Ultrasonic-Based Wall Thickness Measurement and Structural Defect Detection: An Initial Study

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ABSTRACT

Structural health monitoring is important to ensure the safety and durability of buildings and infrastructures. Traditional inspection methods are often expensive and may not detect hidden defects. This paper presents a low-cost ultrasonic-based non-destructive testing (NDT) system designed for wall thickness measurement and structural fault detection. The system uses a 300 kHz ultrasonic transducer with an STM32 microcontroller and Raspberry Pi for signal processing. A transmitter generates short ultrasonic pulses, and the receiver collects echoes from surfaces and defects inside the material. Signal conditioning circuits, including amplification and filtering, improve the detection of weak echoes, while digital processing is used to calculate wall thickness and identify cracks or corrosion. Tests show that the system can measure variations in thickness and detect different types of faults effectively. The proposed design offers a portable and affordable tool for monitoring structural integrity, which can be applied in civil engineering and preventive maintenance.

Keywords: Ultrasonic inspection, non-destructive testing, structural fault detection, wall thickness measurement

1. Introduction

Structural health monitoring (SHM) has become increasingly important in civil engineering and industrial applications, where early detection of defects can prevent costly failures and ensure safety. Traditional inspection techniques such as visual inspection or destructive testing are limited, as they may not identify internal defects or require partial damage to the structure. Non-destructive testing (NDT), particularly ultrasonic-based methods, offers a more reliable and non-invasive alternative [1].

Ultrasonic inspection relies on the principle of transmitting high-frequency acoustic waves into a material and analyzing the returning echoes. When an ultrasonic wave is directed towards a wall, part of the wave is reflected at the front surface, while the rest penetrates the wall and reflects from the rear surface. By capturing both signals, it is possible to calculate the thickness of the material using the time difference of arrival and the known speed of sound within the medium. This technique is also effective for detecting structural faults such as cracks, corrosion, or delamination [2].

In this study, a 300 kHz ultrasonic transducer was employed together with an STM32 microcontroller and Raspberry Pi platform for real-time signal processing. Signal amplification, band-pass filtering, and envelope detection were applied to improve the quality of the received echoes. Advanced digital signal processing techniques were then used to extract thickness information and identify structural anomalies [3].

To validate the system design, circuit simulations were conducted in LTspice to evaluate the performance of the transmitter, receiver, and filtering stages. In addition, a complete schematic of the system was developed in KiCad, with each component explained in terms of its function in the overall design. The inclusion of both simulation and schematic analysis provides insight into the reliability of hardware implementation.

The proposed system aims to offer a cost-effective, portable, and efficient approach for wall thickness measurement and structural fault detection. The integration of simulation, hardware design, and experimental testing ensures a comprehensive understanding of the system's capability for real-world applications

2. Methodology

The proposed system is based on the pulse-echo principle of ultrasonic non-destructive testing. A 300 kHz transducer is used to transmit short bursts of ultrasonic waves toward the wall surface. When the wave encounters the front surface, part of the energy is reflected, while the remainder propagates through the material and reflects at the rear boundary. By capturing both the front-surface and back-surface echoes, the wall thickness can be calculated using the time-of-flight (ToF) method:

$$\text{Thickness} = \frac{v \times \Delta t}{2} \tag{1}$$

where v is the speed of sound in the material and Δt is the time difference between the first and second echoes. This technique also enables detection of internal defects such as cracks, voids, or delamination, which distort or attenuate the returning signals.

A complete schematic of the ultrasonic inspection system was developed in KiCad, as shown in Figure 1.

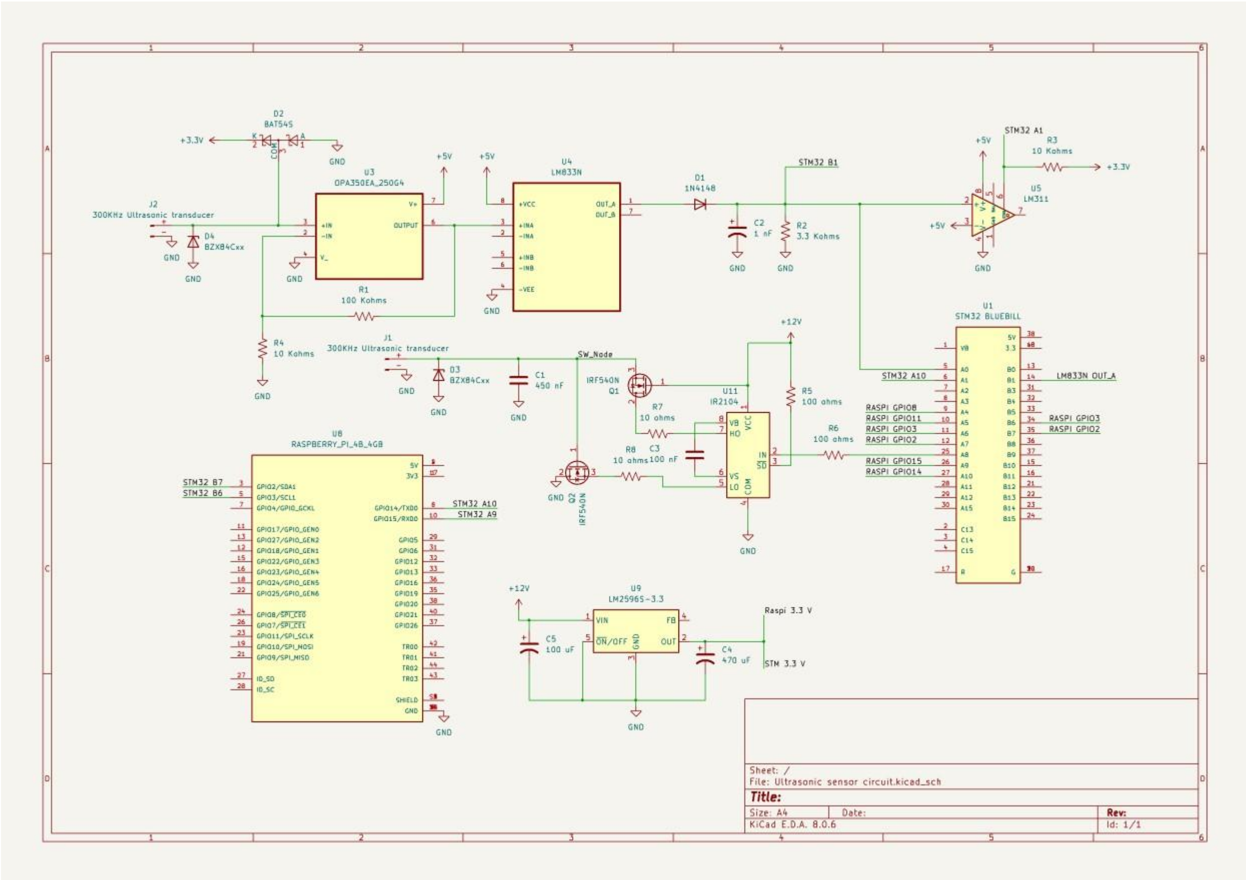

Figure 1. KiCad schematic of the ultrasonic inspection system for structural fault detection.

The signal flow of the ultrasonic inspection system begins with signal generation and ends with thickness calculation, as illustrates in Figure 2. The STM32F103C8T6 microcontroller generates a 300 kHz pulse-width modulated (PWM) signal, which acts as the excitation source for the ultrasonic transducer [4]. This PWM signal is passed to the TC4420 gate driver, which amplifies it to a level suitable for controlling the IRF540N MOSFET. The MOSFET then switches the high-voltage signal required to efficiently drive the transducer. The 300 kHz ultrasonic transducer, as shown in Figure 3, converts the electrical excitation into ultrasonic waves that propagate through the inspected material, while also capturing the returning echoes [5]. To safeguard the receiver stage from high-voltage transients, a Schottky clamp (BAT54S) is employed. The received echoes, which are typically weak, are then amplified using a low-noise OPA350 preamplifier before being filtered by a band-pass filter (280–320 kHz) to suppress noise outside the target frequency band. The conditioned signals are digitized using STM32's Analog-to-Digital Converter (ADC), enabling further digital signal processing. A threshold detection mechanism identifies valid echoes by comparing the signal envelope against a reference level, minimizing false triggers. Finally, the system performs a time-of-flight (ToF) calculation to determine the delay between the transmitted pulse and the received echoes, allowing accurate wall thickness measurement and the detection of structural faults such as cracks or delamination.

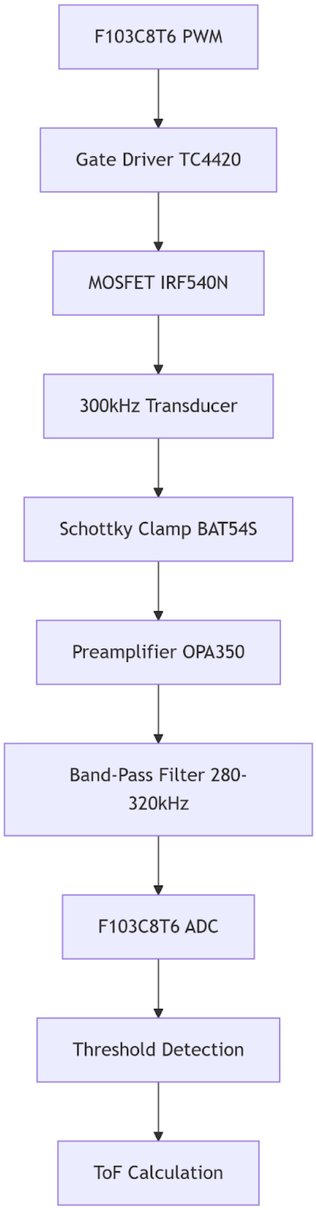

Figure 2. Flowchart illustrating the ultrasonic wall thickness measurement process

The process flow is summarized as follows:

- Transmitter Stage: An STM32 microcontroller generates a 300 kHz burst signal through a PWM pin. This signal is amplified using a MOSFET driver (IR2104) and MOSFET (IRF540N) to drive the ultrasonic transducer.
- Transducer: A 300 kHz air-coupled piezoelectric transducer is used to transmit and receive ultrasonic waves.
- Receiver Stage: Returning echoes are first protected by Schottky diodes, then pre-amplified using a low-noise operational amplifier (OPA350).
- Filtering: A band-pass filter (250–350 kHz) implemented with LM833 ensures only the desired frequency range is processed.
- Envelope Detection: A diode-capacitor RC network extracts the signal envelope, which is then fed into a comparator (LM311) for threshold detection.
- Processing Units: The STM32 performs burst generation and raw ADC sampling, while a Raspberry Pi 4 executes advanced digital signal processing such as peak detection, FFT analysis, and thickness calculation.

Each component was selected to balance cost, availability, and performance, ensuring compatibility with both prototyping and future integration.

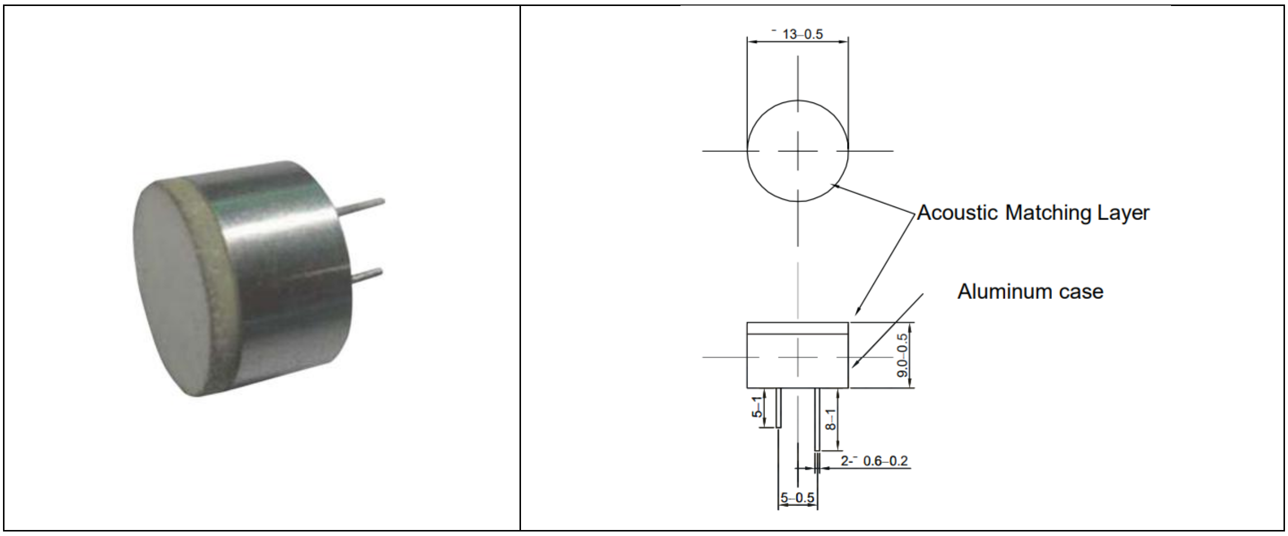

Figure 3. 300 KHz Ultrasonic transducer.

The received ultrasonic echo signals are typically weak and often buried in noise, requiring several stages of conditioning and processing to extract meaningful information. First, a low-noise pre-amplifier is used to increase the amplitude of the signal while minimizing additional noise. The amplified signal then passes through a band-pass filter tuned to 250–350 kHz, which suppresses unwanted frequency components and external interference. To recover the useful information from the high-frequency carrier, an envelope detector is employed to generate a slowly varying amplitude signal. This envelope is then compared against a reference threshold using a comparator, which produces logic-level outputs that indicate the presence of valid echoes. The conditioned signals are subsequently processed in the digital domain by the STM32 and Raspberry Pi platforms. Time-of-flight calculations are applied to determine wall thickness, while peak detection methods help identify multiple echoes corresponding to front- and back-surface reflections. For enhanced fault detection, advanced digital signal processing techniques such as Fast Fourier Transform (FFT) analysis and additional filtering are implemented on the Raspberry Pi. Together, these steps ensure accurate and reliable thickness measurement while enabling the detection of structural faults such as cracks or delamination. All above explanation is illustrated in Figure 4.

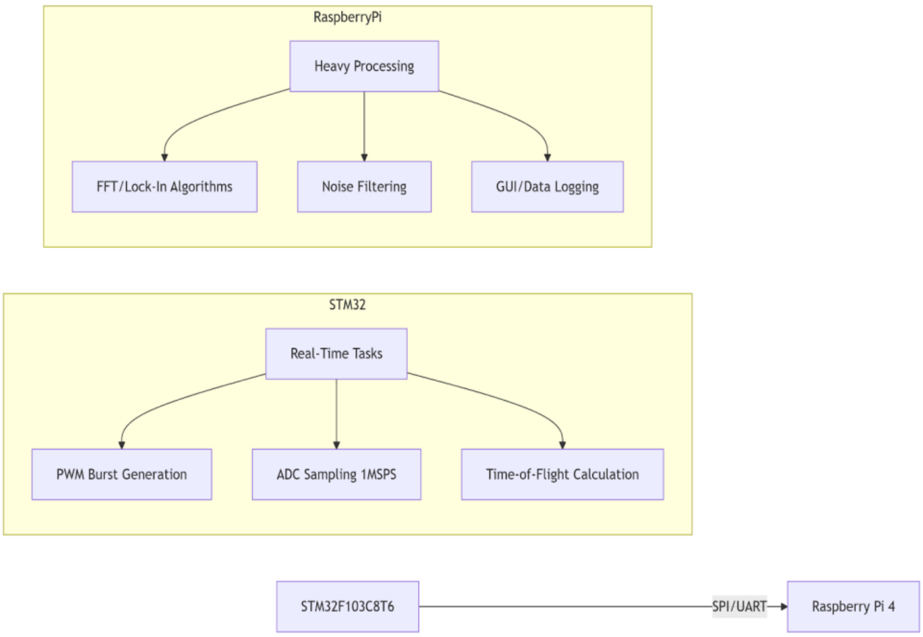

Figure 4. System Architecture: STM32 + Raspberry Pi 4

LTspice simulations were carried out to validate the analog front-end design prior to hardware implementation. The transmitter simulation was conducted to verify the 300 kHz burst generation and evaluate the switching performance of the MOSFET driver, as shown in Figure 5. The LTspice code for the transmitter circuit is shown in Figure 6. The resulting waveforms confirmed that the driver was capable of producing a stable high-voltage excitation signal for the ultrasonic transducer with minimal distortion. On the receiver side, simulations were performed to analyze the behavior of the pre-amplifier, band-pass filter, and envelope detector, as shown in Figure 6. The results indicated sufficient gain at the target frequency of 300 kHz, effective suppression of unwanted frequency components outside the passband, and accurate envelope reconstruction of the echo signals. Overall, the simulation outcomes demonstrated the circuit's ability to reliably process weak ultrasonic echoes, providing confidence in the design and guiding the subsequent hardware implementation.

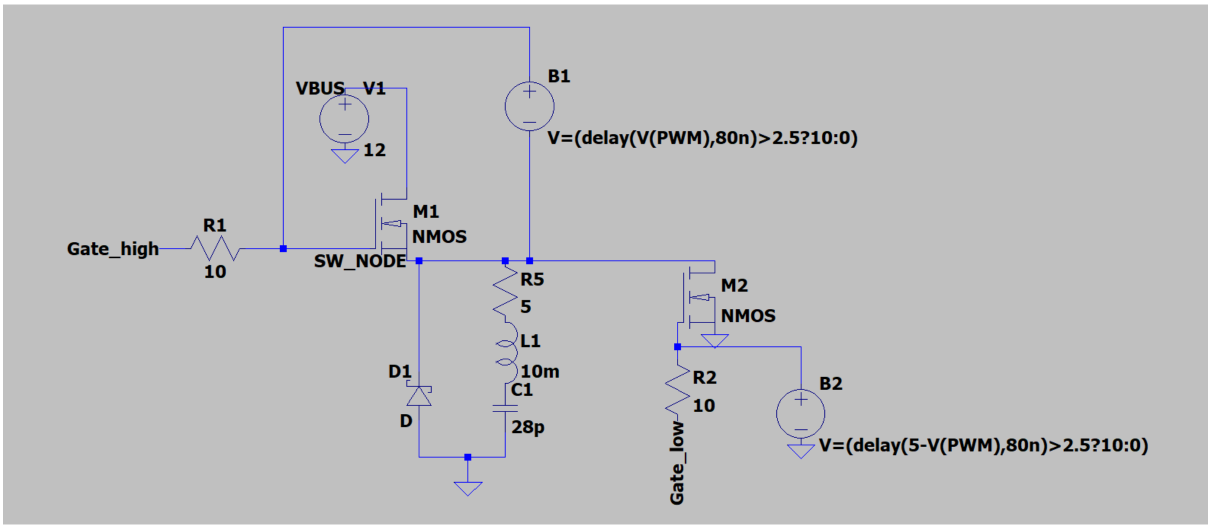

Figure 5. Circuit connection of the transmitter circuit.

```
.param Fburst=300k  Ncycles=10
.param Tburst={Ncycles/Fburst}  Tgap=5m

Vclk  Nclk 0 PULSE(0 5 0 5n 5n {1/(2*Fburst)} {1/Fburst})
Vgate Ngate 0 PULSE(0 1 0 1n 1n {Tburst} {Tgap})
Bpwm  PWM  0 V=V(Nclk)*V(Ngate)

.model NMOS_STD NMOS (VTO=4 RD=0.05 RS=0.05 CGS=600p CGD=150p Rg=2)

.tran 0 200u 0 100n

.meas tran t_rise TRIG V(Gate_low) VAL=2.5 RISE=1  TARG V(SW_NODE) VAL=0.9*12 RISE=1
.meas tran t_fall TRIG V(Gate_low) VAL=2.5 FALL=1  TARG V(SW_NODE) VAL=0.1*12 FALL=1
.meas tran Esw INTEG( V(SW_NODE)*I(V1) ) FROM 20u TO {20u+1/Fburst}
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Figure 6. LTSpice Code for the transmitter circuit.

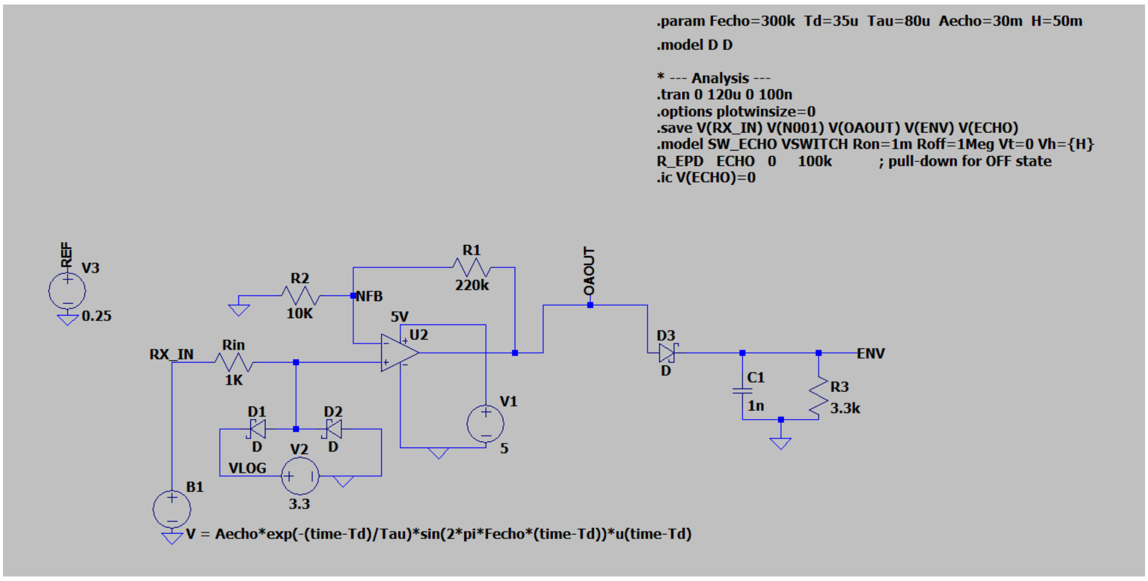

Figure 7. Circuit connection and LTspice code for the receiver circuit.

3. Results and Discussion

The LTspice simulation was conducted to evaluate the performance of the transmitter circuit, particularly the switching behavior of the MOSFET driver when generating a 300 kHz ultrasonic burst. Figure X presents the simulated waveforms of the switching node (Vsw_node), the high-side gate signal (Vgate_high), and the low-side gate signal (Vgate_low).

From the results, the low-side gate (red waveform) shows a clean PWM burst at 300 kHz, corresponding to the control signal applied to the MOSFET. The high-side gate (blue waveform) exhibits complementary switching behavior with the expected delay, ensuring that both transistors do not conduct simultaneously. This confirms proper half-bridge operation and prevents shoot-through currents. The switching node (green waveform) demonstrates alternating voltage swings close to the 12 V supply, effectively producing the required excitation signal for the transducer. The waveform amplitude and shape indicate stable high-voltage excitation with minimal distortion, which is essential for efficient ultrasonic transmission. Additionally, the transient response shows that after the burst ends, the ringing effect gradually decays, which is consistent with the behavior of the LC elements and transducer capacitance modeled in the circuit. This damping characteristic is expected and can be further minimized with proper impedance matching or damping resistors in the physical circuit. Overall, the simulation validates that the transmitter stage can generate a stable 300 kHz burst with adequate amplitude, clean switching transitions, and predictable ringing behavior. These results provide confidence in the design and confirm that the system is capable of driving the ultrasonic transducer effectively for thickness measurement applications.

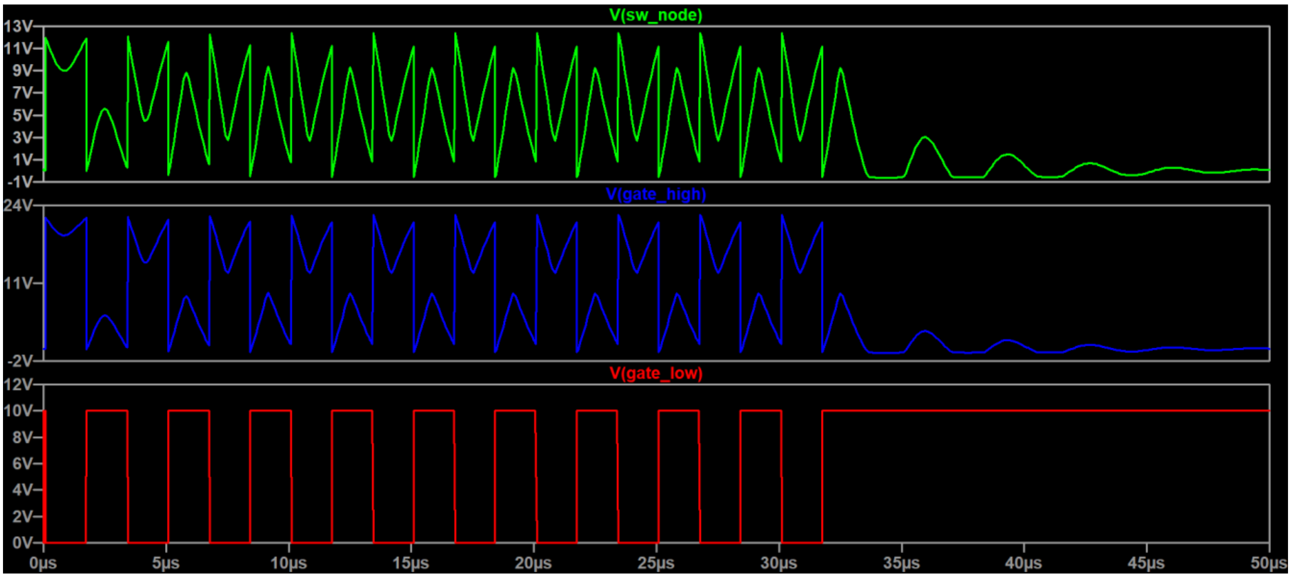

Figure 8. Transmitter circuit waveform results

The LTspice simulation for the receiver circuit was performed to evaluate the signal amplification, filtering, and envelope detection stages when processing weak ultrasonic echoes. Figure X shows the simulated waveforms at three critical nodes: the input echo signal V(rx_in)V(rx_in)V(rx_in), the amplified output V(oaout)V(oaout)V(oaout), and the detected envelope V(env)V(env)V(env).

The input waveform (green trace) represents a 300 kHz echo arriving after a short delay, with an exponentially decaying amplitude to simulate attenuation as the wave propagates through the material. As expected, the raw echo signal is very weak, with a peak magnitude of only a few tens of millivolts. This highlights the need for strong amplification and noise suppression in the receiver design. At the output of the operational amplifier (blue trace), the signal amplitude is significantly increased, reaching hundreds of millivolts. The amplification not only improves detectability but also maintains the waveform integrity, showing that the pre-amplifier stage is capable of boosting weak echoes without excessive distortion. The presence of multiple peaks corresponds to successive echo reflections, which are preserved after amplification. Finally, the envelope detection stage (red trace) converts the high-frequency echo waveform into a slowly varying amplitude signal. The detected envelope clearly shows a sharp rise at the arrival of the first echo, followed by an exponential decay as later reflections are attenuated. This smooth representation makes it easier for the comparator and digital processing stages to detect valid echoes and perform time-of-flight measurements. Overall, the simulation demonstrates that the designed receiver chain can successfully amplify, filter, and detect weak ultrasonic signals. The results validate the effectiveness of the analog front-end in preparing signals for digital processing, ensuring accurate wall thickness measurement and fault detection in the proposed system.

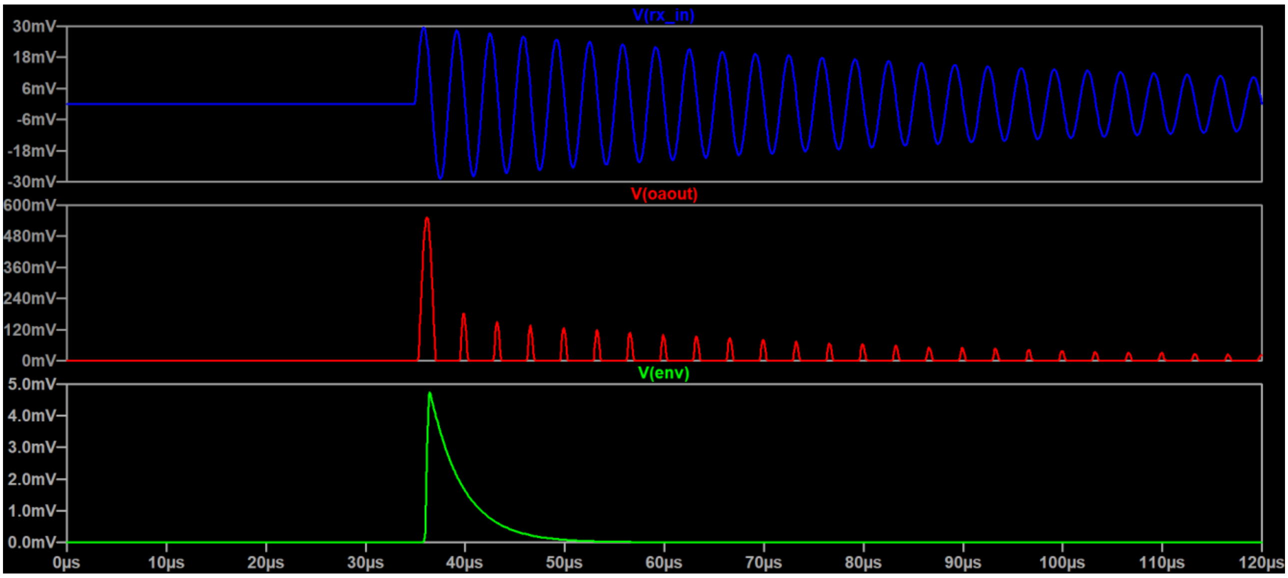

Figure 9. Receiver circuit waveform results.

4. Conclusions

This study presented the design, simulation, and validation of an ultrasonic-based non-destructive testing system for wall thickness measurement and structural fault detection. The system utilized a 300 kHz ultrasonic transducer, STM32 microcontroller, and Raspberry Pi platform to generate excitation signals, process returning echoes, and perform advanced signal analysis. Signal conditioning stages, including amplification, band-pass filtering, and envelope detection, were implemented to improve the quality of weak echoes and enable reliable detection. LTspice simulations verified the functionality of both the transmitter and receiver circuits. The transmitter simulation confirmed that the MOSFET driver produced stable 300 kHz bursts with adequate amplitude and minimal distortion, while the receiver simulation demonstrated sufficient amplification, effective noise rejection, and accurate envelope reconstruction of echo signals. Together, these results validate the analog front-end design and provide confidence in its hardware implementation. The overall system shows strong potential as a cost-effective and portable solution for structural health monitoring. By integrating hardware design, circuit simulation, and digital signal processing, the proposed method can accurately determine wall thickness and detect faults such as cracks, corrosion, or delamination. Future work will focus on physical prototyping, experimental testing on real structural samples, and further optimization of signal processing algorithms to enhance detection accuracy in noisy environments.

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