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Development and Implementation of Portable Ultrasonic Sensor Circuit with USB Interface and Signal Processing to Detect Damages in the Mild Steel Structure

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Abstract

Mild steel is one of the widely used structures for commercial use. In this paper, we present a PZT-based portable ultrasonic wave interfacing circuit with a USB interface to detect the damages in the mild steel structure. The designed circuit amplifies and shifts the level of the ultrasonic waves. The wave is then digitized by the microcontroller with a sampling rate of 2 MHz. The digitized wave is then transferred to the PC via USB communication. The CDC class was used in USB communication to generate a virtual com port and capture the data in real-time. The wave was then filtered and processed in the PC to detect damage to the structure. The dimension and weight of the used mild steel are 570mm x 205mm x 10mm and 10 kg respectively. To detect the damage to the structure, the 200 kHz tone-burst signal was induced in it through the PZT actuator. The ultrasonic wave was then captured in both intact and damaged conditions of the structure. The induced damage was of dimension 1mm x 10mm x 5mm. The RMS value of the captured wave in intact condition and the undamaged condition was calculated. This run-in of the RMS values in the intact and damaged condition of the structure solidifies the capability of the device to gather the ultrasonic wave correctly.

Introduction

Mild steel structures are one of the essential structures with crucial economic importance. They are widely used in pipelines, buildings, bridges, etc. However, due to aging, wear and tear, earthquakes, external loads, and other environmental factors, mild steel infrastructures are susceptible to deterioration over time. Stress loads and environmental conditions affect the structural properties and contribute to its degeneration [1~3].

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If not adequately monitored, this structural degeneration could result in catastrophic failure and significant incidents. It is now required to offer the greatest degree of quality and safety precautions to prevent such failures. Structural health monitoring with ultrasonic waves is one of the most widely used technologies to ensure the health of metallic structures including mild steel structures [2~6].

In recent years many researchers have inspected the practical usage of the ultrasonic wave for SHM systems. Frome [7], has successfully investigated and determined the sensitivity of the ultrasonic sensor to detect the damage by location and orientation of the defect in the structure. He has detailly monitored the incidence angle and defect size with the orientation of the sensor. Baptista [8] showed that the transducer loading and the increase in the cross-sectional area of the structure reduce the sensitivity of ultrasonic sensors to detect damage. Lee et. al. [9] have developed a time reversal process considering the temperature effect on the PZT self-diagnosis schemes.

In this paper, we present a sensor interface circuit for a mild steel structure of dimension 570mm x 205mm x 10mm. The iron structure weighs 10 kg. The sensor circuit described by Shrestha et. al. [9], doesn't consider the cross-sectional area and thickness of the structure. Although ultrasonic waves are relatively easy to use to determine the nature and size of defects, it is slightly challenging to implement them in mild steel as its heterogeneous structure and composite composition are known to be treated as highly attenuated materials to ultrasonic vibrations [10]. To tackle the signal attenuation, we have developed a two-phase amplifier with a voltage level shifting and clipping circuit. The amplifying circuit is based on an operational amplifier IC as it is small and has established itself as one of the most reliable IC for ultrasonic wave operations [11][12]. The first stage amplifier is a charge amplifier circuit and the second stage amplifier is a non-inverting amplifier circuit. The voltage level shifting along with the clipping circuit ensures that the voltage is in the range of the ADC of the microcontroller. The microcontroller digitizes the ultrasonic wave with its in-built ADC and DMA controller, then sends the data via an inbuilt USB 2.0 port. The usage of USB increases the data throughput more than that of traditional UART and wireless communication.

Overview

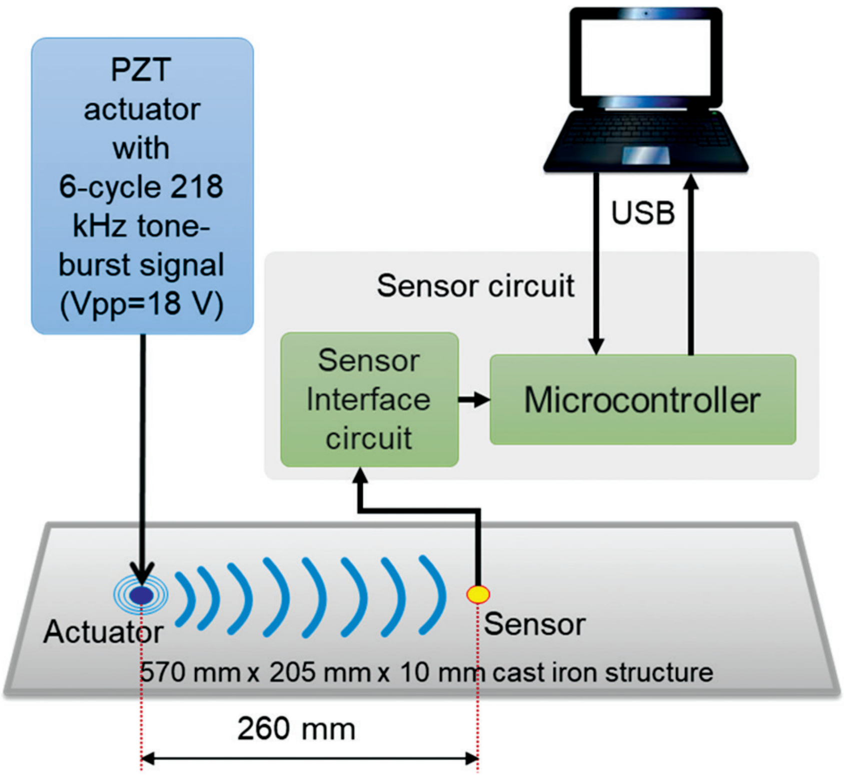


Figure 1: Overview of the system

Figure shows the overview of the sensing system. The system uses PZT actuator and PZT sensor. PZT actuator is actuated with 6 cycle, 218 kHz tone-burst signal with 18Vp-p. The PZT actuator then produces ultrasonic in the mild steel structure. This ultrasonic wave is then captured by the PZT sensor. The captured wave is then amplified and shifted via a sensor interface circuit. The wave is then digitized by the microcontroller with a sampling rate of 2 MHz. The digitized wave is then transmitted to the computer through USB communication. The wave is then processed in the PC to see if there is damage in the structure or not.

Specification	**Performance**
Power supply	15 V (DC)
Microcontroller	168 MHz, ADC: 10 bit, 2.5 MSPS, FPU
Sampling rate	2 MHz
Interface	USB

Development of sensor circuit

The sensor circuit mainly consists of two circuits: the sensor interface circuit, and the microcontroller. The sensor interface circuit consists of two amplifier circuits, a voltage level shifting circuit, and a voltage level shifting circuit. The gain of the amplifiers is set to 70 and 10 respectively. Due to the thickness of mild steel, the single amplifier couldn't amplify the signal to the required voltage level, hence a second amplifier was added to the circuit. The voltage level shifter ensures that the output signal from the circuit lies in the range of 0V to 3.3V. The microcontroller then digitizes the signal and sends it to the PC. The microcontroller used is stm32f407. It is a 32-bit ARM-cortex M4 microcontroller with built-in ADC, DMA controller, and USB communication support. The microcontroller samples the signal with a sampling rate of 2 MHz.To achieve this sampling rate, a DMA controller is used. The digitized wave is then stored in the internal buffer of the microcontroller. To communicate with the PC, the microcontroller uses USB communication. The CDC class of the USB is used in the firmware of the microcontroller for USB communication. When the USB pin of the microcontroller is connected to the computer, it creates a virtual com port in the PC. Any UART terminal software can be used to extract data.

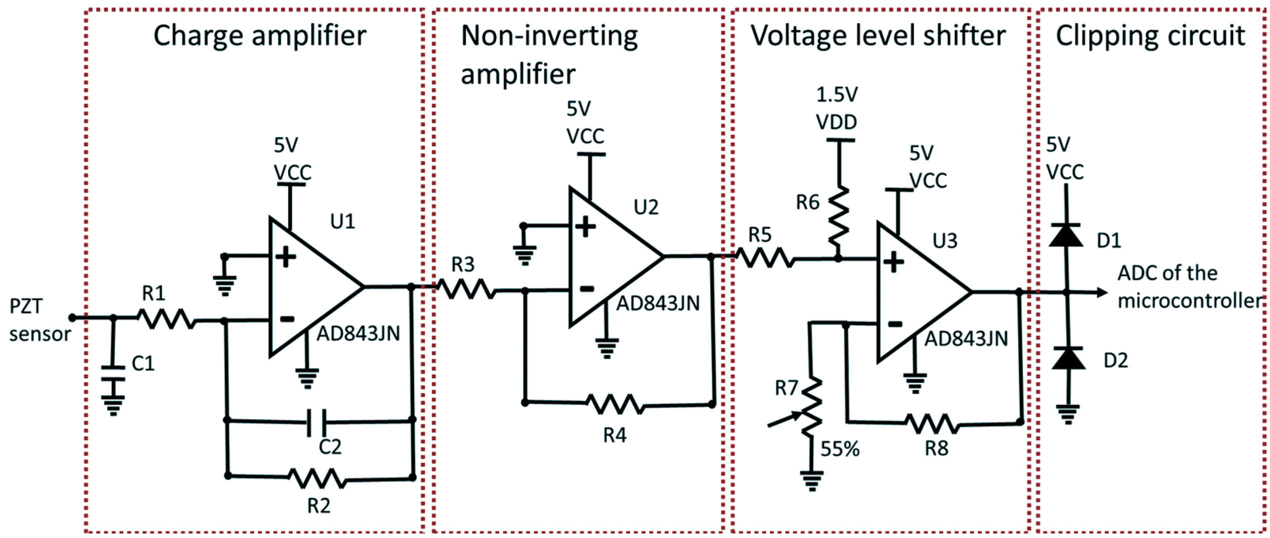


Figure 2: Overall circuit of the sensor interface circuit

Figure 2 shows the overall circuit diagram of the sensor interface circuit. To test the circuit, the PZT actuator was actuated with an 18 V 6-cycle 218 kHz tone-burst signal. The actuation signal and the ultrasonic wave after passing it through the sensor interface circuit are shown in the figure below.

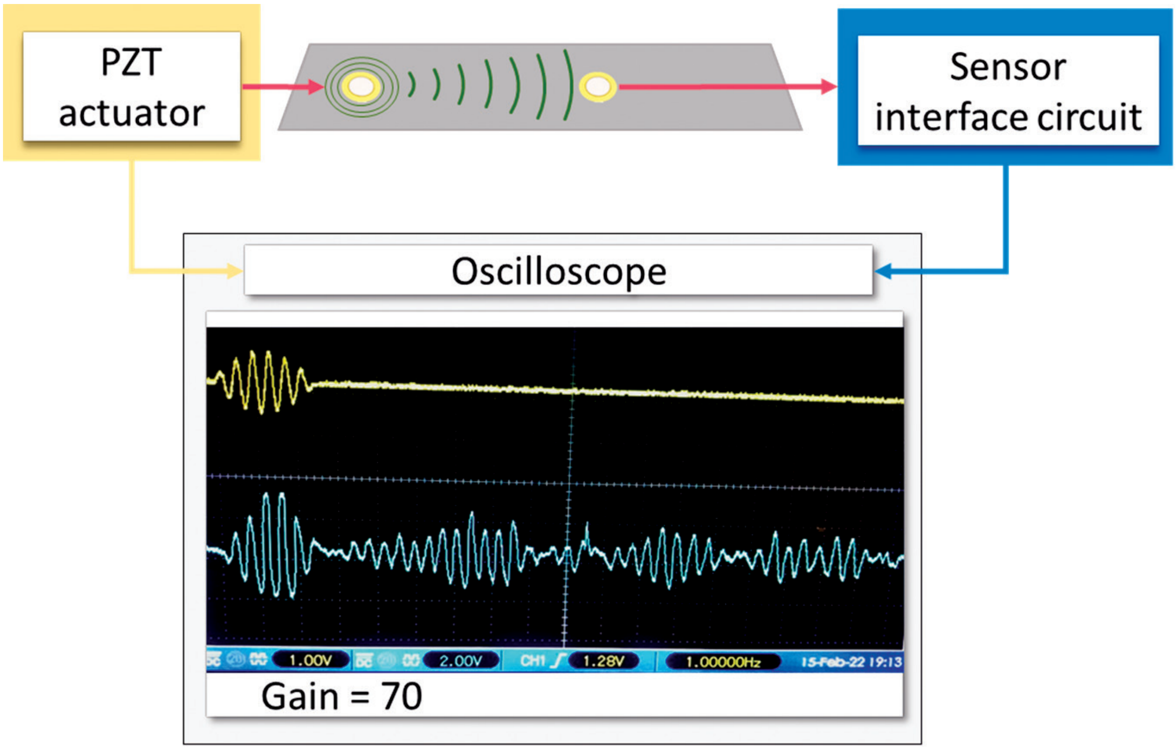
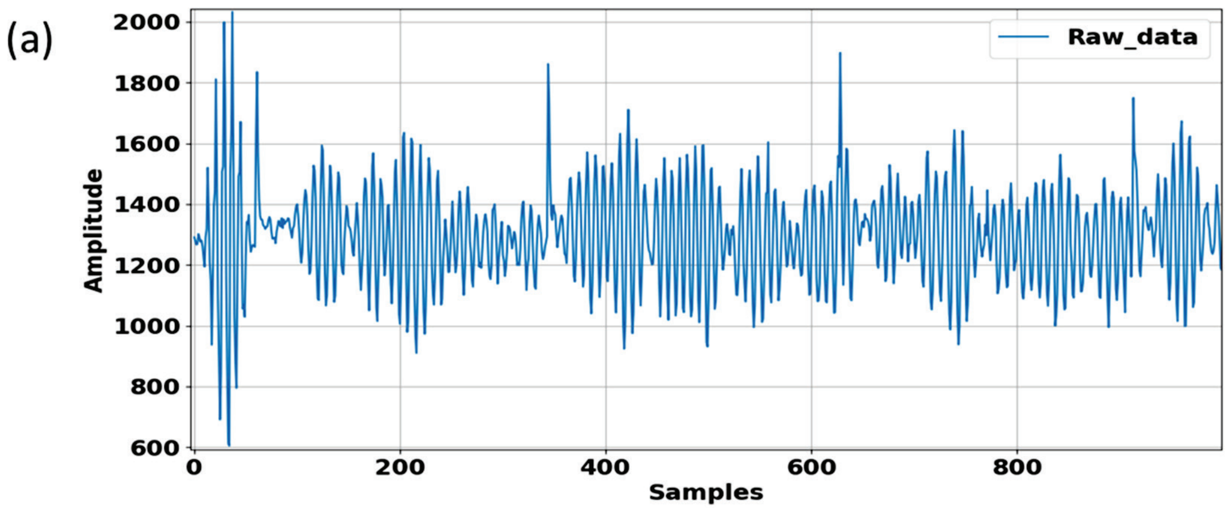
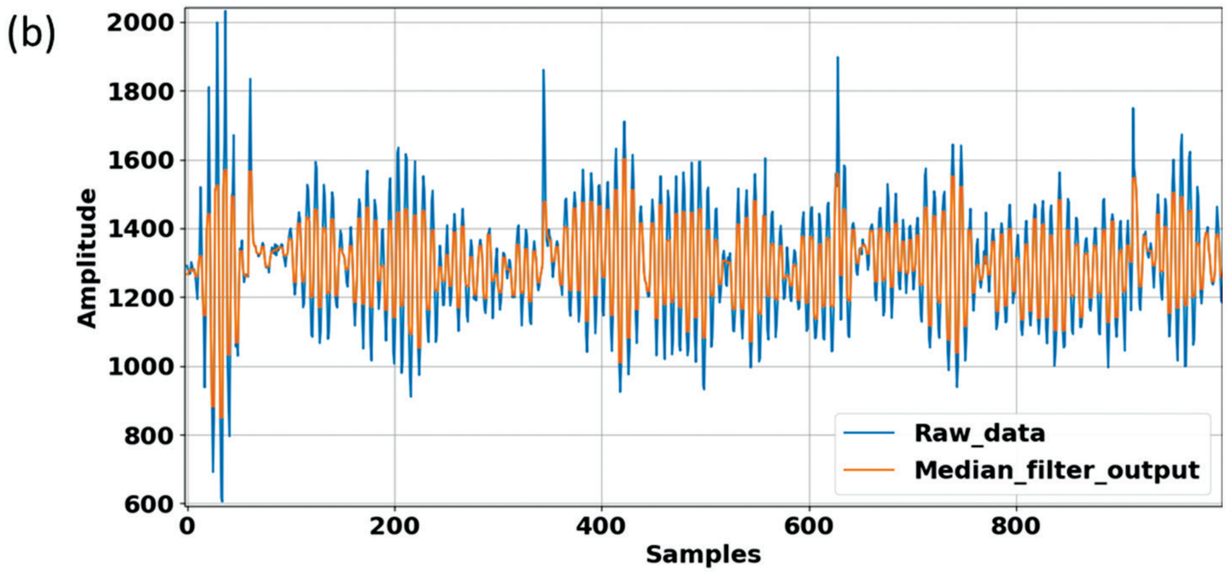


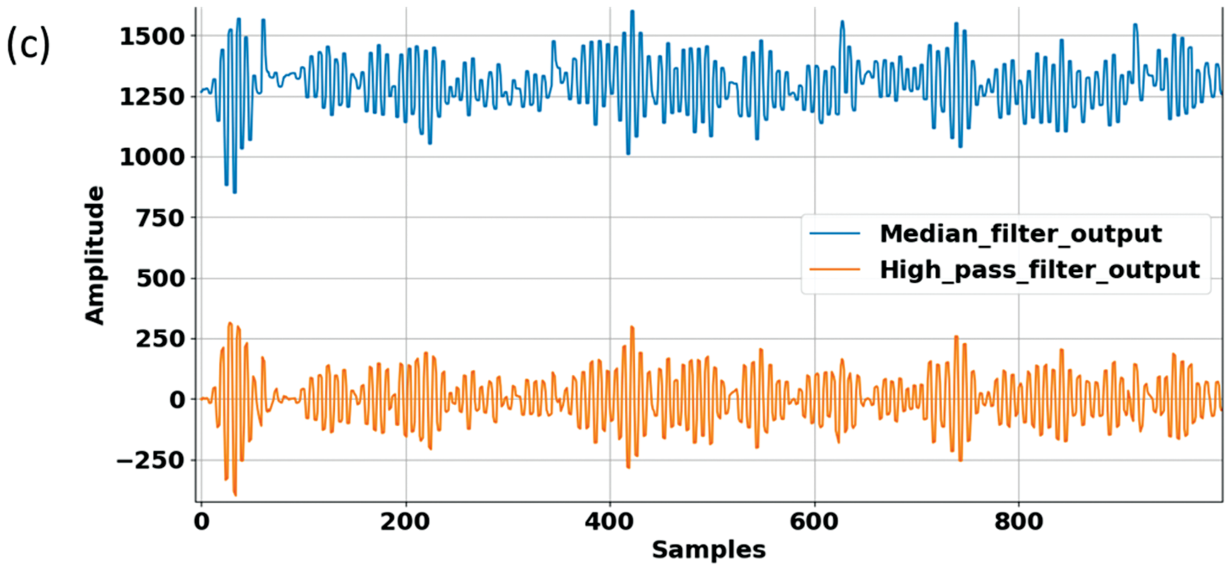
Figure 3: Testing of sensor interface circuit

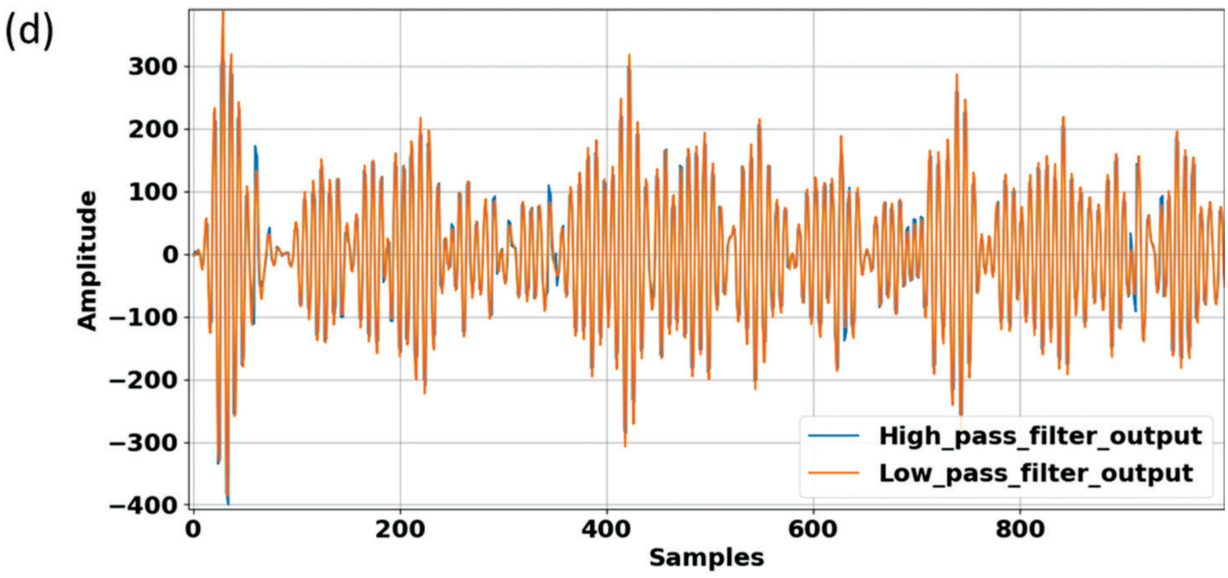
Signal processing in PC

The received ultrasonic wave is filtered and its RMS value is then calculated in the PC. The received ultrasonic wave had spikes, high-frequency noise, and low-frequency noise. To filter out the spikes, a median filter with a 5 window size was designed, to filter out high frequency, a low pass filter with a cut-off frequency of 300 kHz was designed, and to filter out the lower frequencies the Butterworth high pass filter with a cut-off frequency of 100 kHz was designed. The unfiltered and filtered signals are shown in figure 4.




(b)
Amplitude
Samples
Raw_data
Median_filter_output


(c)
Amplitude
Samples
Median_filter_output
High_pass_filter_output


(d)
Amplitude
Samples
High_pass_filter_output
Low_pass_filter_output

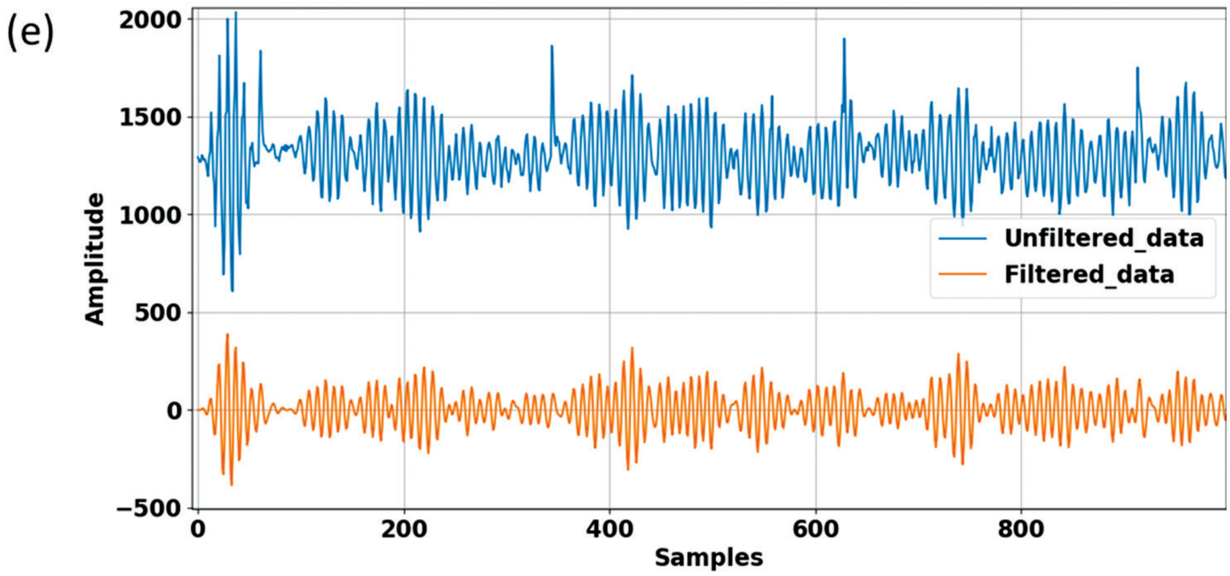
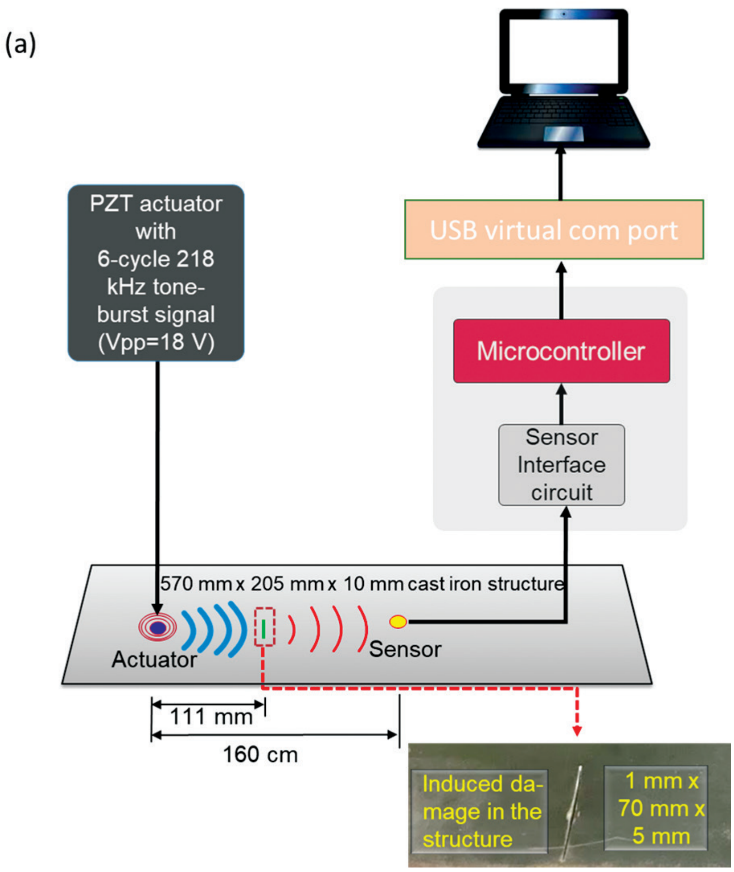


Figure 4: Unfiltered and filtered signals; (a) unfiltered raw signal; (b) Comparison between raw signal and median filter output; (c) Comparison between the signal from median filter output and high pass filter; (d) Comparison between the signal from high pass filter and low pass filter; (e) Comparison between unfiltered and filtered signal.

Testing of the sensor interface circuit for damage detection

To test the circuit, it was arranged as shown in figure 5.



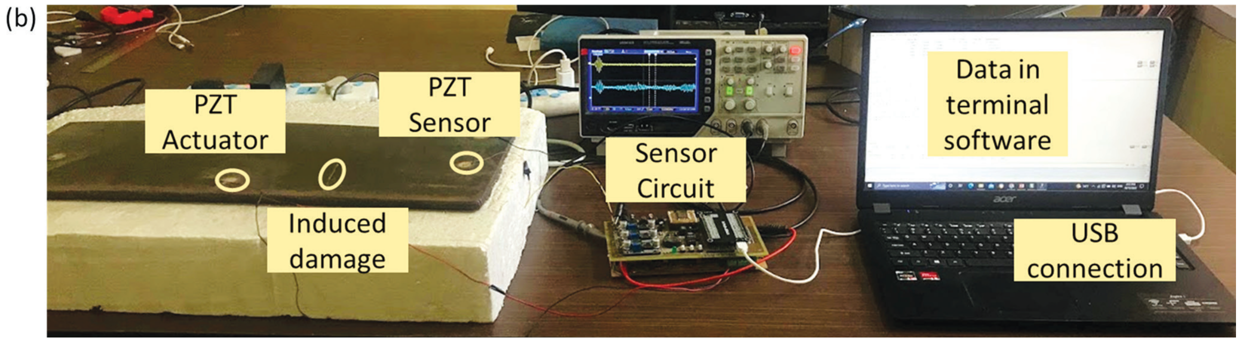


Figure 5: (a)Experimental setup configuration (b) Experimental setup

The actuation signal and ultrasonic waves are first observed in the oscilloscope. The wave is captured in the PC using the open source google terminal software. The Baud Rate on the terminal was set to 5000000. To test the integrity of the system, the ultrasonic wave was first captured in the intact condition of the structure, and then it was captured in the damaged condition of the structure. Both the waves were filtered and RMS was calculated. The figure 6 shows the wave comparison between two signals.

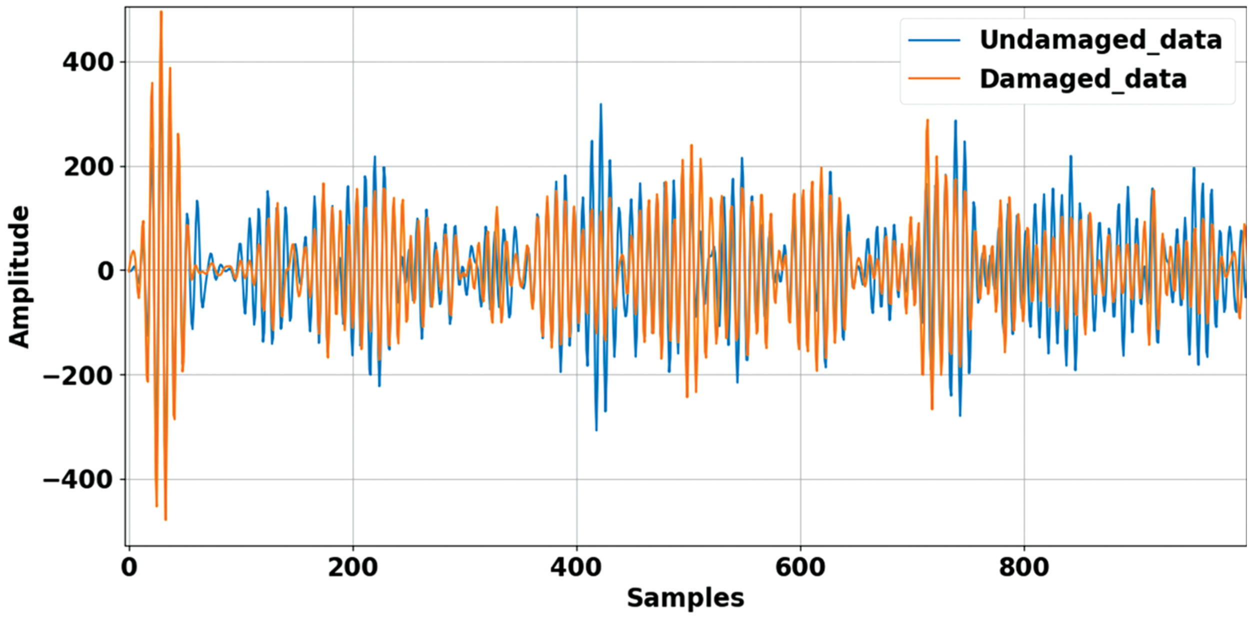


Figure 6: Comparison between damaged and undamaged ultrasonic wave

The calculated RMS value in the intact condition is 95, and in the damaged condition is 87. This difference in RMS value during impact and damaged condition shows the integrity of the system to detect damage in the system.

Conclusion

In conclusion, the ultrasonic wave can be used to detect a crack in the mild steel structure. By using a two-stage amplifier model, we get ultrasonic waves which can be evaluated to detect the damages in the structure. Furthermore, the median filter is a reliable filtering method to remove spikes from the ultrasonic wave. Similarly, Butterworth LPF and HPF are suitable to remove noise from the signal. The data throughput of the device can be increased significantly via USB communication. Although with the circuit configuration and filter designs damage can be detected, the main limitation of the device lies in the resolution of the device to detect the damage which is 5 mm depth in size.

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Conflict of interest

“Not declared by the author(s)”.

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