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A hybrid method for the integration between an instrumented wheelset and the measure of the deflection of the primary suspension

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Abstract

Different methods are available to provide an estimation of the force exchanged at wheel-rail interface. Focussing on on-board systems generally the instrumented wheelset is the most used. Strain gauge bridges are typically applied on the axle and/or the wheel web to infer wheel-rail interaction forces generating a deformation field on the wheelset. It can be proved that the estimation of the lateral and vertical components of the contact forces on a generic wheelset results in a problem where six unknowns should be defined taking into account that the position of the contact points (even if unique) on the wheel affects the deformations measured both on the axle and/or on the wheel itself. Thus, at least six independent quantities must be measured in order to obtain a correct estimation of the contact force components. Other approaches rely on the instrumentation of the primary suspension in order to estimate at least the vertical component of the contact force. A hybrid method, that is combining the typical instrumented wheelset with the measurement of the deflection of the primary suspension, can be used if, for different reason, it is not possible to obtain six independent measurements related to the deformation of the wheelset. In the paper this hybrid approach will be presented as a means to overcome some problems in the instrumentation of the wheelset. The effectiveness of the proposed solution will be proved both on static and dynamic tests performed on a dedicated test-rig used for the calibration of the instrumented wheelset but also considering in-line test.

Keywords: Wheel-rail contact forces; Instrumented wheelset; Nonlinear effects

1. Introduction

The measure of the contact forces at the wheel-rail interface is a relevant issue in railway engineering. In fact, guiding forces and traction/braking forces determine the dynamics of a rail vehicle affecting the conditions of the track, in terms of wear of the rail profile in longitudinal and transversal direction and degradation of the ballast or the subgrade. Thus, it is clear that the possibility of measuring these forces has an important implication in the comprehension of several theoretical phenomena such as wear of components and riding dynamics, but, more important, it is fundamental for practical applications such as assess the running-safety of a vehicle and for the diagnostics of the track conditions.

A standard approach for the condition monitoring of the track and/or the vehicle relies on acceleration measurements. Several attempts are found in literature where the measures of the acceleration at primary and secondary suspension level are used in order to detect track defects or faults to vehicle components.

The paper by Weston *et al.* [1] presents a view of the current state of monitoring track geometry condition from in-service vehicles. Weston *et al.* [2-3] proposed to use different sensors mounted on the axle-box and on the bogie in order to identify track irregularity both in vertical and lateral directions.

Japanese researchers [4] developed a system with the aim to identify vertical and lateral track geometry irregularities using accelerometers placed on the body of in-service vehicles, requiring a modelling of the dynamics of the primary and secondary suspension systems and relying on the fact that irregularities of the track geometry pass into the vehicle body, due to a small filtering effect of the suspension stages. In order to remove this last assumption a further attempt was made and described in details in Ref. [5].

As far as the vehicle is concerned, the paper [6] presents a state of the art review on the techniques for railway vehicle on-board health monitoring systems, distinguishing between model-based and signal-based approaches. Among the first group, the contribution by Weston *et al.* [7] tries to use a similar sensor arrangement with respect to [1-2] for the estimation of suspension parameters of the vehicle by means of the implementation of a specific particle filter. Other attempts in the same direction using different approaches like recursive least square (RLS) algorithm or a signal-based approach using random decrement technique (RDT) are presented respectively in [8-9].

Anyhow, in many of the work present in literature the focus is on defects which are detectable by means of acceleration measurements, which, on the contrary, may lack precision as regards the identification of some track defects related for example to the track twist.

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However, it is important to point out that these kind of defects are not affecting only the passenger comfort, but more important, may lead to critical conditions which may affect the safety of the vehicle. The best way to infer information about these defects is to measure the forces exchanged at the wheel-rail interface, which, for the time being, is not feasible using in-service vehicles but it should be demanded to a diagnostic train.

For this purpose, a regular bogie for a metro vehicle was instrumented both with a series of accelerometers and with a system for the measure of the contact forces. In order to measure the contact forces instrumented wheelsets have been used. Both bogie wheelsets were instrumented with strain gauges in order to measure their deformation field and to infer the forces that caused it.

The aim of this paper is to propose a hybrid method which integrates into the typical instrumented wheelset also the information about the vertical deflection of the primary suspension. The proposed method permits to obtain an accurate estimate of the wheel-rail contact forces, even when the optimal measurement set is not available.

The paper is organized as follows: in Section 2, the layout of the instrumented wheelset will be presented. In particular, the possibility and the critical aspects related to the integration of the measurements of the primary suspension deflection in the contact forces measurement system will be analysed. In Section 3 the process followed in order to characterise the contact forces measurement system will be presented, while in Section 4 the effects of the non-linear behaviour of the suspensions will be analysed. In Section 5 the complete layout of the instrumented bogie will be presented and some results from an in-line tests campaign will be presented. Finally, Section 6 reports some concluding remarks.

2. Concept of instrumented wheelset

There are six components of the contact forces to be measured: one vertical, one lateral and one longitudinal component for each wheel. As reported in [10-11], being six the number of unknown, six independent signals must be derived from the wheelset. In reality, excluding the effects of the traction and braking and neglecting friction in the bearings, it is possible to state that the longitudinal forces acting on the two wheels are equal and opposite. Depicting the torque diagram for the axle (Fig. 1), it is clear that, it is possible to estimate both the longitudinal forces measuring the torsional stress between the wheels on the axle.

For the definition of the vertical and lateral forces four independent quantities are needed. In fact, the diagram of the bending moment in the vertical plane along the axle, shown in Fig. 2, is determined by the lateral and vertical forces acting on the wheelset. In order to discern correctly the four components of the contact forces acting on the axle, four independent quantities must be available: these are the strains measured in two sections placed on the axle-boxes and the strains gathered in two additional sections in the central part of the axle as well.

In order to reconstruct continuously during the rotation of the axle the bending moment, two full Wheatstone bridges, able to measure the bending strains, are mounted with 90° phase shift in four measurement sections of the axle. The measure of each bridge is squared and then summed in order to obtain the magnitude of the bending deformation in each section.

However, it is possible to demonstrate [10] that two more independent sections are essential to compensate for the effects of the lateral displacement of the wheelset with respect to the rail, which determines a displacement of the actual contact points from the nominal ones. Fig. 3 shows the bending moment diagram on the axle due to the lateral displacement of the wheelset, causing a lateral displacement of the contact point Δy. The variation of the rolling radius is neglected under the assumption that $\Delta y \ll r$. The shape of the diagram is totally undistinguishable from the bending moment due to the lateral force (Fig.2). Thus a variation of the position of the contact point is the same effect of the variation of the lateral force. Being all the bending diagrams piece-wise linear, it is impossible to derive any further linearly independent signal.

To overcome this problem the wheel-webs are also instrumented with a full Wheatstone bridge in order to get a continuous signal almost independent from the vertical load and proportional only to the lateral load applied to the wheel. In fact, using a FE analysis of the deformation field of the wheel subjected to lateral and vertical components of the contact force, it is possible to find a section which is almost neutral with respect to the bending caused by to the vertical force.

However, for the particular application presented in this paper the optimal measurement set was not available. In fact, it was impossible to place the strain gauge bridges directly on the axle-boxes due to the reduced space available. As shown in Fig. 4 the only possibility was to fix the bridges on the base of the wheel-web, but this solution resulted in a low quality of the output signal.

Therefore the number of independent sections was reduced to four with the final outcome of a significant reduction in the estimation capability of the instrumented wheelset.

In order to solve the problem, the two linearly independent signals due to the bending deformation of the sections on the axle-boxes were replaced by the measure of the vertical deflection of the primary suspension. The measurement was done by means of two linear potentiometers placed between the bogie frame and the axle-box, as reported in Fig. 5. In this way, considering that the vertical deflection of the primary suspension is mainly a function of the vertical load acting on the wheel, a pair of independent measurements was added to the system in order to guarantee an optimal measurement set, necessary for an accurate estimation of the wheel-rail contact forces.

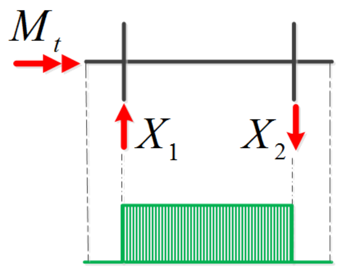

Figure 1. Effects of the longitudinal forces

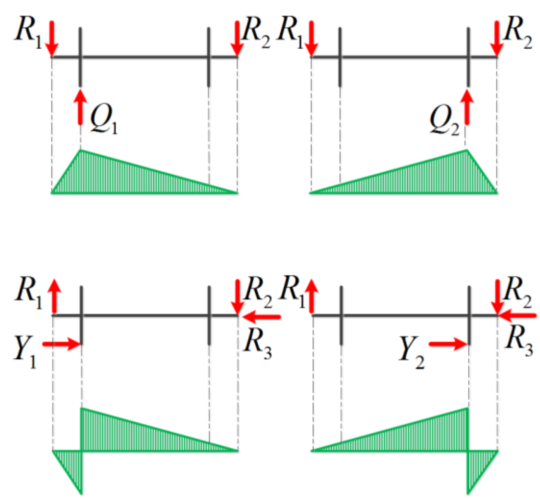

Figure 2.Effects of vertical and lateral forces

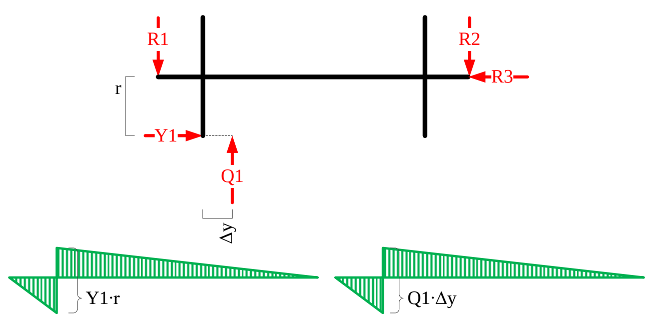

Figure 3. Effect of the lateral displacement of the wheelset

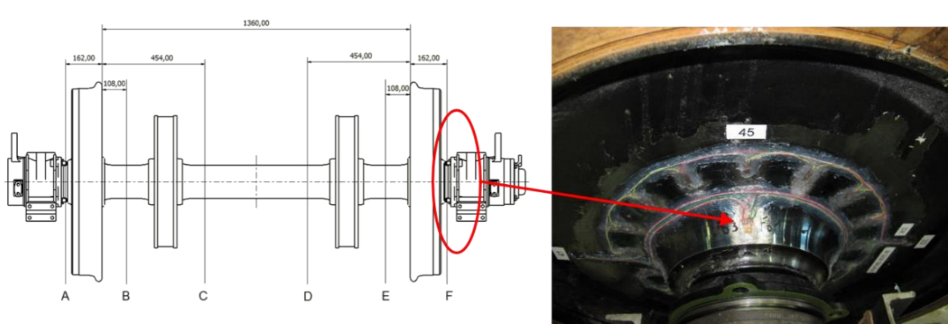

Figure 4.Disposition of the flexional bridges on the instrumented wheelset

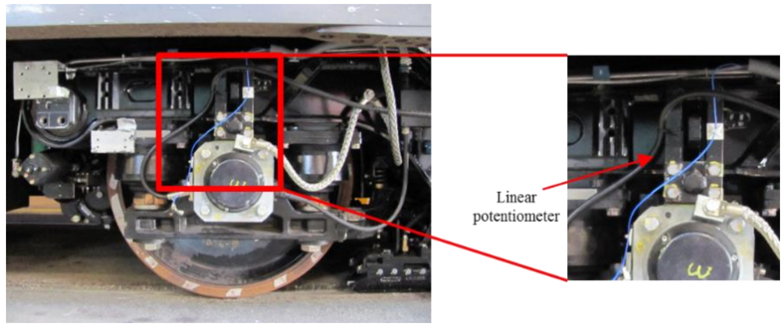

Figure 5. Positioning of the linear potentiometer on the primary suspension

3. Calibration of instrumented wheelset

The static calibration of the instrumented wheelset combined with the potentiometers for the measure of the primary suspension deflection has been performed by means of a dedicated test-rig. This test-rig has been designed to be a totally reconfigurable system, capable to house the entire bogie which the dynamometric wheelset. Due to this fact the boundary conditions on the wheelset are exactly the same experienced during inline tests. It is important to remember that the deformation field, especially on the axle, is influenced by the boundary conditions imposed through the suspensions. Moreover the forces are applied to the wheels by means of two pieces of rail having a UIC 60 rail profile with a 1/20 cant angle. These solutions permit to reproduce correctly the geometrical conditions of the wheel-rail contact.

Fig. 6 shows the layout of the test-rig: the vertical load is imposed by a couple of hydraulic actuators, while a third actuator, mounted on one side of the structure, is used to generate the lateral reaction force necessary to keep in place the bogie. The six forces acting on the wheelset are measured directly at the contact points by means of two dynamometric balances. Those balances have seven components and the particular configuration of those elements combined with the presence of independent actuators allows generating a great variety of loads also in conditions which could not be reproduced imposing only the sum of the lateral forces on the wheelset.

The calibration was performed using a procedure [12] which envisages that a series of loads are imposed to the wheelset by means of the test-rig and the output of the measurement system is measured. The output and the output were then correlated by means of a least square regression. In order to generate a consistent calibration model the test-plan has been derived considering the full factorial combination of the load condition presented in Table 1.

Using a full factorial approach, the number of tests results to be too large but several load cases are not feasible neither significant to the calibration (e.g. high level of lateral forces on both wheels or low level of vertical forces). To overcome the problem, an algorithm was designed with the aim of extracting from the full factorial test plan only the significant tests, defining also the lateral position that should be set in order to make each test feasible (i.e. central, left or right flanging).

Given the test plan it was possible to carry out the calibration and define the calibration matrix according to the Moore Penrose pseudoinverse matrix formulation as defined in Eq. 1, where Δl_v, ε and F denote respectively the measurements of the deflection of the primary suspensions, of the deformation of the instrumented wheelset and of the wheel-rail contact forces. The measurements obtained in each test are then grouped into the corresponding matrices.

$$\left[K\right]=\left[F\right].\left[\varepsilon,\Delta l_v\right]\left(\left[\varepsilon,\Delta l_v\right]\left[\varepsilon,\Delta l_v\right]^T\right)^{-1} \tag{1}$$

In order to evaluate the quality of the estimation associated to the calibration model $\left[K\right]$ the index σ_F described in Eq. 2 has been defined. The index was then used to compute the total uncertainty associated to the estimation of the i-th component of the contact force, defined as the combination of $\sigma_{F,i}$ and the uncertainty associated to the measure of the balances $u_{b,i}$, as defined in Eq. 3.

$$\sigma_F = std\left(F-\left[K\right]\left\{\varepsilon,\Delta l_v\right\}\right) \tag{2}$$

$$u_{F,i}=\sqrt{\sigma_{F,i}^2+u_{b,i}^2} \tag{3}$$

4. Non-linear effects of the primary suspensions

The results of the calibration are reported Fig. 7, showing the comparison between the estimated vertical force on wheel 1 and the measured one. Each point in the figure corresponds to a calibration test; blue points represent tests where the wheelset is centred, red points test where wheel 1 is flanging, while tests where wheel 2 is flanging are represented by green points. The straight lines identify the μ±σ band. It is possible to observe certain dispersion in the estimated values around the imposed levels. This is mainly due to the fact that the primary suspensions are non-linear elements, whilst in the calibration model, as defined in Eq. 1, the contribution of the primary suspension, made by rubber elements, and was considered to be linear. Thus, non-linear terms associated to the deflection of the primary suspension in the calibration process were added into the calibration process to improve the accuracy of the measurement system.

In order to find the maximum degree of the polynomial terms, the characterisation of the primary suspension was obtained by means of a specific test. In particular, a pure sine between (15–90) kN was imposed as vertical component of the contact force on both the wheels. As depicted in Fig. 8, it is clear that using a linear regression in order to describe the relationship between the measured primary suspension deflection and the applied force introduce an error in the estimation of the contact forces. On the contrary, it is possible to observe that the cubic interpolation provides a good approximation of the non-linear behaviour of the primary suspension.

However, a simple modification of the equation (Eq. 4) defining the estimated force is not sufficient. In fact, the estimate of the coefficients of the non-linear terms is not accurate on account of the fact that the calibration is made only on three levels of the vertical force and an infinite number of cubic curves can pass by three points.

$$F = \left[K\right]_l \cdot \left\{\varepsilon, \Delta l_v\right\} + \left[K\right]_{nl} \cdot \left\{\Delta l_v^2, \Delta l_v^3\right\} \tag{4}$$

In order to overcome this problem, five additional levels of the vertical force were extracted from the previously described sinusoidal test and used for the identification of the calibration matrix. The test-plan was increased only by 50 load cases extracted from the characterisation test so to avoid overfitting problems.

The result of the new calibration process is shown in Fig. 9, where it is possible to observe that the introduction of the non-linear terms and the modification of the test plan caused an improvement of the estimation quality close to 35%.

The effectiveness of the reformulated calibration model was tested on the test-rig imposing quasi-static actions to the wheelset. A series of continuously varying loads were applied to the wheelset, position in a random angular position. The results of the test are depicted in Fig. 10, and Fig. 11, where the comparison between the measured and the estimated values for the vertical component of the contact force on wheel 1 is reported.

The non-linear model (Fig. 11) provides a better accuracy in the estimation of the forces especially when large values of the vertical force are reached, on the contrary, the linear model (Fig. 10) is accurate only in a smaller range of values.

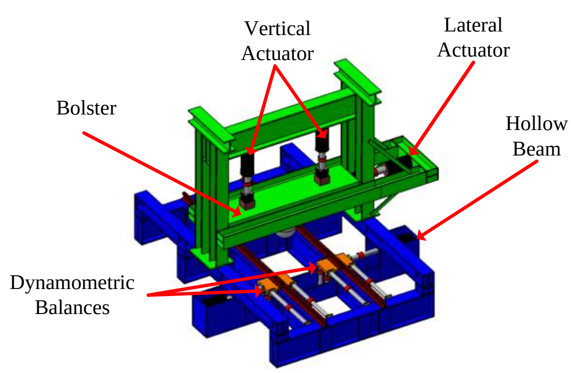

Figure 6. Calibration test-rig lay-out

Table 1. Summary of the load condition applied in the calibration process

Factor	Symbol	Levels	No. of levels
Vertical Force (kN)	Q1 – Q2	15, 35, 70	3
Lateral Force (kN)	Y1 – Y2	14, 7, 0, -7, -14, -28, -42	7
Longitudinal Force (kN)	X1 – X2	0, 5, 7, 10	4
Angular position (°)	θ	0, 90	2

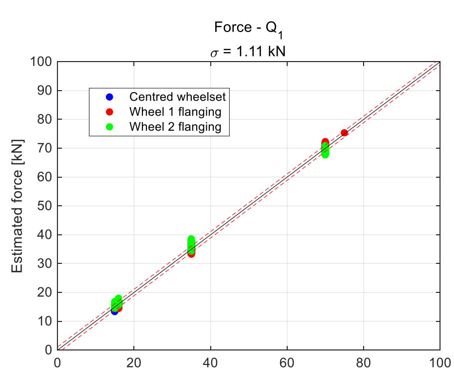

Figure 7. Vertical force estimation on wheel 1

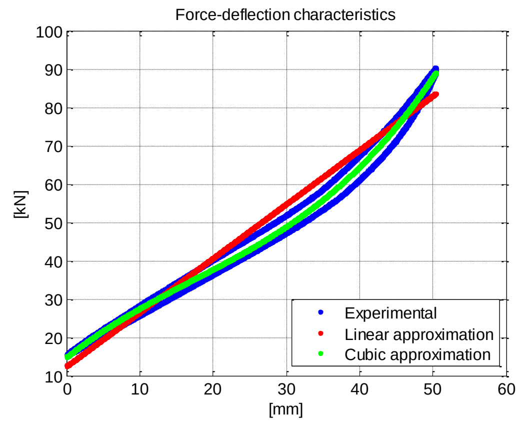

Figure 8. Primary spring characteristic

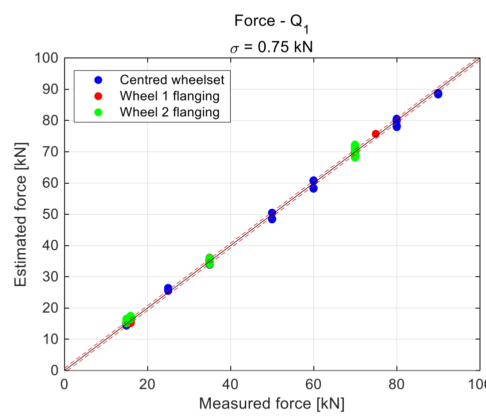

Figure 9. Vertical force estimation on wheel 1 by means of the non-linear model

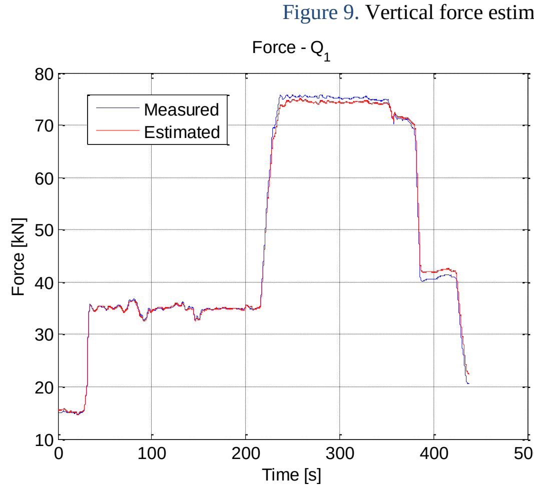

Figure 10. Vertical force estimation on wheel 1 by means of the linear model

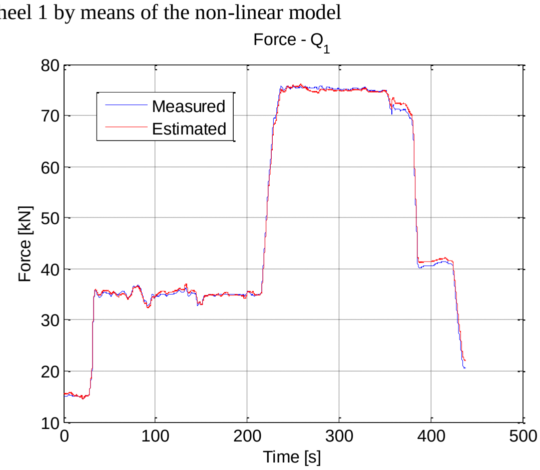

Figure 11. Vertical force estimation on wheel 1 by means of the non-linear model

5. In line tests

In order to allow the diagnostics of the track two different systems for the measure of the contact forces were installed on a regular bogie (one system for each wheelset) together with telemetry systems for the on board data transmission. Additional instrumentation was mounted on the bogie for the measurement of the accelerations. In particular, there were mounted three tri-axial accelerometers on the axle-boxes and the bogie frame was instrumented with three accelerometers in vertical direction, mounted just above the axle-boxes and two lateral accelerometers in the same position. Moreover, the configuration included two accelerometers in vertical direction and two in lateral direction on the carbody positioned above the bogie pivots.

The speed was measured using an encoder mounted on one axle, which is also used for the odometry system. The positioning of the train was determined considering also two linear potentiometers which were installed between the carbody and the bogie frame with the aim of measuring their relative rotation, thus generating a curve signal. Fig. 12 shows the layout of the instrumented bogie, where the side 1 of the bogie is the right side and side 2 is the left one with respect of the travel direction of the vehicle. The contact forces acting on all the wheels and the accelerations are considered positive according to the reference system.

For the sake of brevity, just one section of the line will be presented and briefly analysed. The instrumented bogie, in the case under analysis, was in leading position on the vehicle. Fig. 13 shows the speed profile and the curvature of the track along the section analysed, which is characterised by a series of three curves.

Analysing the signals of the vertical acceleration measured on the axle-boxes and the bogie frame (Fig. 14) it is possible to observe a significant vibration level in the first curve. This is caused by the presence of short pitch corrugation. In fact, as showed in the zoom of the vertical acceleration on the axle-boxes the most relevant accelerations have a wavelength of around 10 cm, which is a typical wavelength associated with these phenomena. These high-frequency components of the acceleration are strongly filtered by the suspensions as shown in the vertical bogie accelerations.

On the other hand, the analysis of the contact forces permits to identify defects on the track which do not have any influence on the vertical accelerations. Considering the contact forces on the leading wheelset depicted in Fig. 15, it is possible to observe a severe track twist irregularity at the transitions in the curve of 250 m radius.

The diagram referred to the vertical forces (Fig. 15 left) shows a sudden increase of the force on the right wheel just before the entrance of the curve, meanwhile the lateral force on the same wheel rose to -30 kN being the wheelset already in flanging position. At the exit of the curve (0.3 km) the track twist causes a reversed effect, the vertical force on the external wheel suddenly drops when the lateral force is still at -30 kN.

The latter condition has an important impact on the derailment coefficient Y/Q on the outer wheel, as depicted in Fig. 16. In fact, in the transition an increase of the coefficient up to values close to 0.8 is observed, highlighting the presence of a defect on the track which may lead to severe conditions with respect to safety if the evolution of the defect is not monitored or a maintenance operation is not programmed.

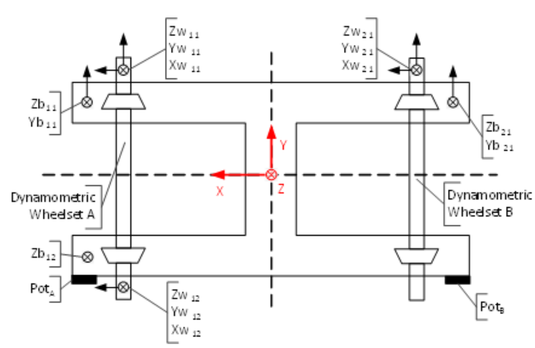

Figure 12. Sensors positions on the instrumented bogie

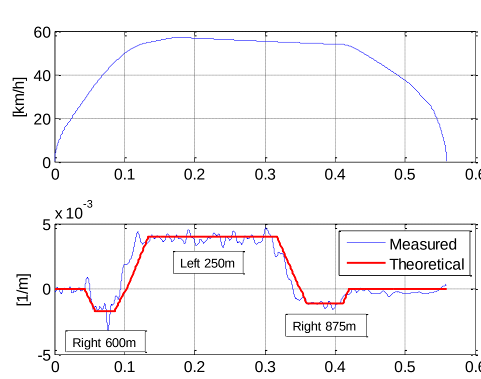

Figure 13. Speed profile and curvature of the track

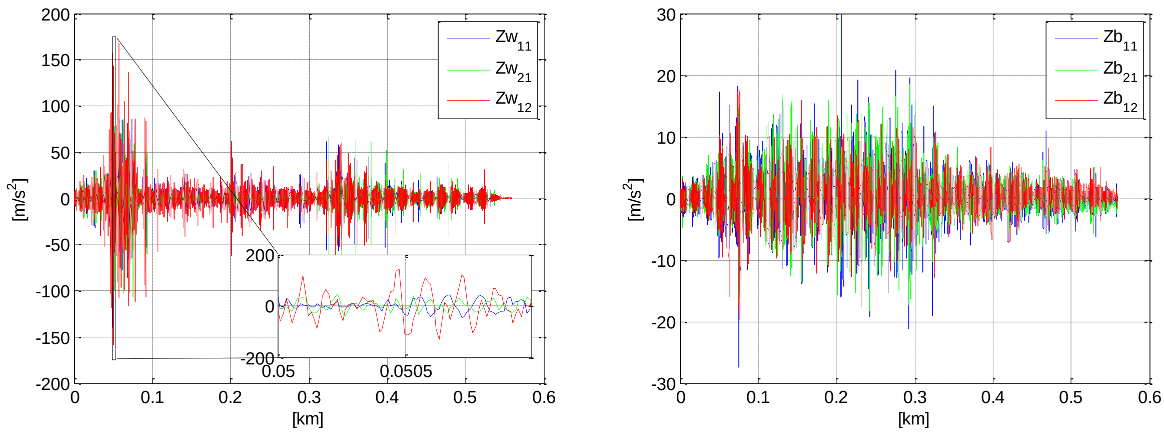

Figure 14. Vertical acceleration on the axle-boxes (left) and on the bogie frame (right)

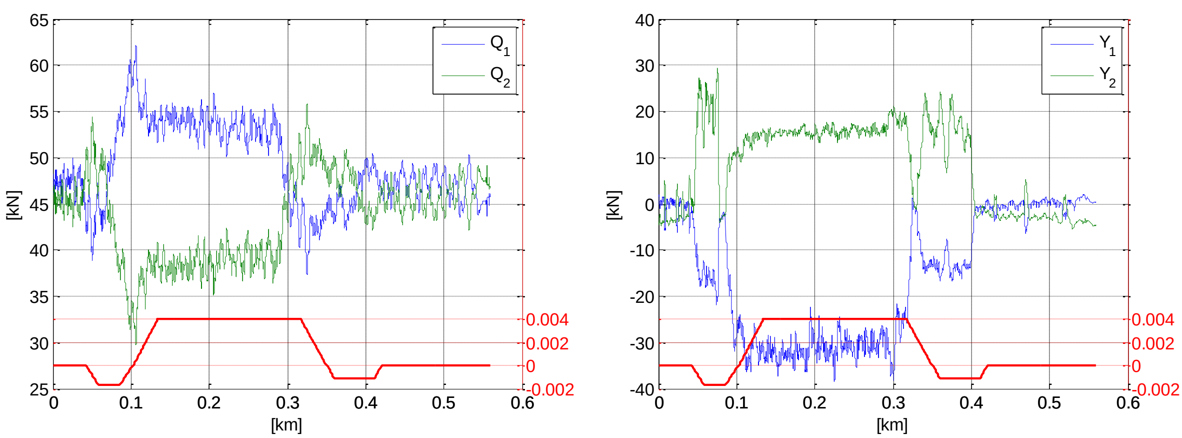

Figure 15. Contact forces in vertical (left) and lateral direction (right)

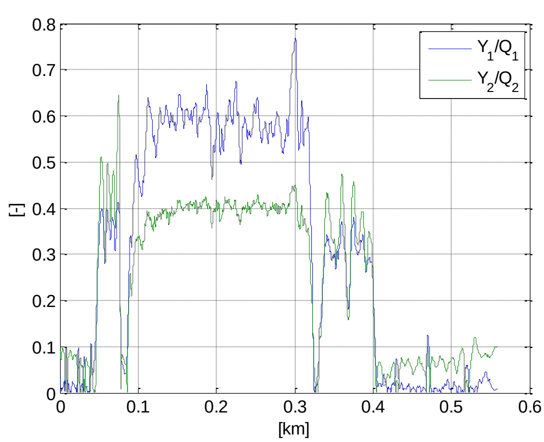

Figure 16. Y/Q ratio on the leading wheelset

6. Conclusions

In the present paper a system for the diagnostics of the track was presented. The measurement system was composed by a series of acceleration measurements from the axle-boxes, bogie frame, and carbody integrated with the measure of the contact forces. The measurement of the contact forces was made available by means of instrumented wheelsets.

However due to the particular configuration of the wheelset, it was not possible to obtain the optimal measurement set, defined by six independent measuring sections on the axle and the wheel webs (plus a torsional bridge for the estimation of the longitudinal forces). The section on the axle boxes were replaced by the measure of the primary suspensions deflections obtaining a hybrid solution.

The typical calibration procedure was performed for this solution and highlighted some peculiarities for this approach. In fact, a linear model was not sufficient to obtain a satisfactory accuracy of the estimation in a wide range of contact force values. Nonlinear effects associated with the force-displacement characteristics of the primary suspension were taken into account in order to improve the accuracy of the estimation. The model was then modified including cubic terms and further levels of the vertical force were added to the test plan.

The diagnostic system was used during in-line tests, showing the capability of recognising a variety of track defects, included specific defects (such as track twist defects) which result are difficultly detectable with a traditional accelerometric diagnostic system..

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