NEW SENSOR FOR LATERAL & VERTICAL WHEEL-RAIL FORCES MEASUREMENTS

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ABSTRACT

Damage accumulated in rails can lead to railway disasters. The authors propose a new sensor which is able to measure at the same time the vertical and the lateral forces applied by the wheels on the rails. The sensor is based on very well-known and absolutely reliable strain gauge techniques with simple electronics and processing procedures. The transducer is very simply mounted on the rail and any maintenance, due for example to cables torn during unwise track tamping, is possible with simple operations and does not require specifically trained personnel.
When complemented with a system capable to detect the lateral position of the wheel tread relatively to the railhead, the use of such a sensor is absolutely necessary to develop rail life prediction models to prevent failures and to increase rail performance.
The results coming from some applications of the sensor are shown, including considerations on the applications to damage accumulation, vehicle dynamics and general condition monitoring (axle counting, speed measurement, train identification) problems. The sensor is self-checking, opening possible applications in the signalling field.

INTRODUCTION

The measurement of train-track interaction force has been faced in many different ways as it is clearly critical to find out potentially dangerous situations. Typical solutions include the use of instrumented vehicles to check out continuously the running dynamics conditions of the vehicle (CEN, 2002). The approach to the measurements of trackside forces can be split, accordingly to Figure 1, analysing separately the different components of the forces acting on the rail:

- the vertical force Q is due primarily to vehicle weight. In curves and during severe hunting it can increase due to flanging of the wheel against the railhead. Nowadays there is a great interest in this type of measurements as a result of the access of different operators (mainly in the goods transportation field) whose vehicles must be carefully checked against unbalance before allowing their circulation;
- the lateral force Y is due to vehicle attitude in tangent track due to running dynamics (*hunting* phenomena) and mainly in curves due to angle of attack and general considerations about rolling contact equilibrium considering lateral creepage and centrifugal forces (Wickens, 2003). The ratio Y/Q is normally looked at as a safety parameter (CEN, 2002);
- the longitudinal force is due to creepage forces, always acting during non-centred rolling and responsible for the typical self-centring behaviour in tangent track of the railway vehicle with restrained wheels and for the guidance forces in curves. These forces can be extremely high and can saturate the adhesion coefficient leading to *squeal* phenomena in tight curves and to severe corrugation when coupled to vehicle and rail vertical dynamics. Another important reasons for strong longitudinal forces are the thermal stresses typical of current CWR practice.

The rail is therefore subjected to shear and bending in both horizontal and vertical planes and to torsion along its axis. This combination of loads makes difficult to identify a simple system capable to find out the components *Y* and *Q* that generated a particular stress distribution.

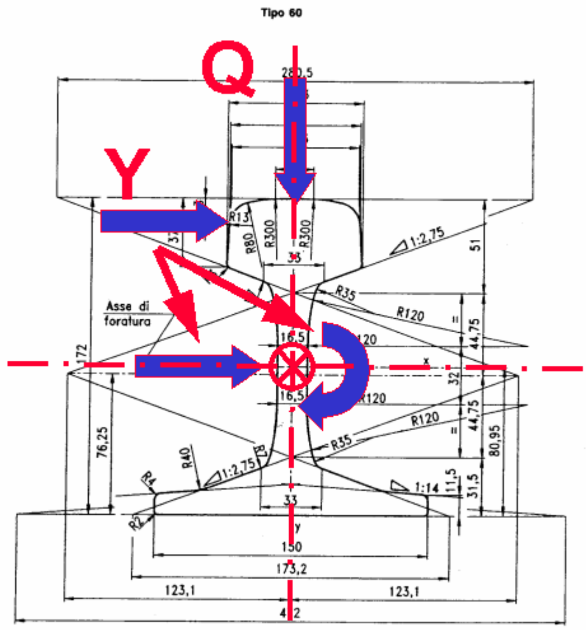

Figure 1. Cross section of a UIC 60E1 rail with indication of acting forces and resultants on the rail centre of mass. *Q* force is responsible for bending and shear in the vertical plane, *Y* force is responsible for bending and shear in the horizontal plane plus torsion along the rail axis. Longitudinal forces are uniformly distributed across the rail section.

MARKET ANALYSIS

Several equipment can be found that tackle normally the first of the goals, i.e. the measurement of vertical load *Q*. They can be grouped as follows:

- systems with strain gauges bonded or welded on the rail. These systems are hard to install and to maintain --- any failure must be repaired by specifically trained personnel with non negligible costs and out-of-service times. As an advantage, they may not need trackwork like sleeper change or concrete foundations;
- systems with load cells below the rail. They normally include load cells with laboratory precision, requiring a concrete foundation which keeps its properties in time;
- systems consisting of short rail lengths instrumented in the laboratory that are then welded to the existing track. These systems are complicated and are mentioned just for completeness;
- systems with rail deflection devices clamped to the rails. The intrinsic difficulty in these systems is that the external surface of the rail is subjected a combined displacement field which can partially impair the efficiency of these systems.

THE CONCEPT OF THE NEW SENSOR

All the existing systems aim at the measurement of the main mechanical stress, mainly bending and/or shear as they results from the application of the external forces on the entire track. As long as discretely supported track is concerned, reaction forces can only be located on the sleepers; the set of vertical and lateral forces reacts to loads in a way that depends on numerous parameters, like pad damping and stiffness, ballast compactness and modulus, beyond the intrinsic properties of the rail which are, after all, very well known and predictable.
Limiting the discussion to vertical forces, the wheel load in normally shared between several sleepers. Supposing that the wheel is resting statically in correspondence of a sleeper, the load supported by that sleeper is approximately a half of the load. Neighbouring sleepers have lower loads and may also have negative loads (the track tends to uplift). The idea of the new sensor comes from the consideration that

around half of the wheel load is transferred from the rail head to the rail foot passing through the rail web, which is relatively thin and that is the only region of the rail that can be machined (drilled) respecting safety regulations.

The rail web has the great advantage to be where the neutral planes for bending cross, individuating the neutral axis. Drilling a hole in correspondence of the horizontal neutral plane makes available a region where each component can be measured and analysed separately.

THE FIRST VERSION FOR VERTICAL LOADS

The idea of installing strain gauges on the vertical plane made available by drilling has been abandoned soon as it is extremely complicated to bond sensors in that area on a track in normal service.
The concept of an instrumented bush has been instead developed and investigated with numerical tools (Bracciali, 2001). They include (see Figure 2):

- a linear static FEM analysis which has allowed to find out stresses and strains due to the stress concentration induced by the hole, varying the position of the vertical load. The application of lateral load has allowed the determination of the lateral sensitivity of this first type of sensor;
- a dynamic analysis varying different parameters (train speed, pad stiffness, pad damping, sleeper spacing, etc.) to find out the sleeper reactions by using an internally developed software (Bracciali, 2001A).

As the simulations led to encouraging results, a short measurement campaign was set up in December 2000 in Florence (Italy). Two transducers were built and installed leading to homogeneous and consistent readouts (Figure 3). Weighing capabilities of the sensor were confirmed and, thanks to the extreme simplicity of installation and very low costs, the design process of a new version capable to measure both lateral and vertical loads immediately started.

DEVELOPMENT OF THE NEW SENSOR FOR VERTICAL AND LATERAL LOAD MEASUREMENTS

The good results obtained with the vertical force transducer needed a further effort to make it sensitive to lateral loads. As one of the disadvantages of the first version was the intrinsic uncertainty in mounting with a hammer, resulting in a hardly predictable angular position of the bush, the design of the entire sensor was re-examined. A possible solution was investigated splitting the single bush in two bushes, each measuring strains due to a linear combination of vertical and bending due to lateral forces. With some simplifying hypotheses on the wheel-rail contact point position, it was possible to derive simply the vertical load and the lateral load.

All the simulations conducted for the simple sensor were repeated for the new version, taking particular care of the different position of the strain gauges that are not anymore mounted on the vertical neutral plane. Only after carefully checking all possible combinations of lateral and vertical loads the design process was started.

The new sensor mechanical components are shown in Figure 4. It consists of a special screw which integrates a sort of washer to press the bushes, two instrumented bushes, two precision washers and two self-locking nuts. The overall mass is around 0.2 kg.
Very simple metal parts are made of weldable carbon-manganese steel. Only bushes are ground to obtain the correct interference to press fit the sensor. Protection from corrosion can be achieved by using stainless steel but not on the bushes (for expansion coefficient reasons). Assembly and disassembly precision and forces needed to slide bushes in the correct position are ensured by the different washers and by the generous dimensions of the M12 screw.

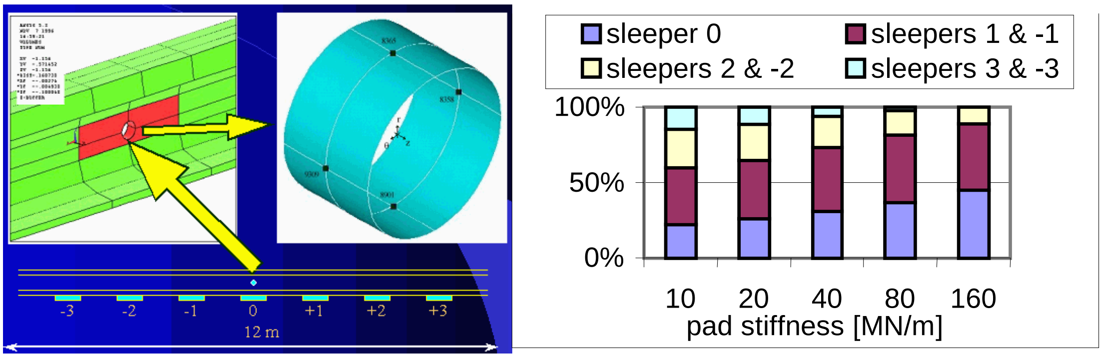

Figure 2. FEM mesh of a railway track with close-up on the bush shape and location over a sleeper (left). Contribution to overall vertical load given by the sleepers changing rail pad stiffness (right).

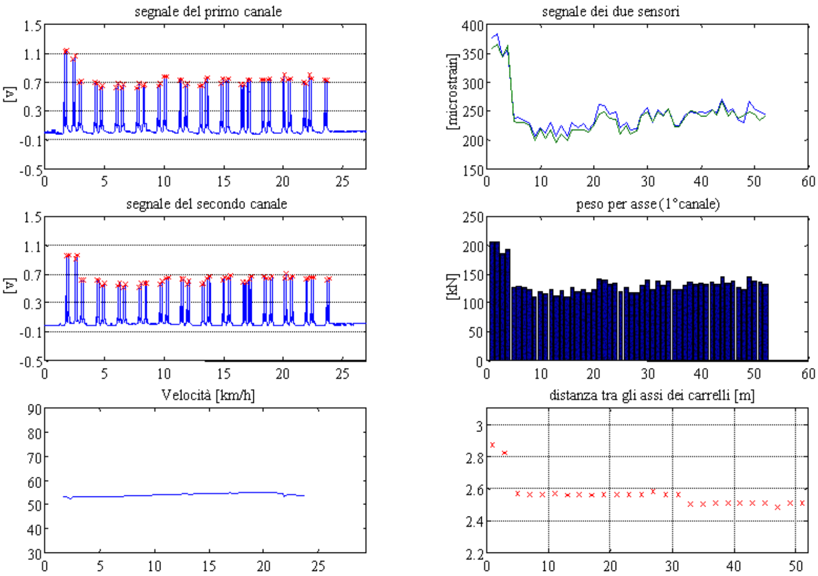

Figure 3. Voltage signal from sensor 1 (top left) and from sensor 2 (mid left). Strain signal of the two sensors (top right) and estimated weight for sensor 1 (mid right). Estimated speed (left bottom) and wheelbase (right bottom). Data for an Italian Express Train (Loco E656, coaches Z1 and Gran Confort).

The main advantage of the new construction is that the sensor positioning requires, after some training, less than 3 minutes. Moreover, as mounting is assisted by a lightweight mask and uses two common socket spanners, no special training is required. For reasons that will be detailed later, a typical measuring site could consist of 16 to 32 sensors. It is estimated that two persons, one drilling holes and the other mounting the sensors, can complete the trackside installation of a 16-sensors site in less than 3 hours. It was decided not to make the sensor repairable, as the overall cost of the sensor is less than a complete overhaul.

Figure 4. Mechanical parts (nuts not shown) of new sensor before application of strain gauges (left). Final mounting on the rail web, still without wiring (right)

MEASUREMENT CAMPAIGN PLANNING AND SETUP

To verify the performances of the new sensor on a line in normal service, four prototype sensors were built and installed in a curve in the railway station of Compiobbi, east of Florence, in March 2003. Two sensors per rail were mounted in a 480-m radius curve with a 150 mm cant. Maximum train speed is 90 km/h; the line is operated by regional trains and by freight trains, with a maximum load of 20 tonnes/axle. Many trains stop at the station, allowing a quasi-static calibration by using locomotives (whose weight is reasonably known and constant).

Some phases of sensors mounting and two pictures taken during the experimental campaign are shown in Figures 5 and 6.

Figure 5. Mounting sequence of a sensor: drilling the rail (left), mounting the sensor with the appropriate mask, the final aspect of the sensor before sealing with silicon rubber

Figure 6. A freight train running at 90 km/h is approaching the measurement section (left); a regional train stopped just over the sensor (note the high level of railhead wear on the opposite high rail) (right).

Data acquisition were done with a National Instruments SCXI rack containing two strain gauge conditioning modules; data were transferred to a notebook equipped with a low-cost National Instruments PCMCIA card. Sampling frequency was set to 2000 Hz, a value that later was confirmed to be more than sufficient for the scopes of the work. Acquired data were converted to ASCII format and off-line analyses were performed by using Matlab©. Figure 7 shows the acquisition stuff inside the Compiobbi station.

EXPERIMENTAL RESULTS

The results obtained during the second measurement campaign are hardly comparable to those obtained during the first one. This is mainly due to the small radius of curvature of the line and to the high level of cant, leading all the time to lateral forces.

Figure 7. Acquisition equipment with SCXI rack on the left.

Also in the case of complete compensation of centrifugal acceleration, bogies negotiate the curve with a non negligible angle of attack, leading to lateral forces which can be extremely different for the front or the rear axle and for the high-rail and the low-rail wheel.

As a calibration with static devices was not possible, no absolute values can be given to acquired signals. **A**n indirect calibration could be given anyway as the sum of the vertical forces must equal the dynamic weight of the train (i.e. the static weight plus the apparent weight increase due to cant) and the sum of the lateral forces must equal the vehicle mass times the non compensated acceleration.
Unfortunately these methods are too sensitive to the real mass of the vehicle and proved to be ineffective; it can also be due to, but there is no way to prove it, to swaying movements of the train in the curve, even if no clear hunting was observed during the tests.

From the results shown in Figures 8 and 9 it can be concluded that:

- the effect on cant deficiency is not as high as expected, as the other guidance forces give apparently illogical behaviour for high and low rail;
- even if the trains run at the same speed, a distinctively different behaviour of the two vehicles can be recognised, whose sole difference is the type of suspension and bogie;
- the trend of vertical forces correctly highlight the difference of weight of the different vehicles;
- peak forces last for a short time, thereby eliminating the effect of neighbour wheelset in the readout of the sensor.

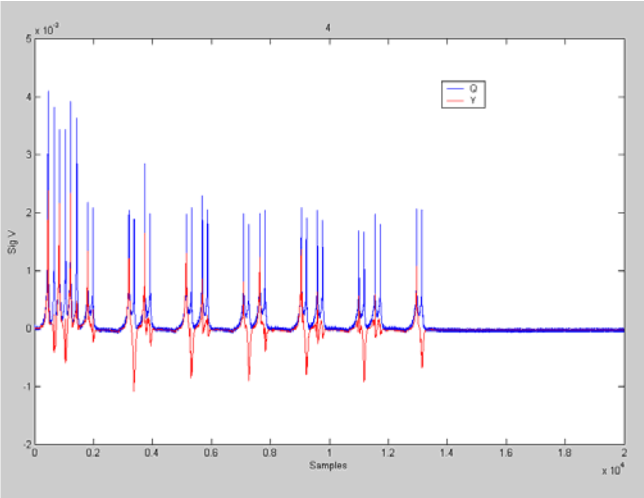

Figure 8. Vertical and lateral signals detected by the first sensor on the high rail during the pass-by of a regional train (loco E646 + MDVC coaches) at 90 km/h. It can be seen that lateral forces change direction from the leading axle to the trailing axle of the same bogie.

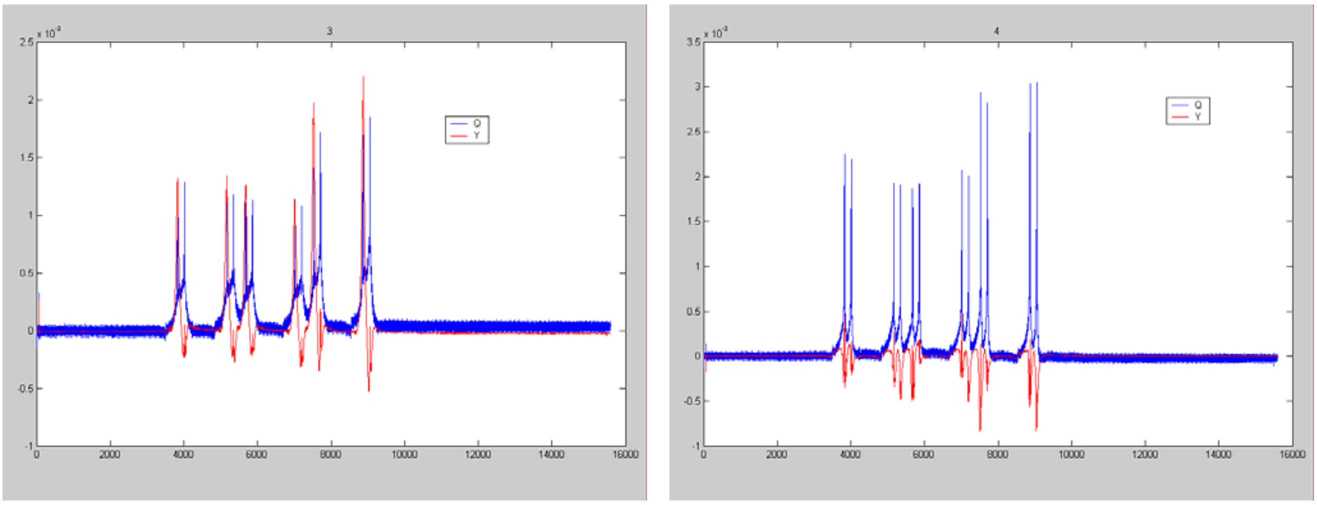

Figure 9. Vertical and lateral signals detected by the first sensor during the pass-by of 3 coaches EMU (2 trailed + 1 motor vehicle) at 90 km/h. Left: low rail, right: high rail.

CONCLUSIONS AND ACKNOWLEDGEMENTS

The design and testing of a new sensor able to measure both lateral and vertical forces during train pass-by has been successfully conducted. The results obtained from the first installation of the prototypes lead to the conclusion that the estimation of contact forces due to running dynamics can be a tricky process if the vehicle conditions are not perfectly known.

The development of the sensor is well advanced and it can be said that the sensor is ready for the application in permanent monitoring stations. Its unique features make it particularly interesting where hunting proneness of vehicles is to be checked (for example in tangent track with artificially tight track gauge) or where curve negotiating feature must be validated (for example in transition or constant radius curve). Needless to say, weighing capabilities can be obtained at a fraction of the cost of the competitors, with an intrinsically high reliability and with extremely low maintenance costs.

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