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Review of Instrumented Wheelset Technology and Applications

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Abstract

The measurement of wheel-rail interaction is crucial to quantify the running behaviour of a railway vehicle. The best way to continuously perform this measurement is to use a so-called “instrumented wheelset”, i.e. a wheelset of the vehicle under tests with some transducers fitted without large modifications. Current technologies consist primarily of a set of strain gauges glued onto the wheel web and/or the axle body that senses the elastic strain of these bodies allowing reconstruction, through a proper calibration, the forces that are mutually exchanged at the wheel-rail contact. The methods that are currently used are analysed and compared according to the most recent scientific literature.

Keywords: axle, wheel, wheelset, web, contact force, instrumented wheelset, strain gauge.

1 Introduction

Vehicle (or running) dynamics is, generally speaking, the entire dynamic behavior of a railway vehicle that runs along a railway line. Running dynamics is fundamental to determine the safety of a vehicle, i.e. the margin that exists with respect to derailments and the deterioration of track geometry quality considering the mutually exchanged forces between the wheels and the rails.

Wheelsets are assembled classically by using two wheels (with somewhat tapered tread profiles) and an axle; they are connected to the bogie frame with a suspension stage which normally includes a spring and a damper. As long as there is some lateral play between rails and wheel flanges, a vehicle can negotiate a given route in different ways depending on its inertial, viscous and elastic parameters. At the curve entrance, for example, the different wheels of a vehicle may give different thrusts to the rails; in tangent track, on the other hand, the presence of these clearances can contribute to parasitic motions that give rise to exceptional forces in the wheel/rail contact which may result in a lateral displacement of the track and eventually in a derailment.

Although computational tools are increasingly reliable, thanks to sophisticated wheel-rail contact models and the use of solvers in the time domain of highly non-linear multi-body models, regulations require in any case an online measurement of the behaviour of the vehicle, including the simultaneous measurement of the vertical forces Q (V in the American literature) and lateral forces Y (L in the American literature) exchanged at the wheel-rail interface. These forces are used to define the derailment coefficient for each wheel (known as Y/Q or *Nadal's coefficient*) and the total lateral force for each wheelset (also known as *ripage force*, ΣY), the latter being responsible for track geometry quality deterioration according to the Prud'Homme formula.

Although the European standard in force [1] does not prescribe any particular method to measure contact forces, these measurements are better performed *on-board*, i.e. installing some instrumentation on the vehicle rather than measuring trackside. The advantage is evident, having the possibility of continuously measure and keep under control the running behaviour of the vehicle under test.

Measuring systems of contact forces installed on vehicles are designed and built to be the less invasive as possible on the standard vehicle configuration. Systems capable of directly measuring contact forces do not exist; contact forces are always indirectly estimated from the effects that these forces have on some selected components of the vehicle. The nearest the measuring points will be to the wheel-rail contact the best the measurement quality will be, and this makes the wheels and the axle the best candidates to get the highest possible signal-to-noise ratio even if local variations such as those related to high frequency interactions (rail corrugation), actual profiles and contact point positions may get a higher relevance.

This paper reviews measuring systems found with a literature search. All the methods found wheelsets instrumented with electrical resistance strain gauges (ER) as transducers, even if some alternative and less performing methods exist that can estimate forces at the wheel/rail contact without the use of an instrumented wheelset [2]. They have the advantage of not requiring telemetry systems to transmit signals on board. They can be classified as follows:

- estimation of Q loads through the measurement of primary suspension displacement. Displacement transducers applied between the bogie frame and the axleboxes can estimate radial loads on the two wheels only for linear springs and low primary suspension damping. To keep the displacement-force relation linear, measurement bandwidth must be limited well below the natural frequency of non-suspended masses (around 5 Hz). Friction elements and complicate designs make this measurement virtually impossible. Moreover lateral forces Y cannot be obtained with this method;

- direct measurement of wheelset- axlebox lateral force *Y*. A force transducer is positioned on each axlebox to detect lateral force exchanged with the wheelset. This force is related to the sum of lateral forces acting on the wheels. Although the bandwidth is higher, the forces on the each wheel cannot be distinguished. The method is accepted by [1] for service authorisation in certain cases but in general is not sufficient to perform a full analysis of the dynamic behaviour of a vehicle.

Considering in the following only instrumented wheelsets, measurement techniques can be classified in three main families:

- systems where axle strains are measured;
- systems where wheel web strains are measured;
- systems where both axle and wheel web strains are measured.

2 Historical background

Although reference [3] gives interesting information from the historical development of wheel-rail contact forces measurement, it does not provide technical details on instrumented wheelsets. Literature review [4], published in 1991, describes instead different methods of configuring instrumented wheelsets that were developed since the '70s in the USA and in Europe. Deutsche Bundesbahn (DB) focused the research on measurement of axle strains; British Rail (BR) measured deformations in spoked wheels; Electro-Motive Division (EMD) of General Motors Corporation, ENSCO Inc., IIT-IITRI and Swedish State Railways (SJ) focused their attention on the measurement of deformations of solid wheel.

More recently Interfleet Technology Inc., that took over the former branch of Swedish Railways developing instrumented wheelset, released in 2006 the IWT4 wheelset ([5],[6]). The main advantage of this method is that the influence of the geometry of the wheel is reduced by the solution of a system of equations with a DSP (Digital Signal Processor) system, making the instrumentation readily applicable to any type of wheel. Wheel web drilling is no more necessary thanks to a wireless transmission system which furthermore reduce cables lengths, reducing installation costs and making the wheels immediately available for revenue service.

The gradual achievement of interoperability of the European railway system led to fund in 2005 the WIDEM (Wheelset Integrated Design and Effective Maintenance) research project to which manufactures, universities and research institutes participated [7]. The project aimed at reviewing the way railway wheelsets are designed and maintained by using a roller test bench to simulate real operation. One of the outcomes of the project was the analysis of the existing methods to instrument wheelsets ([8]). The results contained in this report will be shown in the following chapters.

The literature search found a large number of particularly detailed papers published by Italian authors ([2], [9] to [17]). Wheel web strains were considered by the University of Rome while Milan Politechnic developed a hybrid method [9]that includes measurements both on the wheel and on the axle. Further researches, although not available for industrial confidentiality reasons, appeared to be conducted by companies such as Alstom and Lucchini RS.

3 Requirements of the measuring chain

3.1 General requirements

Any measuring chain has its properties and limitations. Considering the peculiarity of instrumented wheelsets, where contact forces are estimated by strains in the wheelset, the requirements and limitations of this type of measurements are listed in [18] referring to earlier studies:

- sensitivity and resolution – where the first has a marked influence on the signal-to-noise ratio;
- ripple – resulting from the rotation of the wheel;
- cross-talk, noise in the acquisition channels, for example an output on the x axis of the transducer caused by a force applied on the y-axis;
- centrifugal effects, i.e. signals related to rotational deformation of the wheel;
- thermal effects, i.e. signals related to deformation due to temperature changes;
- linearity and hysteresis.

Another source that describes the desired properties of such measuring system is [10] (see Table 1). It is important to highlight that not all properties have the same importance, e.g. the biuniqueness is essential while different tolerances are allowed for other properties considering cost issues.

Measurement technique	Measuring system
biuniqueness	completeness
linearity	versatility
continuity	controllability
immediacy	suitability
accuracy	
rejection	
sensitivity	
pass band	
repeatability	
filterability	

Table 1: Characteristics of technique of measurement and measurement system (from [10]).

3.2 Requirements fulfilling by different measuring methods

The paper [10] proposes a description of how four methods fulfil the aforementioned requirements:

- the method of “rigid wheel” that considers this particular behaviour of the web, results in a good continuity of the measure while it is inappropriate about completeness. Other requirements are satisfied;
- the method of “elastic wheel” considers the use of a rubber element between the web and the tread. As rubber is not linear both in static and dynamic conditions, this method does not satisfy the linearity and continuity requirements. Also applicability is impaired since the use of wheels of this type changes the behaviour of the bogie;
- the method of “bending” considers the wheelset as a rigid frame made of a horizontal beam (the axle) and two columns (the wheels). Knowing the stress state on each member, the acting system of forces can be reconstructed. It is the only method that fulfils the requirement of completeness, while its application turns out to be as expensive in terms of installation;
- the “torsion” method gives straightforwardly longitudinal forces and torques acting on an instrumented wheelset by measuring axle torsional strains. As long as torsional stresses do not vary along the circumference regardless of the considered section, this results in the insensitivity to angular position assumed by the axle during rotation. This interesting feature is nevertheless contrasted by the major drawback of the method, i.e. the lower amplitude of the torsional strains compared to those resulting from bending (5÷10 times lower); moreover completeness requirement is not satisfied as long as this methods does not allow the measurement of the other forces.

4 Contact forces reconstruction by measurement of axle bending strains

The feasibility of the estimation of contact forces with strain gauges mounted on an axle was first described by the researchers at the Deutsche Bundesbahn research centre located in Minden, Germany [11]. The method was steadily developed over the years, although the principle remained the measurement of the axle strains to reconstruct the bending moment and eventually to estimate the contact forces.
Figure 1 shows the three dimensional set of forces acting on the wheelset, resulting in bending moments in vertical and horizontal planes.

Writing and inverting the linear relationships linking applied forces and bending moments it is possible to estimate vertical, lateral and longitudinal forces starting from strains measured on the axle. The main limitation is the intrinsic approximation of the method that assimilates the axle to a simple De Saint Venant beam. Coefficients of influence must be therefore found in advance with a proper calibration of the instrumented wheelset.

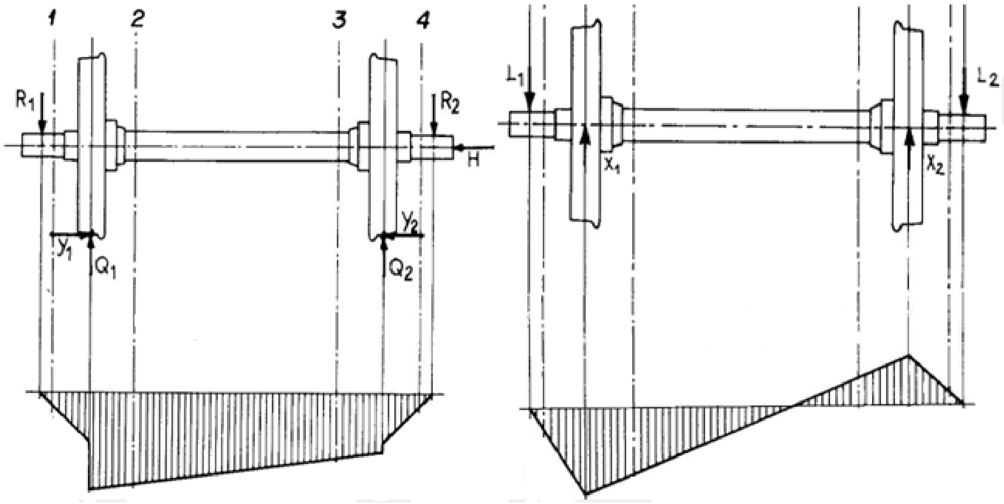

Figure 1: Forces acting on a wheelset and bending stress diagrams in the vertical (left) and in the horizontal (right) planes [10].

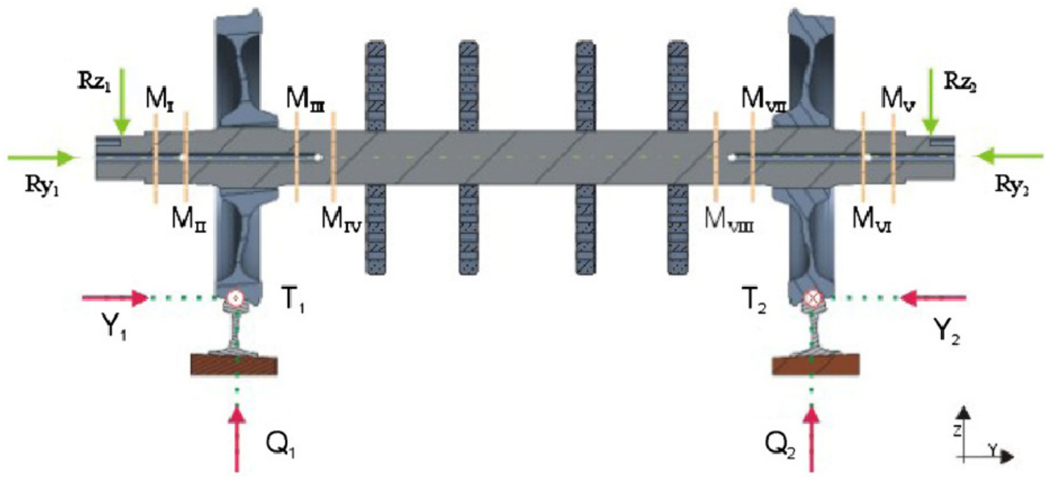

Figure 2: General layout of strain gauge instrumented sections of a wheelset. Difficulties in the application of all the sensors pictured here are evident [19].

Methods based on axle instrumentation are affected by many "sources of error" mainly due to the wheel-rail contact position change, worsened by the fact that inertia effects of the mass between the contact point and strain gauges are neglected [19]. One way to compensate for errors due to inertia is to measure also the acceleration of the wheelset. These inertia errors grow with the mass between the contact point and the measuring points, thus affecting the methods based on the axle instrumentation more severely than methods based on wheel web instrumentation.

Signals of strain gauges mounted on the axle also are affected by the rotation of the axle resulting in signals that are amplitude modulated with a purely sinusoidal disturbance in phase with the axle rotation. This modulation signal is easier to be removed compared to modulation signals observed on strain gauges installed on wheel web. Figure 3 shows the typical connection of strain gauges with Wheatstone bridges that provide signals respectively in-phase and in quadrature [19].

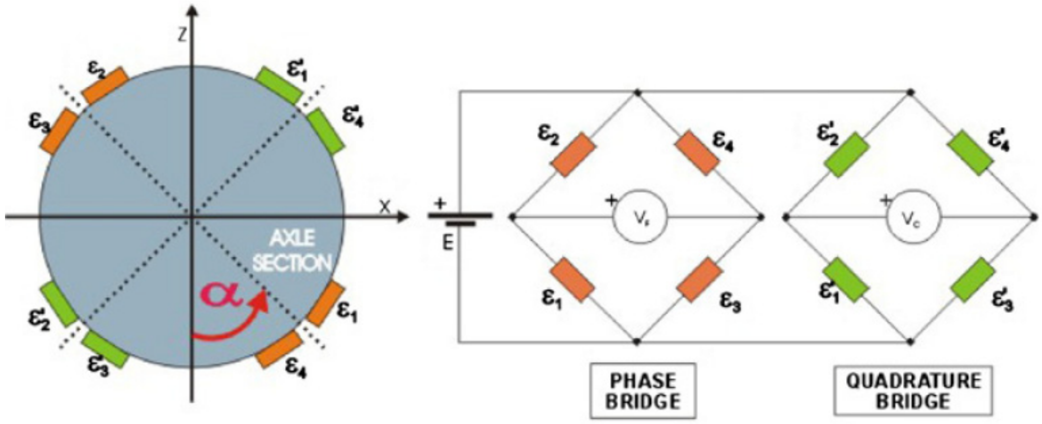

Figure 3: Strain-gauge wiring for axle-based methods [19].

Another version includes the use of strain gauges on the wheel to correct systematic errors due to the continuous variation of the contact point during line tests. Advantages and disadvantages of the application are described in [10]. It satisfies the requirement of completeness since it allows the measurement of contact forces *Q*, *X* and *Y*, but at the cost of important complications for calibration and signal processing. Moreover, the presence of other axle bending forces (traction, braking and axlebox load shifts, etc.) further complicates the system of equations that must be solved to reconstruct the bending moment and the input forces, unless systematic errors are accepted. Additional strain gauge bridges are needed to identify any further source of bending moment; practical difficulties therefore arise to implement the method on motor wheelsets.

5 Contact forces reconstruction by measurement of wheel web strains

The earlier applications of the reconstruction of contact forces by using instrumented wheels was the use of specifically designed spoked wheels, where stress measurement in spokes allow to reconstruct vertical and lateral loads. This method, used and developed especially in England and in Japan, makes use of the peculiarity of the wheel shape design that hase the advantages of virtually zero cross-talk and insensitivity to changes in the lateral position of the contact point for the lateral and longitudinal bridges.

This method requires wheels that have a completely different shape from that of the wheels that are normally used, which may result in a lower sensitivity and in high costs. Moreover, the method was abandoned in practice because it introduces changes in the global behaviour of the wheelset (and therefore of the vehicle) which can hardly be taken into account. The reader is referred to [3][12] for further details.

A large number of solutions using strain gauges on the web are found in the analyzed literature. Generally speaking, these methods do not require large wheel modifications (with the exception of minor modifications detailed below) and have the following advantages [11]:

- their application is rarely hampered by particular transmission systems and/or brakes;
- the wheel always exists, while in the case of independent wheels axle may not exist;
- the contribution of inertial forces is presumably lower as measuring forces are closer to sensors;
- the methods based on axle bending measurements are limited to a bandwidth lower than the first bending mode of the wheelset (around 80 Hz) and so are not suitable for the detection of phenomena that have frequencies above 40 Hz. The first bending mode of a wheel is around 200 Hz; this enhances the bandwidth at least up to 100 Hz, allowing to detect dynamic phenomena related to the superstructure.

The complete definition of the measuring chain requires to choose radial and angular strain gauges installation positions. While the choice of radial position makes it possible to measure all the three components of the contact force (*X*, *Y*, *Z*), a proper angular position selection is useful to reduce as much as possible the influence of wheel rotation on acquired signals.

There are various strategies aimed to the determination of the radial position of the strain gauges [20]. They can be placed in fact on points on the web in which the sensitivity to one of the components is zero, on points with the same sensitivity to contact forces to be properly combined in post-processing or close to holes specifically drilled on the web. Some examples of strain gauges mounting are shown in Figure 4. With reference to the letters shown in the figure, the following considerations apply [20]:

- configuration (a): strain gauges are applied on a circumference. Their signals are added in order to obtain a signal that tends to the continuous component of radial strain;
- configuration (b): the measurement is performed only when the strain gauge passes through a pre-determined position. This eliminates the influence of variation of angular position but it gives a very low band pass (one point per revolution). This method is therefore not recommended;
- configuration (c): two strain gauges are positioned in quadrature on the same circumference. The two deformations, indicated as ε_c and ε_F , are multiplied by two sinusoidal signals in phase with the angular position of the wheel. Intermediate results are then summed with a demodulated amplitude value. This can be accomplished through demodulation $(\varepsilon_c^2 + \varepsilon_F^2)^{1/2}$ but paying the price of the loss the sign of the force which, as known, can change in the case of longitudinal and lateral forces. This type of solution is equivalent to that used in methods where the measurements are performed on the axle, but in

this case it is incorrect to assume that a pure sinusoid can provide an accurate model for deformation, as the point of contact varies. The output signal is affected by ripple which depends on the weighs of all the harmonics other than the first, that are contained in ε_c and ε_F. To reduce the ripple some authors combine the signals from multiple gauges, mounted in different angular positions, although the first harmonics is never perfectly demodulated.

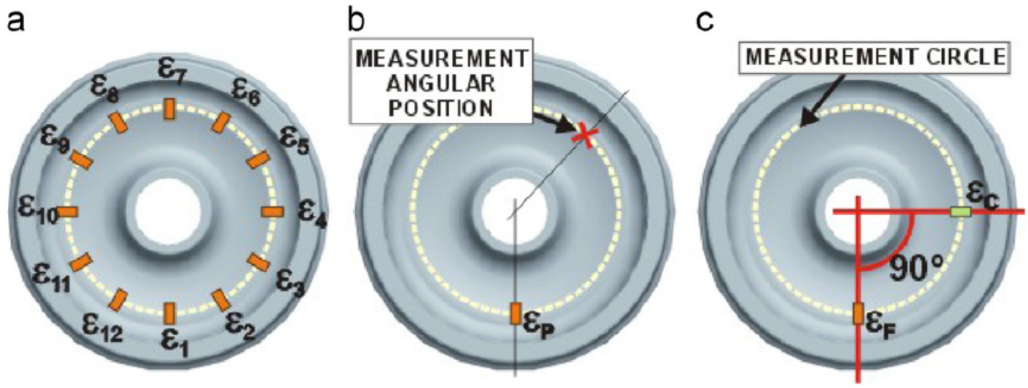

Figure 4: (a-c) Different strategies for the angular positioning of strain-gauges

Improvements in strain gauge technology allowed to estimate the lateral Y component of the contact force which is responsible for the largest strains on the wheel web. Lateral force effects are superimposed on those due to vertical force Q and those due to the load variation of the contact point position d_R. According to [11], only some of the more recent systems measure directly the load Q with strain gauges mounted on the wheel web.

Higgins et al. [21] estimated all the components of the contact force (including the distance d_R) by instrumenting a wheel web with a large number of strain gauges. Wheel web must be machined, an extensive use of FEM results is needed to choose strain gauge positions and a large number of calibration conditions must be performed at a calibration bench if FEM results are not directly used.

The methods presented in [22] and [23] consider the use of holes drilled in the web to maximize the sensitivity to Q by introducing stress concentration, but do not consider the actual contact point position. More recently, the results of an investigation performed to measure also the position of the contact point was published [24]. Figure 5 shows the strain gauges arrangement to estimate the lateral and the vertical components of the contact force. Four holes are needed to position the sensors devoted to the measurement of the vertical component minimizing the influence of the lateral component, which in turn is measured through the bending of the disc.

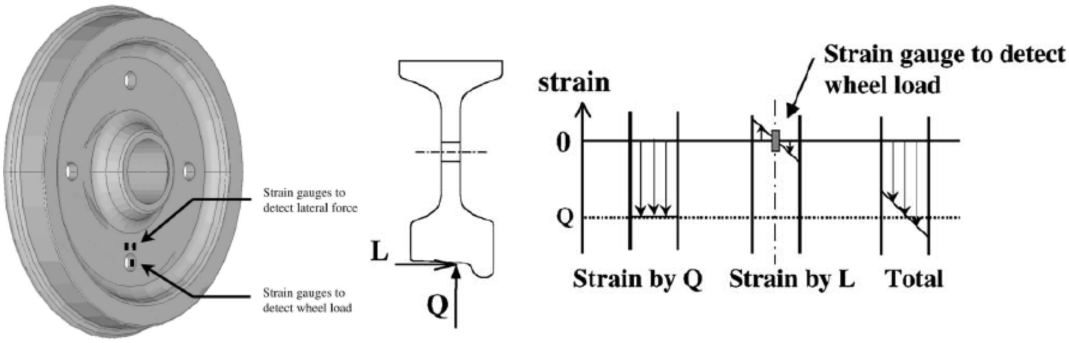

Figure 5: Typical location of strain gauges for measuring wheel load and lateral force (left). Strains in the web induced by *Q* and *Y* contact forces (right) [24].

The measuring method developed at Rome "La Sapienza" University [11][13] estimates *Y* and *Q* by measuring only the strains of the internal and the external surfaces of the web, by separating the effects induced by the components *Q* and *Y*, obviously requiring the estimation of the lateral contact point location d_R. The strain state of wheel web was found in [2] to be characterized by an area near the hub where the sensitivity to the axial force *Y* was maximum and by an area near the tread where the sensitivity to lateral force is zero changing its sign. The first area is used to estimate lateral forces, while the second is to estimate vertical forces and the distance d_R. Bandwidth resulting from this method is high, the method can be applied on many vehicles (also with independently rotating wheels), uncertainties in the measurement can be easier quantified than with other strain gauges arrangement (Figure 6). Centrifugal forces and thermal effects (both supposed axisymmetric) are minimized while signal/noise ratio is optimized by using full Wheatstone bridges and an optimization procedure based on the use of a pseudoinverse matrix is used to maximize an objective function [11].

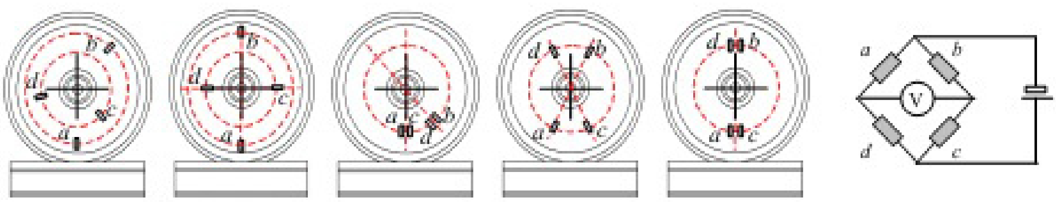

Figure 6: Possible full-bridge strain gauge configurations arrangements insensitive to thermal and centrifugal deformation. The rightmost configuration is optimal as it has the highest gain, two maximum sensitivity outputs per revolution and the maximum signal-to-noise ratio.

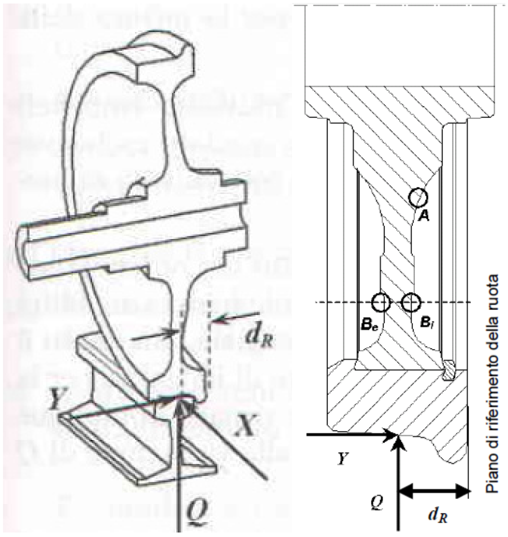

Figure 7: Nomenclature of acting forces and contact point lateral position (left). Vertical cross section of the wheel (right). Radial strains in measuring points B_e and B_i, are insensitive to *Y* force. Point A is used to estimate lateral force [13].

The measuring method developed by Alstom, described in [15], is an evolution of the previous one. Diametrically opposed full strain bridges (so-called "discrete" method) result in insensitivities at some angular position that may be overcome by using a larger number of sensors (so-called "continuous" method) installed on several circumferences resulting in an output of the strain gauge bridges which is approximately constant during wheel rotation. Thirty-two strain gauges are wired as shown in Table 2, 16 on each side. The measurements result to be affected by centrifugal effects that must be compensated for. Signal-to-noise ratio is very good up to around 100 Hz, but costs are quite high.

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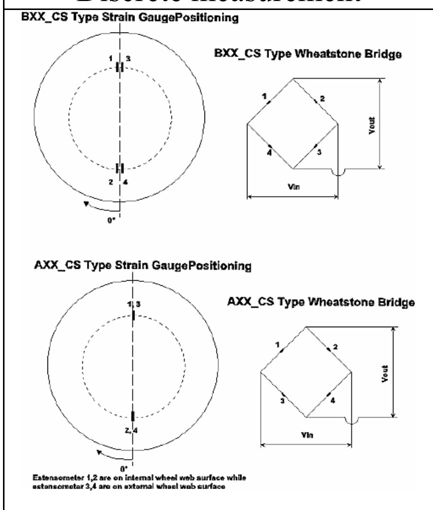
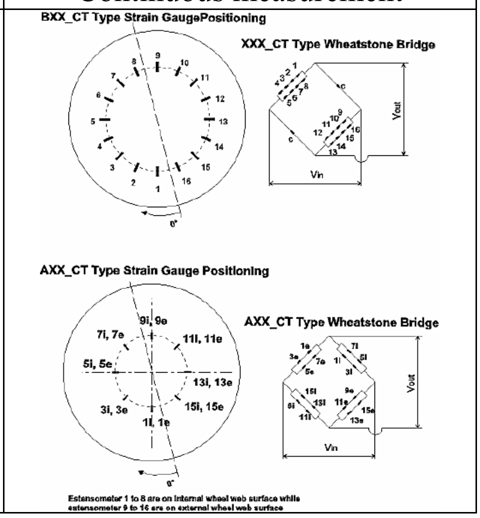
<tr><th>Discrete measurement</th><th>Continuous measurement</th></tr>
<tr><td>
</td><td>
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Table 2: Layout of strain gauges for the "discrete" (left) and the "continuous" (right) methods [15].

6 Contact forces reconstruction by simultaneous measurement of axle and wheel web strains

In 2002 Milan Polytechnics and Lucchini RS published the results of a research where both the axle and the wheels were instrumented with strain gauges [9]. In this method the instrumented wheelset was calibrated on a roller rig, a minimization approach to find the input forces-strains relationship, uncertainties were quantified and all the three components of the contact force were measured.

An initial FEM analysis showed the best location for strain gauges with considerations similar to those already mentioned, under the hypothesis of the existence of a neutral section of the axle allowing, at least in principle, to get results less affected by the geometry of the wheels, either solid or with rubber elements between the tread and the web (elastic wheels).

The choice of strain gauges location is shown in Figure 8. It can be seen that the wheel is instrumented with 32 strain gauges, 16 per side, positioned on a circumference close to the axle with the an angular step of 22.5°. As long as six components of the contact forces are to be reconstructed, six independent sections were identified on the axle where bending in both vertical and horizontal planes is estimated. Two bridges measuring torsional stresses are added. With this choice a sufficient set of mutually independent measurements is available to reconstruct all the components of the contact force.

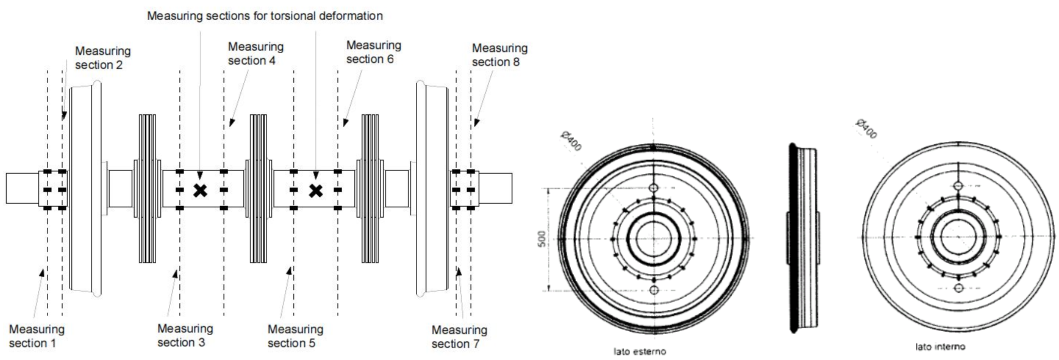

Figure 8: Measuring sections location (left) [25]. Circumferential and angular positions chosen for the installation of strain gauges (right) [26]

Contact point instantaneous location must be estimated to reconstruct the actual values of contact forces as long as no assumptions can be made on the existence and/or the location of the neutral section on the axle. This estimation can be done either numerically coupling wheel/rail profiles or by using image analysis techniques.

The number of sections on the central part of the axle to estimate bending could be reduced to 2 (instead of 4) if distributed and concentrated masses (e.g. brake discs) were known. Similarly, only one section could be needed to estimate torsion. Nevertheless, including all the sections previously mentioned the robustness and reliability of the method is improved. Continuous measurements are possible as bridges in quadrature are installed on each section. Data are transferred by telemetry systems either in synchronous or asynchronous sampling. In the first mode a proximity transducer sensing a cam triggers the acquisition, in the second mode the same angular reference is used anyway to correctly decompose the force vector identified according to the instantaneous angular position.

Similarly to the approaches already described, the method estimate the contact forces by inverting a set of linear equations that were written in order to minimize the uncertainties in the measurements. Paper [9] discusses in detail the methods used to reconstruct the contact point lateral position and all the components of the three dimensional contact force.

7 Calibration and signal processing considerations

7.1 Overview

Strain gauge measuring chain is analogue and data must be digitized to perform acquisition and the required calculations. Sampling performed in the A/C converter can be done in two ways according to the strategies depicted in [27]:

- constant time interval (CΔt) techniques, normally known as "continue", in which signal is sampled at regular time intervals, chosen to obtain a space resolution sufficient to satisfy at any speeds criteria set by international standards ($\Delta s \leq 0.5$ m according to [1]). Signals must be valid throughout a turn. Resulting sensitivity is lower and signals are affects by periodic disturbing waves. They can provide information at relatively high frequency with a reduced number channels although with reduced accuracy;
- constant space sampling (CΔs) techniques, also known as "discrete", where the signals are sampled at regular angular intervals according to the number of pulses per revolution of the triggering system. Sampling rate is therefore proportional to the speed. Sensitivity is higher and with theoretically better accuracy. More channels are required if continuous phenomena at high frequency are to be investigated along a turn.

Measuring methods using instrumented wheels are normally continuous and CΔt sampling is therefore used [11]. In particular, gauges used in the methods found in [21], [22], [23] and [24] use electrical radial connections resulting in alternating signals due to the rotation of the wheel that requires the application of rather complex techniques (correction of gain and/or combination of more bridges) to make the output continue rejecting the non-sinusoidal carrier. These methods are wheel-specific; for example, in [21] the wheel web is drilled is particular positions and the results cannot be generalized to other wheels. Measuring chain complication makes the detection of malfunctioning harder.

The use of a CΔs sampling technique is proposed in [12], where signals are sampled when the instrumented radius passes above the contact point. Strains due to contact forces are the highest in this position. A greater number of instrumented radii results in a greater number of samples per wheel revolution.

7.2 Sampling frequency

Sampling frequency should be chosen considering the natural behaviour of the wheelset [28] and the low-pass "filter effect" that increases with the distance from the contact point and the measuring points. Low-pass filtering also has a positive effect on anti-aliasing. As standards require a minimum cut-off frequency of 40 Hz, according to Shannon's theorem sampling should be done at least at 80 Hz but in practice a minimum value of 200 Hz is recommended. The first bending frequency of a wheelset is in the order of 80 Hz while the first axial mode of a mounted wheels has a frequency of around 200 Hz; this makes the extensions to frequencies greater than 40 Hz (such as those required to identify local features of the signals, e.g. peaks arising from rail joints) highly questionable.

As already mentioned, CΔs sampling technique must be able to supply a sample every 0.5 m. The cut-off frequency of 40 Hz is reached at 72 km/h (20 m/s), and this therefore strongly limits the maximum running speed. The behaviour of the primary suspension should be clearly observable as it lies around 15 Hz.

The choice of the CΔt or CΔs sampling technique depends on the purposes of the measurement campaign:

- CΔt sampling technique require strain gauges with a "crown" arrangement and suffers from a reduced sensitivity, but data are immediately continuously available although accuracy is often low due to a lack of biuniqueness or poor interference rejection;

- CΔs sampling technique provide higher sensitivity and accuracy as the signals are sampled when the gauges are in the part of the disc more sensitive to contact forces. They can offer an exceptional linearity, good noise rejection (high signal-to-noise ratio) and very high accuracy [12]. As a drawback, bandwidth may result limited.

8 Conclusions and further developments

The existing literature on instrumented wheelsets was described. It will be the basis of the development of future wheelsets and of their calibration devices. The analysis of existing telemetry and data acquisition systems will be described in a future paper.

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