

Influence of support conditions and temperature on the EMI characteristics

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Abstract. The present work reports results from an extensive set of measurements which has been performed in order to formulate standard method to remove temperature changes from impedance measurements. The other issue addressed here is the investigation of influence of boundary condition and temperature changes on electromechanical impedance measurement for structural member. Due to electromechanical coupling, changes in dynamic characteristics can be seen in electrical impedance of piezoelectric transducer. Two different systems have been used during this measurement process. System based on FBG sensors has been used for temperature changes measurement while PZT transducers mounted on the structure with impedance analyser were used for electrical parameters measurement. During research electrical impedance and resistance of piezoelectric transducer were measured in order to analyze changes in amplitude of peaks and the frequency shift of peaks due to temperature variations and different configurations of the beam.

1. Introduction

Fiber Bragg gratings (FBG) are widely used in-fiber sensors [1-5] based on their core-refractive index modulation. This modulation along the fiber axis creates periodic structures of refractive index change, δn . In most of the cases, these refractive index changes are produced upon the optical fiber exposure to UV radiation. Various techniques to increase fiber photosensitivity have been reported [6, 7]. The theory behind the operation of FBGs is that periodically modified refractive index induces interference effect for some light's wavelength in the form of a reflected wave from the grating. For other wavelengths the light is transmitted through the grating. The condition for the light to be reflected is that its wavelength of the incident optical signal equals to the Bragg resonance wavelength, λ_{Bragg} . If the grating period, Λ , and the refractive index change, δn , are constant over whole length of grating, then the fiber is uniform. Investigations and practical applications show that FBG sensors are becoming one of the key elements in long-term temperature and strain monitoring. Technologies in this domain are widely used in applications from bio-medicine to Structural Health Monitoring (SHM)



for buildings, vehicles, planes, bridges, trains or wind turbines. Due to their properties such as: low mass, low dimensions as well as the immunity to electromagnetic interference, FBG are being found in various applications in space systems or Earth Monitoring. Two important characteristics define Bragg sensors applications domain: their sensitivity to temperature, pressure and mechanical strain.

Sensors included in a Structural Health Monitoring system are often susceptible to damage themselves. Many damage detection systems require a large number of sensors distributed over a structure for effective coverage. Various studies have been focused on the influence of the bonding layer on impedance measurements [8-10]. The authors of these studies investigated the electromechanical impedance models of piezoelectric sensors incorporating the effects of the boundary layer in the measured electrical admittance signals. The sensitivity of the susceptance, or imaginary part of the admittance measurement, to changes in the bonding layer has also been pointed out in these works.

An impedance-based sensor diagnostics model uses a mass-spring-damper system to come up with an expression revealing that the electrical admittance of a PZT patch $Y(\omega)$ is a combination of the structure's mechanical impedance $Z_s(\omega)$ and the electrical impedance of the piezoelectric $Z_a(\omega)$, as follows [11]:

$$Y(\omega) = i\omega \frac{wl}{t} \left[\epsilon_{33}^T (1 - i\delta) - d_{31}^2 Y_p^E + \frac{Z_a(\omega)}{Z_a(\omega) + Z_s(\omega)} d_{31}^2 \hat{Y}_p^E \left(\frac{\tan \kappa l}{\kappa l} \right) \right] \quad (1)$$

where w , l , and t are the width, length, and thickness of the PZT, ϵ the dielectric constant of the PZT, δ the dielectric loss factor for PZT, d the piezoelectric coupling constant, and Y_p^E is the complex Young's modulus of the PZT at zero electric field. The κ is the wavenumber of the PZT patch described by:

$$\kappa = \omega \sqrt{\frac{\rho}{Y_p^E}} \quad (2)$$

where ρ is the material density of the PZT patch. The magnitude of the mechanical impedance of the PZT is generally several orders of magnitude lower than that of the structure they are bonded to. The PZT mass and stiffness are nearly negligible, especially at lower frequencies. The problem with the PZT sensor is that any temperature fluctuations can change the slope of the susceptance just as much as a damaged sensor. For this reason, a technique needs to be developed to compensate any temperature variation. This compensation could be used to correct the real part of impedance or even the imaginary part of the admittance [12].

The work here is an initial attempt to generate a standard method to remove temperature changes from impedance measurements in Structural Health Monitoring. Authors of this work evaluate the change in the temperature sensitivity as well as the reproducibility of temperature measurements using selected commercial Bragg grating sensors. The influence of temperature and boundary conditions on electromechanical impedance characteristics of piezoelectric transducer mounted on the structural elements is investigated. Due to electromechanical coupling, changes in dynamic characteristics can be seen in electrical impedance of piezoelectric transducer. Section 2 presents method and experimental details. Results from data analysis are also presented here. Section 3 gives concluding remarks and further possible directions of research.

2. Method and experimental procedure. Results.

The experiments were conducted in order to: *a*) compare the stability of electric characteristics of five PZT transducers and to chose the suitable one for further investigations, *b*) obtain the influence of

different boundary conditions on electromechanical impedance characteristics of the piezoelectric transducer mounted on the structural elements; c) obtain the influence of temperature changes on electromechanical impedance characteristics of the piezoelectric transducer mounted on the structural elements. In these experiments the FBG temperature probe was used for temperature monitoring during impedance measurements in temperature chamber.

Two important characteristics define Bragg sensors applications domain: the sensitivity to temperature and strain, both being affected by the optical fiber types that we use, and the performance of their parameters. Before using the FBG were subjected to the calibration procedure aiming to: a) study their parameters at constant temperature and b) study the parameters during the heating - cooling cycles. In the first case, the Bragg grating sensors parameters were stored in databases being simultaneously recorded with respect to the Bragg Peak Shift. The measurements have been made in the presence of a thermocouple in order to compare, in real time, the temperature values as given by sensor and thermocouple itself. These measurements have been conducted in the presence of a thermocouple of high sensitivity (below 0.1°C).

Five Sonox P5 PZT transducers were utilized for measurement of real part of electrical impedance or resistance characteristics. These measurements were performed at different temperatures starting from the room temperature up to 50°C . Measurements of electric quantities for freely hanging PZT transducers in temperature chamber were made regarding resistance shift with temperature. Once determined the most stable electric characteristics, the corresponding PZT sensor was mounted on an aluminium alloy beam of 18.5cm length and 2cm width using cyanoacrylate adhesive. Next, one end of the beam was clamped in the vice and this configuration was inserted into a temperature chamber. This setup was subjected to controlled heating from 25°C to 50°C with 5°C step. With an impedance analyser (Hioki IM3570) the data was collected for each temperature step, and analysed from the point of view of induced changes observed in resistance R_s (serial resistance) due to the temperature shift. The temperature has been measured with a FBG sensor and corrections have been made in the final calculated data results.

The similar procedure was applied to the same beam fixed to two vices. The beam with PZT transducer has been clamped on both ends using vices, and the set of measurements has been repeated. The setup was heated from 25°C to 50°C . During each step the impedance measurements on PZT sensor have been recorded until the temperature was stable in the chamber. The temperature has been monitored using the FBG probe. From this research it was concluded that the shift of impedance curves with temperature for the 5 PZT sensors under test, is constant for the considered narrow frequency interval of the excitation signal.

The setup consisting of aluminum beam fixed by only one vice and PZT transducer bonded to the beam was monitored at room temperature. After that it was subjected to heating cycles up to 50 degrees. Resistance peaks changes (R_s) have been determined at different temperature steps and different frequencies. Following these measurements authors conclude that the impedance shift with temperature for the 5 PZT sensors under test is related to frequency of the excitation signal. In other set of experiments, authors have conducted similar test with two vices on the beam. Tests were run in order to compare and find differences between the two set-ups, containing one and two vices. The set-up with the beam plus one vice inside the heating chamber and the configuration of the beam with two vices are presented in Fig. 1. Fig. 2 and Fig. 3 present the changes in impedance shift at different values of temperature and frequency, for given experimental configuration: beam fixed by only one vice, and with two vices on the beam, respectively. These figures show the influence of temperature on impedance shift for wide frequency interval where the sensitivity of electrical impedance to temperature is also dependent on frequency range considered.

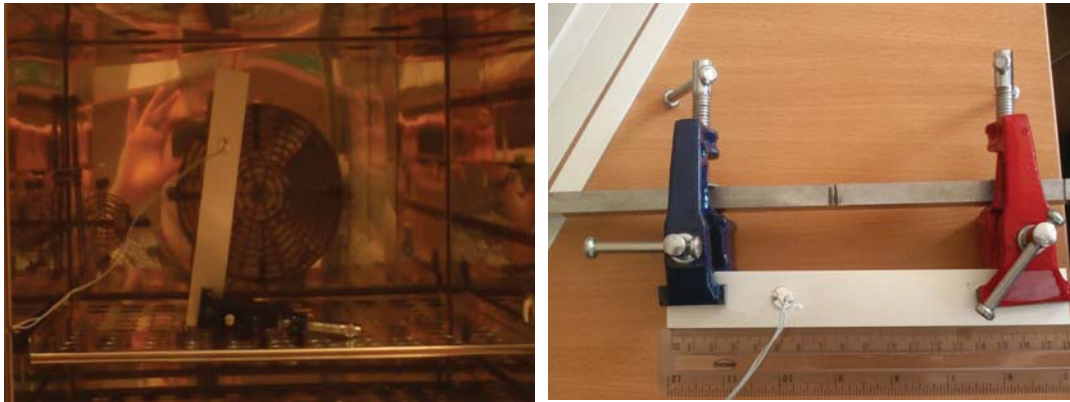


Figure 1. The PZT mounted on aluminium beam: (left) the beam with one vice inside the heating chamber, (right) the beam with two vices

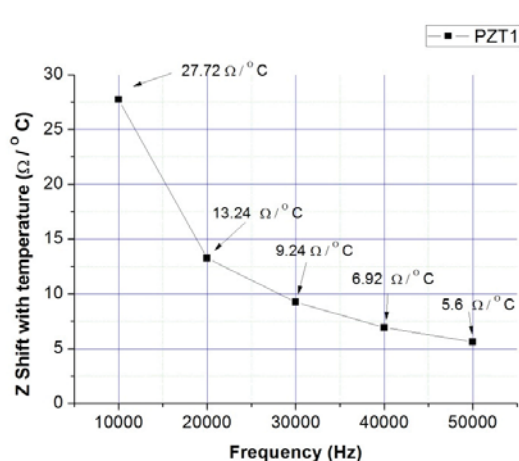


Figure 2. The impedance shift related to temperature for wide frequency interval (beam mounted on one vice)

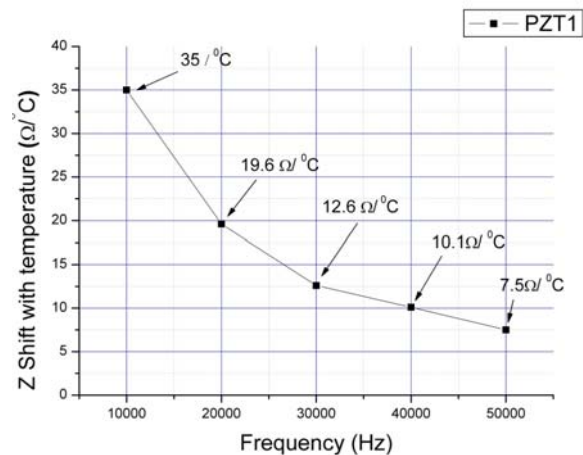


Figure 3. The impedance shift related to temperature for wide frequency interval (beam with two vices)

The piezoelectric sensors used in the EMI method are also significantly pyroelectric. Therefore, the temperature can be determined by measuring the electrical impedance of the piezoelectric sensors. If we consider variations in the amplitude of the electrical impedance resulting from temperature changes, the natural frequencies (*i.e.*, the resonance peaks in the impedance signatures) of the structure are temperature dependent. The natural frequencies decrease as the temperature increases. These variations in the natural frequencies cause frequency shifts in the electrical impedance signatures, as shown in Fig. 2 and Fig. 3.

Several tests over amplitude and frequency shift of resistance peaks R_s caused by temperature have been performed for beam with one vice and with two vices, respectively. Selected results are plotted in Fig. 4 and Fig. 5, respectively, for chosen peaks. For the beam with one vice (Fig. 4) it can be observed that resistance peak is shifted to the left with increasing temperature. The same situation can

be observed for beam with two vices, see Fig. 5. Moreover in Fig. 5 characteristic monotonic amplitude reduction of resistance with increasing temperature can be noticed. Similar situation was noticed in paper [13]. This monotonic behavior does not exist for all peaks which were measured here; see for example Ref. [13]. In all experiments the temperature measurements have been done using one FBG temperature sensor. As discussed before, the FBG sensors have been monitored comparing their response with that offered by a thermocouple under same experimental condition.

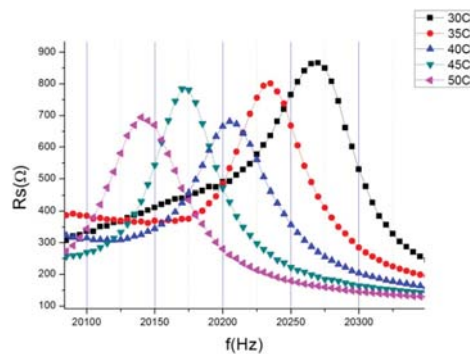


Figure 4. The influence of temperature on frequency shift of chosen peak for beam with one vice.

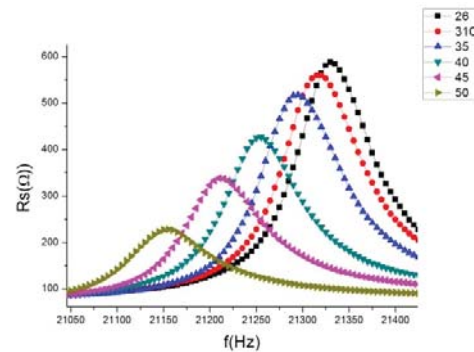


Figure 5. The influence of temperature on frequency shift of chosen peak for beam with two vices.

In Fig.6 and Fig. 7 resistance characteristics are presented for the two cases of applied boundary conditions: one vice and two vices. This simulates condition of beam fixed from one and both sides.

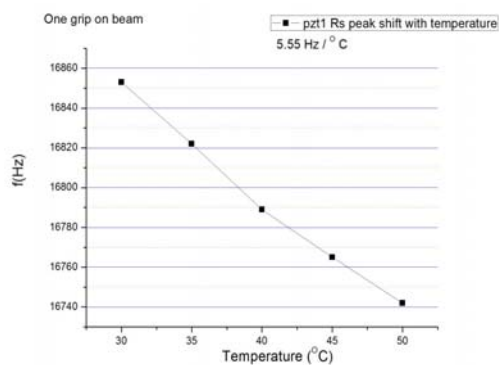


Figure 6. The influence of temperature on frequency shift of chosen peak for beam with one vice: the Rs peak shift measured is equal to 5.55Hz/°C

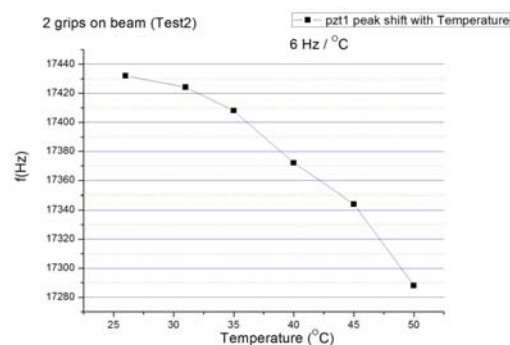


Figure 7. The influence of temperature on frequency shift of chosen peak for beam with two vices: the Rs peak shift is equal to 6Hz/°C

In the impedance approach [12] to model PZT-structure electromechanical interaction, the analytical model is bilaterally symmetric in both the longitudinal and the width directions. The strains of the PZT are uniform distributed. The selected resonance peaks plotted in Figures 4 and 5 clearly exhibited different behaviour as temperature increases. Using one vice (Fig.4) can produce erroneous

or misleading results, such as over estimation of peak amplitudes. The results presented in Fig. 2 to Fig. 5 show that the width of the frequency band is a critical issue for compensation techniques based on the frequency shift. From the resistance characteristics presented in Figures 4 and 5, and the corresponding shifts presented in Figures 6 and 7 authors conclude that in one case, namely the beam with one vice, the shifts comprise almost linear line but change in amplitude of peaks is not consistent with temperature variation, while for the second configuration set-up, the shifts do not comprise linear line but amplitude decreases monotonically with increase in temperature.

Fig. 8 gives EMI results from measurements taken in the temperature 25°C from different beam configurations. Comparing these results it can be concluded that support conditions (boundary condition) has very large influence on vibration characteristic and in turn on resistance characteristic of piezoelectric transducer mounted on this structure.

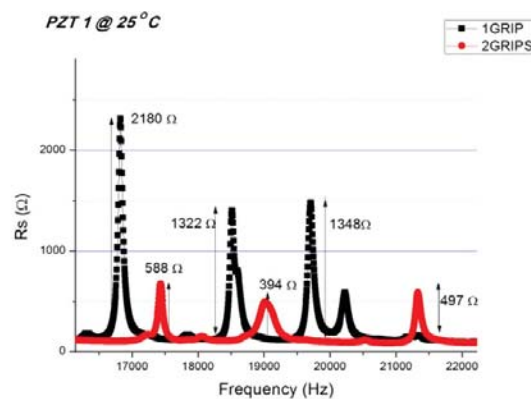


Figure 8. Comparison of the results for the beam with the two experimental configurations.

The temperature variation and strain change due to additional mass hanged on the beam is shown in Fig. 9. The graph shows that FBG strain sensor is influenced by both the tension and temperature changes. The difference between total strain (ϵ_c) and mechanical strain (ϵ_m) is well visible in Fig. 9 on the right.

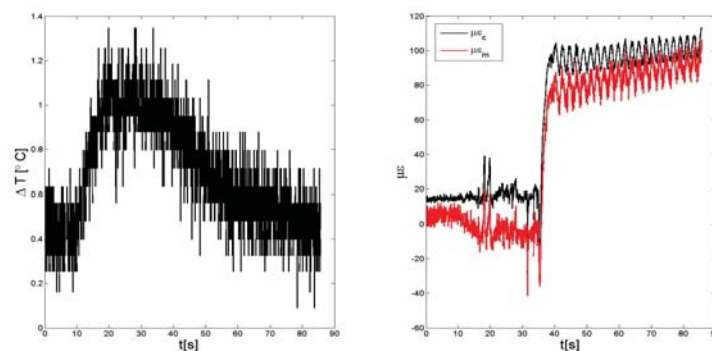


Figure 9. The FBG sensor response to the temperature changes (left, ΔT in $^{\circ}\text{C}$) and to the strain (right, ϵ in $\mu\text{m}/\text{m}$); with ϵ_c - the total strain and ϵ_m - mechanical strain.

3. Conclusion

The paper presents results from an extensive set of measurements on EMI using combined methods with PZT transducers and FBG sensors in order to provide more insight in Structural Health Monitoring. Authors studied the influence of boundary condition and temperature changes on electromechanical impedance characteristics of the piezoelectric transducer mounted on the structural elements. Due to electromechanical coupling changes in dynamic characteristics can be seen in electrical impedance characteristics of piezoelectric transducer. Two conclusions follow to the present work: a) consistent decrease of frequency of the peak with increase of temperature (fig 6, 7) in the frequency interval considered regardless the type of boundary conditions used; b) the appearance of different resonance peaks for different boundary conditions of the beam.

Further research work is focused on dedicated experiments to determine the influence of strain on EMI characteristics.

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