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Structural monitoring: a new wireless strain measuring method

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ABSTRACT
In the Structural Health Monitoring (SHM) as well as in laboratory tests of new structures and materials strain gauge measurements are required to check the mechanical stress. In large and complex structures which require several sensors and the measurement points are difficult to access, a wireless measurement of the strain gauge response is increasingly desirable to avoid the cost and the difficulty of a wired sensor network. This work experiments with a wireless strain gauge which is a hybrid between an RFID tag and a usual thin-film resistive strain gauge. A large set of measurements has been performed using reference specimens and readings in order to validate the sensor and to develop a calibration procedure that makes the sensor suitable for a large number of different applications in civil engineering. Installation and maintenance problems of the wireless sensor networks are overcome. A high level of measurement accuracy is achieved, comparable to that of wired strain sensors, together with a long measurement distance.

1 INTRODUCTION

Wireless Sensor Networks (WSNs) are suitable for Structural Health Monitoring (SHM) of large structures. WSNs were born to be applied in the military and then extended to environmental monitoring, medical treatment and civil engineering, due to their interdisciplinary characteristics (Spencer 2003), (Straser et al. 1998), (Lynch et al. 2003), (Mitchell et al. 2003), (Yu et al. 2004), (Park et al. 2008), (Jeong et al. 2010), (Liu and Yuan 2008), (Melik et al. 2009), (Mohammad and Huang 2011), (Lin et al. 2007), (Gasco et al. 2011). Various types of sensors have been developed during the past decades and SHM technology is becoming important in a wider range of technical fields such as restoration, seismic assessment, etc. Actually, it is more and more understood as SHM system can improve safety and reliability of structures by autonomously monitoring the conditions or detecting critical damage. In (Liu and Yuan 2008) authors state that, in comparison with traditional wired sensor networks, wireless systems for SHM have numerous advantages in terms of better flexibility, software or hardware expandability, cost effectiveness, and fault tolerance. Some advances in research, development and implementation of smart sensor networks and health monitoring systems for civil infrastructures are presented in (Ou Jinping 2006) and (Yu and Ou 2008). Other researches on wireless sensing technology applied to SHM for buildings and civil engineering structures are discussed in (Dyke et al. 2000). During the entire last decade, wireless sensors for continue structural damage monitoring became a so promising research field to be often related with new patented inventions and devices. These structural monitoring systems are composed by modular, battery-powered data acquisition devices which transmit information to a central data collection and analysis device over a wireless data link. Data acquisition devices consist of mechanical vibration sensors, data acquisition circuitry, wireless transmitter, and battery. After a natural hazard or an extreme event, powerful computers may be interfaced with the central device to perform required sophisticated analyses.

A brief summary and comparison among benefits and disadvantages related to active and passive wireless sensors can be found in (Sang-Dong and Jaehwan 2012). It is explained and easily understood that chip-less passive wireless sensors can give real-time structural information for SHM without space and battery constraints in harsh environmental conditions.

In this paper a new kind of sensor node for mechanical stress detection, which is obtained as a hybridization of an RFID (Radio Frequency Identification) tag and a resistive strain gauge, is proposed. It is a semi-passive wireless strain sensor tag, which uses a piezoresistive thin-film strain gauge (like a wired sensor) but it can be passively interrogated as an RFID tag. Like an RFID system, there is an interrogation unit radiating an electromagnetic wave that impinges on the antenna of the sensor tag and wakes it up. The strain gauge varies its resistance in accordance with the applied strain and drives an oscillating circuit that modulates the electromagnetic wave backscattered by the sensor-tag antenna. The modulating frequency is dependent on the applied strain and can be easily measured by means of a spectrum analyzer or a frequency meter once the modulated backscattered wave is received back by the interrogation unit.

The prototype of the proposed sensor tag utilizes a battery to power the oscillating circuit that is maintained turned off for all the time except for a short time interval during the measurement interrogation. For this reason, the life span of the battery can be very long. A detailed description of the sensor tag is reported in (Di Giampaolo et al. 2017) and in section 2. The resulting network has the simple star topology where the central unit is an RFID reader that interrogates one-by-one all the deployed sensor tags. The advantages of this sensor tag over the existing WSNs are: a simpler managing of the system, a lower cost of the overall system and his maintenance, no restriction on data rate because the strain information travels over analogical signals.

In this paper, the assessment of the sensor tag is demonstrated measuring the Young elastic modulus of different materials and comparing the results with those obtained using a calibrated wired system. A calibration procedure of the new sensor tag has been also developed.

2 THE NEW MEASURING SYSTEM

The overall SHM system consists of an interrogating unit (RFID reader) placed in a convenient position (e.g. near the ground in Fig.1) and several sensor tags deployed on the structure to be monitored. Tags are fixed to the structure and they are designed to remain operative for several years, while the interrogation unit is intended to be portable and placed at the measurement location only when needed (it can be also used for a permanent monitoring of the structure). All sensor tags are quiescent (i.e. inactive) for all the time except for the short time interval when interrogated. During interrogation, they measure the strain affecting the portion of structure where each of them is stuck on and they send back to the interrogation unit a signal encoding the strain measured value. The optimal operation of the system is achieved when the interrogation unit has a line of sight with each sensor-tag, but the system is able to work even in non-line of sight conditions. As shown in figure 1, the distance among the interrogation unit and the sensor tags can be of several meters. The number of tags that can be handled by a single interrogation unit is large, but that number can vary in agreement with the repetition time of interrogations. In case of static objects (i.e. the change of the status of the monitored structure is slow compared to the measurement time) the interrogation rate can be low and as a consequence, the number of tags that can be handled by an interrogation unit is limited only by the maximum interrogation distance.

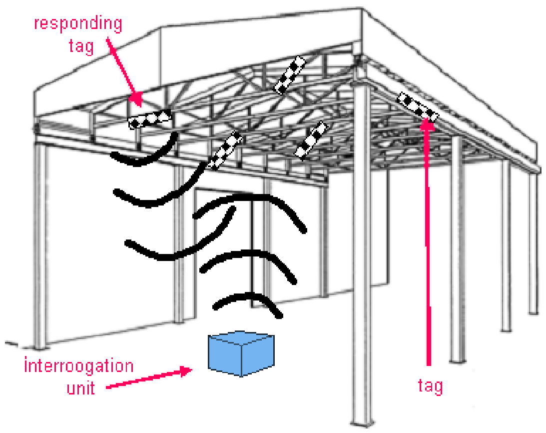

Figure 1. Scheme of the system measurement set-up.

The developed sensor consists of three main circuital blocks: an RFID block, a supply block and a sensing block as shown in figure 2.

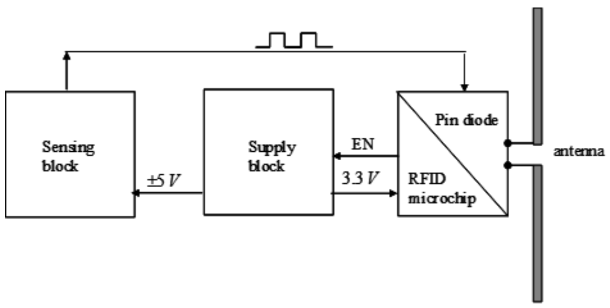

Figure 2. Scheme of the sensor tag, three main circuital blocks. The sensor tag is quiescent and can be activated on demand.

The RFID block consists of an antenna, a commercial RFID microchip and a pin diode with its feeding network. The antenna is a dipole-like antenna operating at 868 MHz, the pin diode is connected to the antenna terminals by means of a feeding network and it is used to modulate (on-off) the backscattered signal. The RFID microchip, powered by an external battery, allows the reading/writing distance of the sensor tag up to 30 *m* (nominal) and allows the remote control of the voltage level of a logic pin by means of an appropriate writing of the configuration word in its memory. This voltage level is used to switch the supply and sensing blocks on and off.

The sensing block is a resistance-to-frequency converter circuit whose output is a squared wave signal that is used to drive the pin diode connected to the antenna terminals. Under the squared wave signal, the input impedance of the pin diode switches between two values (low and high impedance) performing an amplitude modulation of the electromagnetic wave that is backscattered by the antenna (figure 2). Since the frequency of the squared wave signal is proportional to the strain gauge stretch, the backscattered signal, amplitude modulated by the squared wave signal, carries the information concerning the strain measured by the strain gauges. The resistance-to-frequency converter is composed of a full Wheatstone bridge strain gauge circuit (four piezoresistive thin-film strain gauges like in a wired sensor) and an operational amplifier that amplifies the small voltage changes across the bridge. A deeper description of the resistance-to-frequency converter is provided in (Di Giampaolo et al. 2017). The unbalance voltage due to the resistance change is then integrated and its polarity is fed back to the bridge as the bias voltage to sustain the oscillation. The oscillation frequency changes quite linearly with the stretching of the strain gauges. The output of this circuit drives a pin diode circuit for modulating the backscattered signal.

The interrogating unit consists of a commercial RFID reader and a spectrum analyzer connected to an antenna and to a personal computer (figure 3). At the start of measurements, the interrogation unit sends, by means of the RFID reader, an electromagnetic wave which delivers both the energy to wake up the tags and a query command to boost the tags to reveal themselves. Awaken tags modulate the electromagnetic wave that scatters back from their antennas with a random numeric code revealing their readiness for communication. Then the RFID reader performs the inventory of all the responding tags which identify themselves sending back their ID. Once the inventory is completed, the interrogation unit starts with the measurements of the strain gauge status of the inventoried tags.

The measurement procedure is repeated identically for each one of the responding tags. Therefore the sensing circuit is kept turned off all the time except for the short time interval during the measurement interrogation.

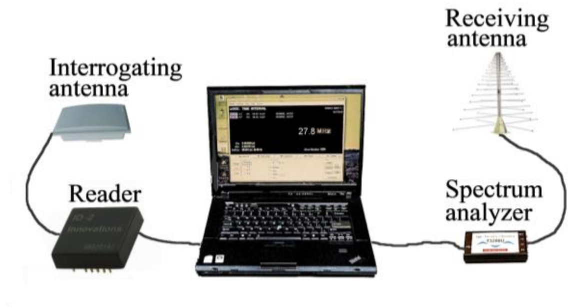

Figure 3. Scheme of the interrogation unit: a RFID reader and a spectrum analyzer connected to an antenna and to a personal computer.

3 THE EXPERIMENTAL TESTS SET UP

A campaign of measurements was performed to evaluate the effectiveness of the proposed sensor tag.

The elastic properties of two materials, steel and brass respectively, have been investigated using wireless sensor tags in place of the wired strain gauges. In particular, the estimation of the elastic modulus of steel and brass samples was first performed according to a common wired strain gauges technology, then was repeated with the wireless technology.

The experimental tests were performed using a specific apparatus, consisting in a manual compensator (working with the Wheatstone bridge principle) and a vertical metal frame designed to apply controlled forces up to 10 kN in tension. A variable tensile force is applied to the specimen causing it to extend. A load cell allows the measurement of the tensile force applied during the tensile test, so the Elastic modulus can be assessed.

Two identical specimens of steel and brass, respectively, were previously machined to have a dog's-bone shape, with the two hands kept bigger to secure the specimen to the testing apparatus and to promote a regular strain diffusion along the central, cylindrical portion of the specimen when applying tensile forces. The cylindrical portion of the specimens measures 8 mm in diameter and about 100 mm in length (figure 4).

Figure 4. The instrumented steel specimen.

During the experiments, tensile strains have been detected and measured by means of several strain gauges previously mounted on the specimen and electrically connected to the compensator. In particular, each specimen has been instrumented with two single grid strain gauges glued on the opposite side of the specimen, the grids being aligned with the longitudinal axis of the specimen. Common strain gauges 3/120LY4x type, characterized from R = 120 Ω and a scale factor k = 2 were adopted.

The reason for multiple gauges mounted on the same specimen first comes from the undesired possibility that applied tensile force could act eccentrically with respect of the ideal longitudinal axis of the specimen. Average signal computed from strain gauges mounted on opposite sides of the same specimen allows to compensate for this undesired effect and accounts for the ideal, uniform tensile strain to be considered in the tensioned specimen. On the other hand, when more arms of the Wheatstone bridge have been made active the sensitivity of the bridge increased. Moreover, due to possible temperature change during the test, the need for a second signal compensation rises as well. For this reason, signals from gauges mounted on the loaded specimen are combined with those recorded, at the same time, from gauges mounted on a second, identical specimen kept unloaded. In these experimental tests, both the mechanical and thermal compensation of the strain measurements have been performed at once, recording signals from gauges in a whole bridge configuration.

4 RESULTS

4.1 Experimental data from the wired method

Experimental curves obtained from separate tensile tests carried out on the steel specimen and on the brass specimen respectively, have been reported in the graph of figure 5. The values of the applied stress σ have been reported in relation to the measured strains ε. The experimental data clearly proved the elastic behavior of the specimens, as expectable. According to the Hooke's law $(\sigma = E \cdot \varepsilon)$, the estimation of the elastic modulus E of each different material was than obtained as slope (angular coefficient) of the linear regressions built on the experimental data. In these calculations, both the ascending and descending branches of each experimental curve were considered, but the loops amplitude due to hysteretic phenomena was negligible and does not affect the test repeatability, so loops are not visible from curves plotted in figure 5. On the other hand, linear regressions built on experimental data are characterized by R^2 values almost equal to 1.

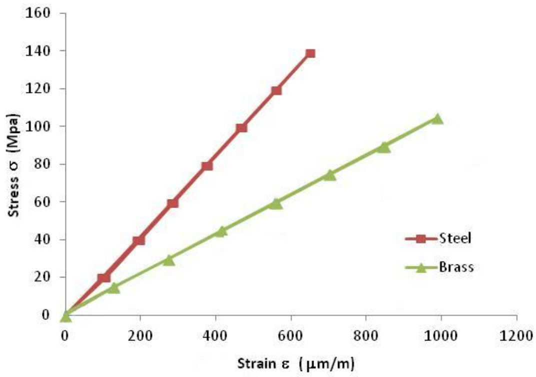

Figure 5. Experimental stress-strain curves obtained from tensile tests on the steel and brass specimens using the wired method.

In this experimental work, the mean value of three measurements repeated on each metal specimen was assumed as the reference value for the elastic modulus E_{ref} of the considered material. Single experimental results and E_{ref} values are reported in Table 1.

Table 1. Estimation of the reference elastic modulus Eref of the materials. Wired method.

Material	Cycle 1	Cycle 2	Cycle 3	E_{ref} (MPa)
	E_1 (MPa)	E_2 (MPa)	E_3 (MPa)	
Steel	219200	223700	223100	**222000**
Brass	106100	106600	105400	**106000**

choice of the electronic components (as shown by R^2 value calculated for the linear regression plotted in figure 6, approaching unit).

Moreover, also the frequency response of the sensor tag changes when different values of the electronic components of the oscillating circuit are chosen (Di Giampaolo et al. 2017). Therefore, the sensor tag can be tuned to have different frequency responses and each response is characterized by a different reference frequency value f_0 (frequency in unstressed condition). In particular, sensor tags characterized by initial frequencies higher than 8648 Hz result to be less and less sensitive to the same stress (strain) increments applied to the specimen.

4.2 Experimental data from the wireless method

To prove the wireless sensor tag is a reliable measuring tool, the elastic modulus assessment previously carried out with the wired method was performed with the wireless method. In figure 6, the results of a tensile test performed on the brass specimen and recorded in accordance with the new wireless method are plotted. Values of the applied stress σ are reported in relation to the recorded bridge frequency changes. To be consistent in the experimental procedure, stress increments and load sequence were repeated as in the previous tests carried out with the wired method.

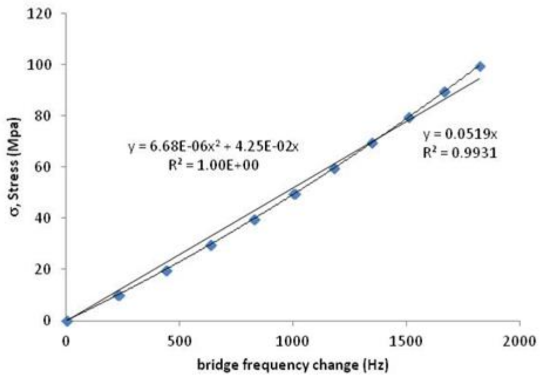

Figure 6. Wireless sensor tag frequency variation recorded during the tensile test on the brass specimen.

As can be seen from figure 6, a relationship exists among the applied load increments and the frequency changes (the modulation frequency of the backscattered signal) measured from the interrogation unit. Actually, a linear regression built on the experimental data was found to be very satisfactory, with the coefficient R^2 approaching unit (R^2 = 0.9931). On the other hand, considering experimental data more into details, it is noted that the experimental curve yet consists of a very narrow loop (as for wired gauge strain measurements) in which the ascending and the descending branch tend to a unique monotonic curve perfectly fitted by a second order polynomial regression (R^2 = 1.00). This was confirmed also for the steel specimen.

The weak non-linearity of the experimental curve mainly depends on the actual value of the hardware parameters that makes the response of the sensor tag not perfectly linear, as explained in (Di Giampaolo et al. 2017). Fortunately, the level of non-linearity can be overcome with an accurate

4.3 Calibration of the sensor

According to the wired method, a unique, direct proportion exists among the strain variations, the gauge resistance changes and the consequent current change in the Wheatstone bridge of the compensator. Similarly, the sensor tag gives a change of the modulating frequency of the backscattered signal in accordance with the real strain increment occurring in the gauge, but it depends on the reference frequency in unstressed condition and it suffers from possible non-linearity. In order to investigate these characteristics of the sensor tag, a large campaign of new tensile tests has been carried out making the initial frequency f_0 variable in a wide range of values, operating a suitable tuning of the electrical resistance of the circuit. To obtain a general validation of the proposed method, tensile tests were extended to both steel and brass specimens. As already done in figure 6, linear regressions are calculated on the experimental data and the angular coefficient $E_{app} = \Delta\sigma/\Delta f$ of each of these regressions is regarded as an apparent value of elastic modulus for the tested specimens. Results of these calculations, made with respect of a significant number of different f_0 values and extended to the two considered materials, are reported in figure 7.

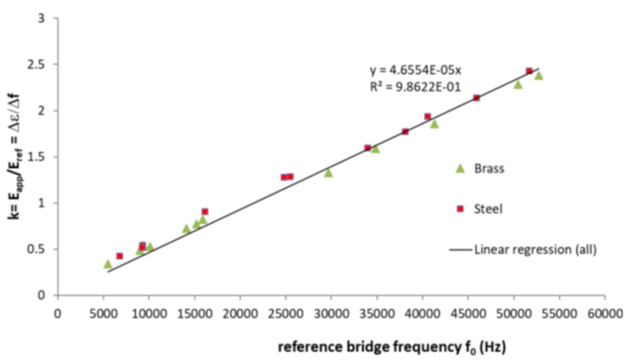

Figure 7. Experimental values for $k = E_{app}/E_{ref}$ as function of the initial frequency f_0. Values of k also express the ratio among the real strain increment in the gauge ($\Delta\varepsilon$) and the measured frequency variation Δf.

As can be noted, a unique linear relationship is highlighted among experimental k values and f_0 ones, independently from the considered materials, with k defined as the ratio $k = E_{app} / E_{ref}$. But k represents also the ratio among the real strain increment to be measured $\Delta\varepsilon$ and the measured frequency change Δf. This ratio depends on the consider frequency f_0. Then, linear regression calculated in Fig. 7 provides the calibrating law to translate the measured frequency changes into the actual strain variation experienced by the specimen. The ratio k between these two variables is modelled as a continuous function of the instantaneous frequency f while strain increments (and consequent frequency changes) are taking place.

Assuming $k = k\ (f_i)$ as a continue function of f_i, the differential $k = \Delta\varepsilon / \Delta f$ can be considered and the real strain variations $\Delta\varepsilon$ can be calculated in accordance with the following expression:

$$\Delta\varepsilon = 1.1912 \cdot 10^{-5}\left(f_2^2 - f_1^2\right) \tag{1}$$

It is to note that equation (1) is independent from the material of the specimen. Also, the validity of equation (1) extends to a very wide range of frequency values (from just few Hz up to 60 kHz). On the other hand, measurements performed with a sensor-tag which has a lower initial frequency result to be more sensitive than those ones with higher initial frequency. In fact, in the former case the ratio $k = \Delta\varepsilon / \Delta f$ is less than unity. In this condition, the frequency variation of 1 Hz corresponds to a strain variation lower than 1ε, representing a great improvement with respect of strain measurements performed with traditional methods. The proposed new method may enhance the strain measurement resolution even below 0,2 ε if the initial frequency is set lower than about 10 kHz.

5 CONCLUSION

In this study a new method for measuring strains is proposed. It consists in a wireless technique based on the traditional strain gauges integrated into an electrical circuit together with and RFID tag. In the proposed new method an interrogating antenna is used to detect the modulation frequency of an electromagnetic signal that varies in accordance with the strain to be measured.

Several tensile tests were carried out on metal specimens made of steel and brass. The feasibility of this new method was proved determining a unique clear relationship among the strain values and the measured frequency changes.

A calibration of the measuring system is proposed, showing it to remain valid for a large range of working frequencies and for large strain intervals. The accuracy of the proposed new technique is proved to be higher in comparison to a traditional strain measuring method. Effectiveness of the proposed wireless method was proved up to a maximum interrogating distance of 20 meters in a laboratory room, making this new strain measuring technique suitable for structural monitoring.

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