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Structural Health Monitoring Using Sensors with Application of Wavelet Analysis

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Abstract. Structural Health Monitoring (SHM) establishes a damage detection system to maintain safety in the current structure. Owners and maintenance managers are looking for cost-effective and dependable inspection and monitoring solutions to ensure the safety and reliability of capital-intensive assets. A longer overhaul time is envisaged with today's software technology and design codes. The visualization aims to put advanced technology into practice to provide consumers and the government with value-added services. Meanwhile, the wavelet transforms, a signal processing technique based on a windowing approach using enlarged 'scaled' and shifted wavelets, is being applied in various industries. By bypassing many of the restrictions of the Fourier transform (FT), the wavelet transform has proven to be effective in SHM systems. Structures tend to get damaged in situations such as accidental fire, aggregate contraction, salinity exposure, corrosion due to bacterial influence, physical and material damage. Also, structures tend to lose their tensile strength when exposed to long-term factors such as moisture, heat, rains, storms, etc. Structural Health Management plays a vital role here to monitor the health conditions of structures to prevent any loss. To stand up for this need, it is imminent to provide a safe structure for people to ply through. The proposed methodology shows a clear picture of how to assess any structure condition at any time and gives a clear view of its current stature on whether it is damaged. Hence in this article, the behavior of the structure is assessed using wavelet transformation. The hardware configurations, including the MSP430FR6989 microcontroller with TDC1000-TDC7200EVM, are embedded with the aggregate, making it smart enough to detect the defects through the software interpretation with a signal processing toolbox of MATLAB coding.

Introduction

In recent past decades, concrete has been used as the foremost construction material. In contrast, the worsening or weakening of these concrete structures is said to be unavoidable due to the atmospheric and external climatic features [1]. Cementitious composite [2–4] similar to soil [5–7] can change its properties when there is a modification in constituents of materials. Many innovations are brought in the infrastructure in materials [8–10] as well as structures [11–13]. But the damage to concrete structures is inevitable. The methodology described here monitors the health of concrete structures and paves the way for detecting the imperfections in the tunnels, wind

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energy plants, pavements, aircraft structures, etc. The initial work has experimented with the concrete structure, which can be implemented in the above-mentioned areas based on feasibility.

The structures, including bridges, energy plants, pipelined architectures like water, gas, and oil pipelines, tunnels, rig wells, pavements, or others, are subjected to various factors that malfunction as the days pass on. The funds spent on the maintenance and repair is a vast sum that can be substituted by an innovative SHM approach with the help of the sensors and the signal processing techniques [14,15]. The flaws can be detected in the early stages, making it cost-effective and avoiding making it functionally obsolete. The idea of replacing routine-based maintenance with circumstance-based maintenance is the future of civil infrastructure, providing the following benefits: Uninterrupted observation, Automation, Facilitating the proactive response by identifying dent in an early stage, economic and feasible.

Structures tend to get damaged in climatical situations such as fire, aggregate expansion, sea water effects, bacterial corrosion, physical damage, and chemical damage. Also, structures tend to lose their tensile strength when exposed to long-term factors such as moisture, heat, rains, storms., etc. Structural Health Management plays a vital role here to monitor the health conditions of structures to prevent any loss [16]. To stand up for this need, it is imminent to provide a safe structure for people to ply through. This is done as the product assesses any structure condition at any time and gives a clear view of its current stature on whether it is damaged.

The research article describes the various conventionally used non-destructive techniques for the health monitoring of structures. In this work, the specimen of concrete was baked in the laboratory. It was embedded with a few electronic modules like MSP430FR6989 with inbuilt ultrasonic sensor to check its strength using the continuous wavelet transform resulting from signal processing. The irregularities in the output waveforms characterize the internal flaws in the concrete material.

Traditional Non-destructive methodologies of Health monitoring:

The non-destructive testing of concrete has been in use for a few decades past. It is said to be the influential tool for monitoring or assessing the concrete in terms of strength, durability, longevity, and structure quality. This method is used to know the cracks in terms of depth and severity, deformations, and even the micro defects that can be identified. The traditional non-destructive health monitoring methodologies include surface hardness detection, rebound test, penetration, pull-out techniques, combined test, dynamic test or vibration testing, radioactive or nuclear methodology, Magnetic and electric method, acoustic emission technique, etc.

The material characteristics can be better understood by performing the non-destructive tests on the various scale for assessing the parameters like electrical characteristics, material absorbency, scattering, the transmission of waves like Gamma-rays and X-rays, acoustic waves, ability to transmit and receive ultrasonic signals inform of pulse velocity thereby determining the moisture density and thickness. As shown in Fig. 1, many non-destructive techniques are available for the health monitoring of concrete structures. To elaborate on a few of these tests before entering into the details of the proposed methodology is listed as follows:

Surface hardness test: The concrete strength is a replication of its age; hence it can be tested by traditional methodologies like William’s pistol test and the various hammer tests. This helps us calculate the strengths of concrete, but it requires a variety of equipment and manpower to derive at the estimation.

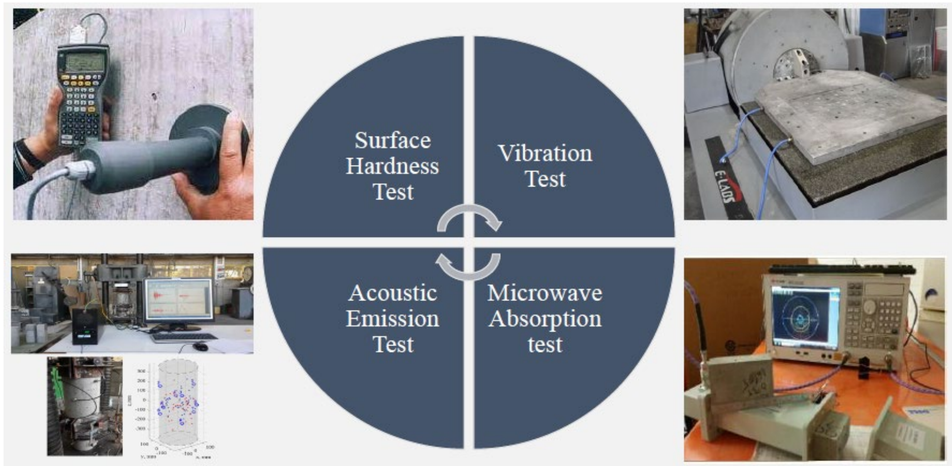

Fig. 1. Traditional Non-destructive methodologies of Health monitoring

Dynamic test or vibration testing: Under this category, a list of parameters could be analyzed like resonant frequency, ultrasonic signals inform of pulse velocity, and mechanical nature of sound waves. This helps in determining the lifespan, homogenous nature, and elasticity property of the concrete material.

Acoustic Emission test: Acoustic sensors play a vital role in performing this test. These sensors are embedded onto the concrete and checked for the reception of the same by applying force. If no deformation occurs, the original and the retrieved signals will be a replica.

Microwave absorption test: The electrical and magnetic tests are performed to know the concrete material's moisture and thickness. Microwave absorption is one such credential for performing the above characteristic.

Proposed methodology

The methodology proposed for the SHM can be termed as an innovative means to assess the health of any structure in concrete materials [17–19]. The work involved in the composite development and health monitoring is shown in Fig. 2. The methodology has an overall workflow where the work progressed from casting a specimen as per the standard norms of IS10262:2009 with fine aggregate, coarse aggregate, and cement. The concrete structures are baked and then tested with the hardware comprising of MSP430FR6989 microcontroller and TDC1000-TDC7200EVM, which has a built-in ultrasonic sensor module for the PWM generation and analysis. The signal interpretation was followed by the above-mentioned process, thereby detecting the flaws in the concrete.

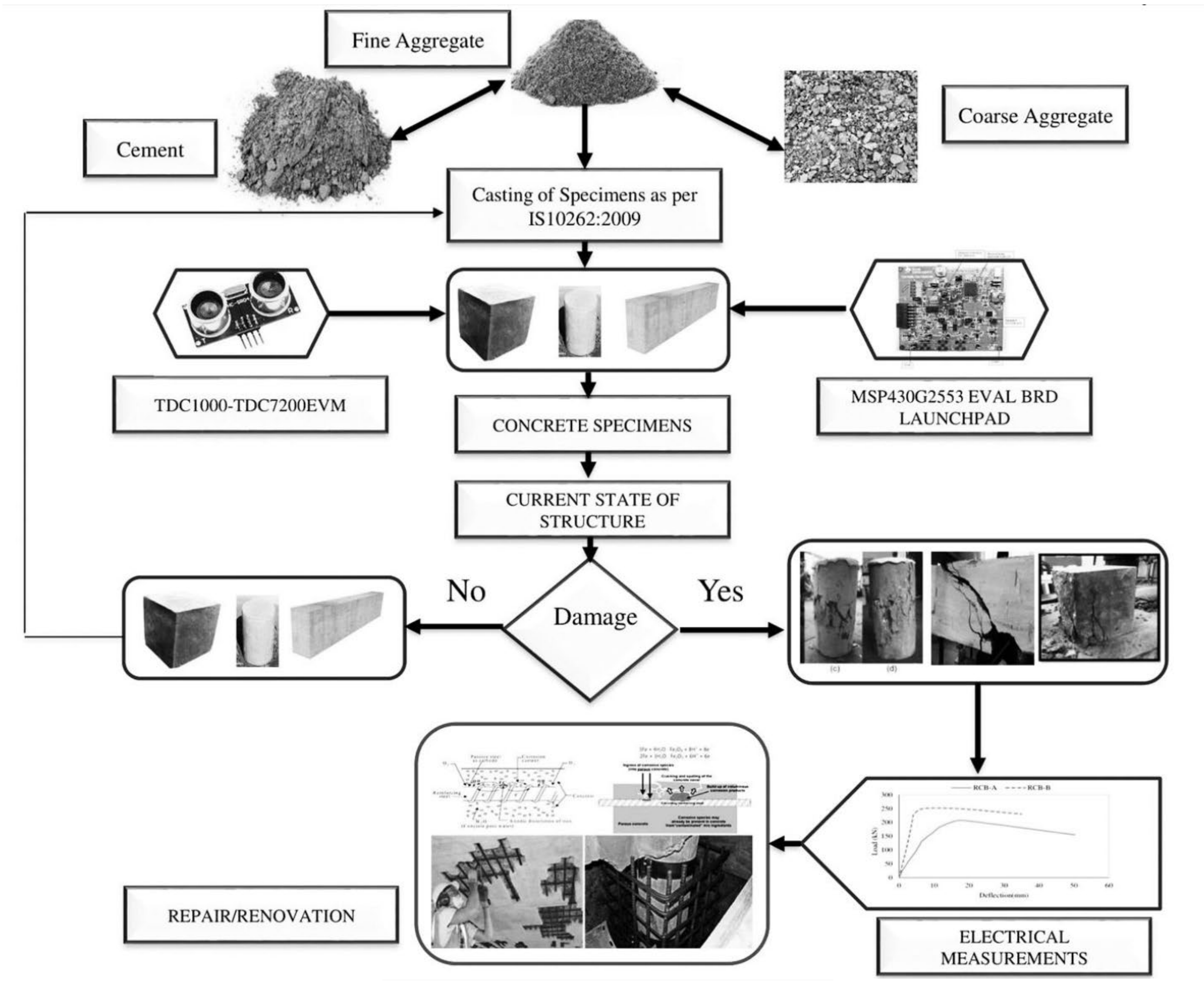

Fig. 2. Proposed flowchart for SHM

Sensor components for SHM

MSP430FR6989: It is a launchpad kit that is under evaluation mode by the Texas instruments. The benefit of the toolkit is it consumes ultra-low power comprising of FRAM, which can act as a real-time emulator for varying dynamic scenarios of atmospheric and climatic conditions. It also features a 320 segment LCD display. The FRAM and non-volatile memory can ensure high access speed and good endurance, so the replacement of hardware requirements will be minimal [20].

TDC1000-TDC7200EVM: TDC1000 is an ultrasonic wave generator with Time-of-Flight applications acting as an analog ultrasonic device that is functional up to 4MHz frequency. TDC7200 is a digital converter of time used to measure the time elapse and can function as a stopwatch device [21]. The TDC 1000 provides a complete wireless ultrasonic sensing solution.

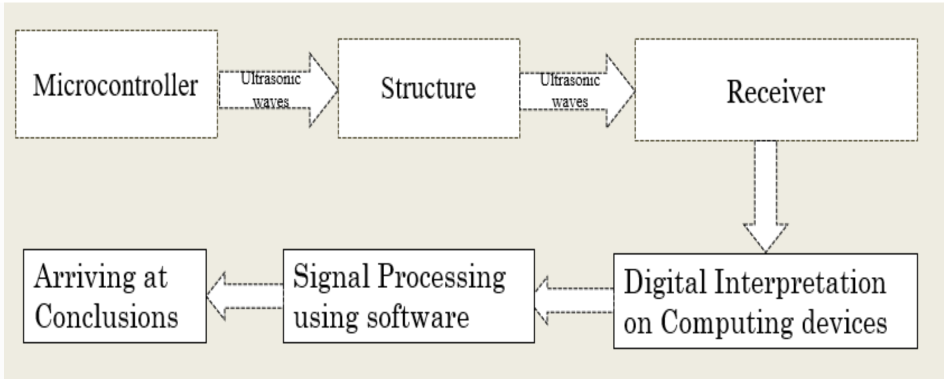

Fig. 3. The layout of innovative Structure

As shown in Fig. 3, the concept behind the ultrasonic wave is the piezoelectricity which is produced by the vibration of quartz crystal. The piezoelectric strain sensors help generate strong voltage signals without requiring intermediate devices like gauges, bridges, amplification modules, and conditioning units [22]. This can provide a significant result in terms of vibration and dynamic means. The piezoelectric equations are expressed as the strain and electric displacement in terms of applied stress, electric field, and temperature using the constitutive tensile factor as shown in equation (1) and equation (2).

$$S_{ij} = s^{D}_{ijkl}T_{kl} + g_{ikl}\,D_k + \delta_{ij}\,\alpha_i^{D\theta} \quad (1)$$

$$E_i = -\,g_{ikl}T_{kl} + \beta^{T}_{ik}\,D_k + \breve{E}_{i\theta} \quad (2)$$

Where g_{ikl} is the piezoelectric voltage coefficient

β^{T}_{ik} is the impermittivity coefficient.

$\breve{E}_i$ is the pyroelectric voltage coefficient

The above equation is called the sensor equation, which predicts how much electric field, i.e., voltage per unit thickness, is generated by "squeezing" the piezoelectric material. Fig. 4 and Fig. 5 depict the coding for ultrasonic wave generation using pulse width modulation and reception of the same, respectively.

```
const byte ANTENNA = 9;

void setup()
  {
  // set up Timer 1
  TCCR1A = bit (COM1A0);  // toggle OC1A on Compare Match
  TCCR1B = bit (WGM12) | bit (CS10);   // CTC, no prescaler
  OCR1A =  9;       // compare A register value to 10 (zero relative)
  }  // end of setup

void loop()
  {
  pinMode (ANTENNA, OUTPUT);
  delay (500);
  pinMode (ANTENNA, INPUT);
  delay (300);
  }  // end of loop
```

Fig. 4. Ultrasonic Waves production using pulse-width modulation

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```
const int pingPin = 7; // Trigger Pin of Ultrasonic Sensor
const int echoPin = 6; // Echo Pin of Ultrasonic Sensor

void setup() {
   Serial.begin(9600); // Starting Serial Terminal
}

void loop() {
   long duration, inches, cm;
   pinMode(pingPin, OUTPUT);
   digitalWrite(pingPin, LOW);
   delayMicroseconds(2);
   digitalWrite(pingPin, HIGH);
   delayMicroseconds(10);
   digitalWrite(pingPin, LOW);
   pinMode(echoPin, INPUT);
   duration = pulseIn(echoPin, HIGH);
   inches = microsecondsToInches(duration);
   cm = microsecondsToCentimeters(duration);
   Serial.print(inches);
   Serial.print("in, ");
   Serial.print(cm);
   Serial.print("cm");
   Serial.println();
   delay(100);
}

long microsecondsToInches(long microseconds) {
   return microseconds / 74 / 2;
}

long microsecondsToCentimeters(long microseconds) {
   return microseconds / 29 / 2;
}
```

Fig. 5. Receiving Module Reception of Waves in Ultrasonic sensor

Structure: The work initially commenced with a laboratory-baked concrete cube of dimensions 150mm x 150mm x 150 mm (length x breadth x width). The cube is fully baked with mortar and cement. This is considered as a test structure, and the initial testing was run on it.

Receiver module: The Values obtained from the MSP430FR6989 controller were interpreted using MATLAB, and later the plot was done and analyzed. The digital interpretation and the signal processing modules go hand in hand under the receiver module, resulting in a conclusion of measured results.

The codes for producing the ultrasonic waves and their corresponding reception are shown below. In the transmitter end, the output and the input pin are given a delay of 500µsec, thereby avoiding interference. The PINs 6 and 7 are activated in the reception module to felicitate the trigger mode and echo signal.

Signal Processing: This is carried out by the MATLAB and the signal processing toolbox. The Wavelet transform function is used to plot the data received from the structures used for testing.

Wavelet Transform for SHM

The issue with Fourier transforms, specifically, the FFT is that it can change a signal of the entire signal length. The signal acquired and decomposed cannot give the information related to the time of their occurrence of the transient state. The DFT lags in time resolution but has a good frequency resolution. If DFT is used, the damage detection will be based only on the frequency domain analysis, and the time analysis will be lost. If this is the case, then the vibration signal will not be considered, leading to the loss of all-time related information. Hence a wavelet-based analysis was taken for experimentation purposes. Fig. 6 (a) – (d) shows the various wavelet types based on time frequency response.

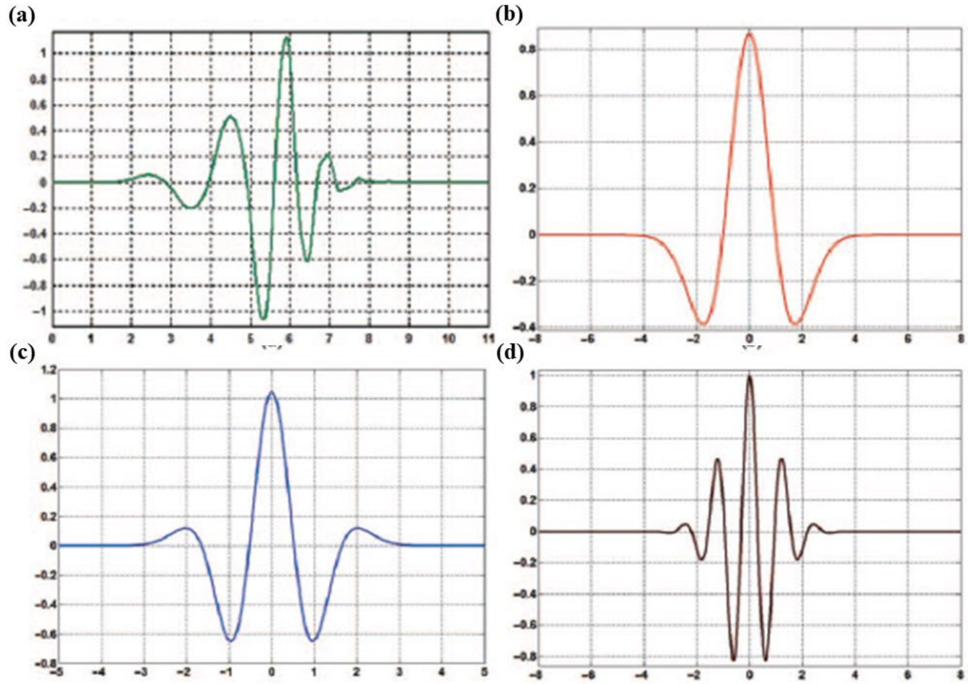

Fig. 6. Example representation of some mother wavelets (a) Daubechies wavelet (b) Mexican hat wavelet (c) Gaussian wavelet (d) Morlet wavelet [23]

The main difference between them is CWT uses an infinite number of scales and locations while the DWT uses only a finite set of scales and locations. Equation (3) represents the continuous wavelet transform (CWT), and equation (4) represents the discrete wavelet transform (DWT) is given below.

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi \frac{(t-b)}{a} dt \tag{3}$$

$$T_{m,n} = \int_{-\infty}^{\infty} x(t) \psi_{m,n}(t)\, dt \tag{4}$$

Besides the hardware module and data reception from the microcontroller, data analysis plays a vital role in this proposed work. The main objective is to analyze the wavelets bypassing the ultrasonic wave in a proper and damaged structure and compare them and conclude their deformations with the help of wavelet transform. The below diagram represents the comparison of waveforms when passed through an appropriate and defective structure. The waveform with inadequate structure has undergone an extreme level of stress and strain. The model represents that the waveform passing through a proper structure can be reproduced harmonically. In contrast, Fig.7 (b) on the right side depicts that the waveforms are lagging in harmony and the original waveform cannot be replicated, indicating a level of deformation.

The structure was subjected to heavy mechanical stress under the influence of specific mechanical instruments held in laboratory use. For every particular unit of stress applied to the structure, there was a certain amount of deformity. Each step was monitored digitally and on a continuous time pattern by using the sensor and the controller. The analysis of undamaged and damaged signals to be obtained is shown in graphical means as shown in Fig 7 (a) and (b).

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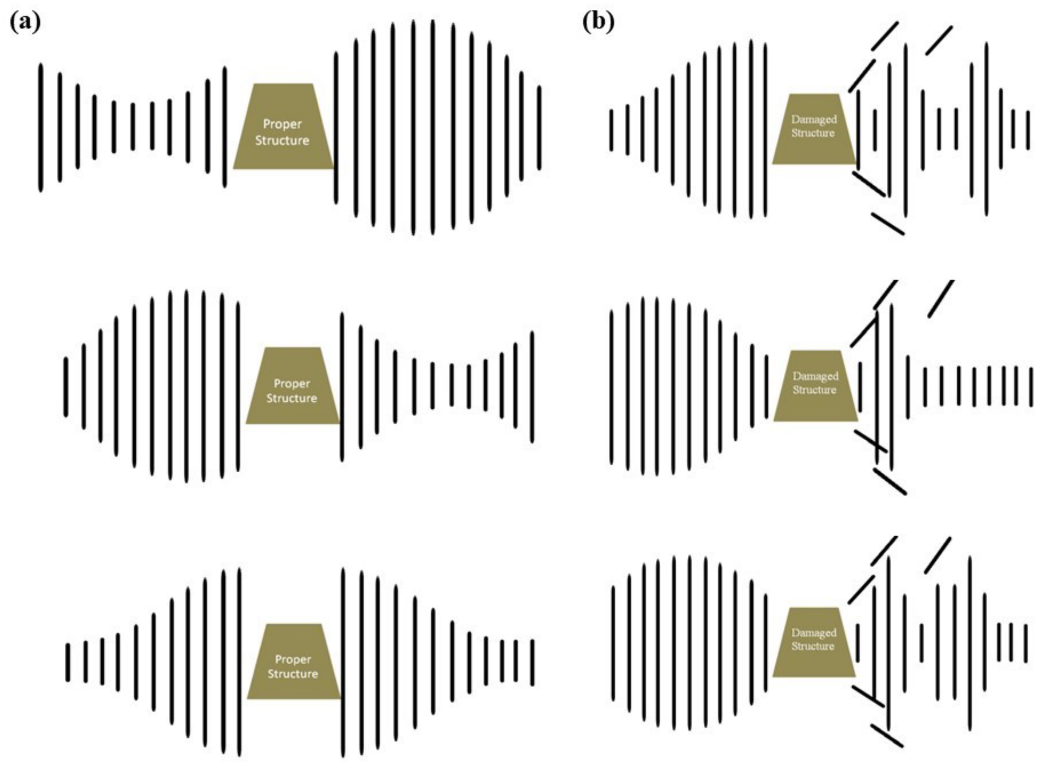

Fig. 7. Signal passing through (a) undamaged structure and (b) deformed structure

The values obtained from the MSP430FR6989 controller after passing the ultrasonic wave through a cube baked in the laboratory as shown in the below Fig. 8 (a) and (b) (damaged and undamaged respectively) is retrieved in the excel sheet is then plotted with the wavelet transformation function (DCT) to obtain the plot as shown in Fig. 9 (a) and (b). The test structure was baked with the dimension of 150mm x 150mm x 150 mm and then applied pressure under the mechanical conditions to undergo deformation; hence the test results can be compared and analyzed.

Fig. 8. Concrete specimens (a) before damage and (b) after damage

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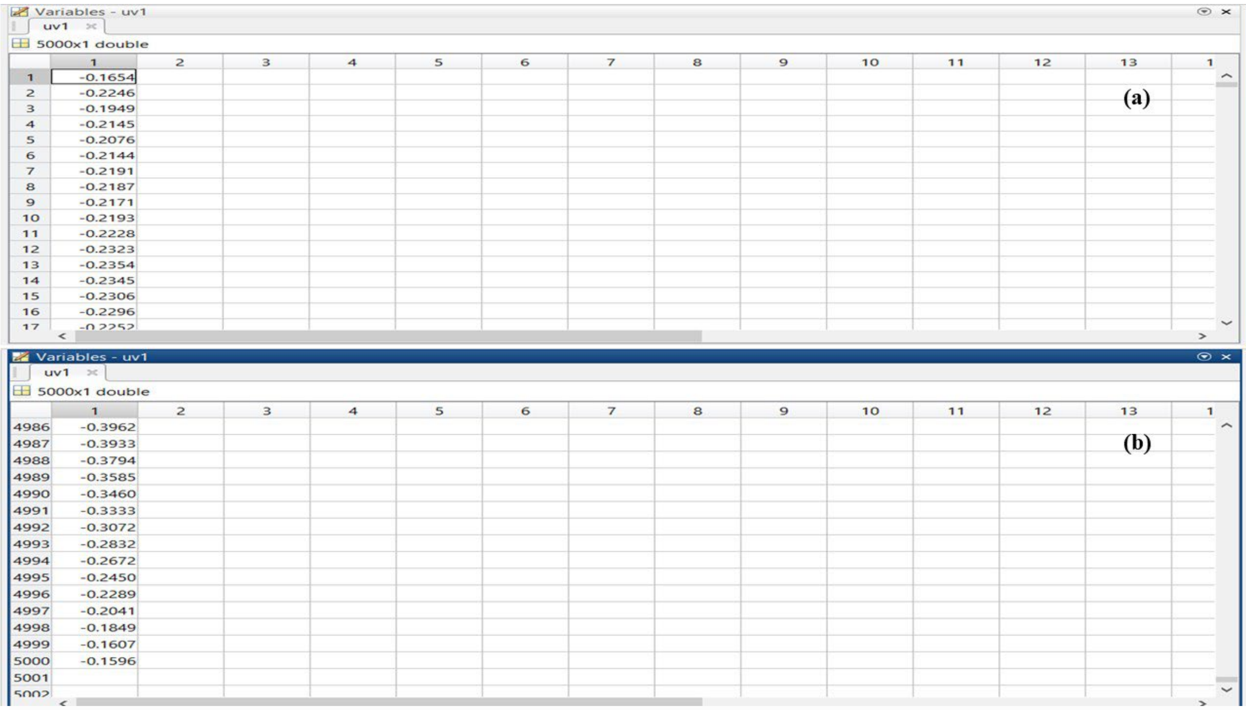

Fig. 9. Wave values interpreted for 150mm x 150mm x 150 mm structure (a) before damage and (b) after damage

The wave readings interpret time and voltage along the x and y-axis, as shown in Fig.10. Fig.10 (a) has a constant spike value of wavelets ranging from 0.8V to -0.2V depicting the outcome from the ultrasonic reception where the cube was in a proper shape (as shown in the test structure a), and Fig.10 (b) depicts the wavelets after passing through an irregular cube as shown in the test structure b in Fig. 8 (b). The latter influences noise signals which degrade the wavelets with irregular spikes so as to mention the deformation. These resultant wavelets are scaled and shifted versions of the mother wavelets

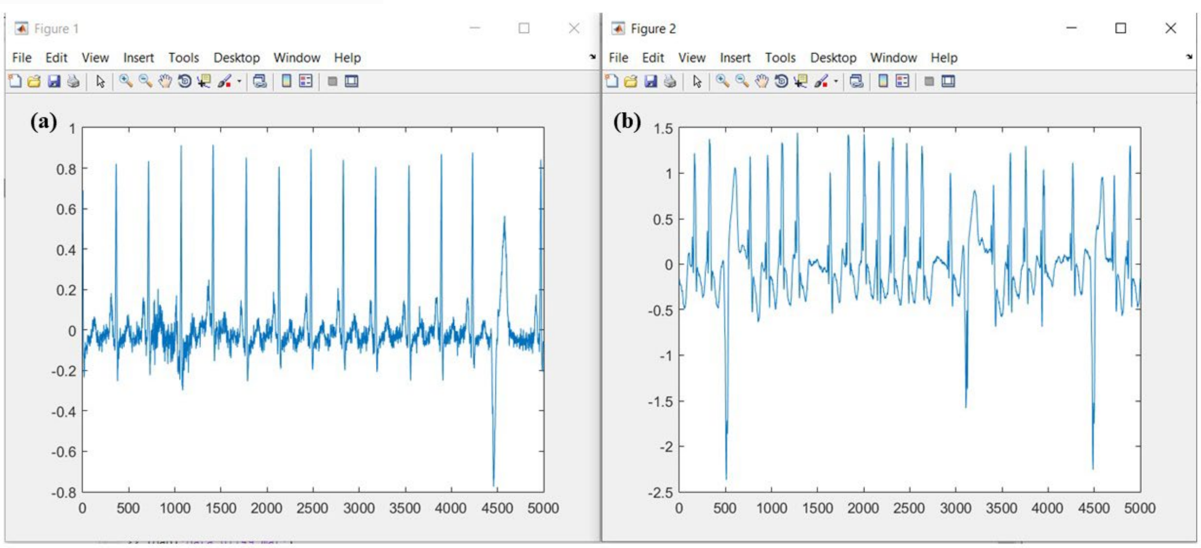

Fig. 10. The wave readings of the cube (a) before deformation and (b) after the deformation

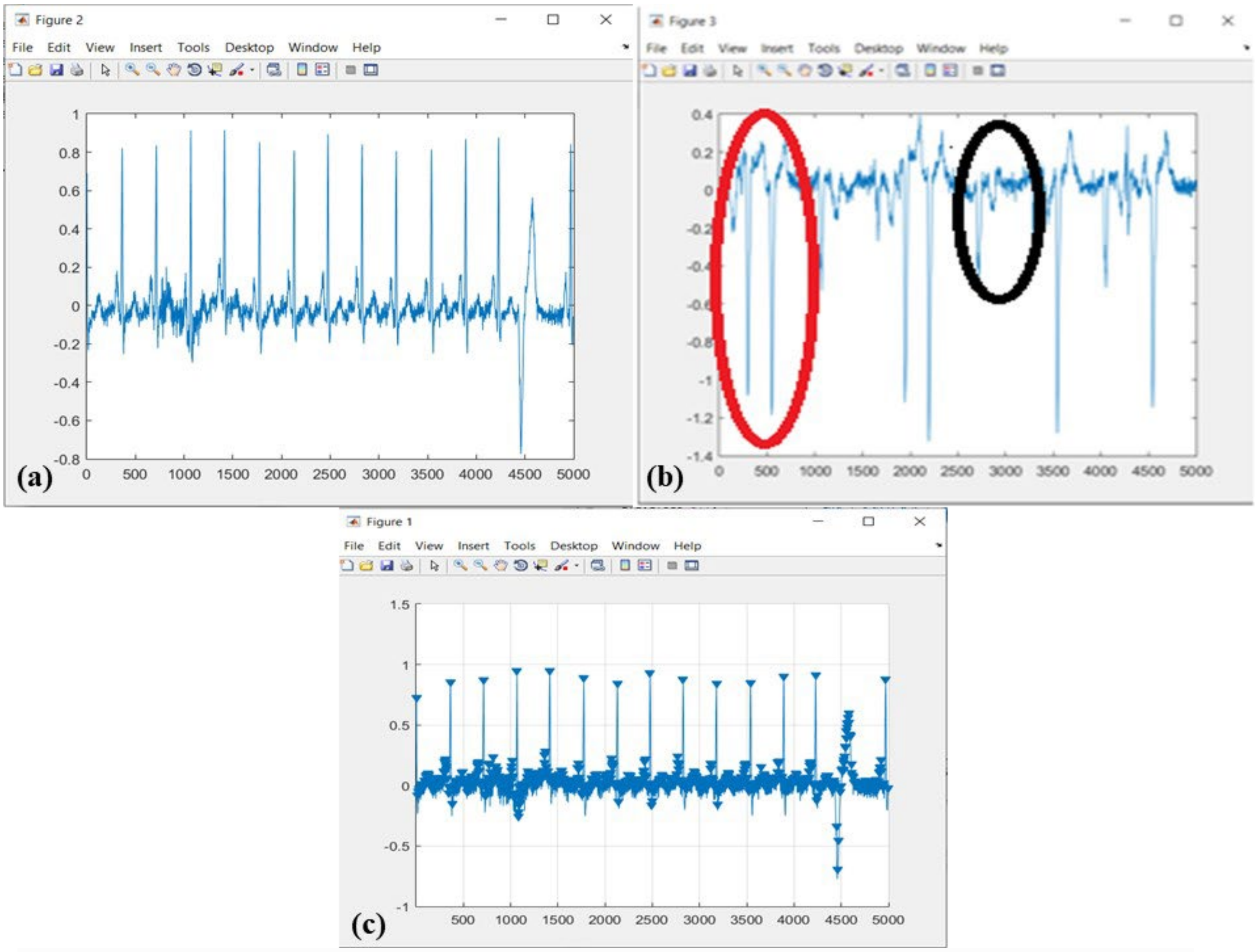

Fig. 11. (a) Wavelet of the normal cube, (b) Wavelet of the wrecked cube, and (c) After wavelet analysis

The wavelet functions are used to detect events like anomalies, change points, and transients. They extend their application with de-noising and data compression. Along with Wavelets, many other multi-scale techniques can be used to analyze data at different times and frequency resolutions, thereby decomposing them into various functional components. The dimensional features can be reduced, and extracting the discrimination features can also be performed. Fig. 11 (a) shows the wavelet of the normal cube. In Fig.11 (b), the wavelets represented in the red and black markings cannot be reproduced by using a definite function: the influence of noise in them, which indirectly shows the deformation or cracks in the concrete structures. The same experimentation was done in a 200 mm thick solid wall in our college premises which has given the result as shown in Fig.12 (a) and (b). Fig.12 (a) has a proper wavelet resulting in a healthy structure, whereas Fig 12(b) represents a wall with minor cracks and flaws.

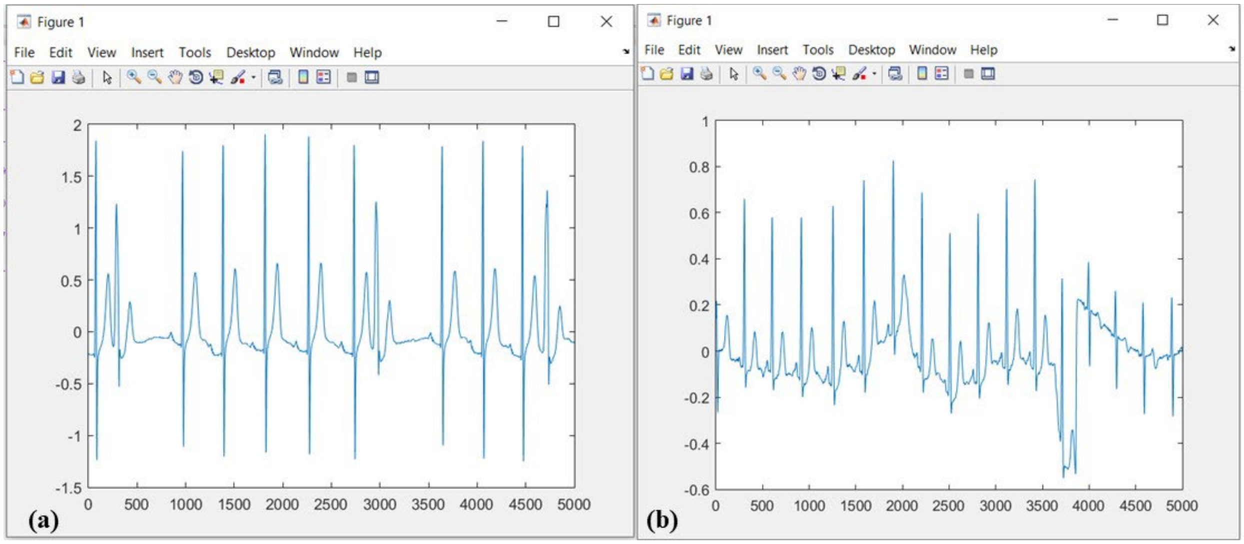

Fig. 12. Waveform of a 200 mm thick solid wall (a) without visible cracks and (b) with visible cracks

Conclusion and future scope

The waveforms of the test structure (the cube) taken before and after the impact of applying a force under laboratory conditions were tested. The wall with the defect was also tested, and the results were obtained. The waveforms have significant differences between them. From this, it can easily be proven that the structure has undergone severe skeptical damages that may not be shown to the human eye but can be easily portrayed. The Piezo-electric concept, instead of the traditional vibration method, is cost-effective. Signal processing gives more accurate and reliable results and consumes less energy. This work can also be further developed to monitor the signal in continuous means for a more extended period, and the toolkit protection has also to be ensured.

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