Weighing of trains in motion as a part of health monitoring system for a railway bridge

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ABSTRACT: This paper presents an *in situ* implementation of the *weigh-in-motion* (WIM) concept. The presented WIM system constitutes a part of a larger *structural health monitoring* (SHM) 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 measuring sessions carried out *in situ* have been presented and verified by a numerical model of rail-sleeper-ground interaction with success.

1 INTRODUCTION

This work has been stimulated by an increasing interest from the railway industry in implementing 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 structural health monitoring 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 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 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 schematically depicted in Fig. 1.

Further on, this paper is focused on the first block of the mentioned SHM system only. Some existing railway applications of the WIM concept are described first. Then the attention is drawn to the authors' methodology of WIM accompanied by hardware solutions using piezoelectric sensors. Some measuring 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. These measurements were verified by a proposed numerical model. Results and conclusions are presented hereafter.

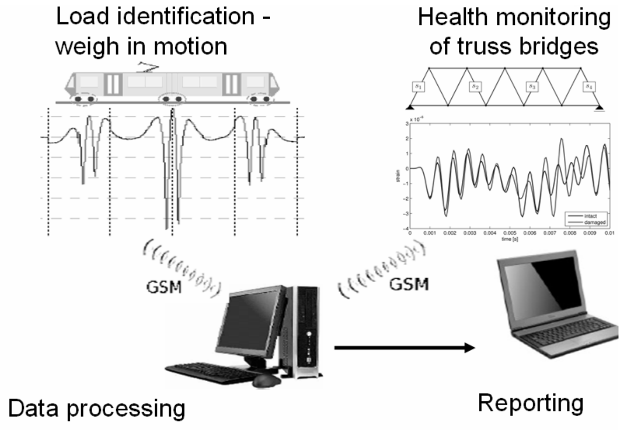

Fig. 1 The proposed SHM system for a railway bridge: left - weigh in motion block, right - damage identification block

2 WEIGH IN MOTION – BRIEF STATE OF THE ART

There are several solutions and implementations of the WIM problem, already known from literature. One of the first methods to weigh vehicles in motion was successfully applied using an instrumented bridge [5] and consequently named *bridge weigh-in-motion* (B-WIM). Most frequently, standard strain gauges [6] 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 [7]. For newly-designed bridges, the fibres are usually embedded in the structure [8] at the stage of its construction, allowing for permanent monitoring of such a bridge from the very beginning of its exploitation.

Non-destructive WIM applications in railways are based on measuring rail strains caused by the vertical force exerted on the rail through train wheels. The measuring ways can be classified by the types of sensors used. The most popular method is still based on strain gauge measurements. These applications require a solid foundation to which the sensors are mounted. The foundation has to be well-integrated with the rail track, therefore installation of such systems is both time- and cost-consuming. Alternatively, strain gauges may be mounted directly to the side of the rail below its head [9]. A serious drawback of strain gauge-based WIM solutions is their ability to measure only quasi-static loads with strict velocity limitations [10, 11] e.g. a train moving at 5-8 km/h. A growing competition for strain gauges are optical fibres. They can be mounted either to the side of the rail [12], or to the foot of the rail [13, 14] with the help of special clamps. A great advantage of optical fibres over the strain gauges is their usefulness to dynamic measurements, which means weighing at operational velocities of running trains.

There are also intrusive solutions of WIM applications in railways. The idea is to bore a small hole in the rail web and insert a sensor in it. One option is a force sensor of cylindrical shape [15], another one is a sleeve equipped with strain gauges on the inside surface [16].

All the described solutions in existing WIM applications involve a considerable cost. One of the motivations of the authors is to propose an alternative to the existing solutions, characterized by similar durability and accuracy at affordable cost. Another motivation is to integrate the proposed WIM solution with the damage monitoring block (see Fig. 1) of the SHM system mentioned in the Introduction.

3 PROPOSED WIM SOLUTION

3.1 *General idea*

The proposed solution relies on a non-destructive way of recording histories of strains evolving in the rail as a result of train motion. The strains are collected by piezoelectric sensors mounted on the bottom part of the rail foot in between the sleepers as schematically shown in Fig. 2, depicting major elements of the proposed WIM system.

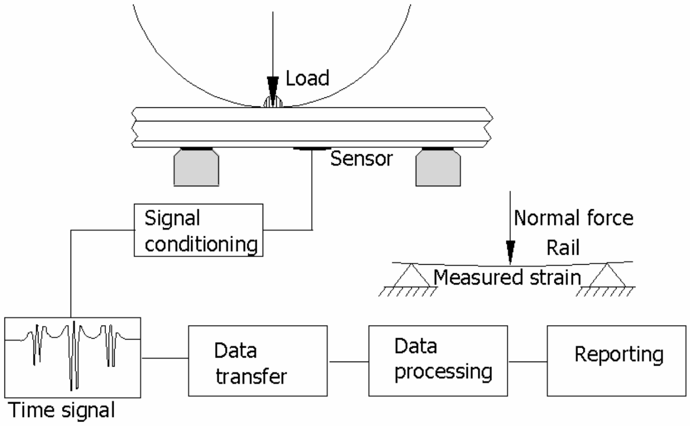

Fig. 2 Scheme of data acquisition & processing for the proposed WIM system

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 protocols e.g. SSH. When the data is captured by a remote server, it is first archived and then analyzed. Some useful information can be retrieved from the signal e.g. the magnitude of load exerted on the rail by each axle of a car bogie, mass of each car and train velocity. Results of the analysis are available to the user via an internet browser with password protection.

3.2 *Dynamic load identification methods*

The load identification problem belongs to the general class of inverse problems [17, 18]. In the proposed solution, the pattern recognition scheme has been adopted as the first option. The method needs some preliminary information at start. The information is a collection of strain histories induced by various types of car bogies weighed in different operational conditions (e.g. covering a range of train velocities). All the histories are stored in a data base. A component of the data base may be a strain history which depends upon essential factors influencing its shape in time t, e.g. magnitude of dynamic load Q, number of axles in a car bogie n_a, train velocity v, outside temperature T, etc.

$$\varepsilon^{base}(Q, n_a, v, T, t)$$

The biggest problem is where to take the data from to fill in the data base. The data can be obtained from experiments by examining many railway cars of known mass 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 well-calibrated, which again implies some experimental work in a limited range. The pattern recognition method consists in comparing the actual measurement with the ones previously stored in the data base. The point is to retrieve the most similar case [19] (with the assigned characteristic parameters Q, n_a, v, T, etc.) from the data base, which can be formally expressed as finding the minimum of the following function:

$$\min\left[\varepsilon^{\mathrm{base}}(Q, n_a, v, T, t) - \varepsilon^{\mathrm{new}}(Q, n_a, v, T, t)\right]^2$$

Because of the problems with building a representative data base, the second option of load identification considered by the authors is on-line calibration of the measured signal. The idea is to scale the measured signal for each train independently, knowing the mass of 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 ton. The proposed on-line calibration seems to make the analysis indifferent to environmental influences such as temperature or condition of the rail track. The Q^{ref} value, determined on-line for a specific train in given operational conditions, includes these influences.

Except for the magnitude of dynamic load Q, we can also determine other useful information from the strain history. Train velocity can be trivially calculated if the distance between two following sensors is known. Once the velocity has been determined, the type of railway bogie may also be roughly identified by looking at time windows for subsequent bogie axles. This allows for calculating the distances between the axles and comparing the values with catalogue dimensions of 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.

3.3 *Hardware issues*

The installation of the proposed WIM system should include some extra sensors in order to protect the system from the out-of-service state in case of a sensor failure. It is planned to mount sensors in pairs on both the rails to achieve this. It is also important to design such a way of sensor mounting, which makes the devices well hidden in the rail track 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 will 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 measuring point. When the train is gone, it will switch to a passive mode. Additional sensors, operating in a stand-by mode to detect the coming train first, are needed to realize this energy-saving idea.

3.4 *Transfer of data*

Transfer of data in the proposed WIM system takes place on two levels – locally and remotely. Wireless transmission of data is a very important component of the system, making it automatic and almost free of *in situ* service. In the proposed solution the wireless transmission of data will utilize the GSM communication.

All the sensors in the WIM system will be locally connected by wires forming a star topology i.e. all sensors linked to one module. In the on-line mode (train passing over the WIM point), the signals from all sensors will be stored in a central buffer. In the off-line mode (train gone), the signals will be wire-transferred from the buffer to a microcontroller module for processing i.e. amplifying, filtering, digitizing and compressing, before the commencement of a far range transmission of data.

The far range wireless transmission is supposed to use a GSM modem. The device will communicate with a remote analysis center utilizing up-to-date protocols e.g. GPRS, EGDE to transfer data. The transmission will be encrypted to ensure the security of data.

The local (nearby range) wireless transmission for the WIM system is also planned. It will perform the task of activating the companion system of damage identification, mounted on the nearby bridge. Additionally, local wireless communication will be realized between sensors and a corresponding data processing module both mounted on the bridge.

4 MEASURING SESSIONS IN SITU

Measuring sessions were carried out in 2007 and 2008 in a location selected together with Polish Railways. The investigated structure is a typical truss railway bridge spanning a channel in Nieporet near Warsaw. About 50 m ahead of the bridge, the proposed WIM system has been installed and tested.

This paper is focused on analysis of the WIM system only. The damage identification system mounted on the bridge will be described in another paper. A scheme of the integrated SHM system with location of WIM sensors is depicted in Fig. 3. Two types of piezoelectric sensors were tested – piezoelectric fibre composites (PFC) shown in Fig 4a and sensors made of the piezoceramic material PZT-7 shown in Fig. 4b. For comparison, strain gauges in the half-bridge configuration (Fig. 4c) were used. Additionally, laser sensors for measuring vertical displacements were mounted beneath the rail foot (Fig. 4d).

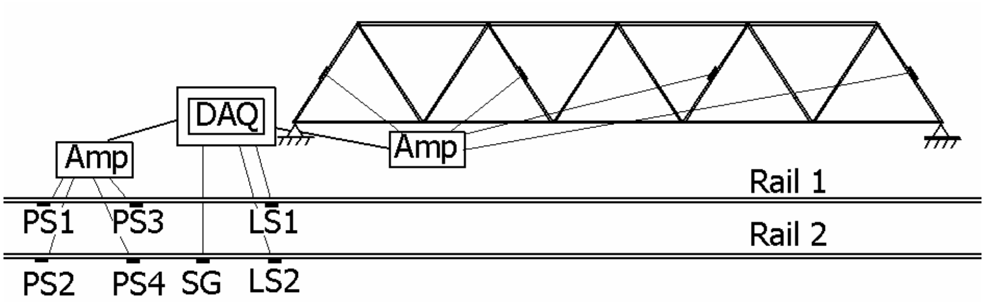

Fig. 3 Components of the proposed WIM system during *in situ* tests: PS1, PS2, PS3, PS4 – piezoelectric sensors measuring strains, SG – strain gauge, LS1, LS2 – laser sensors measuring displacements, AMP – amplifier, DAQ – data acquisition unit

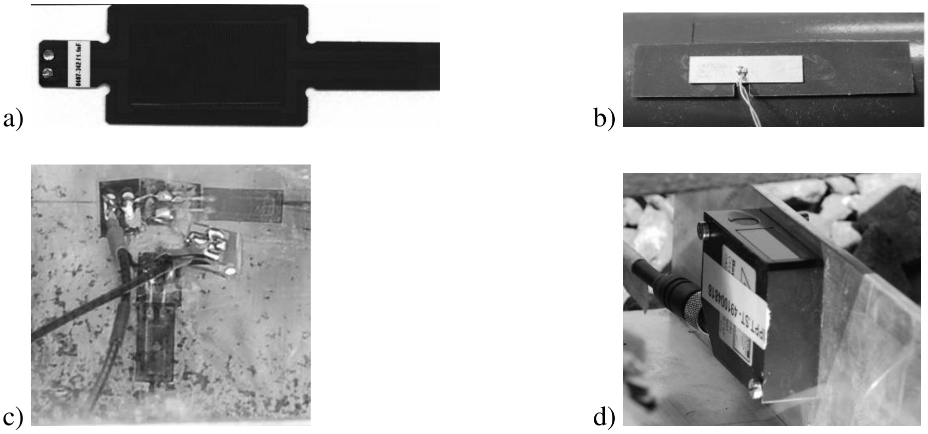

Fig. 4 a) piezo fibre composite (PFC) sensor, b) piezoceramic sensor, c) strain gauges in the half-bridge configuration, d) laser sensor

Fig. 5 illustrates a time signal collected by the piezo-sensors during a passage of a freight train at 40 km/h. Each axle of a bogie running over the WIM measuring point can be recognized. The first part of the signal corresponds to a locomotive with three-axle bogies, the rest – to cars with two-axle bogies. The basis for identification of train load are 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. A mass of a car is calculated as a sum of peak values from all axles belonging to this car.

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 relation between mass and voltage recorded by piezo-sensors of the proposed WIM system can be found for trains running at their regular velocities. The results of such operation are presented in Fig. 6. It can be observed that the relation between the measured mass and recorded voltage is linear despite generally poor condition of the railway track in the place of installation of the WIM system.

The reason for mounting various types of strain sensors was to compare their performance. Fig. 7 shows such comparison for signals induced by a locomotive passage at 40 km/h. The signal from strain gauges was filtered with a high-pass filter in order to be matched with the signal from piezo-sensors recorded with the use of voltage amplifier, which discards low frequencies by definition. Good agreement between piezo-sensors and strain gauges was obtained.

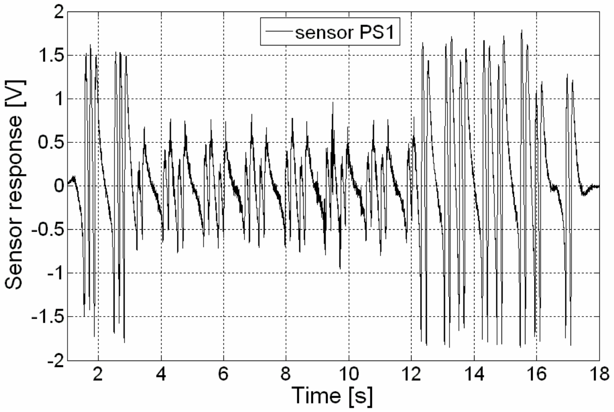

Fig. 5 Time signal from the piezo-sensors as a response to passage of a freight train

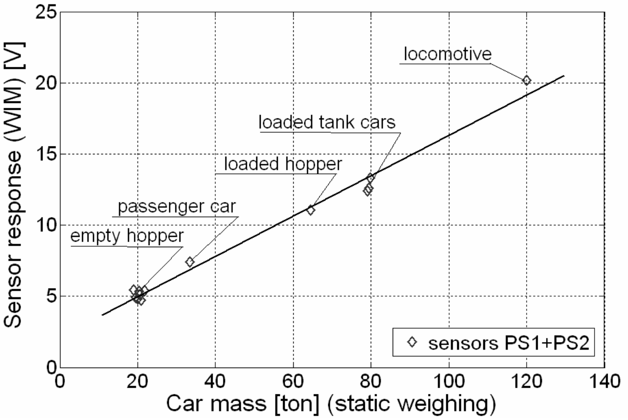

Fig. 6 Mass-voltage relationship obtained on the basis of calibration by static weighing

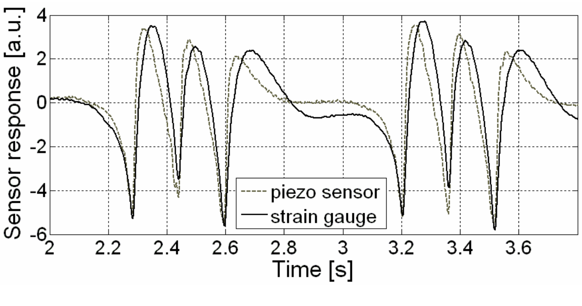

Fig. 7 Performance comparison of the piezoelectric and strain gauge sensors

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 measuring point back and forth. The peak levels in the signal seem to be not very sensitive to varying velocities. The accuracy of repeated measurements obtained for the selected range of velocities (20-80 km/h) is about 5%.

5 NUMERICAL MODELLING

For verification of the *in situ* measurements, a numerical model for analysis of the rail-sleeper-ground interaction was built using the FE package ADINA. The scheme of the model is shown in Fig. 8. The model is confined to the 2D analysis of one rail only. It includes a section of 60 sleepers supporting a rail with the fixed-fixed boundary conditions. The analysis is focused on the middle part of the model (about 20 sleepers) to eliminate the influence of the boundary conditions on results. The Timoshenko beam with proper material data was used to model the real S60 rail. The Kelvin-Voigt model was used to describe the interaction between the sleeper of mass m=50 kg and the ground. The stiffness k for the Kelvin-Voigt model was determined thanks to the *in situ* measurements. Due to the poor condition of the real rail track, a bilinear characteristic reflecting this fact was adopted (k= 0.25 MN/m up to 10 mm displacement, k= 4 MN/m above 10 mm displacement). The viscous damping coefficient c was taken from literature [20]. The load was applied as vertical force vectors moving along the rail with a constant velocity.

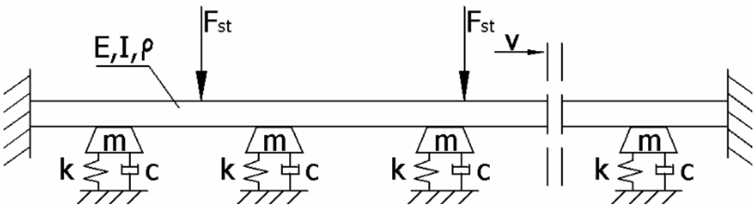

Fig. 8 2D numerical model of the rail-sleeper-ground interaction

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 measuring point and corresponding stresses in the rail foot are depicted in Fig. 9, evidencing a decent conformity of numerical and experimental data.

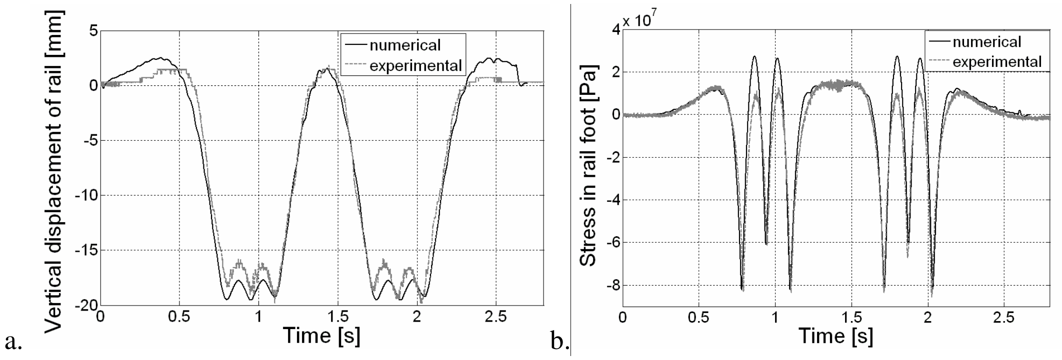

Fig. 9 Numerical vs. experimental results: a) vertical displacements of rail, b) stresses in rail foot

6 CONCLUSIONS

This paper presents numerical and experimental results of a WIM procedure, which is meant to be a part of an integrated SHM system dedicated to railway truss bridges.

The general idea of the proposed WIM system and the methods employed for the identification of load exerted on rail by a moving train have been explained. The accompanying hardware and data transfer issues, including the far range wireless transmission, have been discussed. Results from *in situ* measuring sessions have been presented. A practical proposition of the on-line calibration making the measurements insensitive to environmental conditions has been put forward. The experimental data have been successfully verified by a FE numerical model.

System accuracy, integration and durability issues will be the subject of further investigation.

ACKNOWLEDGEMENTS

The financial support from the projects “Smart Technologies for Safety Engineering - SMART and SAFE” – TEAM Programme – granted by the Foundation for Polish Science and “Health Monitoring and Lifetime Assessment of Structures” – MONIT – POIG.01.01.02-00-013/08-00 from the EU Structural Funds in Poland is gratefully acknowledged.

The authors express their gratitude to Polish Railways (PKP PLK S.A.) for making the truss bridge in Nieporet near Warsaw available for field testing, with special thanks to Mr. Kazimierz Szadkowski for his administrative efforts.

The authors would like to kindly thank Dr. Jerzy Motylewski and Mr. Piotr Pawlowski for their assistance in measuring sessions.

The free-of-charge delivery of two PFC sensors by ERF Produktion Wuerzburg GmbH is appreciated.

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