# Implementation of SHM system for a railway truss brigde

Przemysław Kołakowski[1,2], Damian Sala[2], Piotr Pawłowski[2], Andrzej Świercz[2], Krzysztof Sekuła[1,2]
[1]Adaptronica sp. z o.o., R&D company, Szpitalna 32, 05-092 Łomianki, Poland
[2]Smart-Tech Centre, Institute of Fundamental Technological Research, Pawińskiego 5b, 02-106 Warsaw, Poland
email: pkolak@adaptronica.pl, dsala@ippt.gov.pl, ppawl@ippt.gov.pl, aswiercz@ippt.gov.pl, ksekula@adaptronica.pl

ABSTRACT: A railway bridge has been the object of investigation since mid 2007 as a response to increasing interest in structural health monitoring (SHM) from Polish Railways. It is a typical 40 m long, steel truss structure spanning a channel in Nieporęt near Warsaw. There is over 1500 similar bridges in the railway network in Poland. The paper presents various aspects of 3-year monitoring of the truss bridge. The final objective of the investigation is to design, test and implement an SHM system dedicated to railway infrastructure. The system consists of two integrated subsystems - the weigh in motion (WIM) and the actual SHM. Piezoelectric sensors collecting strain responses are used in both systems as an alternative to strain gauges or optical fibers. The measurements are then processed by a customized system for wireless transmission of data. Numerical model of the bridge corresponds well to the experimental data. This is a good starting point for considering different scenarios of simulated damage in the structure by adding local masses in future research.

KEY WORDS: SHM; Piezoelectric sensors; Wireless transmission; Bridge dynamics; Railway infrastructure.

## 1 INTRODUCTION

The patent-pending monitoring system [1] consists of two integrated parts. The first part is focused on identification of dynamic load generated by trains which are weighed in motion (WIM). The second part is the actual structural health monitoring (SHM) system suited for a railway truss bridge. There are many aspects of the whole system to be investigated e.g. selection of sensors, design of customized electronics for data acquisition and transfer, development of monitoring software. Some of them have already been reported in [2] - [5].

The intention of the paper is to present the variety of aspects of the pioneer SHM system ranging from numerical simulations to field experiments. Dynamic strain is the measured physical quantity. Direct registration of strains with piezoelectric patch sensors and standard strain gauges is described. Responses of numerical models of the railway track and the bridge are matched with the data collected in field. Wireless transfer of data in short- and far-range configurations is tested.

## 2 IDEA OF THE SYSTEM

The investigated object is a typical railway truss bridge spanning a channel in Nieporęt near Warsaw. There are several hundreds of similar bridges of various spans all over Poland. The bridge, shown in Fig. 1, is made of steel, has a span of 40 m and height of 8 m. The rail traffic on the bridge is rather low. Like many other bridges it is just visually inspected once in a few years, which is the basis of maintenance decisions.

The integrated monitoring system under investigation incorporates two parts (depicted in Fig. 2) of complementary objectives - WIM and SHM.

Figure 1. Investigated railway truss bridge in Nieporęt.

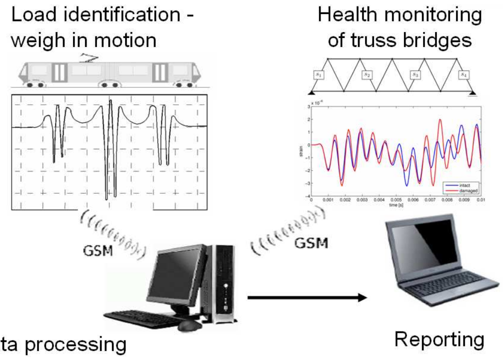

Figure 2. The integrated monitoring system for railway truss bridges: left - weigh in motion part, right - structural health monitoring part.

The WIM part of the system provides dynamic load input for modeling of bridge responses. The idea is somewhat similar to the ambient excitation in the sense of using an existing source of vibration to make the structure respond, but is different in the sense of quantifying the input force. The WIM part is supposed to weigh the passing trains at their actual velocities. It should be mounted in the vicinity of a monitored bridge e.g. 50 m away. This part may also exist on its own to provide information about rail traffic. More details about the WIM part of the system can be found in [5].

The SHM part for assessing bridge condition assumes a calibrated numerical model regularly supplied with measurement data sent remotely via the Global System for Mobile (GSM) communications. The newly-designed wireless transmission system has been described in [3], [4]. The transferred data include both the load information from the WIM part and the bridge responses to passing trains (see Fig. 2). By determination of deviations in the measured bridge responses, exceeding a pre-defined threshold value, the damage detection stage is satisfactorily completed. The more advanced stage of damage identification employs numerical analysis based on the Virtual Distortion Method (VDM) [6], which points out defective elements of the monitored truss structure and quantifies the intensity of damage in such elements. With a record of archived results e.g. 5-year regular monitoring, the structural degradation rate and remaining lifetime may be assessed.

## 3 HARDWARE IMPLEMENTATION

### *3.1 Measuring instrumentation*

Piezoelectric sensors are usually used as accelerometers. Similarly to strain gauges or optical fibers, the piezoelectric sensors may be suited to measure strains. Two kinds of piezoelectric sensors of similar performance are considered in this paper - the cheap ceramic ones made of the PZT material and more expensive piezo-fiber-composites (PFC). They are able to operate in an extraordinary range of frequencies (0.1 Hz - 100 MHz) due to high stiffness of piezoelectric materials. Their measurement range in terms of signal strength may reach up to 100 million, which is absolutely distinctive compared to other sensors. Piezoelectric sensors are less laborious at the stage of mounting compared to strain gauges and less expensive in terms of driving electronics compared to optical fibers. The authors use both PZT and PFC sensors in their investigations on the truss bridge, however they prefer the PZT ones because of low price. If equipped with an extra waterproof housing, the PZT sensors are as durable as the PFC ones, which are fabricated in a polymer coating.

Vibration responses of the bridge due to passing trains were collected by the three types of sensors pictured in Fig. 3a-c. Standard resistance strain gauges were used to obtain reference responses. They were operating in the half Wheatstone bridge configuration. Piezoelectric sensors were connected to charge amplifiers in order to provide proper processing of the low-frequency content in the acquired signal. The voltage amplifiers used at the commencement of field tests in 2007-2008 turned out to be useless for capturing low-frequency vibration responses of the bridge.

In Fig. 4, the configuration of all sensors, mounted for the WIM and SHM parts of the system, is shown.

### *3.2 Wireless transmission of data*

The main assumption is that both parts of the integrated monitoring system transfer data independently. The reason for making the transmission independent is a much more frequent need to process the WIM data. Apart from identifying dynamic load (WIM subsystem), they can also be used to monitor daily railway traffic. The analysis of the current bridge state (SHM subsystem) is performed regularly but not necessarily on daily basis. Therefore the amount of data and frequency of transmission for the WIM and bridge data processing (DP) units are different. Another explanation is that the WIM point may be located too far from the bridge, so one unit for the whole monitoring system might be impractical.

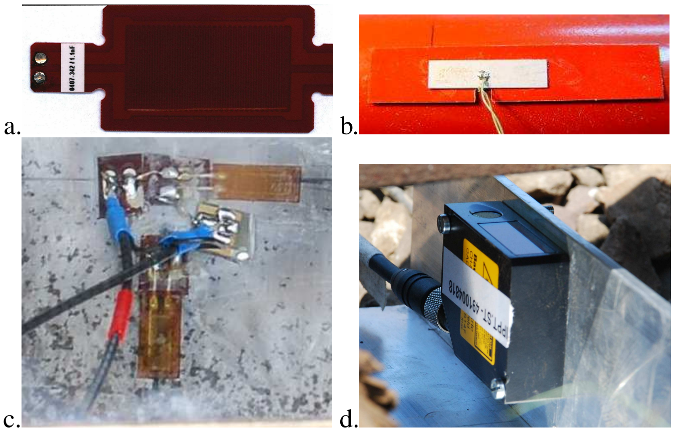

Figure 3. Types of the sensors mounted: a) PFC, b) PZT, c) strain gauge, d) laser sensor for displacements.

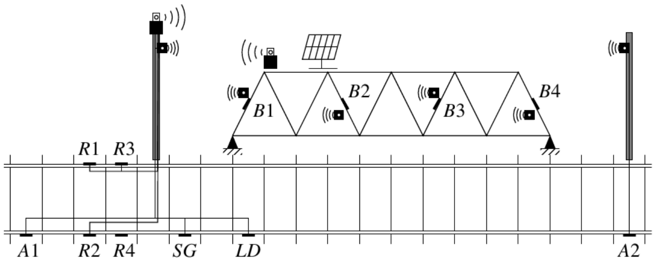

Figure 4. Scheme of the sensors mounted: B1-B4 - piezo sensors mounted on the bridge, R1-R4 - piezo sensors mounted on rails, A1-A2 - activating piezo sensors, SG - strain gauge, LD - laser sensor for displacements.

Each measuring unit collects analogue signals from the piezoelectric sensors mounted on the bridge and transfers them to the local DP unit via an embedded transceiver using a local mode of wireless transmission. A scheme of the integrated bridge sensor is shown in Fig. 5.

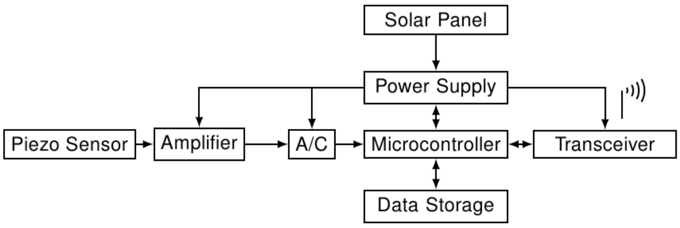

Figure 5. Scheme of smart bridge sensors B1-B4 utilizing short-range wireless transmission.

The proposed electronics associated with each measuring unit is designed so as to keep the power supply at the 50 mW level. At first stage of testing, a lithium-ion battery was used. Subsequently, a solar cell was provided to recharge an in-built accumulator for long-term, maintenance-free operation.

A crucial feature of the system resulting in significant energy savings will be its intermittent operation. The system is activated by A1 or A2 sensor from each direction. It remains active only during the passage of a train over the bridge. Otherwise it switches to a passive, energy-saving mode. The only sensors operating in the stand-by mode are the two activating sensors A1 and A2. The difference in energy consumption is 3 orders of magnitude as the micro-controller of the DP unit needs 0.4 mA in the active mode and just 0.6 $\mu$A in the passive one.

The integrated bridge sensor performs analogue to digital conversion of a signal before sending it to the DP unit. To this end, a 12-bit analogue-digital converter providing proper sampling is used. The available short-range transmission distance is estimated to reach up to 100 m. All measuring units are supposed to start data acquisition simultaneously thus have to be properly time-synchronized using triggering signals sent by the internal clock of the DP unit.

The tasks of the DP unit are sequential collection of digital signals from the piezoelectric sensors, signal compression and transfer to a remote computing centre for analysis. Thus the DP unit should consist of a transceiver to collect the signals from various measuring units, micro-controller for signal processing, sufficient memory buffer enabling storage of data and additional RS-232 port for possible emergency in-situ acquisition. A scheme of the DP unit is depicted in Fig. 6. Advantage of the GSM technology is taken to transfer the digital data to a remote computational centre.

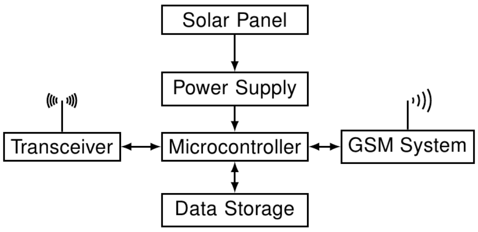

Figure 6. Scheme of long-range wireless transmission performed by the DP unit.

## 4 COMPUTER MODELING

The WIM part of the system provides input for the SHM part. Knowing the dynamic load exerted on rails by a passing train, one can perform time- or frequency-domain VDM-based dynamic analysis as explained in [6], [7]. The model of the rail-sleeper-ground interaction is shown in Fig. 7 and has been described in [5]. The railway track was modeled using the FE package ADINA. 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) with proper geometry and material data is 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 some simplification. The rail pad is not additionally modeled, which can be justified by the poor condition of the investigated real track. The loading is applied as vertical force vectors moving along the rail with a constant velocity.

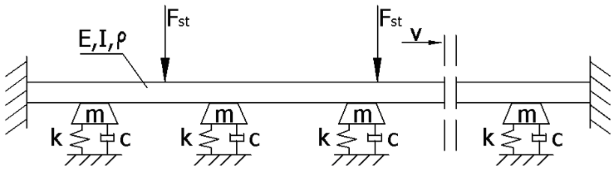

Figure 7. Numerical model of rail-sleeper-ground interaction in ADINA.

With the numerical model of the bridge, schematically depicted in Fig. 8, we can determine responses of the bridge excited by a passing train using the Newmark method of integration of equations of motion. The model has also been built using the FE commercial program ADINA based on technical documentation made available by PKP PLK S.A. The justification of building the model in ADINA is the possibility of visualizing it in a user-friendly way. Our in-house code lacks a professional post-processor. All mechanical characteristics of the bridge are contained in the influence matrices, which are series of responses due to local perturbations calculated with the ADINA model and required for the VDM-based analysis. If the matrices are extracted from the commercial program, damage identification can be further handled by our in-house software.

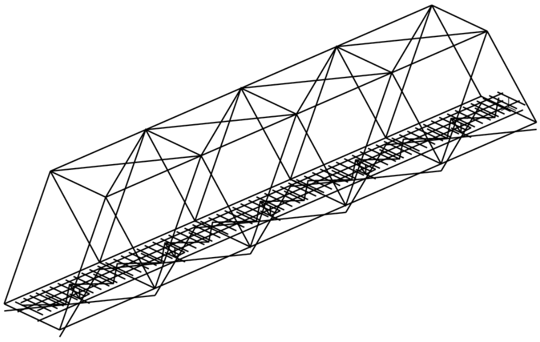

Figure 8. Truss-beam model of the bridge built in ADINA.

The numerical model is supposed to represent the behavior of the steel truss bridge shown in Fig. 1, which carries a single railway track. The load-carrying structure of the bridge is a truss structure consisting of 2 main plane truss girders (7 groups, 34 elements) situated vertically on the left and right side of the railway track. Some minor truss elements (7 groups, 96 elements) are placed to bind the 2 truss girders together. The truss structure is fixed at one support and allowed to move freely on rolling bearings at the other support. For increasing the stiffness of the bridge, 2 portal frames (2 groups, 42 elements), connecting the 2 truss girders over each support, are combined with the truss structure of the bridge.

The load-carrying truss structure is riveted at its lower nodes with a frame grillage (3 groups, 364 elements) consisting of 6 equidistant transverse I-section beams (2 outermost as bridge supports) and 5 pairs of in-between longitudinal I-section beams. This grillage provides support for the railway track and transfers the load exerted by trains to the truss structure of the bridge. Each transverse beam of the grillage is joined at its ends with lower nodes of the 2 main truss girders. Minor elements like stiffening ribs of the beam elements were disregarded. The railway track itself consists of 64 wooden sleepers (1 group, 960 elements) and 2 rails (1 group, 252 elements).

The total number of truss elements in the model is 130 and Bernoulli beam elements is 1618, which results in the overall number of 1748 elements divided into 21 groups and connected by 1728 nodes. Standard steel properties (density 7850 $\mathrm{kg/m^3}$, Young modulus 205 GPa) were assumed as material data. In the dynamic analysis, a passing railway car was modeled as a sequence of concentrated forces moving along the bridge with constant velocity.

The stage of calibration of the model to experimental responses has been successfully accomplished (see Section 5). This is an important reference point before consideration of simulated damage scenarios on the real bridge in an experiment.

## 5 TESTS OF THE SYSTEM

### *5.1 Modeling vs measurements*

The numerical results obtained from the model of rail-sleeper-ground interaction were confronted with the experimental measurements for a passage of the typical 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 Fig. 9, 10, evidencing a decent conformity of the numerical and experimental data.

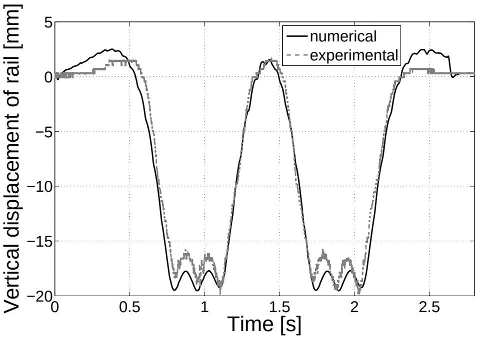

Figure 9. WIM system: numerical vs. experimental displacements.

Fig. 11 presents a comparison of measurements collected simultaneously for the same passage of the locomotive by the standard strain gauge and piezoelectric PFC sensor in location R2 (cf. Fig. 4). Both the sensors captured a very similar response. The numerical model returned a much smoother curve, which is depicted together with the two experimental ones. The fact that the model neglects high-frequency content of the bridge response is due to simplifications of modeling. For instance, the steel paddings between the rails and sleepers are disregarded in the model. In reality, these paddings are quite worn-out with the tendency to loose contact with the rail during train passage, which implies unpredictable impact-like components transmitted to the bridge structure.

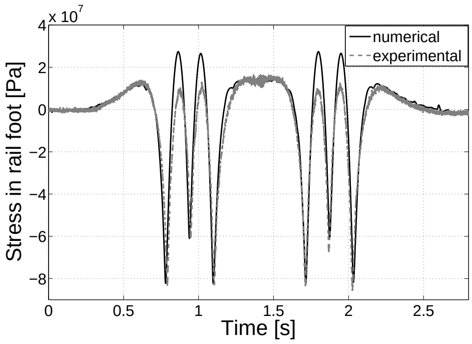

Figure 10. WIM system: numerical vs. experimental stresses.

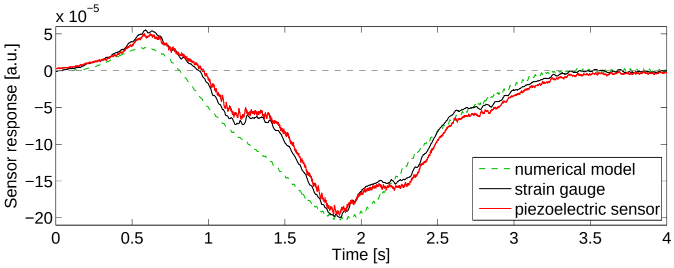

Figure 11. SHM system: numerical vs. experimental responses in location B3.

Figure 12 depicts a comparison of experimental responses collected in location B2 with both the types of strain sensors and confront the measurements with the described numerical model. The bridge was excited by the ET-22 locomotive again. Generally, good conformity can be observed although the numerical model tends to disregard high-frequency components evidently present in the experimental curves. Unfortunately the adopted simplified skeletal model of the bridge is not able to reflect the real behavior of the bridge in such details. Comparisons with a high-frequency technique using ultrasonic piezo-probes in location B2 can be found in [8]. Again, good conformity of the vibration-based and ultrasonic results has been reported.

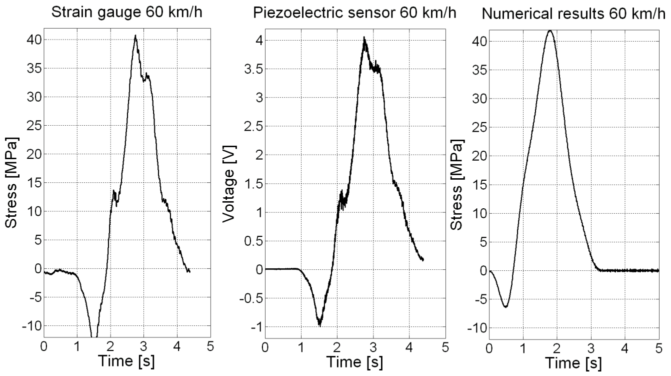

Figure 12. SHM system: numerical vs. experimental responses in location B2.

### 5.2 *Data transfer tests*

Short-range transmission tests were performed using a 2.4 GHz transceiver and an 8-bit micro-controller. One part for data collection was connected to a PC and the other one responsible for packet transmission was placed in different locations. This test was performed outdoors. Results of the short-range experiment are presented in Fig. 13. This is supposed to simulate the communication between a bridge sensor B1-B4 and the bridge DP unit.

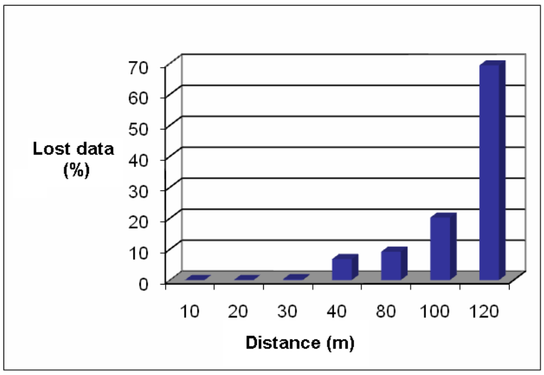

Figure 13. Packages lost during wireless transmission in short-range (performed outdoors).

The far-range tests were carried out in lab conditions. They relied on a GSM G24 modem, which was connected to a PC computer via the RS-232 port. A server application for reception of data was running on another PC computer connected to the Internet via a mobile phone. The initial signal from a piezo sensor perfectly matches the data transferred by the wireless system, which is depicted in Fig. 14.

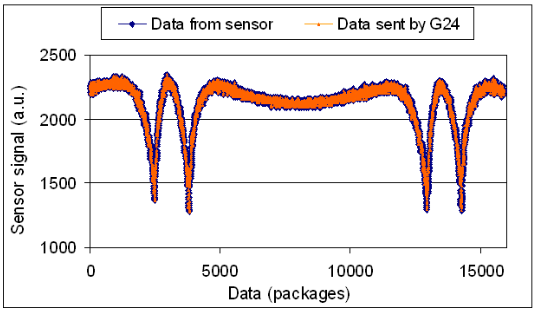

Figure 14. Comparison of the in-situ collected signal with the one after long-range wireless transfer.

## 6 CONCLUSIONS

The paper presents various aspects of 3-year monitoring of a railway truss bridge. Implementation of an integrated monitoring system – consisting of the weigh-in-motion and structural health monitoring subsystems – is described.

Piezoelectric patch sensors collecting strains are used for monitoring. They were mounted at the commencement of field measurements in 2007 and are still in good shape, providing reliable data. For comparison, standard strain gauges are used. Readings from both the types of sensors are almost alike, however the piezo sensors outperform strain gauges in many aspects e.g. sensitivity, durability.

A customized, solar-powered system for wireless transfer of measurement data was developed. The transfer takes place in two ranges – short range for communication between smart sensors and the local data processing unit, and far range for sending data to a server via GSM protocols. Satisfactory results for both the ranges of wireless transfer are presented.

Two numerical models were built – one for the sleeper-ground interaction, the other for the railway bridge itself. The conformity of the models with field measurements is very good. This fact is crucial for further research, which will aim at considering some simulated damage scenarios for the bridge by adding local masses.

The ambient type of excitation generated by passing trains is cost- and hardware-free, however it does not produce much difference between the responses of the intact and 'damaged' bridge. Therefore alternative types of dynamic load, generated by an electromagnetic shaker of high power for harmonic excitation or by a specially-designed device capable of performing controled-impact excitation, will be examined.

## ACKNOWLEDGMENTS

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