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Digital Ultrasonic Sensing Device with Programmable Frequency: Development and Analysis

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Abstract

Ultrasonic wave is widely used in Structure Health Monitoring (SHM) systems. A piezoelectric transducer (PZT) is one of the most widely used sensors to acquire the structure's ultrasonic wave. As today's world is digital, it isnecessary to digitize the traditional analog PZT sensing system. This paper describes the development and analysis of a digital ultrasonic sensing device (DUSD) for PZT sensors. We removed the complexities of the analog circuit by interfacing the microcontroller directly with the charge amplifier circuit. The microcontroller used in this research is a 32-bit ARM Cortex-M4 with in-built FPU (Floating Point Unit) and DSP (Digital signal processing) instructions. These features make it possible to compute complex signal processing algorithms and methods in the controller itself. The developed sensing device can communicate with the user and other devicesusing Universal Asynchronous Receiver/Transmitter (UART). The user can select cut-off frequencies of both high pass filters (HPF) and low pass filters (LPF) as well as types of data (ultrasonic waves, damage index) that the user wishes to collect from the device. To illustrate the proficiencies of the device, the ultrasonic wave was collected and evaluated to detect the damage in the test specimen.

Keywords: Ultrasonic wave, structure health monitoring, Digital ultrasonicsensing device, Programmable filter

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1. Introduction

Digital devices surround today's modern world.Many researchers worldwide are engaged to find out how to digitize the analog signal so that they can evaluate the data more precisely. Due to factors such as aging, fatigue, external loading, and other environmental parameters, the structures' health degrades day by day. Regular monitoring of the structures has become prominent to prevent unwanted accidents. It is well established that the ultrasonic wave is used to detect the damages in the structures[1~6]. The ultrasonic waves are elastic waves that can be generated and sensed by the PZTs. These waves can travel a relatively long distance and are sensitive to damage. Giurgiutiu [2] has compared and showed the reliability and limitations of the methods to detect the damages using ultrasonic waves.Ciampa et al. [14] have shown that wavelet transforms in the ultrasonic wave improve the signal-to-noise ratio.An operational amplifier is one of the most widely used interfacing circuits for PZT sensors [8][9]. The noise component of the piezoelectric transducer and accelerometer are well analyzed by Yanez et al. [10] and Levinson [11][12]. Hopkins [13] has compared different operation amplifiers used in the PZT sensor and concluded that the charge amplifier circuit gives the best noise performance.

Many researchers have digitized the ultrasonic wave in recent years and evaluated it to detect the damages in the structures [3~6]accurately. Heo et al. [3] developed smart monitoring with Transmission Control Protocol/ Internet Protocol (TCP/IP) network protocol over Bluetooth technology. Lynch J. P. et al. [5][6] developed the low-power wireless monitoring system and successfully detected the structure's damage. However, these devices send large numbers of raw data, which need to be further processed on the PC. Pertsch et al. [7]showed thestand-alone intelligent wireless device for continuous monitoring of the structure. However, the device uses an analog filter and does not have the option to select cut-off frequency. Guo et al. [16] has successfully shown the possibility of digitizing the sensor with microcontroller usage. However, the author uses the IC AD5933, a high precision impedance converter system with inbuilt digital signal processing capabilities. With a modern microcontroller, it is possible to exclude such IC and do the signal processing in the controller itself. Peipei et al. has used FPGA to collect wave from PZT sensor and compare the collected wave to detect the damage; however, the device only monitors impact and does not do signal processing and use of FPGA make the device expensive.

This paper discusses the development and analysis of digitalultrasonic sensing devices with embedded signal processing capabilities. The device used UART (Universal Asynchronous Receiver/Transmitter) to communicate with other data acquisition devices or personal computers.The device has an inbuilt digital filter with selectable cut-off frequencies. Digital filters are a type of filter that performs the filter process on discrete-time signals. The signal is sampled through the analog to digital converter (ADC), which can be then filtered by doing the mathematical operation on the data and the calculated filter coefficients. The selectable cut-off frequencies for HPF are 10 kHz and 100 kHz and for LPF are 200 kHz and 100 kHz. It can also calculate the damage index of the structures using an embedded algorithm for damage detection. The user can acquire either raw-unfiltered data, filtered data, or only damage index of the structure.

2. Materials and methods

2.1. Overview

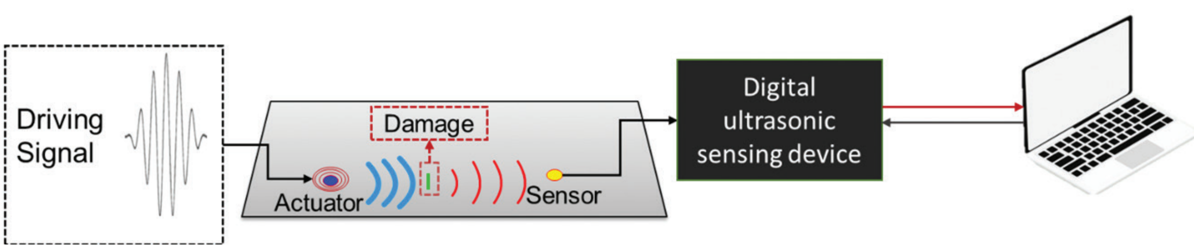


Figure 1: Overview of digital PZT sensing system

Figure 1 shows the overview of the DUSD. The digital ultrasonic sensing device captures the ultrasonic wave from the sensor. The device condition the signal according to the user's requirement. The device communicates with the user using UART.The user can collect either unfiltered or filtered ultrasonic waves or only damage index.

2.2. Development of digital PZT sensing system

Figure 2 shows the block diagram of the system. The device has a sensor interface circuit and microcontroller.

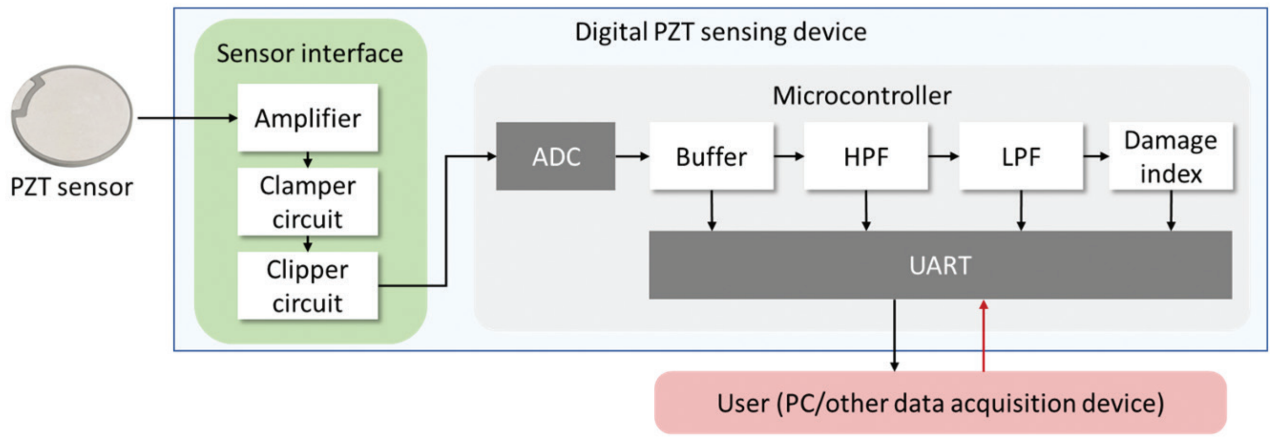


Figure 2: Block diagram

Table 1: Specification of DUSD

Specification	Performance
Power supply	15 V(DC)
Microcontroller	168 MHz, ADC: 10 bit, 2.5 MSPS, FPU
Sampling rate	20 KSPS to 2.5 MSPS
LPF	200 kHz, 100 kHz
HPF	10 kHz, 100 kHz
Interface	USB
Sensor	PZT (radius 1 cm)

2.2.1 Sensor interface circuit

The ultrasonic wave from the sensors is first passed through the sensor interface circuit. It amplifies and shifts the voltage level of the wave and passes it on to the ADC of the microcontroller. It consists of an amplifier, clamper and clipper circuit. The amplifier circuit used is a charge amplifier. A PZT sensor uses the piezoelectric effect to convert mechanical energy into electrical charge. Generally, the charge produced in response to mechanical force is relatively small. Although PZT does produce an output voltage proportional to the force, the voltage amplifier does not consider the cables' capacitance that connects the sensor to the circuit. Any source of capacitance that appears in parallel with the sensor will affect the relationship between the output voltage and applied force. To solve this problem, the charge amplifier is used in the circuit. The charge amplifier is a current integrator and has a very high input impedance. The integrator converts charge into voltage, and high input impedance ensures no loss of charge from the sensor through the leakage. The clamping circuit shifts the negative voltage to positive voltage as the ADC of the microcontroller can only detect voltage between 0V to 3.3V. The clipper circuit ensures that the input voltage is in the voltage range of the ADC of the microcontroller.

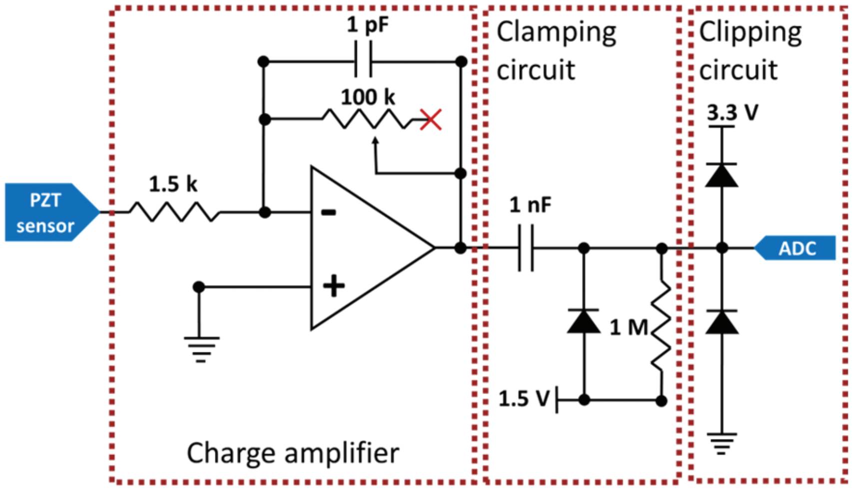


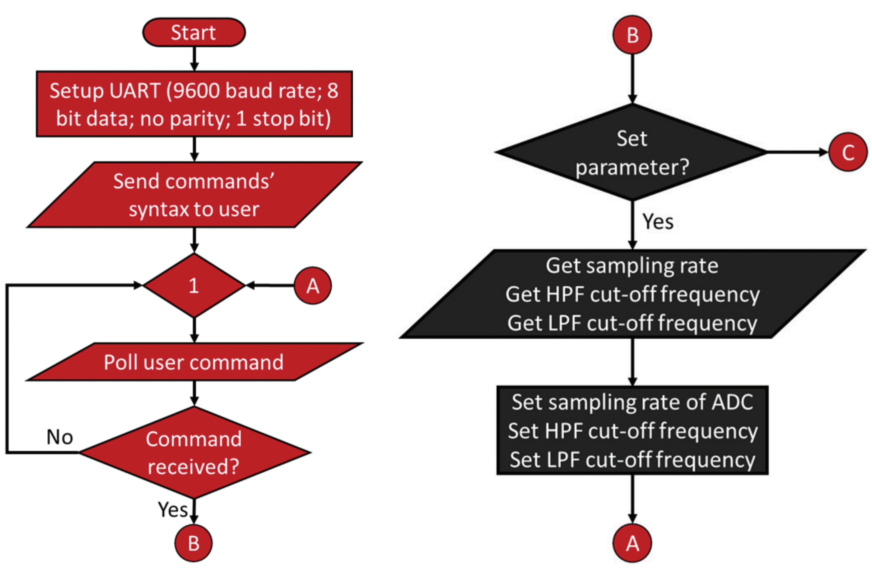
Figure 3: Sensor interface circuit

2.2.2 Microcontroller

The microcontroller used in this research has Arm 32-bit Cortex – M4 core processorwith FPU (Floating Point Unit). The controller supports DSP (Digital signal processing) instructions and supports many peripherals, including UART and ADC. These features make the controller ideal for the research. The firmware was developed to get the digitized data, signal processing on data, and communicate with the user accordingly. The firmware was written in the freeRTOS platform. Two tasks were created; 1) Signal process task to gather ultrasonic wave and 2) User communication task to communicate with the user through serial communication.

User communication task

The UART has beenused to communicate with the user. Using UART, the controller communicates with the PC as well as other data acquisition devices. The firmware is written to send information and data to the user and to parse the commands sent by the user. In freeRTOS, a separate task was created to handle user communication. The set of commands was created to communicate with the user. The flowchart of the task is shown in the figure below.



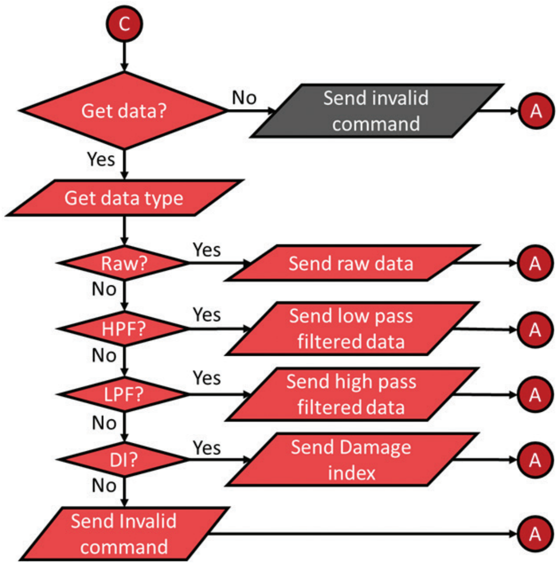


Figure 4: Flowchart of user communication task

Signal process task

The ADC of the microcontroller first digitizes the ultrasonic wave from the sensor interface circuit. The default sampling rate was ADC was set to 2.5 MSPS. The user can set the sampling rate of the ADC through the UART. The DMA controller was used to achieve the sampling rate of 2.5 MSPS. The data is then filtered through HPF and then LPF. Finally, the damage index is calculated using the filtered data. A flowchart of the signal process task is shown below.

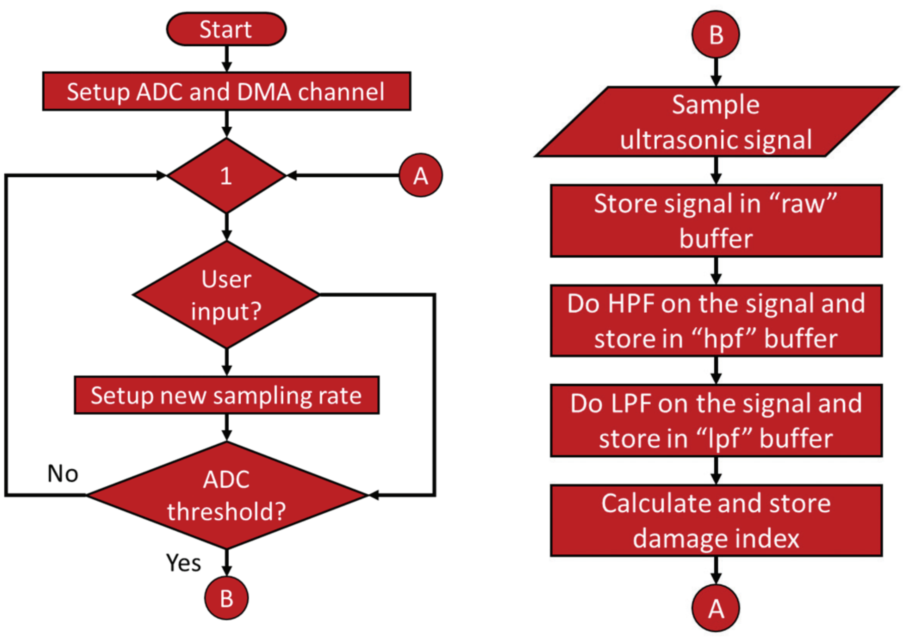


Figure 5: Flow chart of Signal process task

High pass filter

The signal is filtered through a high pass filter to remove low frequency from the signal.The filter coefficients for cut-off frequencies 10kHz and 100kHzwere set up in the firmware. The default cut-off frequency was set to 10 kHz. The user can select the preconfigured cut-off frequenciesof the high pass filter. The designed HPF is a fourth-order Butterworth filter.

The filter coefficient for cut off frequencies of 10 kHz high pass filter is

Numerator				
a0	a1	a2	a3	a4
0.7601538590971	-3.040615436389	4.560923154583	-3.040615436389	0.7601538590971
Denominator				
b0	b1	b2	b3	b4
1	-3.453185137587	4.504139091634	-2.627303618228	0.5778338981056

The magnitude response of the filter is

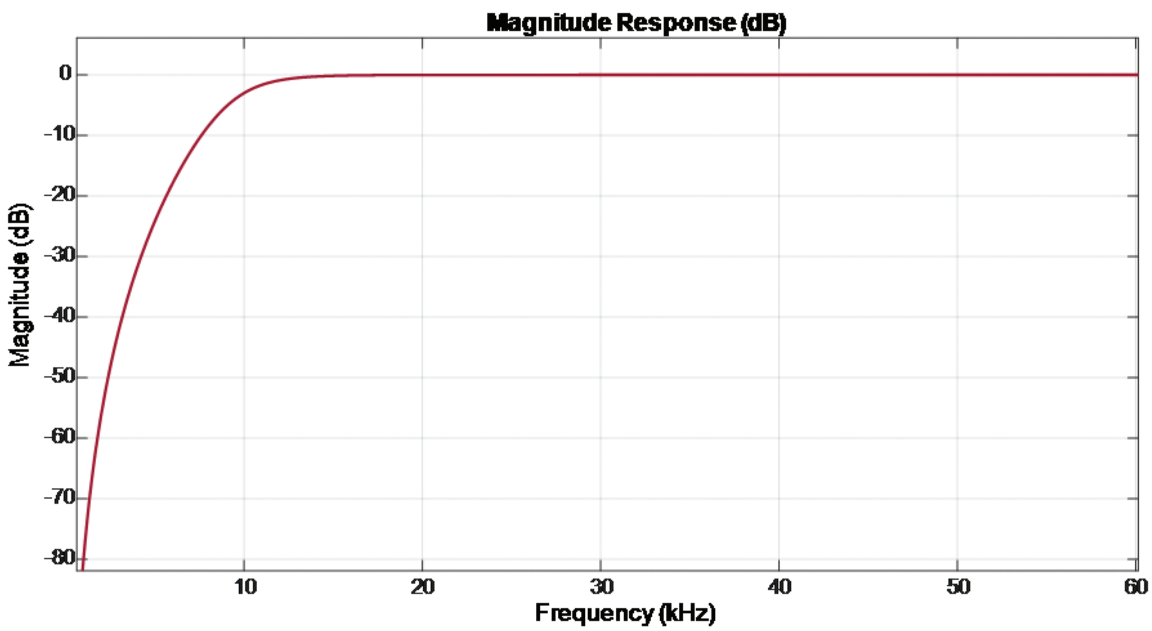


Figure 6: Magnitude response of 10 kHz HPF

The filter coefficient for cut off frequency of 100 kHz high pass filter is

Numerator				
a0	a1	a2	a3	a4
0.8142545568862	-3.257018227545	4.885527341317	-3.257018227545	0.8142545568862
Denominator				
b0	b1	b2	b3	b4
1	-3.589733887112	4.851275882519	-2.627303618228	0.6630104843859

The magnitude response of the filter is

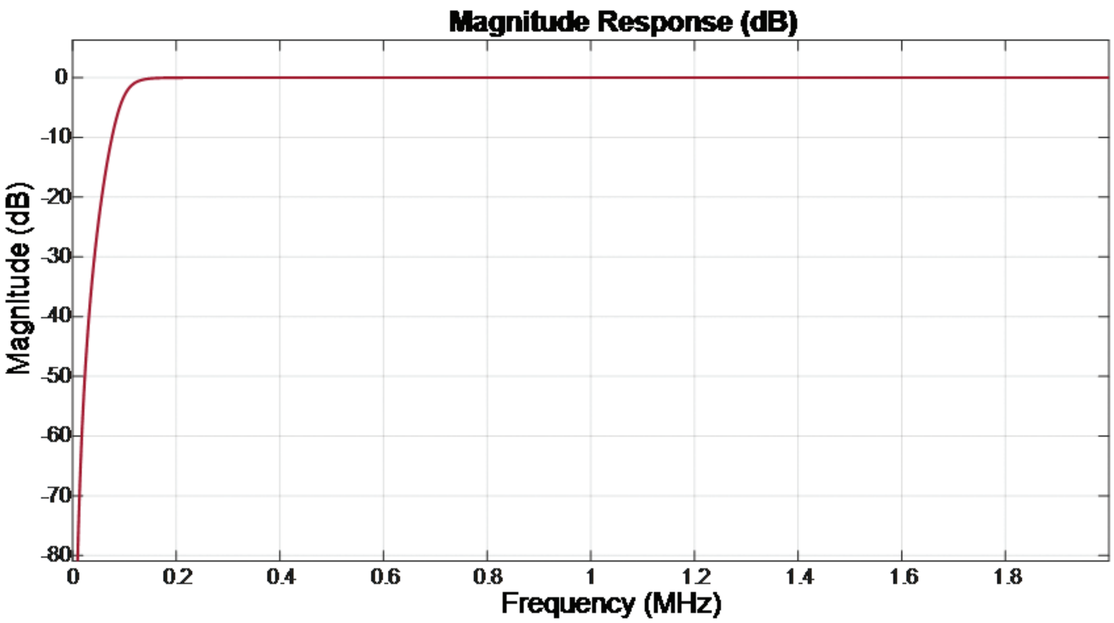


Figure 7: Magnitude response of 100 kHz HPF

Low pass filter

The signal is then passed through a low pass filter to remove high-frequency noise from the signal. The filter coefficients for cut-off frequencies 100 kHz and 200 kHz were set up in the firmware. The default cut-off frequency was set to 100 kHz. The user can select the preconfigured cut-off frequencies of the low pass filter. The designed LPF is a fourth-order Butterworth filter.

The filter coefficient for cut off frequency of 100 kHz is

Numerator				
a0	**a1**	**a2**	**a3**	**a4**
0.0004165992044066	0.001666396817626	0.00249959522644	0.001666396817626	0.0004165992044066
Denominator				
b0	**b1**	**b2**	**b3**	**b4**
1	-3.180638548875	3.861194348994	-2.112155355111	0.438265142262

The magnitude response of the filter is

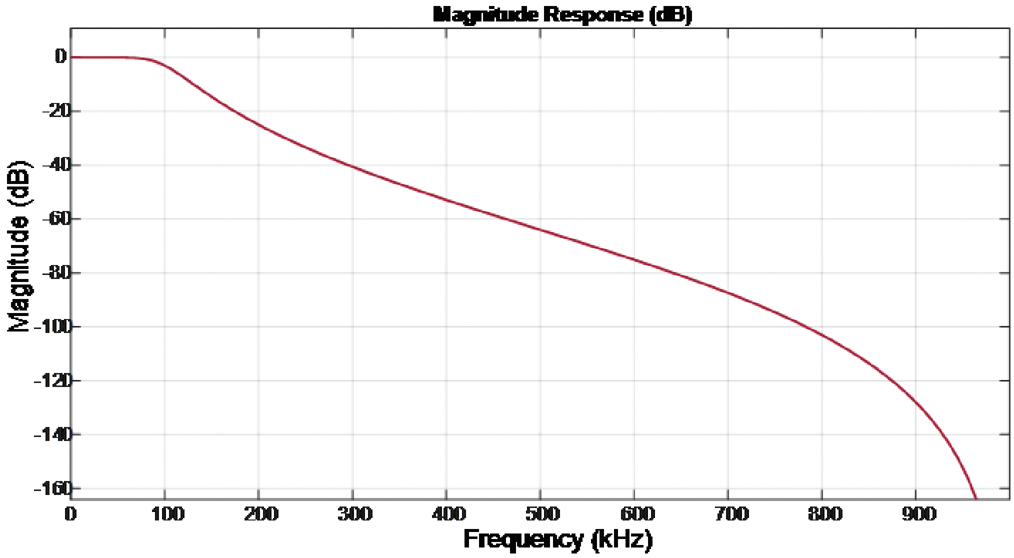


Figure 8: Magnitude response of 100 kHz LPF

The filter coefficient for cut off frequency of 200 kHz is

Numerator				
a0	a1	a2	a3	a4
0.004824343357716	0.01929737343086	0.0289460601463	0.01929737343086	0.004824343357716
Denominator				
b0	b1	b2	b3	b4
1	-2.369513007182	2.313988414416	-1.054665405879	0.1873794923682

The magnitude response of the filter is

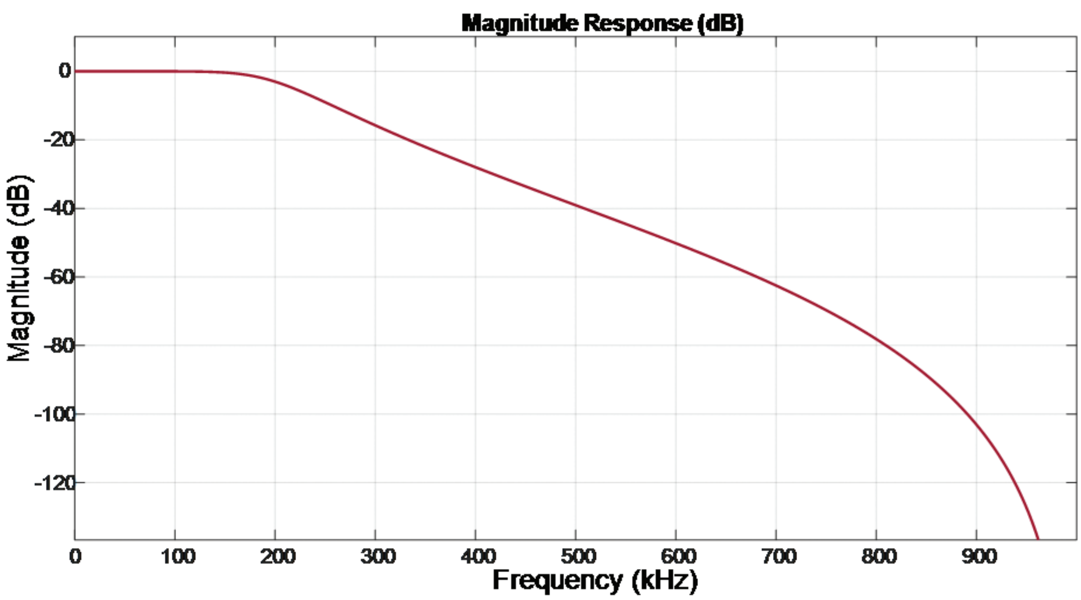


Figure 9: Magnitude response of 200 kHz LPF

Damage index

The signal is then further processed to calculate the damage index. A damage index is a single value representing any damage or change in the structure due to attenuation in the received signal. The algorithm to calculate the damage index is shown in the eq. (1).

$$DI_{TDRMS} = \frac{\int_{t_1}^{t_2} |S_m(t) - S_b(t)|^2 dt}{\int_{t_1}^{t_2} |S_b(t)|^2 dt} \quad (1)$$

Where Sm is a measured signal and Sb is the baseline signal.

3. Results and discussions

3.1. Testing

The actuator and sensor were mounted in the aluminum specimen of dimension 510 cm x 115 cm x 2 cm to test the device. The actuator circuit [18] was integrated into the DUSD to actuate the PZT actuator. The actuator was excited with 6 cycles tone-burst signal of frequency 135 kHz and amplitude 10 Vp-p. The signal was captured in the PC using open-source terminal software from google. The command was sent to set up the cut-off frequency of 10 kHz for HPF and 200 kHz for LPF. The sampling rate sets to 2.5 MSPS. The conceptual testing diagram andexperimental setup of the system are shown in the figure below.

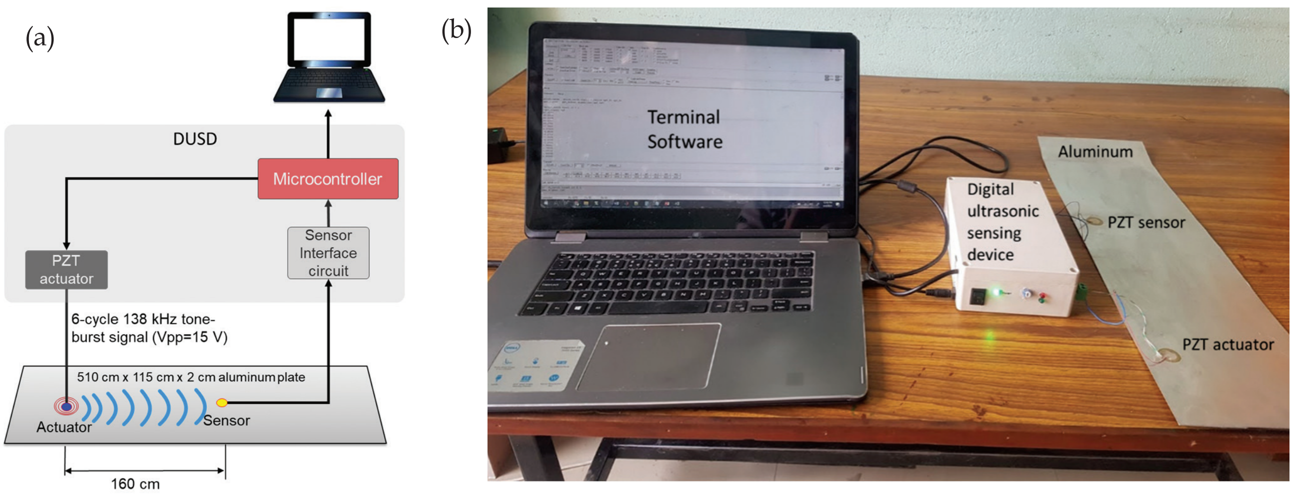


Figure 10: a)Testing conceptual diagram b) Experimental setup.

PZT actuator and sensor of radius 1 cm were used to generate and capture an ultrasonic wave from the structure. After the ultrasonic wave was captured, the command was sent to the DUSD, first to get raw, unfiltered data, then high pass filtered data and finally low pass filtered data.

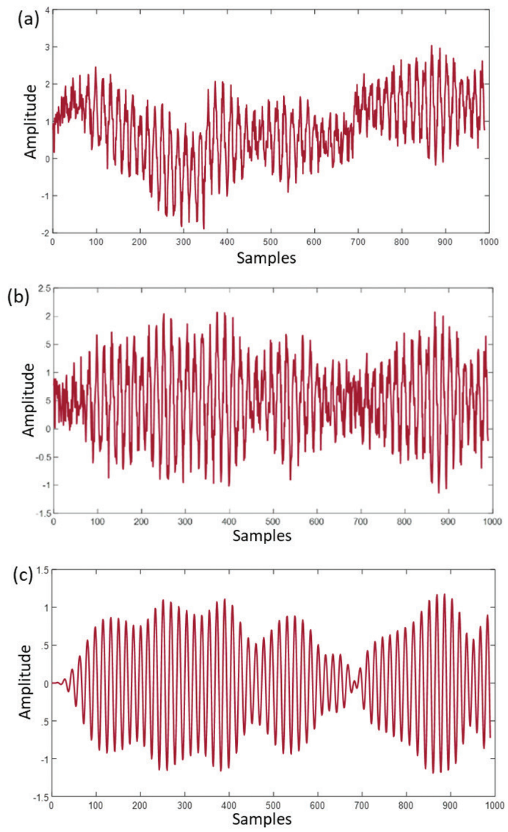


Figure 11: Collected ultrasonic wave (a) unfiltered (b) after HPF (c) after LPF

The figure clearly shows that the developed device is well capable of capturing as well as filtering the ultrasonic wave.

To check the integrity of the device, the data was further analyzed in both intact and damaged conditions of the aluminum species. The induced damage location is shown in the figure below:

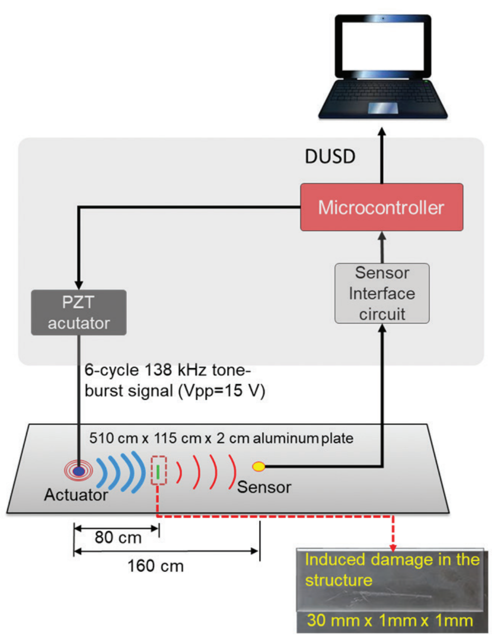


Figure 12: Diagram with induced damage in the structure

The filtered data was collected at the intact condition, and then a crack of 30 mm x 1 mm x 1 mm was induced in between actuator and sensor. Then, the data was again collected in this damaged condition. Figure 13 shows the caparison between the data collected from the same structure in intact and damaged conditions.

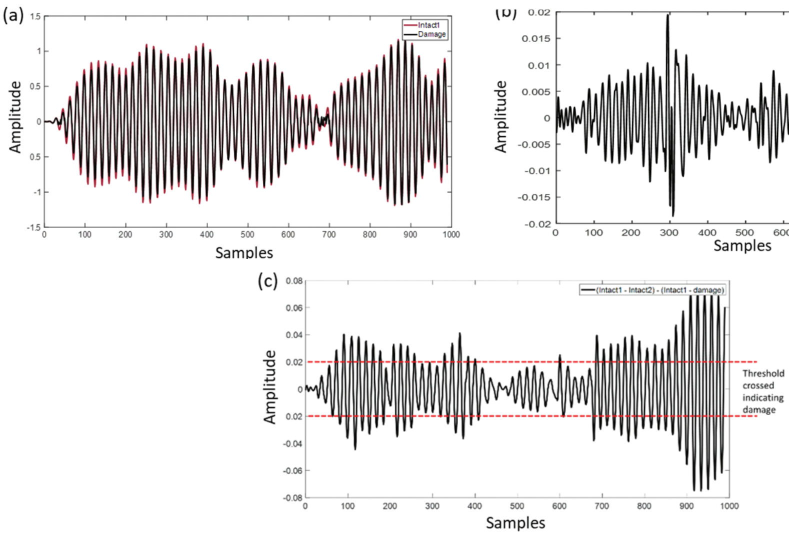


*Figure 13: a) Comparison of ultrasonic wave in intact and damaged condition b) difference between two intact signals to determine the thresholdc) difference between intact and damaged condition***.**

From the graph, it is clear that the device can successfully detect the damage. The first graph shows the signal from intact and damaged structures. The second graph shows the difference between two signals from the same structure in intact conditions. The value slightly more significant than the maximum value of the signal in the second graph is set as a threshold valueto determine the damage in the structure. The third graph shows the difference between signals from the same structure from both intact and damaged conditions. The threshold is determined from two signals: "intact1" and "intact2", acquired from the structure. Here, "intact1" and "intact2" are the signals from the structure in intact conditions taken at different instant of time. The third graph is plotted by taking the difference between two signals in intact condition and the difference between the signal from an intact and damaged (i.e., "intact1" and "damage") condition of the structure. Here, "damage" is the signal from the structure in damaged condition.

During the intact condition of the structure, the damage index sent from the device was 0.192. After inducing the damage, the damage index sent from the device was 0.939. To verify the damage index, the damage index was calculated from the acquired unfiltered signal in the PC.The calculated damage index in the PC was 0.941. The damage indices calculated from the device and the PC are almost identical, implying that the device can successfully calculate the damage index.

4. Conclusions

From this research, we can conclude that it is possible to build a digital ultrasonic sensing device that can be used in a structural health monitoring system. The DUSD can calculate the damage index efficiently by using a charge amplifier and an in-built programmable filter. Further, the capabilities of the device are enhanced with the use of a sophisticated signal processing algorithm.The acquired ultrasonic waves and damage index have shown the device's reliability to detect the damage in the structure. The research also showed that the modern microcontroller is powerful enough to do the precise signal processing on the ultrasonic wave from the structure.However, the device has been tested in aluminum and steel structures only. The further limitations of the device can be tabulated as below:

Table 2: Limitations

Tested sensor and actuator	PZT (radius: 1cm)
Tested structures	Aluminum, steel
Maximum tested frequency	135 kHz
Maximum data throughput	115200 baud rate

The device's sensing and signal processing capability can be used to monitor the structure's health, such as metallic bridges, pipelines, and aircraft.

Conflict of Interest

Not declared by the authors.

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