like the type of applied loads (vertical force and torsional loading), the load magnitude and the fastening stiffness. The present research, supported by Italian Infrastructure Manager (RFI – Rete Ferroviaria Italiana) [16], is the development of a previous investigation made by Bruner et al. [17]. The current method is based on the analysis of bending strains in the cross plane of the rail web surface and it has been tested using finite element simulations and laboratory tests. The numerical and experimental results have shown the clear possibility to decouple the effects of vertical forces from those of lateral ones.

2. Analysis of bending moment on the rail web

As it is known, the application of vertical (Q) and lateral (Y) loads on the railhead produces bending moments on different planes of the rail, Fig. 1. The presence at the same time of these forces generates a complex stress state on the rail web. Precisely, the vertical force, mainly due to the weight of rolling stock, is the reason of the shear stress and the bending moment in the vertical plane (x-z). On the other hand, the lateral force, mainly present during curves, produces the shear stress and the bending moment in the horizontal plane (x-y). Moreover, both forces generate torques on the horizontal axis (x) of the rail. Therefore, it is simple to understand how the identification of the source of strains, produced by wheel-rail contact forces, requires a detailed analysis.

The method proposed by Moreau [7] evaluates the rail web bending strains in four different points, symmetrically disposed respect to the z-axis, on the rail web surface, Fig. 1. In order to decouple the effects of wheel-rail contact forces, Moreau proposed to combine together the bending stress for each of the four measurement points. The equation of the bending stress (1), applied along the horizontal axis (x) of the rail, allows to obtain the following expressions:

$$\sigma_z = \pm \frac{M_x}{I_x} y \tag{1}$$

$$\sigma_{z1} = +\frac{Qe}{I_x}\frac{u}{2} - \frac{Y(a_1 - z_1)}{I_x}\frac{u}{2} \tag{2}$$

$$\sigma_{z2} = +\frac{Qe}{I_x}\frac{u}{2} - \frac{Y(a_1 + z_1)}{I_x}\frac{u}{2} \tag{3}$$

$$\sigma'_{z1} = -\frac{Qe}{I_x}\frac{u}{2} + \frac{Y(a_1 - z_1)}{I_x}\frac{u}{2} \tag{4}$$

$$\sigma'_{z2} = -\frac{Qe}{I_x}\frac{u}{2} + \frac{Y(a_1 + z_1)}{I_x}\frac{u}{2} \tag{5}$$

The sum of the bending stress (6) removes the influence of the vertical force, leaving out only the resulting of the lateral one:

$$\sum \sigma_z = \sigma_{z1} + \sigma'_{z2} - (\sigma'_{z1} + \sigma_{z2}) = \frac{2uz_1}{I_x} \cdot Y \tag{6}$$

$$K = \frac{2uz_1}{I_x} \tag{7}$$

Thanks to the last expression (7), it is possible to notice that the coefficient K depends only on geometrical factors like the rail web thickness (u), the distance from bending neutral axis (z_1) and the inertia moment (I_x) of the horizontal rail web section. However, the coefficient K cannot assume a constant value. The inertia moment (I_x), as a matter of fact, depends on the effective area of