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Design and fabrication of a new fiber-cement-piezoelectric composite sensor for measurement of inner stress in concrete structures

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ABSTRACT

Rare suitable sensors are reported till now for the accurate measurement of inner forces at the concrete structures. In this study, a novel sensor is designed and fabricated for the evaluation of inner stress in the concrete structures under dynamical loads. By embedding this sensor in the critical points of the modern concrete structures (e.g. high-rise buildings, large-span bridges, dams, etc.), the heath monitoring of such structures may be easily done. The proposed sensor is a 5 cm × 5 cm × 5 cm cube made of a novel cement-resin-fiber composite matrix. A number of circular piezoelectric sheets with the same polarization alignment are embedded at the center of the cube with the certain distance from each other. The composite material used in the construction of the proposed sensor is in fact a new matrix composed of Portland cement, resin, water, fine silica and polymeric fibers which guarantees the strength, safety and sensitivity of the sensor at high level of stresses. The performance and reliability of the presented sensor has been proved through experimental tests. By considering different range of input force frequency (ω), it was found that the simple exponential law $\Delta V = 0.8\exp^{(-0.037\omega)}\Delta F$ exists between the amplitude of output sensor (ΔV) and amplitude of input force (ΔF). Compared to optical sensors and other available types of sensors which usually require special fabrication technology, the proposed sensor is low-price and easy to build and install. High sensitivity and precision in the range of 0.5–50 Hz, good compatibility with concrete, high durability, and the generating of strong output signals are other advantages of the proposed sensor.

1. Introduction

Civil structures are always exposed to dynamic forces such as wind, earthquakes, and vibrations caused by machinery and mechanical installations. These dynamic forces may create intense vibrations and large deformations in some of civil engineering structures (e.g. tall buildings, arc dams, large-span bridges, etc.). Intense deflections and vibrations not only endanger the safety and overall stability of the structures but

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also cause distress for users. To remove these drawbacks, the idea of intelligent structures was introduced. Intelligent structures have the ability to respond to environmental stimuli using sensor, actuator, and signal processing control units [1–3]. Sensors are devices that produce an electrical, mechanical or magnetic output signal when they are exposed to environmental conditions such as temperature, force and displacement. There are several types of sensors, such as electrical sensors, thermal sensors, optical sensors and smart material sensors. The actuators are another main constituent of a closed-loop control system, which receives control commands (which are usually a kind of an electrical signal) and cause physical changes in the system. Various types of actuators such as electric actuators, electromagnetic actuators, electromechanical actuators, hydraulic actuators and smart actuators are introduced until now. Thanks to the ability to sensitize, react and minimize the effects of external applied disturbances, intelligent structures have nowadays extensive applications in many engineering fields such as aerospace, civil engineering, electronics, robotics and biomechanics.

The idea of controlling concrete structures and the use of sensors in such structures was first introduced by Japanese researchers [4]. They used electric strain gauges to monitor the strain rate at the critical points of the reinforced concrete structures during the service period. By the addition of a short carbon fibers (0.2–0.4 vol.%) to concrete, Chen and Chung [5] made electrically conducting concrete which can function as smart structure material and allow non-destructive electrical probing for the monitoring of flaws. Han et al. [6] introduced nano materials into cementitious materials to improve/modify the mechanical property, durability and functional properties of these materials due to their excellent intrinsic properties and composite effects. According to Nawy [7], the electric strain gauges are usually attached to the outer surfaces of the concrete structures or become embedded inside the concrete. Electric strain gauges are sensors whose electrical resistivity is proportional to their deformation. Although electrical strain gauges have many advantages (e.g. lightness, ease of installation, affordable prices, etc.), they have a low sensitivity. Researches made by Vishay Micro-Measurements Group [8] show that the gauge factor (the ratio between the output signal and measured property) for this type of sensors is ranging from 2 and 5. Moreover, slip usually occurs at the interfaces between the electrical strain gauges and host concrete structures. This drawback makes electrical strain gauges inappropriate for long-time monitoring of concrete structures [8].

Some researchers used shape memory alloys (SMAs) as sensors to monitor the response of the concrete structures. Thanks to the dependency of the electrical resistivity of these alloys to their strain, SMAs are a suitable option for usage as sensors. Li et al. [9] introduced an integrated self-diagnostic and emergency repair intelligent structure system embedded with SMA bars by utilizing its sensing as well as actuation properties. In their study, Li and colleagues focused on damage repair. By employing two types of intelligent materials (i.e. SMA and piezoceramics), Song et al. [10] presented the concept of intelligent reinforced concrete structure and its application in structural health monitoring and rehabilitation. They showed that SMA significantly increases the concrete's damping property and its ability to handle large impact. Although the SMAs have good durability and resistance against corrosion, the sensitivity of these types of sensors is relatively low. The experimental studies of Liu [11] shows that the gauge factor of SMAs sensors is in the range of 3.8–6.2. In addition to the above limitations, Janke et al. [12] found that SMAs are very expensive materials. They proposed new ideas for using SMAs in civil engineering structures such as an improved concept for the active confinement of concrete members.

In recent years, some researchers have used optical fibers to measure strain, monitor the moisture contents, detect cracks and evaluate the corrosion of reinforced concrete structures. The measurement in these types of sensors is based on the change in the wavelength of light [13]. Kuang et al. [14] provided a concise review on the applications of plastic optical fiber sensors for monitoring the integrity of engineering structures in the context of structural health monitoring. Lau et al. [15] investigated experimentally the response of composite-strengthened concrete structures with the embedment of fiber-optic Bragg grating. They used single- and multiplexed-point strain measuring techniques to measure strains of the structures. Yeo et al. [16] developed and used a fiber-optic-based humidity sensor for the measurement of moisture absorption in concrete. Yeo and colleagues fabricated their sensor by using a fiber Bragg grating coated with a moisture sensitive polymer. Zou et al. [17] studied experimentally the contribution of Fabry–Perot fiber optic temperature sensor to investigate the effects of concrete hydration process. Childs et al. [18] embedded fiber Bragg grating sensors into concrete cylinders to monitor cracking deep within the specimens. Despite the high sensitivity, optical sensors are not an appropriate option for concrete structures. The components of optical fibers not only are expensive but also are very sensitive and weak. After embedding in concrete, the replacement and repairing of them is not possible [19,20]. Due to the optic fiber aging, the durability of optical fibers is not sufficient for long term monitoring of concrete structures [20].

Piezoelectric materials are capable of converting mechanical energy to electrical and vice versa. The coupling of mechanical and electrical properties of piezoelectric materials makes them suitable for use as sensors and actuators. Piezoelectric sensors and actuators have different working modes: thickness mode (k_{33}), extensional mode (k_{13}), and shear mode (k_{15}) [21,22]. Lightweight and compactness characteristics as well as comfort installation in a variety of environments are other features of these materials which have been made them widespread for usage in intelligent structures. Lezgy-Nazargah and colleagues [23,24] introduced a micromechanical approach for predicting the effective coupled thermo-electro-mechanical properties of piezoelectric fiber composites. A family of efficient finite elements models was introduced by Beheshti-Aval and colleagues [25–27] for predicting the sensory and actuator responses of laminated composite piezoelectric beams. Lezgy-Nazargah et al. [28] employed the piezoelectric shunt damping technique for vibration reduction of laminated composite beams. Despite the successful use of piezoelectric sensors and actuators in the mechanical and aerospace industries, these materials cannot be used directly in civil engineering structures, particularly concrete structures. Due to the incompatibility between two materials with completely different mechanical properties (i.e. concrete and piezoelectric material), the direct use of the piezoelectric materials as sensors in concrete structures is encountered with some limitations. One of these limitations is the difference between the acoustic impedance between the concrete and the piezoelectric material. The piezoelectric acoustic impedance (21.2MRayl) is much more than concrete (9MRayl) [29]. The next major problem that limits the direct use of piezoelectric sensors in concrete structures is the change in the physical and mechanical properties of concrete over time [30]. Contrary to mechanical and other industrial structures, which are often made of steel or other metal alloys, concrete structures are often casted and poured directly on the site. The hydration of cement is a long process and may sometimes take several years. During this chemical process, the moisture content and the temperature of the concrete are changed. During these changes, the concrete contracted and expanded, while the volume of the piezoelectric material remains almost unchanged. This inconsistency not only reduces the transmission of energy between the piezoelectric sensor and the host concrete structure but also leads to a significant loss in the transmission of signal at the interface between them. In addition to the above limitations, the lack of complete bonding between piezoelectric sensors and concrete at the adjacent surfaces of two materials is another problem that limits the use of these types of sensors in civil engineering. Therefore, the direct use of piezoelectric sensors is not an appropriate option for concrete structures, and the design and construction of new sensors that are compatible with these kinds of structures seems to be necessary. To overcome these limitations, the 0-3 cement-based piezoelectric sensors were fabricated by mixing of the white cement and piezoelectric powder together [29–32]. Although 0-3 cement-based piezoelectric sensors have the advantage of excellent interface compatibility with concrete structures, the polarization and fabrication process of these types of sensors are complicated and expensive. The new sensors called "2-2 cement-based piezoelectric" [33–35] and "1-3 cement-based piezoelectric" [36] sensors were fabricated by embedding piezoelectric rods/plates into the cement mortar. Similar to 0-3 sensors, 2-2 and 1-3 cement-based piezoelectric sensors can solve the mismatch problems of the traditional piezoelectric sensors for usage in concrete structures. Due to using the Portland cement mortar as matrix material, the compressive strength of the available 2-2 and 1-3 cement based piezoelectric sensors is low and such sensors are not able to work properly at high level of stresses. It is worthy to note here that the piezocomposite materials are classified according to their connectivity pattern of piezoelectric and the surrounding matrix material (e.g. 0-3, 2-2, 1-3, etc.). The connectivity is defined as the number of directions through which the material phase is continuous. The first digit refers to the piezoelectric phase while the second digit denotes the

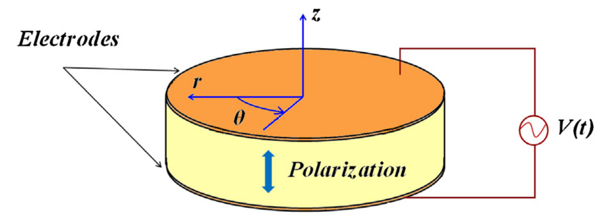


Fig. 1 – Circular piezoelectric sheets: Cartesian coordinate system and poling direction.

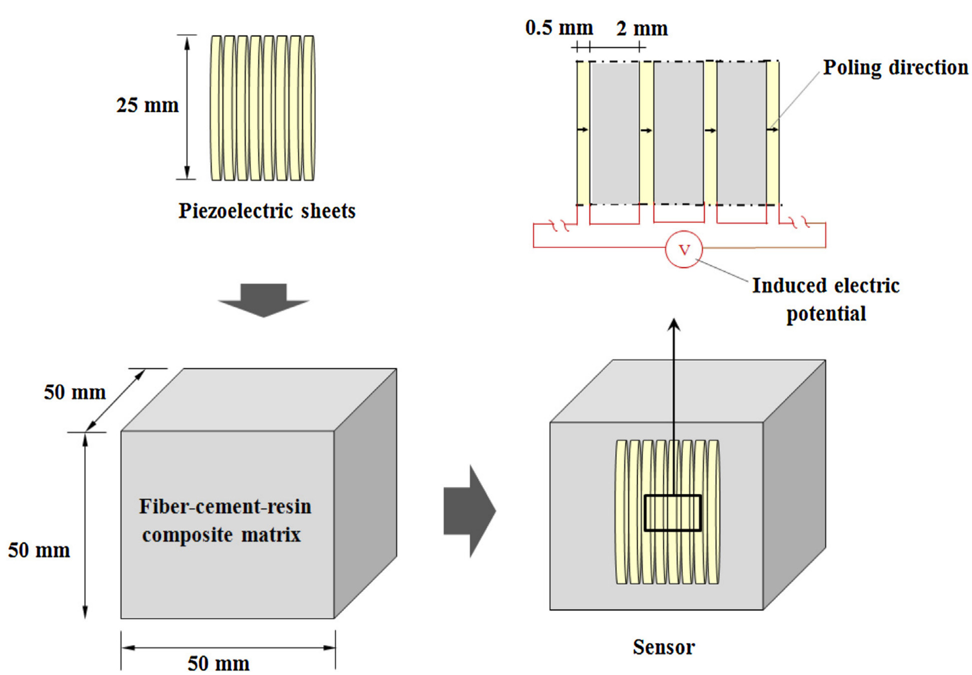


Fig. 2 – Schematic details and steps for the fabrication of the proposed sensor.

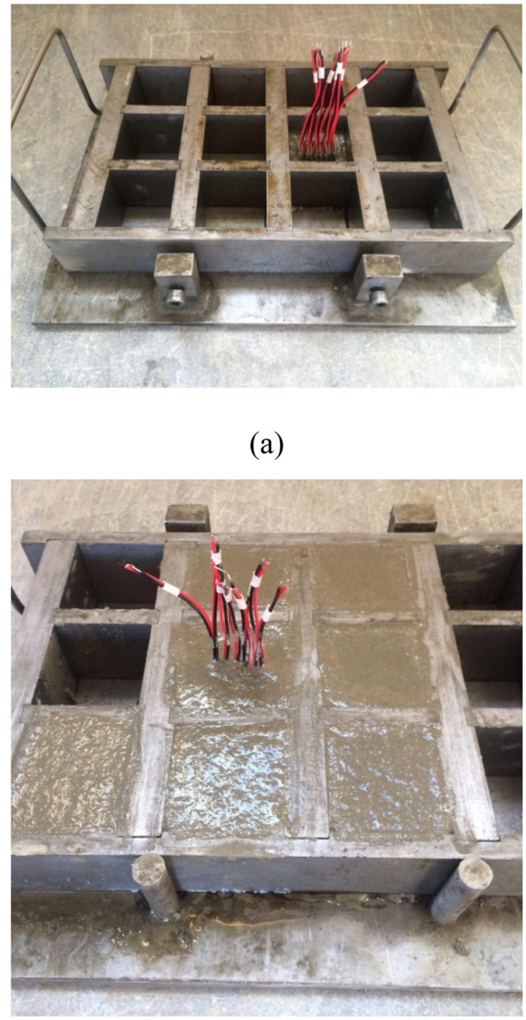
surrounding matrix phase [37]. Han and Ou [38] developed a type of embedded piezoresistive cement-based stress/strain sensor to monitor the local compressive stress/strain of concrete structures. Findings of these researchers showed that this newly developed sensor can be used as one of the alternatives to monitor the compressive stress/strain of concrete structures. Xiao et al. [39] developed a kind of cement-based strain sensor by utilizing the piezoresistivity of carbon black filled cement-based composite. Xiao and colleagues embedded their proposed sensors at three different stress zones in a bending beam, i.e. uniaxial compression, combined compression and shear, and uniaxial tension to investigate the strain sensing properties of embedded sensors under these stress states.

The review of the open literature shows that the researches on sensors which are compatible for applications in concrete structures are still at the early stage. To fill this gap, a new sensor is fabricated for the measurement of stress in the concrete structures. The fabrication of this sensor does not need special technology. Moreover, the proposed sensor is low-price and easy to build and install. The proposed sensor has been fabricated by pouring a cement-resin-fiber composite matrix into a series of prearranged circular piezoelectric elements. The employed matrix has high compressive strength which is essential for the proper performance of the sensor at high level of stresses. Thanks to the presence of polymeric fibers in the mix design of the composite matrix, the fabricated sensor has not brittle behavior. High electrical resistivity of the matrix material is another advantage of the fabricated sensor which assures the electrical stability of the embedded piezoelectric elements. The presence of resin in the matrix has been increased the waterproof characteristic of the fabricated sensor and prevents the penetration of moisture into sensitive piezoelectric sheets. Through applying dynamic loads with different load patterns (e.g. sinusoidal loading, random loading, periodical rectangular and triangular loading), the performance and reliability of the presented sensor has been examined.

The paper is outlined as follows: the fabrication details of the proposed fiber-cement-piezoelectric composite sensor are fully described in Section 2. The descriptions of the experiments are given in Section 3. Experimental results are subsequently presented in Section 4. Finally, conclusion and recommendations for future researches are cited in Section 5.

2. Sensor fabrication

The proposed sensor is consists of eight circular piezoelectric lead zirconate titanate (PZT) ceramic sheets that are arranged adjacent and the space between them is filled with a composite matrix material. A circular PZT sheet is schematically shown in Fig. 1. Poling direction as well as the coordinate system considered for circular PZT sheets are also shown in this figure. As shown in Fig. 1, the z-axis coincides with the elastic symmetric axis of PZT sheets which are the transversely isotropic material. The surfaces of piezoelectric circular sheets are covered with silver as electrodes. The diameter and thickness of the used circular piezoelectric sheets are 25 mm and 0.5 mm, respectively.



(a)

(b)

Fig. 3 – Steel mold and sensor sample: (a) before composite matrix pouring and (b) after composite matrix pouring.

The three-dimensional constitutive relations for the PZT sheets can be written as [40]:

$$\begin{Bmatrix} \sigma_{rr} \\ \sigma_{\theta\theta} \\ \sigma_{zz} \\ \sigma_{z\theta} \\ \sigma_{rz} \\ \sigma_{r\theta} \\ D_r \\ D_\theta \\ D_z \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 & 0 & 0 & -e_{31} \\ c_{21} & c_{22} & c_{23} & 0 & 0 & 0 & 0 & 0 & -e_{32} \\ c_{31} & c_{32} & c_{33} & 0 & 0 & 0 & 0 & 0 & -e_{33} \\ 0 & 0 & 0 & c_{44} & 0 & 0 & 0 & -e_{24} & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 & -e_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{15} & 0 & \chi_{11} & 0 & 0 \\ 0 & 0 & 0 & e_{24} & 0 & 0 & 0 & \chi_{22} & 0 \\ e_{31} & e_{32} & e_{33} & 0 & 0 & 0 & 0 & 0 & \chi_{33} \end{bmatrix} \begin{Bmatrix} \epsilon_{rr} \\ \epsilon_{\theta\theta} \\ \epsilon_{zz} \\ 2\epsilon_{z\theta} \\ 2\epsilon_{rz} \\ 2\epsilon_{r\theta} \\ E_r \\ E_\theta \\ E_z \end{Bmatrix} \tag{1}$$

where σ_{ij} and ε_{ij} (i, j = r, z, θ) are the components of stress and strain vectors, and E_i and D_i are the components of the electric field vector and the electric displacement vector. c_{ij} are the elastic stiffness components, e_{ij} are the piezoelectric coefficients, and χ_{ij}

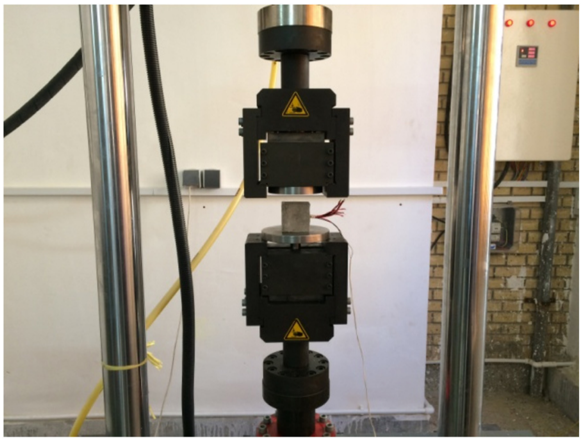


Fig. 4 – Servo-hydraulic test machine.

denote the dielectric constants. The values of mechanical and electrical constants c_{ij}, e_{ij}, and χ_{ij} for PZT materials can be found in [40]. Since the direction of dominant stress is along the thickness of piezoelectric circular sheets, the constitutive Eq. (1) can be reduced to:

$$\sigma_{zz} = c_{33}\epsilon_{zz} - e_{33}E_z \tag{2a}$$

$$D_z = e_{33}\sigma_{zz} + \chi_{33}E_z \tag{2b}$$

Based on the above equations, the piezoelectric sheets in the present fabricated sensors are working at thickness mode.

The circular piezoelectric sheets are located at the center of a cube with size 5 cm × 5 cm × 5 cm made of cement-resin-fiber composite matrix. The piezoelectric sheets are connected together in series. The gap between the piezoelectric plates is 2 mm. The fabrication steps of the proposed sensor are shown schematically in Fig. 2.

The employed matrix material is a new composite material consisting of five components of Portland cement, resin, water, fine silica, and polymeric fibers. In addition to the aforementioned components, superplasticizer of 1 wt.% was also used to increase workability of the composite matrix. In the fabrication process of the proposed sensor, the piezoelectric circular plates were first fixed at the center of the mold and then the cement-resin-fiber composite matrix was poured into the mold (see Fig. 3). In order to remove the air bubbles from the composite matrix material, the mold was placed on a shaking table for 20 s. After 36 h, the sample fabricated sensors were demolded and placed on the water for 28 days. During the samples curing, the temperature was maintained in the range 20–22 °C.

Thanks to special mix design of the composite matrix, the fabricated sensors have a good strength. Compressive tests carried on cubic matrix specimens show that the compressive strength of matrix material is about14 MPa. Thanks to considering safety margin in design codes, the compressive inner stress in concrete structures at service loads rarely violate from this value. This compressive strength of the matrix material not only guarantees the safety and sensitivity of the fabricated sensor at service loads but also allows the proper transfer of the energy from matrix to the piezoelectric sheets. It is well known that the behavior of cement-based materials is relatively brittle. The presence of polymeric fibers in the mix design of the composite matrix significantly increases the toughness, tensile and flexural strength of the fabricated sensor. The electrical resistance of the proposed sensor is relatively high (about 10^{10} Ω cm) which guarantees the electrical stability of the embedded piezoelectric elements. In general, it has been demonstrated that with increasing the resistivity of concrete, the risk of corrosion of embedded elements decreases [41]. The addiction of resin epoxy into the mix design not only increases in some extent the compressive strength of designed composite matrix but also increases its waterproof characteristic by filling the pores. By increasing the waterproof characteristic of composite matrix, the penetration of water into piezoelectric sheets decreases and their life time increases. Note that the PZT is a type of moisture absorption material and should be waterproofed when it is embedded into the concrete structures [42].

3. Experiment details

As shown in Fig. 4, a servo-hydraulic test machine is used for applying different dynamic loads to the fabricated sensor. Dynamic loads with different load patterns including sinusoidal loading, random loading, periodical rectangular and triangular loading can be generated by using the servo-hydraulic machine. Under the dynamic compression loadings, the sensor charge outputs are transferred to voltage using an

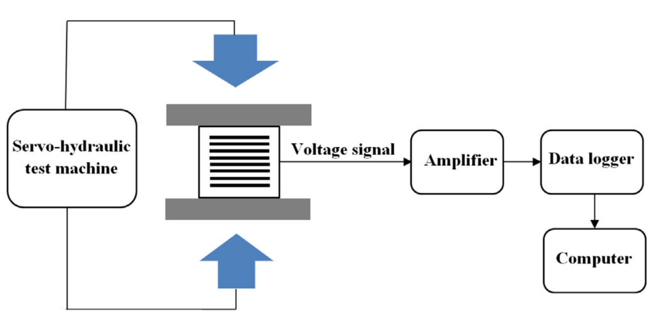


Fig. 5 – Details of test system for the fabricated sensor.

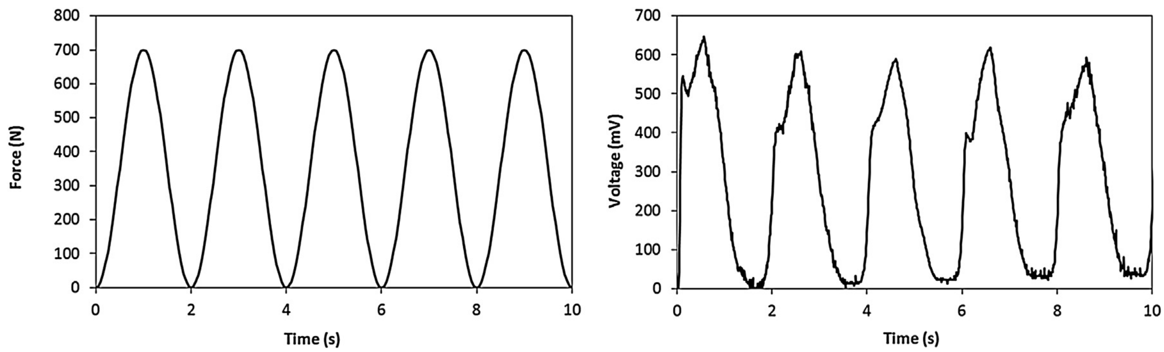


Fig. 6 – Response of fabricated sensor to the sinusoidal force with frequency 0.5 Hz.

amplifier. The amplified voltages are acquired and recorded by a dynamic data logger system. Illustration of the test system is given in Fig. 5.

4. Experimental results

4.1. *Response to sinusoidal loads*

The response of the fabricated sensor to the sinusoidal forces with different values of the amplitude and frequency has been studied in this section. First, a sinusoidal compressive force with the magnitude 700 N and the frequency of 0.5 Hz was applied to the fabricated sensor. The time history of the sensor voltage is depicted in Fig. 6. Then, the amplitude of the applied sinusoidal compressive force was kept constant value 500 N while four values 2, 5, 10 and 20 Hz was assumed for its frequency. The outputs of the sensor are shown in Fig. 7. It can be seen from Figs. 6 and 7 that the fabricated sensor can predict the sinusoidal load pattern well. There is no obvious phase shift between the sensor output and dynamic force input with high frequency. In case of dynamic force input with low frequency, small phase shift appears between the sensor output and input force. This event may be attributed to this fact that all piezoelectric sensors have the phase shift due to piezoelectric effect. It is evident from the results presented in Fig. 7 that the amplitude of registered voltage varies with frequencies despite the constant load amplitude applied. Since there is no perfect bond at the interface between the cement matrix and PZT sheets, the mechanical energy is not completely transferred from matrix to the piezoelectric elements. When the frequency of input force increases, the lower mechanical energy can be transferred to the PZT sheets and consequently the amplitude of output voltage reduces.

In order to find the relation between the amplitude of the input force and output voltage, the frequency of the sinusoidal load was kept as 0.5 Hz and its magnitude was changed from 100 N to 700 N. The same method was adopted for sinusoidal loads with input frequencies 5, 20 and 40 Hz. The obtained results are shown in Fig. 8. It can be observed that a linear relationship exist between the amplitude of the input force and output voltage at different frequencies.

The relationship between amplitude of sensor output and the frequency of input force has also been investigated. To this aim, the amplitude of the sinusoidal load was kept as constant (500 N, 800 N) while its frequency was changed in the range 0.5–50 Hz. The obtained results are given in Fig. 9. It can be seen that with increasing of applied load frequency, the amplitude of sensor output reduces exponentially.

Based on curve fitting studies performed on the depicted graphs of Figs. 8 and 9, it can be concluded that the following relation exists between the amplitude of output sensor and amplitude of input force:

$$\Delta V = 0.8\exp^{(-0.037\omega)}\Delta F \tag{3}$$

where ΔF is the amplitude of input force in Newton and ΔV is the amplitude of output sensor in millivolt. ω is the frequency of input/output force/voltage in Hertz.

4.2. *Response to periodic triangle loads*

A triangle load with magnitude of 100 N and time period of 0.2 s was applied to the fabricated sensor. The output voltage of the sensor has been shown in Fig. 10. It can be seen that the shape of output voltage is similar to the shape of applied dynamic load. The relationship between the magnitude of periodic triangle force and the magnitude of output sensor has been investigated in Fig. 11. Similar to the sinusoidal loads, variations of the magnitude of the input force against the magnitude of output sensor is linear.

The response of the fabricated sensor to another triangle load with magnitude of 500 N and time period of 0.1 s has been investigated in Fig. 12. It is seen that the sensor voltage in the shape is almost identical to the input force.

4.3. *Response to periodic rectangular loads*

In this subsection, the response of the fiber-cement-piezoelectric sensor to periodic rectangular forces has been investigated. The response of sensor to the rectangular forces with mean values 350 N and 450 N is shown in Fig. 13. In this figure, the time period of input force is 0.5 s. The time history of sensor voltage for a rectangular force with mean value 300 N

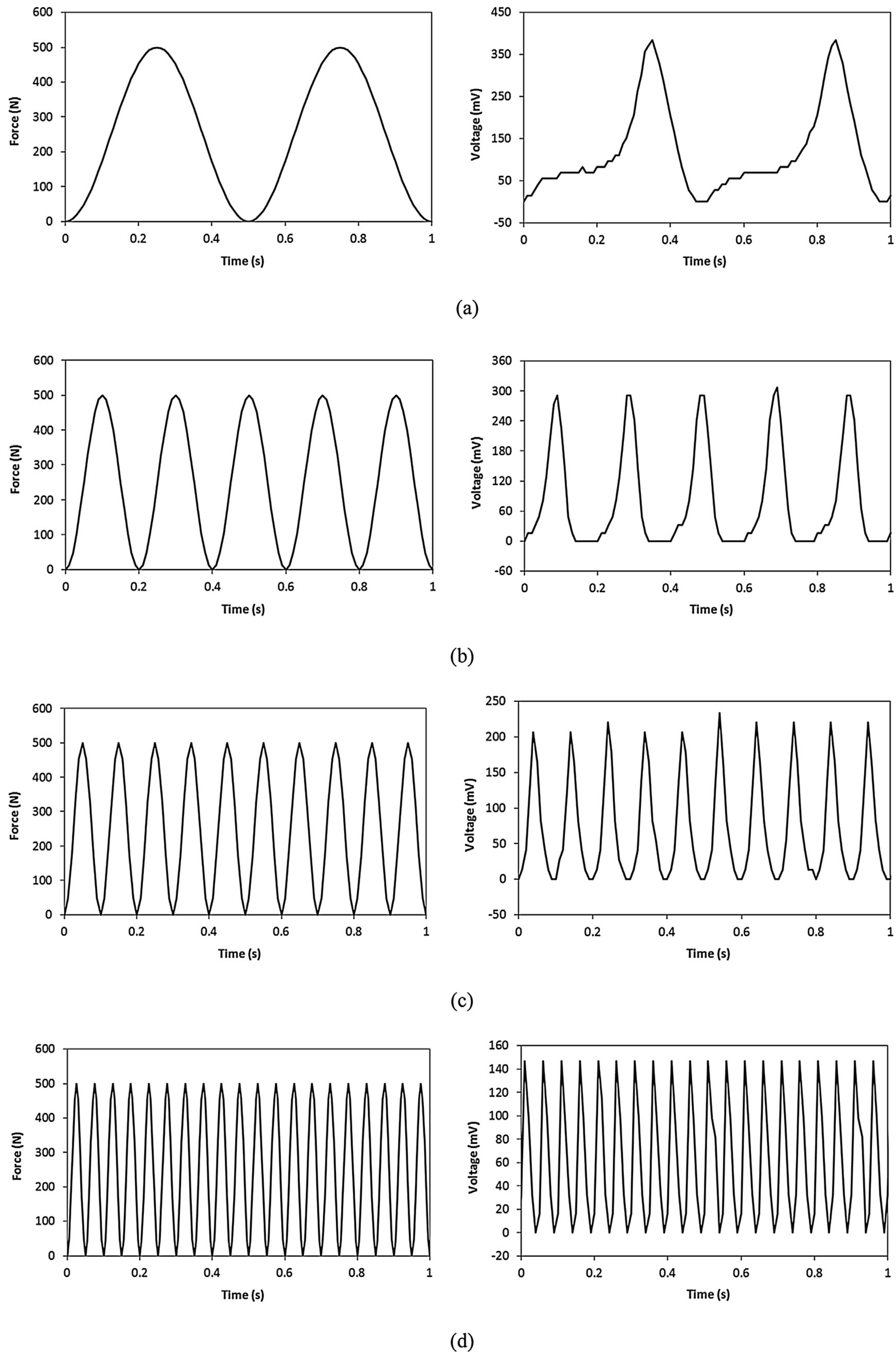


Fig. 7 – Response of sensor to the sinusoidal forces with different frequencies: (a) 2 Hz, (b) 5 Hz, (c) 10 Hz, and (d) 20 Hz.

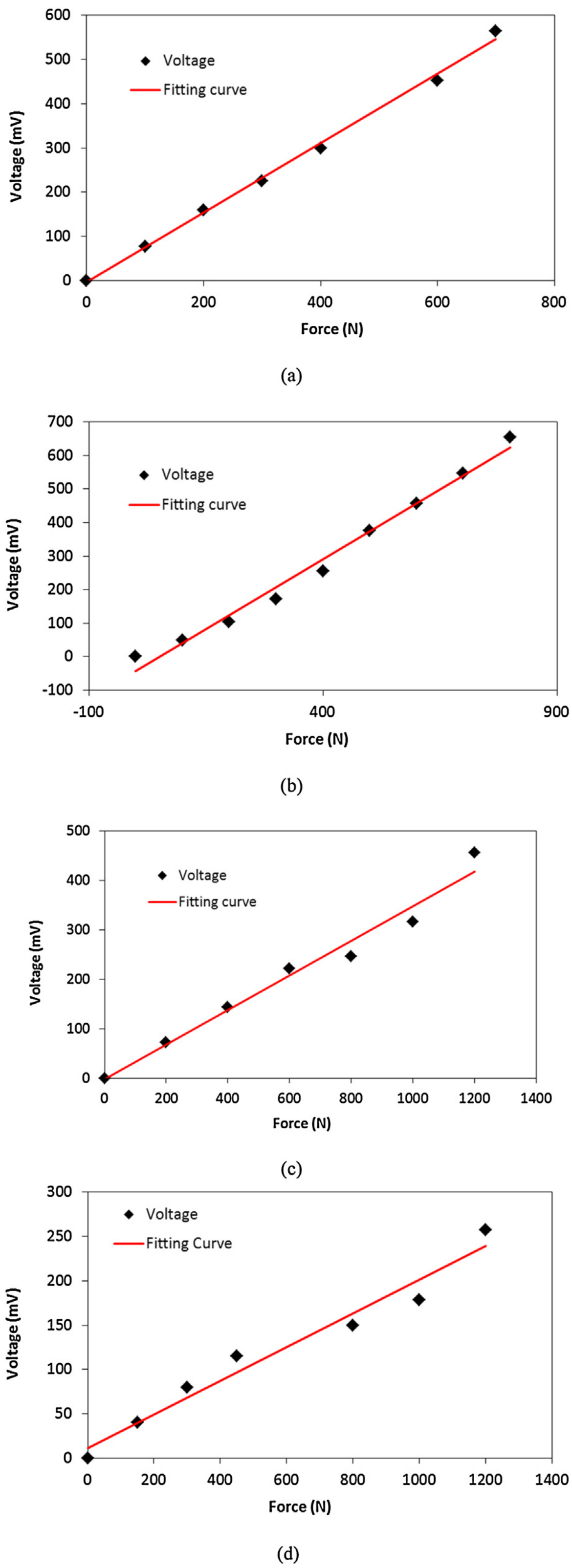


Fig. 8 – Amplitude of input force versus the amplitude of output sensor: (a) 0.5 Hz, (b) 5 Hz, (c) 20 Hz, and (d) 40 Hz.

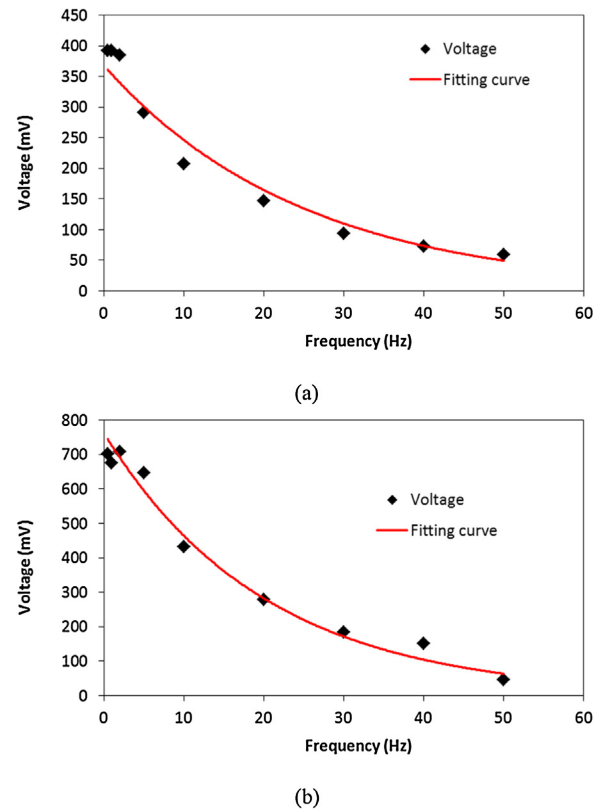


Fig. 9 – Amplitude of output sensor versus frequency of input force: (a) 500 N and (b) 800 N.

and the time period of 0.2 s is also shown in Fig. 14. It can be observed from Figs. 13 and 14 that the shape of sensor output is almost identical to the shape of input force. The error of servo-hydraulic test machine in applying the actual pattern of mechanical load to the fabricated sensor as well as the phase shift of PZT materials due to piezoelectric effect may be the causes of the small discrepancy between the pattern of applied load of and measured voltage.

4.4. *Response to complex dynamic loads*

The concrete structure during their service time may experience the earthquake loads which have random nature. In order to evaluate the reliability of the fabricated sensor in a realistic earthquake condition, it was exposure to a random mechanical force. Fig. 15 shows the random load and the output of the fabricated sensor. It can be seen that the sensor output corresponded very well to the input random forces.

These obtained results prove the efficiency of the fabricated fiber-cement-piezoelectric sensor for usage in health monitoring of concrete structures.

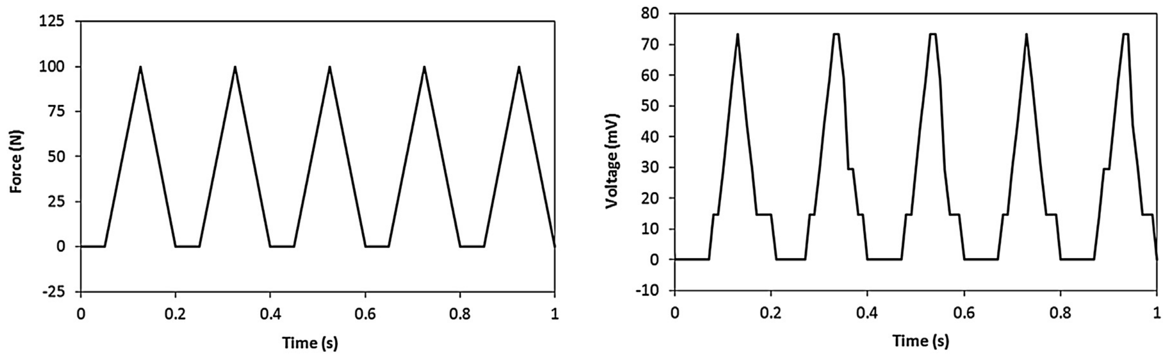


Fig. 10 – Response of sensor to the periodical triangle load-*T* = 0.2 s.

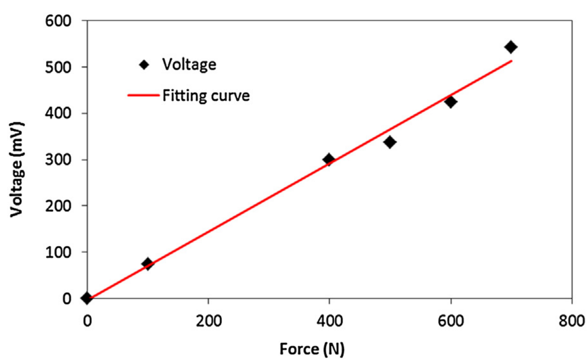


Fig. 11 – Magnitude of periodic triangle force versus the magnitude of output sensor.

5. Conclusions

By pouring a cement-resin-fiber composite matrix into a set of prearranged circular piezoelectric elements connected in series together, a new sensor was fabricated for the measurement of stress in concrete structures. The performance and reliability of the fabricated sensor in response to the dynamic loads with different load patterns was investigated through experimental tests. The experimental results show that the fabricated sensor has high measurement accuracy over a wide range of frequencies. It shows a linear relationship between the output voltage and applied mechanical load in the range of the vibrating frequency of the common concrete structures (0.5–50 Hz). The fabricated sensor has high sensitivity and can generate strong output voltage. Compared to other available types of sensors, the fabrication of the proposed sensor is low-cost and does not require special technology. High compressive strength, waterproof characteristic, high tensile strength, electrical stability, good compatibility and matching with concrete, high durability, ease of construction and installation are other advantages of the proposed sensor.

Future works are toward the structural health monitoring of the large scale concrete buildings using the presented fiber-cement-piezoelectric composite sensor.

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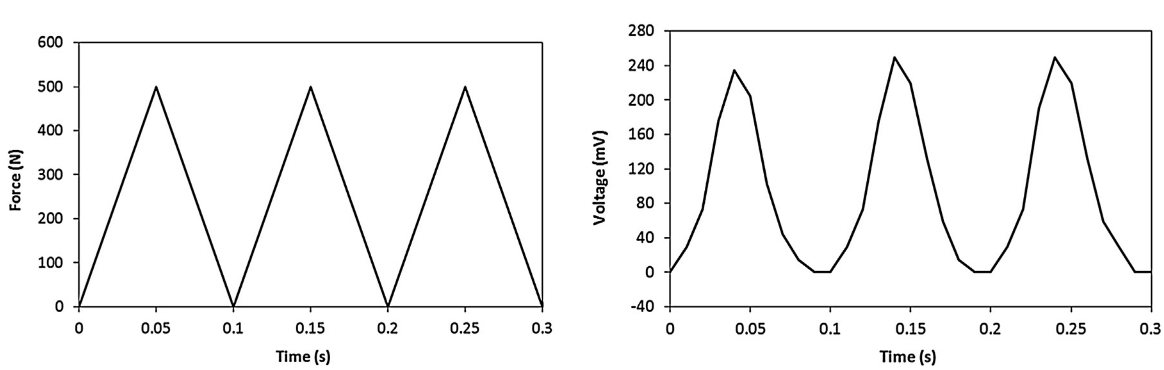
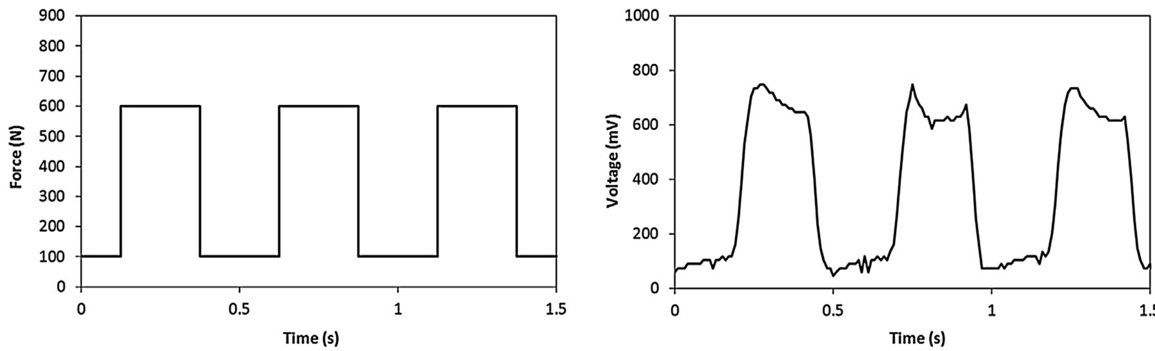
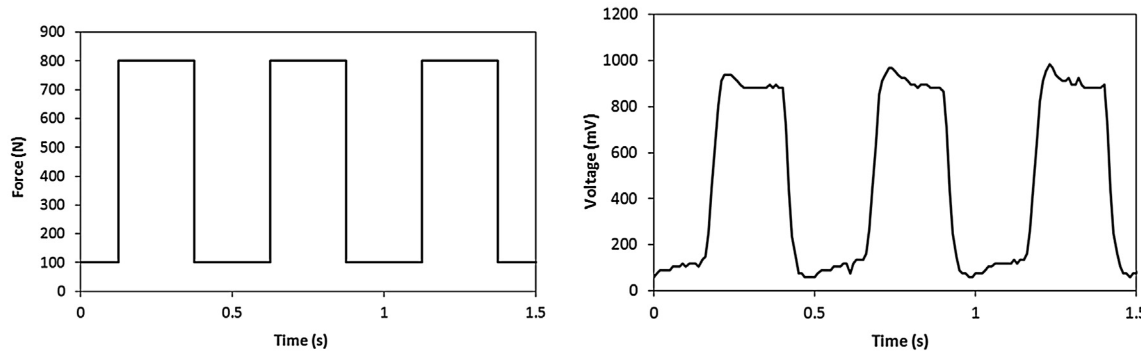


Fig. 12 – Response of sensor to the periodical triangle load-*T* = 0.1 s.



(a)



(b)

Fig. 13 – Response of sensor to the periodical rectangular loads-*T* = 0.5 s.

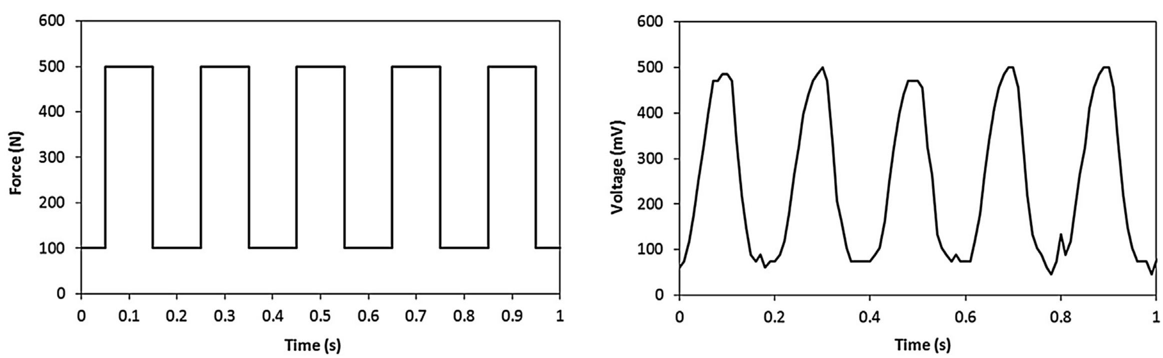


Fig. 14 – Response of sensor to the periodical rectangular load-*T* = 0.2 s.

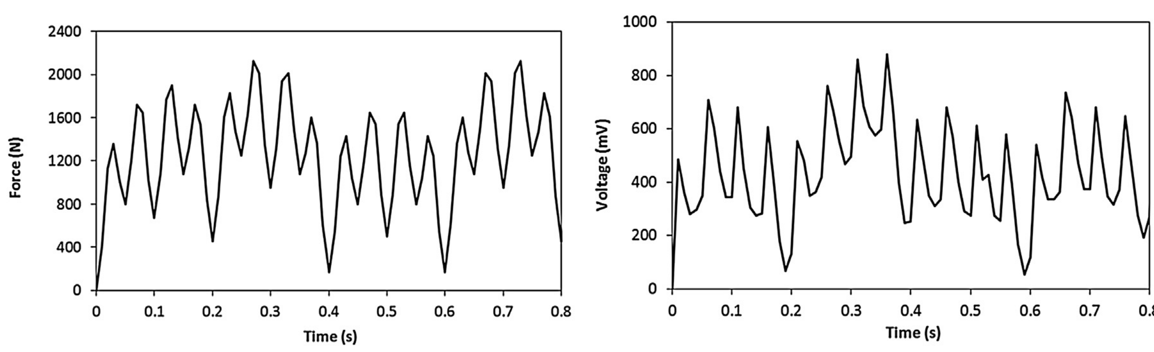


Fig. 15 – Response of sensor to the random load.

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