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Piezo-based weigh-in-motion system for the railway transport

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SUMMARY

This paper presents an *in situ* implementation of the weigh-in-motion (WIM) concept for the railway transport. The presented WIM system constitutes a part of a larger structural health monitoring system dedicated to railway bridges. The identification of train load acting on a bridge is necessary for performing subsequent identification of damage in the analyzed structure. Some existing WIM methods in the railway applications have been reviewed. The authors' implementation based on piezoelectric sensors has been described in detail. Hardware development of the WIM system, including wireless data transfer to a remote analysis centre, has been outlined. Results from measurement sessions carried out *in situ* have been presented and successfully verified by a numerical model of rail–sleeper–ground interaction. Copyright © 2010 John Wiley & Sons, Ltd.

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1. INTRODUCTION

This work has been stimulated by an increasing interest from the railway industry in implementing structural health monitoring (SHM) ideas. The responsibility for maintenance of railway infrastructure makes the administrators think about this problem in terms of both current and future demands. Therefore, an *SHM* system aimed at long-term monitoring is a very appealing solution to the railway people. As a response to this challenge, co-operation with Polish Railways was started in 2007 with the target of *in situ* implementation of a pioneer system for SHM of railway truss bridges.

The general idea of the system has been first described in [1]. The novel SHM system [2] is supposed to be able to identify damage in a truss structure by pointing out defective elements and determining the intensity of the damage. The theoretical background for performing this identification through the solution of an inverse problem has been developed using the Virtual Distortion Method (VDM) [3]. The considered damage may be interpreted as a degradation of stiffness and/or a loss of mass [4].

From the hardware point of view, the system will consist of two blocks, which are necessary to perform damage identification in truss structures using VDM. The first block, mounted in the vicinity of an analyzed bridge, is designed to weigh the running trains in motion in order to get the input load for the model of the structure. The second block is mounted directly on the bridge

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in order to record time responses of selected elements. Collection of these responses allows for a subsequent execution of the *VDM*-based identification procedure. Both blocks are briefly described in Section 3.1.

Further on, this paper is focused on the first block of the mentioned SHM system only. Some existing railway applications of the weigh-in-motion (WIM) concept are described in Section 2. Then, the attention is drawn to the authors' methodology of WIM accompanied by hardware solutions using piezoelectric sensors, which is described in Section 3. Some measurement sessions in 2007 and 2008 were carried out *in situ* to weigh trains in motion at the investigated truss bridge, which was made available for research by Polish Railways. Results of the field measurements are presented in Section 4. These measurements were subsequently verified by the numerical model discussed in Section 5.

2. A REVIEW OF THE EXISTING WIM SYSTEMS FOR RAILWAYS

The need to monitor and control the dynamic influence of trains on railway track has emerged from the infrastructure administrators as a consequence of separation from the train operators (carriers) and establishment of free-market relations between them. Since then, the administrators have started to charge the carriers for using the railway track.

In general, two approaches for the determination of dynamic traffic load are possible: either use a railway car equipped with sensors [5–7] or perform measurements by means of external sensors fixed to the infrastructure outside the train. The first method is not frequently applied and it seems to be less effective from the practical point of view. Hence, the second approach has been more deeply reviewed here.

In the past, one of the first techniques of identification of train load was successfully applied using an instrumented bridge [8]. This approach is also applicable in road transport and consequently named bridge weigh in motion B-WIM. Most frequently, standard strain gauges [9] are used as sensors in such WIM applications. Recently, however, the fibre optic sensors have been gaining more and more attention, especially for newly constructed huge bridges. In existing structures, the fibre optic sensors can be mounted on the surface of the bridge deck [10]. For newly designed bridges, the fibres are usually embedded in the structure [11,12] at the stage of its construction. It allows for the permanent monitoring of such bridges from the very beginning of their exploitation.

At the time, there are a few types of commercially available WIM systems for railways. One of the methods is the indirect measurement of the vertical force exerted on the rail and further transmitted to the sleepers and embankment. This method requires a special preparation of the track by equipping it with a solid foundation. The foundation has to be well integrated with the railway track; therefore, installation of such systems is both time- and cost-consuming. In the above-mentioned application, strain gauges are mounted on the foundation, not on the rails themselves. The main advantage of the method is a high precision of the identified load values. The price to pay for the precision is, however, a strict velocity limitation for trains during measurements [13,14], which should be in the narrow range 3–8 km/h. This is because the foundation should not be subjected to excessive vibrations in order to collect high-quality measurements. This can be regarded as a disadvantage of the system.

To overcome the velocity limitations, the accuracy of results must be sacrificed. One can propose load identification methods utilizing the measurements of rail strains using various sensors. As the rail is in direct contact with the train wheels, the methods are able to provide estimations of relatively many parameters such as individual wheel and axle loads, gross weight of each railway car, the number of railway cars, total train weight, velocity, direction of motion, even the state of the wheel e.g. possible polygonization. The variety of the identified parameters and the lack of velocity limitations during measurements are the main advantages of the mentioned methods. Nevertheless, they are characterized by poorer precision of the parameter estimation (practically $\pm 5\%$), which can be considered as a drawback.

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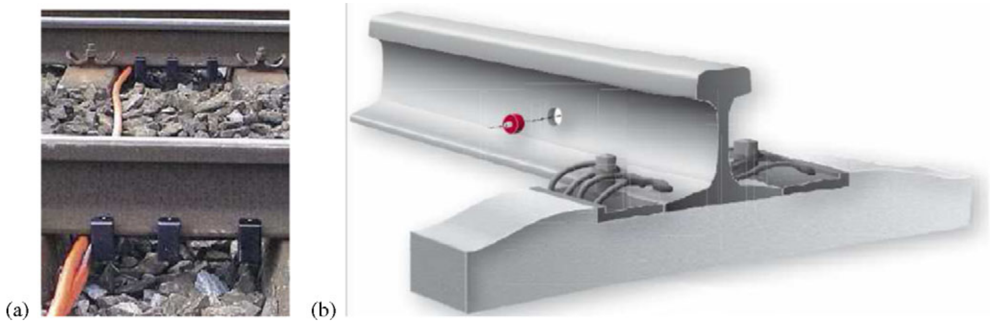

Figure 1. Example of WIM applications for railways: (a) fibre optic sensors TagMaster [18] and (b) intrusive quartz sensor Kistler [19].

The classification of the mentioned WIM systems for railways can be performed on the basis of the type of sensors used and also on the location of their mounting. One of the first systems was utilizing strain gauges [15] welded to the neutral axis or mounted on rail foot [16]. Recently, the growing competition for the strain gauges is optical fibers. They can be mounted either to the side of the rail [17], or to the foot of the rail with the help of special clamps [18] as shown in Figure 1(a). A great advantage of the optical fibres over strain gauges is their insensitivity to electromagnetic disturbances.

There are also intrusive solutions of WIM applications for railways. The idea is to bore a small hole in the rail web and insert a sensor into it. One option is a quartz force sensor of cylindrical shape [19] as shown in Figure 1(b), another one is a sleeve equipped with strain gauges from inside [20]. The direct measurement of force in the case of railway transport is practically difficult to perform because of high magnitudes of train loads, which would mean the use of force sensors of considerable dimensions. Hence, the indirect methods, i.e. strain measurements, are more often applied.

3. THE PROPOSED WIM SYSTEM

It should be emphasized that all the described solutions in the existing rail-WIM applications involve a considerable cost. One of the aims for the authors is to propose an alternative to the existing solutions, characterized by similar reliability and accuracy at an affordable cost. Another aim is to integrate the proposed WIM solution with the damage monitoring block of the mentioned SHM system, which is schematically presented in Figure 2.

3.1. General idea of the WIM system for railways

The proposed solution relies on a nondestructive way of recording histories of strains evolving in the rail due to train motion. The strains are collected by piezoelectric sensors mounted on the bottom of the rail foot in between the sleepers as schematically shown in Figure 3, depicting major elements of the proposed system.

In the majority of applications, piezoelectric sensors are used as accelerometers. In this work, however, they measure strains similarly to strain gauges and optical fibres. Two kinds of piezoelectric sensors are considered—the popular ceramic ones and the more sophisticated fibre-based ones. The performance of both types of sensors is similar. They are able to cover an extremely wide range of frequencies (0.1 Hz–100 MHz) due to high stiffness of piezoelectric materials. Similarly, the measurement range in terms of voltage magnitude (signal strength) reaches up to 100 million for piezoelectric sensors, which is absolutely distinctive compared to other sensors. Other advantages include e.g. less laborious surface polishing compared to strain gauges or lower cost of driving electronics compared to optical fibres. The piezo-fibre-composite (PFC) sensors are more durable as they consist of piezo fibres embedded in polymer, which makes them waterproof and insensitive to electromagnetic noise. However, the PFCs are much

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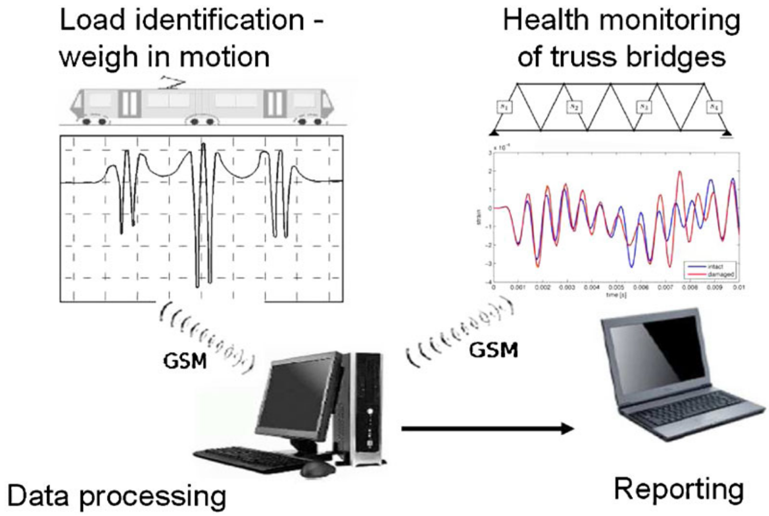

Figure 2. General scheme of the system for SHM of truss bridges integrated with the rail–WIM system.

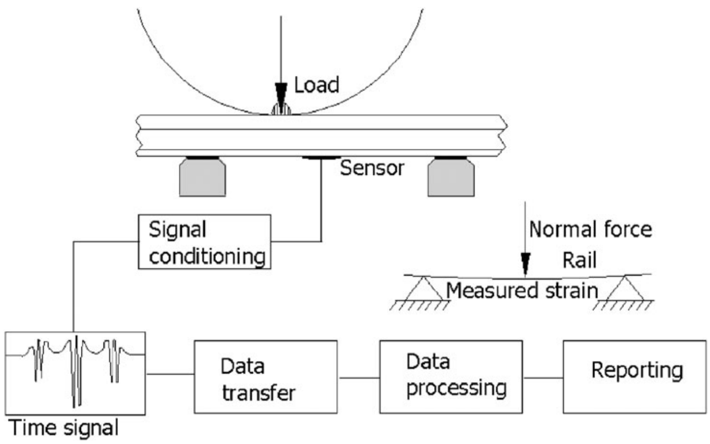

Figure 3. Scheme of data acquisition and processing for the proposed WIM system.

less attractive than the ceramic piezo-sensors as far as price is concerned. Therefore, the authors believe that the ceramic piezo-sensors, well-protected against environmental factors on site, are a cost-effective alternative for the other strain sensors.

Wireless transmission of the measured signals is supposed to be performed as outlined in [21]. The electric signal (proportional to strain) from the piezo sensor is first preconditioned by amplifying, filtering, and digital sampling operations. The objective of this signal processing is to have the signal in its optimal form before sending it to a remote centre using wireless transmission. For security reasons, it is planned to use an encrypted transmission using available Internet cryptographic protocols e.g. Transport Layer Security (TLS). When the data are captured by a remote server, it is first archived and then analyzed. It is planned to make the results of the analysis available to the user via an Internet browser with password protection.

To improve the reliability and accuracy of the proposed WIM system, some extra sensors should be applied. It is planned to mount sensors in pairs on both rails. It is also important to design such a way of sensor mounting, which makes the devices well hidden in the railway track in order to avoid devastation. An important issue is to mount the sensors in reasonable time without much interference with the existing infrastructure, not to expose the rail traffic to serious disturbances.

An important aspect of hardware is to supply power for the system in a reliable manner. In order to make the system independent, the power should be supplied by accumulators permanently charged by photovoltaic modules. For the sake of energy saving, the system will be active only during the ride of the train over the WIM measurement point. When the train is gone, it will switch to a passive mode. Additional sensors, operating in a standby mode to detect the coming train, are needed to realize this energy saving idea.

3.2. Proposed methods of dynamic load identification

The load identification problem belongs in general to the class of inverse problems presented in [5,22]. One way to solve such a problem is a pattern recognition approach. Roughly speaking, it consists of comparing an analyzed pattern with a set of already existing patterns and specifying the most similar one from the set.

In the proposed system, the pattern recognition scheme has been adopted as the first option to solve the inverse problem. In the mentioned method, the crucial task is to prepare a database containing a collection of strain histories for diversely loaded railway cars weighed in various operational conditions. A component i of the database may be a strain history ε_i, which is a function of essential factors e.g. magnitude of load Q, train velocity v, outside temperature T, number of axles n_a in a car bogie, etc., influencing the signal shape in time t:

$$\varepsilon_i(Q, v, T, n_\mathrm{a}, \ldots, t) \tag{1}$$

The biggest problem is where to take the data from to fill in the database. The data can be obtained from experiments using many railway cars of known load distribution, but this way is inefficient due to the time and cost involved. An alternative is to build a numerical model. This is a much more friendly approach, provided, however, that the model is conformable with measurements, which again implies some experimental work in a limited range to tune the model to experiments.

The pattern recognition method consists of comparing the actual single measurement $\varepsilon_\mathrm{actual}$ with the i ones previously stored in the database. The point is to retrieve the most similar (in a defined norm) case [23] with the assigned characteristic parameters (Q, v, T, n_a, etc.) from the database. Thus, the procedure identifies such a value of load Q_id which is a result of the following problem of optimal case search:

$$Q_\mathrm{id} = \arg\min_i [\varepsilon_\mathrm{actual}(Q, v, T, n_\mathrm{a}, \ldots, t) - \varepsilon_i(Q, v, T, n_\mathrm{a}, \ldots, t)]^2 \tag{2}$$

To facilitate the process of data retrieval, one can use sets of in-advance prepared amplitude variations of the measured signal depending on just one driving parameter e.g. train velocity while keeping the other ones constant. However, this is also quite laborious because numerous relations need to be established and some parameters should be known beforehand.

Because of the problems with building a reliable database, another option of load identification considered by the authors is a calibration of the measured signal in the *on-line* mode. The idea is to scale the measured signal for every passing train individually, knowing the mass of the locomotive corresponding to a reference load level Q_ref. Good news is that freight trains are usually towed by standard locomotives of electrical drive, whose mass is quite stable, not influenced by the amount of fuel. For instance, Polish Railways usually use the *ET-22* locomotives of 120 tons with possible mass deviation of ± 1.5 tons. For all freight trains it is feasible to find a scaling coefficient R between the reference signal ε_ref measured for the locomotive and the corresponding value of *a priori* known load Q_ref:

$$R \stackrel{\mathrm{def}}{=} \frac{Q_\mathrm{ref}}{\varepsilon_\mathrm{ref}} \tag{3}$$

When the relation for the locomotive is established, it is possible to determine the load of other railway cars Q_id by means of the following equation:

$$Q_\mathrm{id} = \varepsilon_\mathrm{actual} \cdot R(Q, v, T, \ldots) \cdot A(n_\mathrm{a}) \tag{4}$$

The proposed *on-line* calibration seems to be indifferent to environmental influences such as temperature or condition of the railway track. It is caused by the fact that the parameter R includes these influences. It may reach different values for the same train in different seasons of

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the year, for instance. The role of R is to provide a current reference point for rescaling the signal regardless of environmental conditions. One important factor, however, should be taken into account—the locomotive bogie and the freight car bogie usually do not have the same number of axles. This implies that the load distribution exerted by the bogies on the track is different. Hence, the influence of the axle coefficient A on the identified train load must not be neglected, as prompted by Equation (4). Results of numerical analysis, presented further in Figure 16, show that the coefficient A, unlike R (cf. Figure 7), varies in a non-linear way.

Except for the magnitude of dynamic load Q_{id}, other useful information from the strain history can also be determined. One of such parameters is the train velocity v. The easiest way of its calculation is to use responses from two sensors mounted in a known distance s on the same rail. It is a reasonable solution because the additional piezo-sensors may also serve as extra WIM sensors providing more data for averaging. The ratio of the distance s to the time delay Δt between two signals generated by two successive sensors allows for trivial calculation of the train velocity v. However, it must be assumed that the velocity on the section s is constant. It is a justified assumption as the distance s does not exceed a few meters in practice.

The proposed method of WIM measurements enables to determine the loads from individual axles by Equation (2) or Equation (4) and the train velocity by simple calculation. The type of a railway car may also be roughly identified by looking at time intervals corresponding to subsequent bogie axles. This allows for calculating the distances between the axles and comparing the values with catalogue dimensions for standard railway cars.

A more challenging analysis is the identification of wheel damage, especially polygonization. Irregularities in wheel shapes would cause repeated high frequency components in the recorded signal. Knowing the wheel diameter and parameters of the ride, it should be possible to identify the wheels in which the effect becomes manifest.

To make the identification easier, the measured signals should be pre-conditioned. A low-pass filter is applied to extract the principal contents of the signal corresponding to the car mass while a high-pass filter is used to provide a good representation of signal oscillations accompanying the wheel irregularities. In practice, it might be a reasonable compromise to apply a band-pass filter with a variable frequency range e.g. dependent on the train velocity.

4. PIONEER INSTALLATION OF THE PROPOSED WIM SYSTEM *IN SITU*

Measurement sessions were carried out in 2007 and 2008 in a location selected together with Polish Railways. The SHM system mentioned in Section 3.1 was mounted on a typical truss railway bridge spanning a channel in Nieporet near Warsaw. The accompanying WIM system was installed on rails ca. 40 m away from the bridge. A scheme of the integrated SHM system with the location of WIM sensors is depicted in Figure 4. The investigation described later in the section is focused on the identification of the dynamic load only.

4.1. Experimental tests of the piezo-based WIM system

Two types of piezoelectric sensors were used in experimental tests—piezoelectric fibre composite PFC sensors shown in Figure 5(a) and sensors made of the piezo ceramic material PZT-7 shown

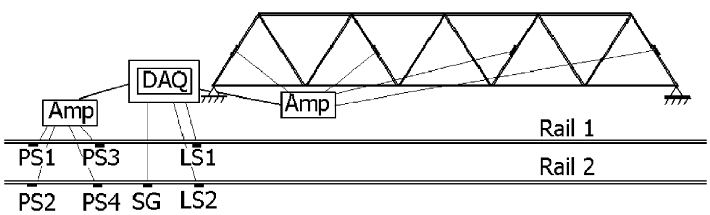

Figure 4. Components of the proposed WIM system during *in situ* tests: PS1, PS2, PS3, PS4, piezoelectric sensors; SG, strain gauge; LS1, LS2, laser sensors recording displacements; AMP, amplifier; DAQ, data acquisition unit.

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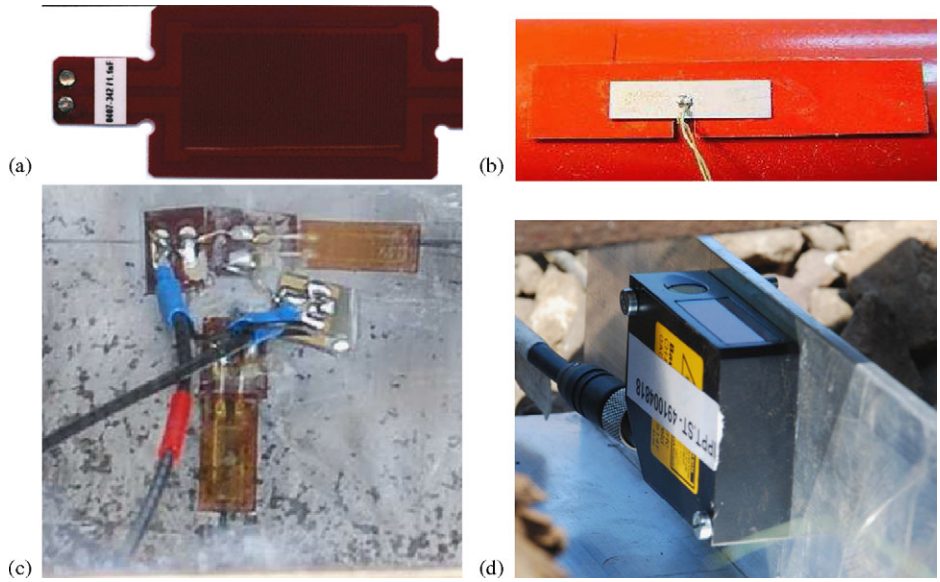

Figure 5. Sensors used in experimental tests: (a) piezoelectric fibre composite *PFC* sensors; (b) piezoceramic sensors based on the PZT-7 material; (c) half-bridge configuration of strain gauges; and (d) laser displacement sensor.

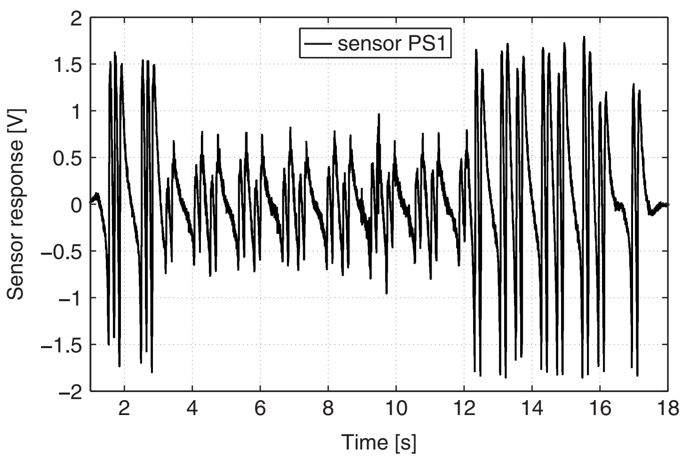

Figure 6. Time signal from the piezo-sensor as a response to passage of a freight train.

in Figure 5(b). For comparison, strain gauges in the half Wheatstone bridge configuration (Figure 5(c)) were used. Additionally, laser sensors for measuring vertical displacements were mounted beneath the rail foot (Figure 5(d)).

Figure 6 illustrates a time signal collected by the piezo-sensor during a passage of a freight train at approx. 40 km/h. Each axle of bogies running over the WIM measurement point can be recognized. The first part of the signal (approx. 3 s) corresponds to a locomotive with two three-axle bogies, the rest to cars with two-axle bogies. It can be noticed that the first seven towed cars were lighter than the last four ones.

The basis for the identification of train loads is the peak values of the time signal. In order to scale the signal in terms of mass, a reference level Q_{ref} is needed. This must be set in a calibration procedure e.g. the *on-line* calibration described in Section 3.2. The mass of a car is calculated as a sum of peak values from all axles belonging to this car. In order to improve the reliability of identification, one spare sensor should be mounted in each location. Then, the calculation can be performed by means of pairs of sensors. If both sensors work well, an average value can be

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calculated; if not, a measurement from just one sensor, providing trustworthy responses, should be considered.

Calibration of the proposed dynamic WIM system may be performed by a quasi-static (at 5 km/h) weighing system using strain gauges. Knowing the mass of a locomotive and each car in the train from quasi-static measurements, a relationship between mass and voltage recorded by piezo-sensors of the proposed WIM system at regular train speed can be found. The results of such operation are presented in Figure 7. It can be observed that the relationship between measured mass and recorded voltage is linear despite generally poor condition of the railway track in the place of installation of the WIM system.

During the passage of the train with known masses, vertical displacements of the rail were measured (see Figure 8). The results correspond to the ones presented in Figure 6, picturing a different quantity (voltage) for the same train passage. In the displacement plot, the whole bogies rather than separate axles can be recognized. The lighter and heavier cars can be clearly distinguished. The displacement measurements were not used for weighing trains. They were rather carried out for having as much data as possible at the stage of tuning the numerical model to experiments, which will be discussed later. In general, the track in the WIM area was in a very poor technical condition. The rail displacement was about one order of magnitude bigger than cited in the literature [24,25] and recommended by design standards.

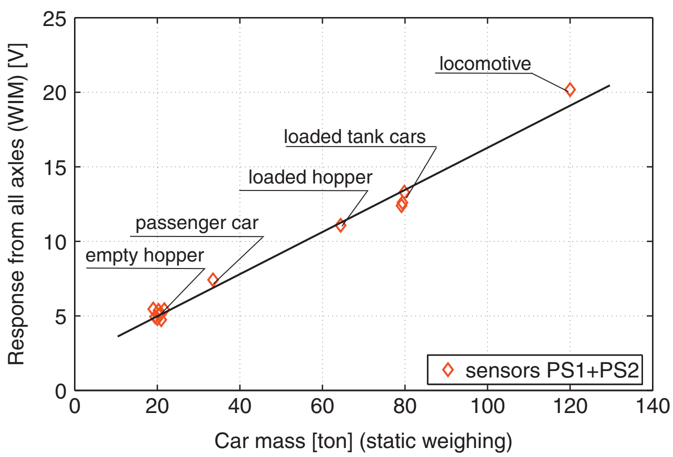

Figure 7. Voltage–mass relationship obtained on the basis of calibration from static weighing.

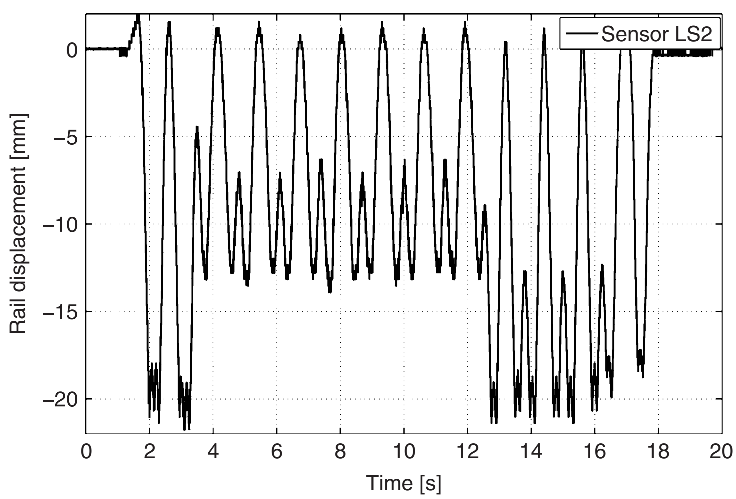

Figure 8. Vertical displacements of rail recorded by the laser sensor.

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4.2. Performance comparison of piezo-sensors and strain gauges

One of the objectives of the *in situ* sessions was to compare the performance of the piezoelectric sensors and strain gauges. The measurements, collected by both types of sensors and corresponding to the passage of the locomotive *ET-22* at the velocity 40 km/h, are presented in Figure 9(a). The time curves match in the lower part and vary in the upper one. Analyzing the problem further, both signals were normalized and transferred to the frequency domain by the Fast Fourier Transform (FFT) as shown in Figure 9(b). It is clear that signal spectra are not the same. In the range of low frequencies, the strain gauge response dominates, contrary to the high frequency range in which the piezoelectric responses are of higher values. It is caused by the fact that voltage amplifiers were used to process the signals from piezoelectric sensors. Unfortunately, they acted as high-pass filters due to the effect of charge drift [26]. This effect can be minimized by applying a charge amplifier for collecting piezoelectric responses, because this equipment is suitable for quasi-static (0.1 Hz) measurements [27] as well. Another advantage is that the output of the charge amplifier does not depend on the input capacitance [26]. It means that the electronics operated by a charge amplifier is insensitive to cable length. Finally, the responses collected by strain gauges and piezo-sensors were filtered by a band-pass filter. As a result, quite good agreement between both types of sensors was obtained as demonstrated in Figure 9(c).

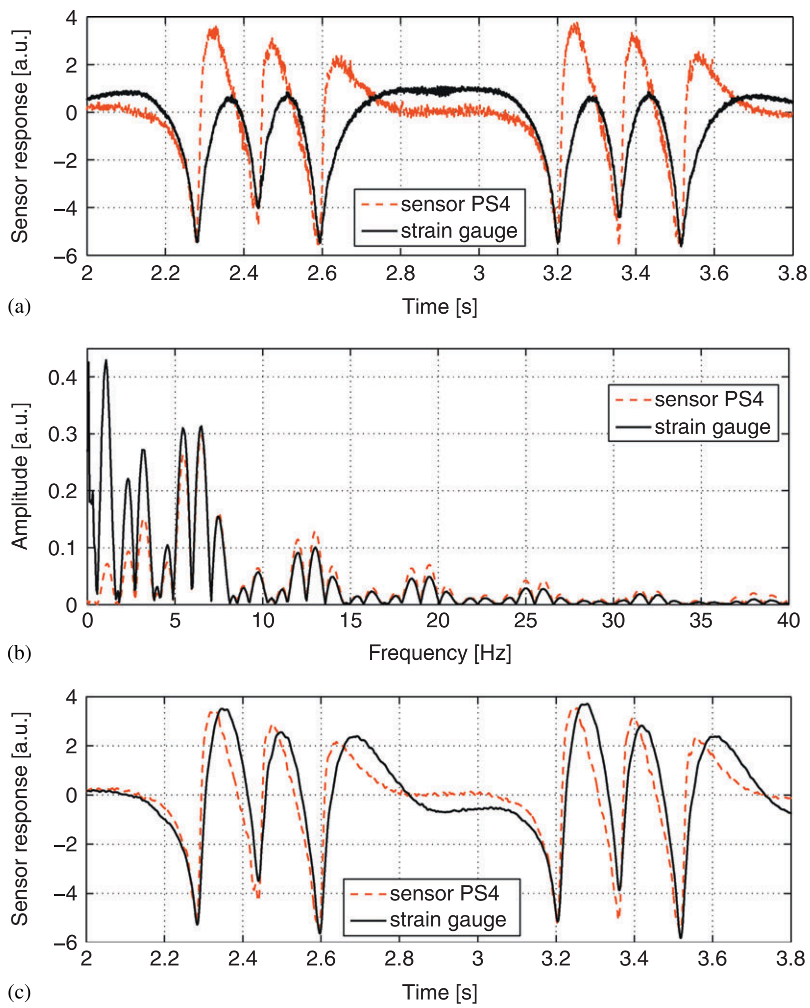

Figure 9. Signals from two types of sensors due to the passage of the *ET-22* locomotive: (a) direct measurements in the time domain; (b) spectra in the frequency domain; and (c) filtered signals in the time domain.

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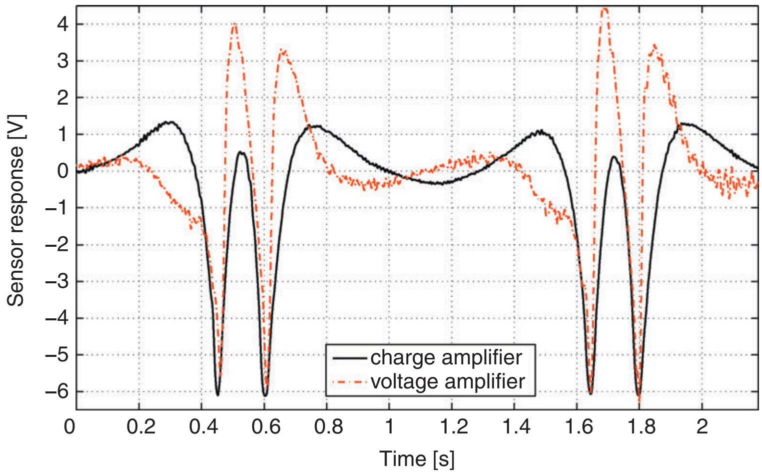

Figure 10. Performance of voltage and charge amplifiers exemplified by differences in time signals.

In summer 2009, the first test of a charge amplifier customized for the piezoelectric sensors was conducted *in situ*. A qualitative improvement of measurement results has been observed. The comparison of time signals recorded with the voltage and charge amplifiers is presented in Figure 10. One can notice that the character of signal processed by the charge amplifier is very similar in shape to the unfiltered response from the strain gauge (cf. Figure 9(a)). This fact gives hope that other measurements conducted by the new charge amplifier will coincide with the strain gauge results too. Further research is needed to tune the charge amplifier precisely to the railway application.

It should be emphasized that only the signal amplitudes in the lower part (below zero) of strain histories are analyzed by the proposed WIM algorithms. Therefore, the differences in upper parts of the plots due to the use of various types of sensors (cf. Figure 9(a), (c)) or different driving electronics (cf. Figure 10) are negligible from the practical point of view.

Another *in situ* test was aimed at examining the repeatability of the time signal at various velocities of the *ET-22* locomotive running over the WIM measurement point back and forth. The runs were repeated for four velocities i.e. 20, 40, 60, and 80 km/h. Figure 11(a–c) presents the selected peak levels of the signal as a function of velocity for strain gauges and piezoelectric sensors operating with voltage and charge amplifiers, respectively. The velocity effect in the case of strain gauge measurements seems to be insignificant in the selected range. The same conclusion was drawn by other researchers [25]. The variability of repeated strain gauge measurements conducted for the selected range of velocities (20–80 km/h) is about 5%. On the contrary, the influence of velocity can be clearly observed in responses collected by the piezoelectric sensors operating with the voltage amplifier, which is again likely to be caused by the drift effect in the device. The use of the customized charge amplifier resolves this problem as can be seen in Figure 11(c).

5. NUMERICAL MODEL VS EXPERIMENTS

The numerical simulation presented in this section aims at the determination of the factors influencing the dynamic response of the rail, e.g. the number of axles per bogie or sleeper–ballast interaction. The main objective of the analysis is to obtain the model calibration factors in order to assure the precision of the load identification algorithm.

5.1. A review of railway track models

Several railway track models are available in the literature. A comprehensive review of this subject can be found in [28–30]. The earliest modeling of the railway track was reported

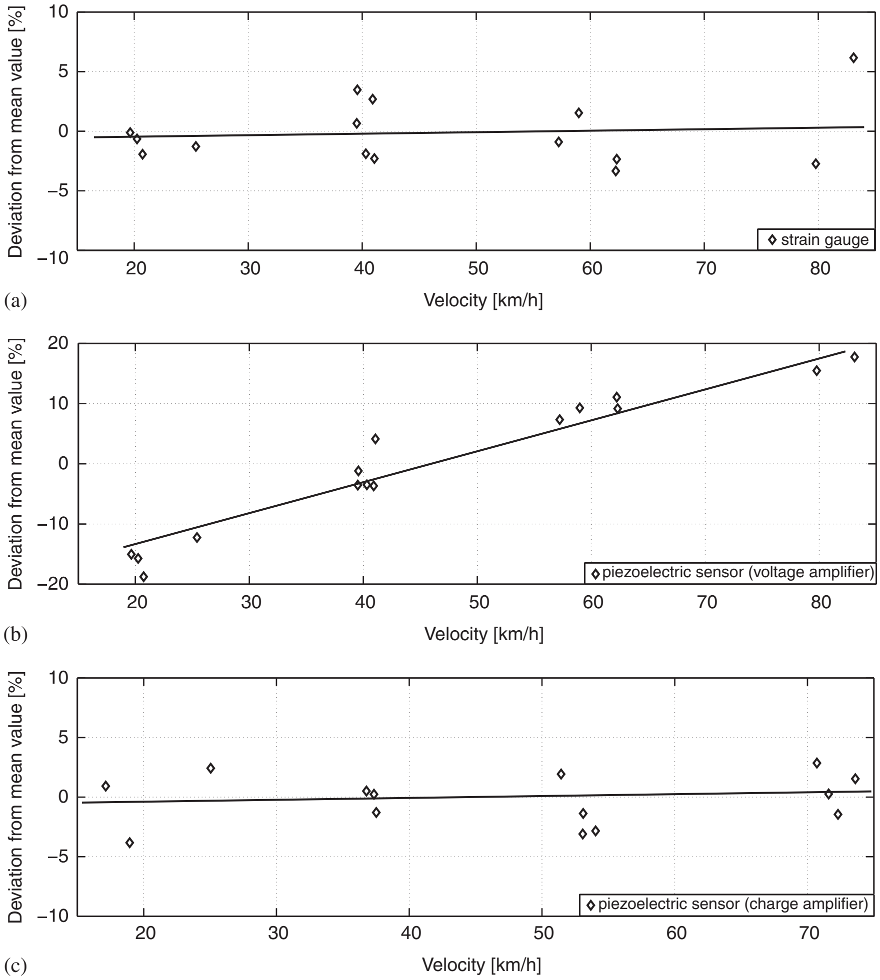

Figure 11. Velocity effect on the measured signal: (a) strain gauge; (b) piezoelectric sensor with voltage amplifier; and (c) piezoelectric sensor with charge amplifier.

by Winkler (1867). In his work, the Euler–Bernoulli model was used to define an infinitely long beam resting on a uniform elastic foundation representing the support (i.e. sleepers and ballast) [31].

The track structure can be modeled as being either finite or infinite in length. Both frequency and time domain models are in use [32]. The most frequent way of the rail modeling is to apply the beam model proposed by Timoshenko [33]. Nevertheless, the Euler–Bernoulli beam is still in use.

The supports can be modeled as a continuous elastic foundation [34] or discrete beams [24]. The supports can be considered as massless spring–damper systems [35], mass–spring–damper systems [36], or models in which the mass of the sleepers, ballast, and also the stiffness of paddings and damping coefficients are considered [37].

The most common configuration for analysis is a half of the track only. This simplification is justified by an assumption of the symmetric load distribution. Nevertheless, the full track model can also be used [38].

Another problem is an appropriate modeling of load at the wheel–rail interface. The simplest way is to use a stationary load, but a moving load (or moving mass) simulating the effect of dynamic load of the train is much closer to reality. The most realistic method modeling the vertical load resulting from the wheel–rail contact is that of moving mass (wheel) rolling on the track as presented in [35]. This way is not often used because it is time-consuming.

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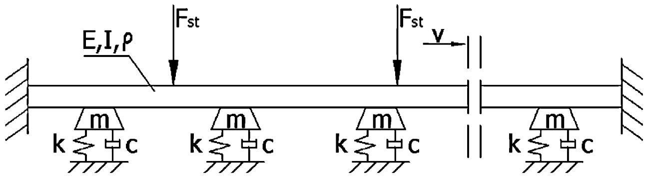

Figure 12. Model of the rail–sleeper–ground interaction.

In general, the complexity of the model depends on the objectives of the analysis to be performed and according to [39] 'the model should be as simple as possible and as accurate as necessary' to meet these objectives.

5.2. Description of the proposed model

For verification of the *in situ* measurements and determination of the calibration factors, a numerical model of the rail–sleeper–ground interaction was proposed. The railway track was modeled using the FE package ADINA. A scheme of the model is shown in Figure 12. The track and loading are assumed to be symmetric with respect to the centerline. Therefore, only half of the track is modeled in order to shorten the computational time.

The considered model includes a section of 60 sleepers supporting a rail with the clamped–clamped boundary conditions. The spacings between the sleepers are 60 cm. The analysis is focused on the middle part of the model (20 middle sleepers) to eliminate the influence of the boundary conditions on results. The two-node Hermitian beam (based on the Euler–Bernoulli beam theory, corrected for shear deformation effects [40]) with proper geometry and material data are used to model the real S60 rail. The Kelvin–Voigt model is employed to model the interaction between the sleepers of mass $m = 100$ kg and the ground. The parameters of all the modeled sleepers are identical, which is a simplification in view of the results presented in [29]. The rail pad is not additionally modeled, which can be justified by the poor condition of the investigated real track. The loading is applied in the form of vertical force vectors moving along the rail with a constant velocity.

5.2.1. Selection of coefficients for the Kelvin–Voigt model. The stiffness k for the Kelvin–Voigt model was determined thanks to the *in situ* measurements. The displacement measurements presented in Figure 8 are the basis for the generation of the experimental force–displacement characteristic of the track depicted in Figure 13(a). The poor condition of the real track was manifested by a very low stiffness at the first phase of rail deformation, in which the sleepers had no contact with the eroded ballast beneath. In order to reflect this behavior of the real track, a bilinear characteristic shown in Figure 13(b) was adopted in the model. The magnitude of force at 21 mm downward displacement was adjusted in Figure 13(b) thanks to multiplication of the *in situ* measured force (100 kN cf. Figure 13(a)) by the ratio of distance between sleepers (0.6 m) to mean distance between bogie axles (1.5–2.0 m). This basically means that a large portion of the force from the axle of a railway car standing over the WIM measurement point is balanced by reactions of the two neighboring sleepers. Thus, the stiffness coefficient in the model is low i.e. $k = 0.25$ MN/m if 10 mm downward displacement is not exceeded and high i.e. $k = 4$ MN/m otherwise.
The viscous damping coefficient c was assumed on the basis of a literature review. In [24], the viscous damping coefficients for the rail pad $c = 1.5 \times 10^4$ Ns/m and for the sleepers $c = 3.1 \times 10^4$ Ns/m were used respectively. The value of $c = 1.44 \times 10^4$ Ns/m was applied in the model presented in [35]. The damping coefficient reported in [41] was related to the unit of length (along sleeper) and equal to $c = 6 \times 10^4$ Ns/m^2. Relatively big scatter of damping parameters can be found in the literature. It is related to various configurations of practically applied ballasts and sleepers.

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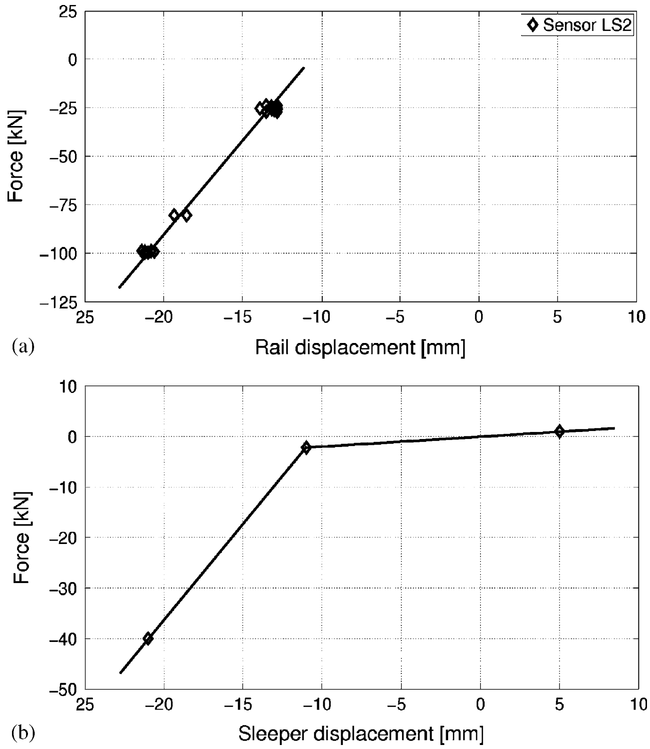

Figure 13. Force–displacement characteristic of the track: (a) measured *in situ* and (b) used in the model.

The track model developed by the authors should correspond to the response of the real track, which is in a relatively poor technical condition. Hence, in the proposed numerical model, a rather low value of damping was assumed i.e. $c = 3 \times 10^4$ Ns/m.

5.2.2. Validation of the track model. The numerical results obtained from the built model were confronted with the experimental measurements for a passage of the 120-ton *ET-22* locomotive. Histories of vertical displacements of the rail at the WIM measurement point and corresponding stresses in the rail foot are depicted in Figure 14(a), (b), evidencing a decent conformity of numerical and experimental data.

As already mentioned, the identification of load parameters by the proposed WIM system is performed using the downward peaks of the strain/stress evolution in time. In the lower part of Figure 14(b), the agreement between the numerical model and experiment is excellent. Discrepancies in other parts do not influence the quality of load parameter identification.

5.2.3. Effect of stiffness of the track support. The parameters that may change, while the proposed WIM system is in use, are certainly the support conditions of the sleepers. Stiffness of the track can be affected by environmental factors e.g. low temperature in winter or maintenance issues e.g. replacement of ballast. Hence, it is important to estimate the influence of the support conditions on the extent of rail deformation. Using the numerical model, an analysis of various support conditions was performed.

Under the assumption of constant load distribution and constant velocity, the influence of the support stiffness k on the stress response of the rail was estimated numerically. The obtained results are presented in Figure 15, showing a relative change of the rail stress as a function of the ratio of the support stiffness to reference stiffness. The reference stiffness was assumed to be equal to track stiffness identified on the basis of *in situ* measurements. The highest stress in the rail foot was observed for the most flexible supports. The obtained relation is strongly non-linear. The support condition was found to be an important factor influencing the stress

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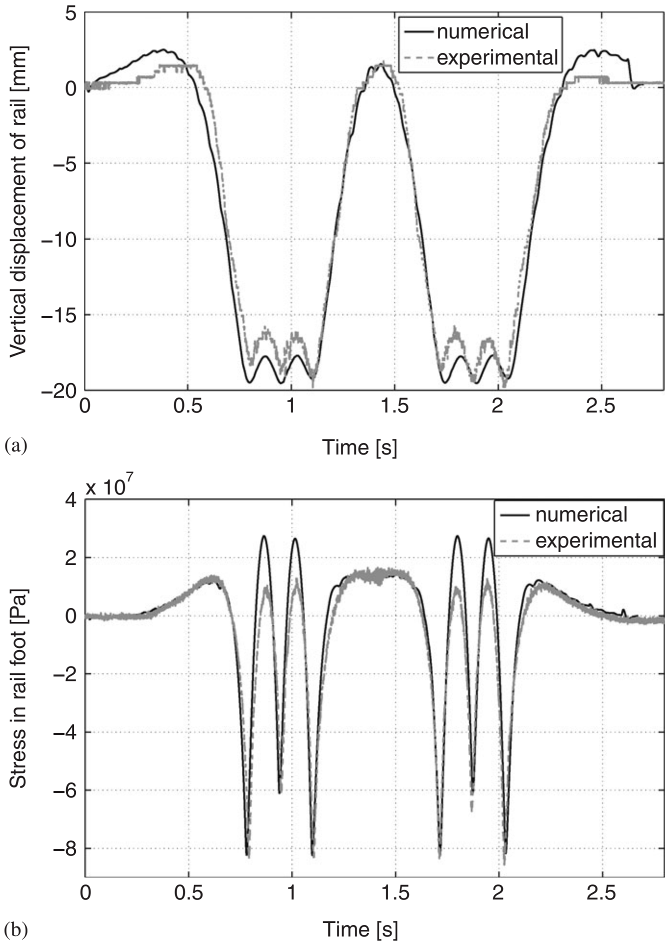

Figure 14. Numerical vs experimental results: (a) vertical displacements of the rail and (b) stresses in the rail foot.

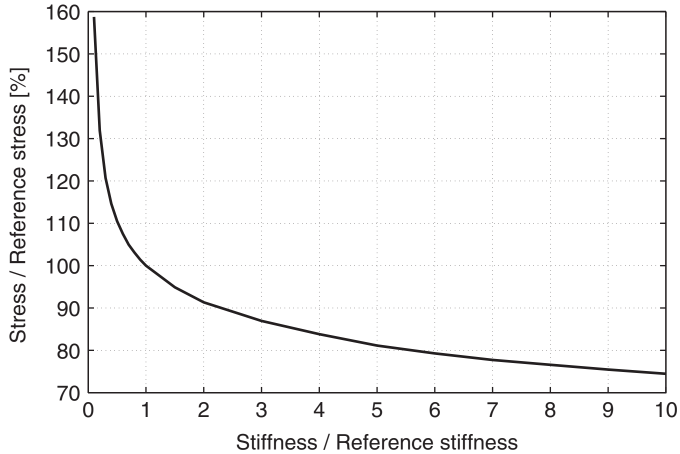

Figure 15. Rail stresses as a function of support stiffness.

response of the rail. Hence it is necessary to account for the support conditions in the load identification algorithm based on pattern recognition, because it is dependent upon environmental factors.

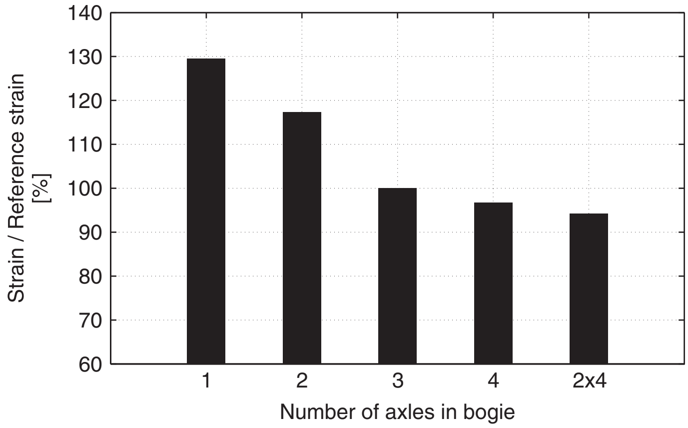

Figure 16. Rail strains as a function of load distribution.

5.2.4. Effect of load distribution. Railway cars may have a different number of axles per bogie. The most common bogies have two axles [13]. Nevertheless, non-typical cars with three, four, or eight axles per bogie are also in use. Hence, the load distribution effect must be taken into consideration. In the analysis, the same total load value acting on the track was distributed among a different number of axles. The axle spacing was averaged from a set of typical freight cars and locomotives. Constant train velocity and support conditions were assumed. The obtained numerical results are shown in Figure 16, which presents a relative change of rail strain as a function of the axle number with the load distribution for the three-axle bogie serving as a reference. The good correspondence between numerical and experimental results for the reference three-axle bogie (cf. Figure 14(b)) makes the authors believe that the load distribution effect obtained just numerically in this paper would find confirmation in experiment too.

The results depicted in Figure 16 show that the load distribution effect must not be neglected. Otherwise, the cars with a smaller number of axles might be identified as heavier than in reality. Hence, a correcting factor should be taken into account in the load identification algorithm. This factor is especially important if the *on-line* calibration method (with the locomotive serving as a reference), described in Section 3.2, is to be applied. The need of such correction comes from the fact that locomotives usually run on three-axle bogies, while freight cars on two-axle ones.

6. CONCLUSIONS

This paper presents numerical and experimental investigations of a new WIM system developed for the railway transport. The system is supposed to identify the dynamic loads generated by a train passing over piezoelectric sensors mounted to the rails. The WIM proposition is meant to be a part of an integrated SHM system dedicated to health monitoring of railway truss bridges.

The general idea of the proposed WIM system and the methods employed for the identification of moving train load have been explained. The accompanying hardware and data transfer issues have been discussed. Two algorithms of load identification have been considered. The method based on the *on-line* calibration, which makes the measurements insensitive to environmental conditions, seems to be much more practical. Responses from *in situ* measurement sessions registered by piezoelectric sensors and strain gauges have been presented.

Both types of piezoelectric sensors proved to be applicable to dynamic weighing of trains. A linear relationship between the identified load and sensor responses was obtained. The velocity effect was apparent for measurements recorded by the piezoelectric sensors and processed by the voltage amplifier. Strain gauge results were much less sensitive to this effect. The use of the customized charge amplifier for processing piezo-sensor responses produced similar results as those obtained by strain gauges (cf. Figures 9 and 10).

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The experimental data have been successfully verified by a FE numerical model. An analysis of the factors influencing the load identification was performed numerically and verified experimentally. The effects of support conditions (cf. Figure 15) and load distribution (cf. Figure 16) were found essential for interpretation of results by the load identification algorithms.

Further investigation will be focused on the wireless transmission of measurement data and the integration of the described WIM system with the mentioned SHM system for railway bridges.

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