Investigation of electrical signals induced in a piezoelectric axle load sensor mounted in asphalt mixture

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ABSTRACT: This paper describes a laboratory test stand and a dedicated FEM model, both specifically designed to study the impact of stress distribution, acting on the axle pressure sensor, on the electrical signal delivered, which is then processed and converted into the vehicle's wheel load. A linear relationship between maximum voltage and applied stress was observed in both laboratory tests and numerical analyses. However the voltage change signal differs between FEM models and laboratory test measurements, what is probably caused with the capacitor discharge or other electric circuit effects.

1 INTRODUCTION

1.1 *Background*

Weigh in Motion (WIM) systems have been developing in order to improve the efficiency of traffic loads control. They may contribute to reduction of the number of overloaded vehicles and minimalize an adverse effect caused by vehicle overloading to road infrastructure, which was discussed by Rys et. al. (2015). Although WIM technology has been in use for several years, its full potential has yet to be fully realized. The primary challenge remains the gradual loss of measurement accuracy over time (Adresi et al. 2024, Masud et al. 2023). The phenomenon arise from temperature variations (Rys et.al., 2024) and the overly simplified treatment of stresses acting on the pressure sensor under the load of vehicle wheels (Burnos &Rys, 2017).

The problem solution needs a deeper investigation of electrical signals induced in a piezoelectric axle load sensor mounted in asphalt mixture, which is the subject of this paper. Despite there are some previous studies presenting full-scale experimental testing of WIM sensors (Hornych et al., 2016) and WIM sensor modeling (Otto et al., 2017), there is still gap in laboratory-scale testing of asphalt mixture-load sensor systems and system modelling.

1.2 *Objective and Scope*

The paper presents preliminary tests of the newly developed laboratory stand of axle load sensor-asphalt mixture system. The main aim is to develop a numerical model of the stand, perform computer simulations of the laboratory test and compare them with laboratory measurements.

2 STAND FOR LABORATORY TESTING

The experimental stand included an asphalt mixture sample embedded with a Weigh-In-Motion sensor. Initially, the asphalt mixture (AC16, containing neat bitumen of grade 35/50) was placed in wooden molds and compacted using a roller. The resulting beam measured 1800 mm in length, 340 mm in width, and 120 mm in thickness. After demolding, a groove measuring 72 mm in width and 70 mm in depth was cut along the center axis of the beam for WIM sensor installation. The sensor, of 1750 mm length, 44 mm width and 52 mm depth, was installed in the cleaned groove, with the remaining gaps filled using a resin-silica sealing compound. The sample is placed on a steel plate of 10 mm thickness, matching the remaining dimensions of the asphalt beam. The WIM sensor was connected to computers with specialized software allowing for signal processing and data gathering. The Universal Testing Machine UTM-130, which is equipped with hydraulic actuator was used to load the system. Figure 1 presents a view on the laboratory stand.

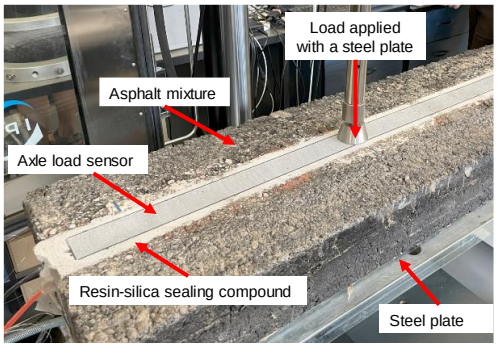

Figure 1. A view on a laboratory stand of axle load sensor – asphalt mixture system under loading in UTM-130 hydraulic press.

The tests aimed to measure the voltage induced in the WIM sensor when subjected to a load transmitted on the asphalt specimen with the sensor. The results discussed in this paper have been obtained through loading transmitted from the hydraulic press to the asphalt specimen using a round steel stamp of 109.2 mm diameter. Three stress levels have been tested – 700, 800 and 900 kPa. The loads were applied in series (for each stress level) of sinusoidal impulses with a duration of 100 ms and a rest interval of 11 s.

3 FEM MODELING OF THE SENSOR-ASPHALT MIXTURE SYSTEM

The numerical model of the experimental stand was created using the Finite Element Method (FEM) and the software Abaqus. The geometry of the model corresponds to the specimen (beam) used in the laboratory test. Half of the beam was modelled using the symmetry of the system with respect to the *x*-*z* plane. The model consists of several elements - an asphalt layer, an axle load sensor made of piezoelectric material, and a resin-silica sealing compound mass in which the sensor is embedded (Figure 2). A steel plate on which the asphalt mix beam is placed was also modelled. The possibility of sliding between the steel plate and the asphalt mix layer was assumed, and the defined contact prevents the surfaces of these elements from penetrating. Full continuity of displacement between the elements was assumed for the sealing compound, the sensor and the asphalt mixture. The steel stamp that the beam is loaded with has also been modelled with respect to the symmetry conditions.

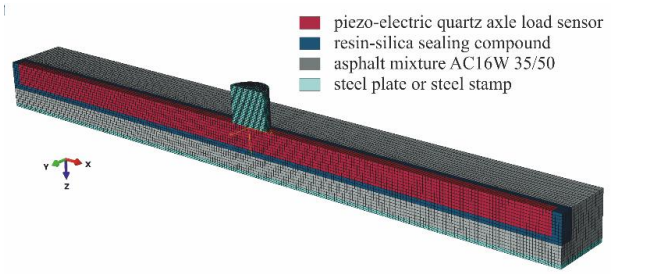

Figure 2. FEM model of Axle Load Sensor – Asphalt Mixture System.

The WIM (Weigh-In-Motion) sensor operates based on the unique piezoelectric properties of quartz-like materials, which couple mechanical and electromagnetic phenomena. Specifically, the piezoelectric effect enables the material to convert mechanical stress into an electrical response, and conversely, an applied electric field induces mechanical strain. This dual functionality is described by the linear piezoelectric constitutive equations, where the stress tensor σ_{ij} and strain tensor ε_{ij} are directly linked to the electric field E_i and electric displacement field q_i.

The mechanical and electromagnetic coupling is expressed through the piezoelectric constants, which define the material's response to external stimuli. Under mechanical loading, stress generates an electric displacement field q_i, which is proportional to the magnitude and direction of the stress. Simultaneously, the induced strain can alter the electric field distribution within the material. These interactions are governed by the linear relationships:

$$\sigma_{ij} = C_{ijkl}\left(\varepsilon_{kl} - d_{mij}E_m\right) \tag{1}$$

$$q_i = g_{ijk}\varepsilon_{jk} + D_{ij}E_j \tag{2}$$

where σ_{ij} – stress tensor [MPa], C_{ijkl} – stiffness tensor at zero voltage [MPa], ε_{kl} – strain tensor [-], d_{ij} – piezoelectric strain coefficient tensor [C/N], E_m – electric field vector [V/m], q_i – electric induction vector [C/m^2], g_{mij} – piezoelectric stress coefficient tensor [C/m^2], D_{ij} – dielectric constant tensor [F/m].

These equations highlight the interplay between the mechanical and electromagnetic domains, essential for accurate modeling of WIM sensors. The mechanical properties of the material are defined by the tensor C_{ijkl}. The tensors d_{ijk} and g_{ijk} describe the piezoelectric properties of the material, the values of these tensors being mutually dependent. The material's mechanical properties are assumed to be isotropic and the electrical permeability is assumed to be isotropic, and the piezoelectric properties occur only in the *z*-axis direction, induced by vertical stresses and horizontal stresses along the *x*-axis.

Table 1. Material properties of the WIM sensor.

E [MPa]	Poisson Coefficient [-]	ρ [kg/m3]	d_{zzz} [C/N]	d_{zxx} [C/N]	D [F/m]
210000	0.3	7850	$8\text{x}10^{-13}$	$-3.2\text{x}10^{-13}$	$1.77\text{x}10^{-8}$

The deviatoric part of the stiffness tensor of the asphalt mixture was modeled as viscoelastic, while the spherical part was modeled as elastic. The viscoelastic properties were considered using a five-branch generalized Maxwell model, which is implemented as a Prony series. The deviatoric part of the stiffness tensor was assumed to exhibit viscoelastic behavior, and the spherical part was modeled as elastic. To determine the model parameters, stiffness master curves for the test section were used, assuming a constant temperature for the asphalt layers in each segment of the pavement. The relationship between the complex modulus and loading frequency is expressed by Equation (3).

$$E^*(\omega) = E_\infty + \sum_{i=1}^{n}\frac{E_i\omega^2\tau_i^2}{1+\omega^2\tau_i^2} + i\left(\sum_{i=1}^{n}\frac{E_i\omega\tau_i}{1+\omega^2\tau_i^2}\right) \tag{3}$$

In Abaqus, the Maxwell model is defined using the dimensionless parameters g_i and τ. The relationship between these parameters and the quantities of a Prony series is presented by Equations (4) - (6). The obtained parameter values and the root mean square error from fitting the master curve are presented in Table 2. To describe the temperature dependence, the Williams–Landel–Ferry model was used. The data were obtained from stiffness measurements at three temperatures (6°C, 20°C, and 40°C). A reference temperature T_r of approximately 20°C was adopted, and the parameters C_1 of 9.436 and C_2 of 55.338°C were determined.

$$E_0 = E_\infty + E_1 + E_2 + E_3 + E_4 \quad (4)$$

$$\tau_i = \frac{\eta_i}{E_i} \quad (5)$$

$$g_i = \frac{E_i}{E_o} \quad (6)$$

Table 2. Maxwell Model parameters assumed for Asphalt Mixture.

E_0 [MPa]	g_1 [1]	g_2 [1]	g_3 [1]	g_4 [1]
17051	0.292	0.206	0.182	0.257
ρ [kg/m3]	τ_1 [s]	τ_2 [s]	τ_3 [s]	τ_4 [s]
2450	0.0002	0.2969	9.5496	0.0183

Linear elastic properties are assumed for filler mass and steel. The material properties are summarised in Table 3.

Table 3. Material parameters for Hooke's Model.

Lp.	Name	Elastic Modulus [MPa]	Poisson Coefficient [-]	ρ [kg/m3]
1	Steel	210000	0.3	7850
2.	Resin-silica sealing compound	75000	0.3	2450

Following the experiment, the beam was loaded with a steel stamp positioned at the center of the specimen. A sinusoidal time-varying load with a period of 100.0 ms and a maximum stress from 700 to 900 kPa was assumed as in the experiment.

A boundary condition specifying zero electric field potential on the lower surface of the WIM sensor is applied. The support has a width of 0.65 m and its center is under the load axis. The boundary conditions of symmetry with respect to the *x*-*z* plane were also applied in the system.

The calculations were performed using the Dynamic Implicite procedure available in Abaqus, which considers the time variability resulting from the movement of the load and the viscoelastic material properties. C3D8R and C3D8E finite elements were used.

4 COMPARISON OF NUMERIC ANALYSIS TO INITIAL LABORATORY TESTS

The numerical calculations provided the distribution of the electric field potential on the upper surface. The difference in potential between the lower and upper surfaces represents the electric voltage across individual points. The resulting potential distribution and the obtained vertical stresses for a pressure value of 900 kPa are shown in Figure 3.

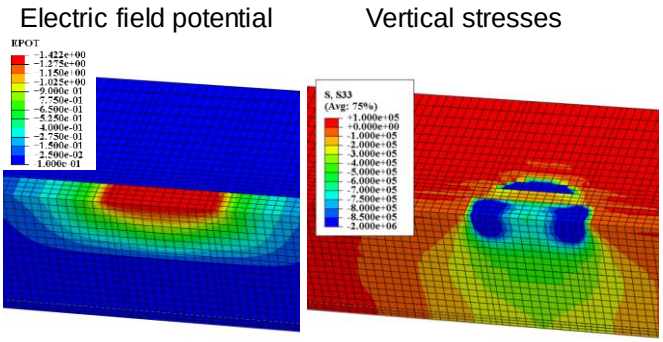

Figure 3. Electric field potential and vertical stresses on the upper surface of WIM sensor.

In practical measurement systems, signal processing circuitry often averages the observed electric potential to determine the effective voltage across the sensor. This simplification facilitates the interpretation of sensor outputs and ensures consistency with the overall response of the measurement system.

To calculate the averaged electric potential, the potential distribution over the top surface of the piezoelectric material was integrated. The resulting integral was divided by the total surface area of the electrode, yielding the area-averaged electric potential. This averaged value represents the effective voltage between the upper and lower surfaces of the piezoelectric material, where the lower surface potential is fixed at zero as a boundary condition.

The computation of the averaged voltage utilized the electric potential values obtained from the nodes on the upper surface of the sensor. Each node was assigned the surface area closest to its location, effectively partitioning the electrode surface. The averaging process involved calculating the sum of the products of the potential values at each node and their corresponding surface areas. This sum was then normalized by dividing it by the total surface area of the electrode.

This approach is particularly justified in scenarios where the readout system inherently integrates spatial variations due to its design or during subsequent signal processing. Averaging also reduces the influence of local anomalies in the potential distribution, providing a robust and representative measure of the sensor's overall response. The values of the averaged voltage over time, obtained from numerical calculations, are presented in Figure 4.

As for the laboratory testing, the voltage in time values were obtained directly from the computer, being a part of the measuring system. For each loading cycle, there was a separate file containing voltage and time information. An example of laboratory-measured voltage in function of time is shown in Figure 5.

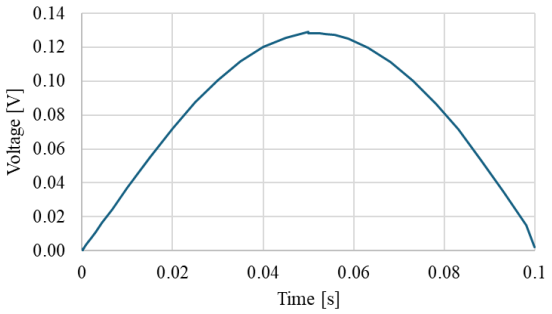

Figure 4. Average value of the electric field potential on the upper surface of the WIM sensor as a function of time at 900 kPa.

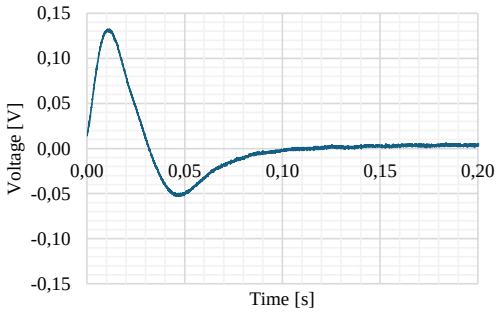

Figure 5. Example of measured voltage in function of time from laboratory testing of WIM sensor at 900 kPa.

Due to the linear physical model, the shape of the voltage curve as a function of time closely resembles the shape of the applied load. The model does not account for the discharge of capacitors in the electrical circuit, which occurs in real measurement systems.

Figure 6 illustrates the relationship between the maximum recorded or calculated voltage value and applied stress. The results obtained from numerical analysis show a very high degree of agreement with experimental measurements, also maintaining a linear characteristic of the relationship.

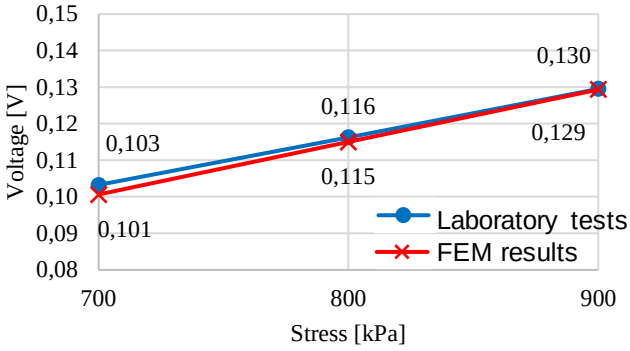

Figure 6. A comparison between maximum voltage values and stress relation from laboratory testing of WIM sensor and corresponding relation resulting from numerical analysis.

5 CONCLUSIONS

This paper provides a comprehensive representation of the axle load sensor system embedded in a mineral-asphalt mixture, along with a comparison of electrical signal measured in experimental results with FEM analysis outcomes.

The voltage change signal exhibits distinct characteristics depending on whether it is derived from the FEM model or actual measurements. The FEM model produces results as an integrated electric potential field, whereas the axle load sensor measurement system reflects a more complex response, primarily influenced by a discharge of capacitors in the electrical circuit.

Nevertheless, the linear relationship between maximum values of voltage and applied stress were found both for laboratory testing results and corresponding numerical analysis.

The results from the numerical modeling are provided in the same form as the output from an actual WIM sensor, taking into account load variation over time. The study can also be considered as a research stage of the interaction within the sensor and the asphalt mixture system – in FEM analysis, the asphalt mixture was modeled allowing for temperature-dependent properties, which is vastly important in practice. Mentioned above features, combined, distinguish the model from others described in the literature.

The developed model and research stand have great potential for conducting further research, including the assessment of the influence of various factors, such as road surface temperature, contact stress at the tire-road interface or system fatigue.

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