



Developing a 2 MHz Ultrasonic Probe: Implications for Practical Non-Destructive Testing of Metallic Materials

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ABSTRACT

Purpose of the study: This study aimed to fabricate and characterize a 2 MHz normal-incidence ultrasonic probe using a PZT element and evaluate its performance in frequency response, near-field characteristics, calibration, and defect detection compared with a commercial probe.

Methodology: An experimental method was employed to fabricate a probe using a 2 MHz PZT element, tungsten oxide powder, Araldite epoxy, electrical connections, and a metal housing. A Krautkramer USL 32 ultrasonic testing instrument, an oscilloscope, a steel calibration block, and oil couplant were used. Frequency characterization was performed using Fast Fourier Transform (FFT) analysis, followed by near-field estimation, distance–amplitude correction (DAC) calibration, and comparative echo-response measurements.

Main Findings: The fabricated probe achieved an operating frequency of 2.011 MHz and detected a 3 mm-diameter steel reflector under the tested conditions. Recognizable echo responses were obtained at reference depths of 95 and 100 mm. At 100 mm, the fabricated and commercial probes both produced an 80% screen-height response, requiring gains of 40 dB and 34 dB, respectively. The fabricated probe also exhibited a measured beam width of 30 mm at a depth of 200 mm.

Novelty/Originality of this study: This study provides an integrated experimental characterization of a conventionally fabricated 2 MHz normal-incidence ultrasonic probe, combining fabrication, frequency measurement, near-field assessment, DAC calibration, and comparison with a commercial probe. Its contribution is configuration-specific evidence of the probe's operational feasibility and performance limitations, providing a practical basis for optimizing backing-material composition, acoustic response, and defect-detection capability.

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1. INTRODUCTION

The structural integrity of metallic components is essential for maintaining operational safety and reliability in industrial systems, particularly those exposed to high temperatures, mechanical loads, and corrosive environments. Internal cracks, corrosion, and other material discontinuities may compromise component performance before damage becomes visible during conventional visual inspection [1]–[3]. Non-destructive

testing (NDT) therefore plays an important role in evaluating material integrity without damaging the inspected component. Among the available NDT techniques, ultrasonic testing is widely investigated because reflected acoustic waves can provide information about internal defects and material conditions [4]-[6]. Recent studies have further demonstrated the potential of ultrasonic methods for evaluating steel degradation and detecting subsurface defects under different inspection conditions [7]-[9].

Despite these advantages, the reliability of ultrasonic inspection depends on transducer characteristics, acoustic beam propagation, signal amplitude, and calibration accuracy. Variations in these parameters may affect the interpretation of reflected signals and the identification of defects at different depths [10]-[12]. For example, Zhao et al. [7] demonstrated that ultrasonic signal parameters can contribute to evaluating steel degradation, whereas Calibration-free SH guided wave analysis (2023) showed that material properties and experimental conditions can influence defect detection performance. These findings indicate that reliable inspection requires not only an ultrasonic instrument but also a transducer whose operational characteristics are adequately understood [13]-[15]. Accordingly, the principal technical problem addressed in this study is how to develop and characterize a normal ultrasonic probe operating at 2 MHz and evaluate its performance in detecting internal defects in metallic specimens [16]-[18].

To address this problem, the present study adopts an experimental approach to fabricate and characterize a normal-incidence ultrasonic probe using a lead zirconate titanate (PZT) piezoelectric element with a nominal frequency of 2 MHz. The fabrication process involves assembling the piezoelectric element, damping material, probe housing, and electrical connections to produce a functional ultrasonic transducer [19]-[21]. The fabricated probe is subsequently evaluated using an ultrasonic testing instrument and an oscilloscope to examine its signal response and operating frequency. Calibration measurements and distance-amplitude correction (DAC) analysis are also employed to assess echo responses at different reflector depths [22], [23]. This approach is consistent with the importance of reference-based calibration and acoustic-response characterization emphasized by Würschig [24], who demonstrated that reflector characteristics and signal amplitudes are important for evaluating ultrasonic inspection performance.

Recent research has investigated ultrasonic defect detection through different transducer configurations, signal-processing techniques, and measurement strategies. Lyu et al. [25] examined a model-based ultrasonic method for detecting flaws in curved components using an immersion spherically focused transducer, highlighting the importance of measurement models in practical inspection. Zhao et al. [7] combined electromagnetic and ultrasonic parameters to evaluate the degradation of 12CrMoV steel, demonstrating the potential of ultrasonic signals for material-condition assessment. Würschig [24], investigated acoustic responses from reference notches and developed quantitative measures to characterize defect quality and inspection repeatability. Meanwhile, research on guided-wave testing has demonstrated that changes in material properties, experimental conditions, and wave modes can influence defect detectability (Calibration-free SH guided wave analysis, 2023). Collectively, these studies establish that ultrasonic inspection performance depends on the interaction between transducer characteristics, acoustic responses, material conditions, and calibration procedures [26], [27], [28].

Although previous studies have advanced ultrasonic inspection through specialized transducers, guided-wave analysis, and quantitative defect characterization, further experimental evaluation of conventionally fabricated normal probes remains relevant. In particular, the relationship between probe fabrication, near-field characteristics, actual operating frequency, calibration response, and comparative performance requires assessment within a clearly defined experimental configuration. Lyu et al. [25] focused on immersion-based inspection of curved components, whereas Zhao et al. [7] investigated combined electromagnetic and ultrasonic measurements for evaluating steel degradation. Würschig [24], in contrast, concentrated on the acoustic characteristics of reference notches and the repeatability of automated ultrasonic testing. These different research emphases provide a basis for examining a simpler 2 MHz normal probe through an integrated experimental evaluation. Accordingly, the present study addresses the need to characterize a fabricated probe and compare its measured response with that of a commercial probe under the specific test conditions used.

The contribution of this study lies in integrating probe fabrication, operating-frequency measurement, near-field analysis, ultrasonic calibration, DAC evaluation, and comparative testing within a single experimental investigation. Unlike studies primarily concerned with advanced guided-wave configurations or model-based inspection, this work examines the practical performance of a fabricated 2 MHz normal probe for detecting internal reflectors in a metal test block. The original experimental results reported a measured frequency of 2.011 MHz and a near-field distance of approximately 1.96 mm for the fabricated probe. The study also compares the responses of the fabricated and commercial probes, providing empirical information about their performance under the reported test conditions. These contributions should be understood as a configuration-specific experimental assessment rather than a claim that normal-probe fabrication or ultrasonic calibration has not previously been investigated.

A systematic evaluation of fabricated ultrasonic probes is important for understanding their practical capabilities and limitations in non-destructive inspection of metallic materials. Such evaluation can help identify

whether a probe produces a usable signal, how its response changes with reflector depth, and which characteristics require further improvement. Accordingly, this study aims to fabricate a normal ultrasonic probe using a PZT piezoelectric element with a nominal frequency of 2 MHz and characterize its principal operating parameters. It further aims to evaluate the probe through calibration and DAC analysis and compare its echo responses with those of a commercial probe. Through these objectives, the study seeks to establish an experimental basis for assessing the feasibility of the fabricated probe and identifying opportunities to improve its sensitivity and inspection performance.

2. RESEARCH METHOD

2.1. Research Design

This study employed an experimental research design to develop and characterize a normal-incidence ultrasonic probe operating at a nominal frequency of 2 MHz. The experimental work involved probe fabrication, frequency characterization, near-field estimation, ultrasonic calibration, distance–amplitude correction (DAC), and comparative testing against a commercial probe. The evaluation focused on the fabricated probe’s frequency response, calibration performance, and echo amplitudes obtained from reference reflectors at specified depths [29]–[31]. The experimental procedures were conducted at the Center for Structural Strength Technology, Agency for the Assessment and Application of Technology (B2TKS–BPPT), PUSPIPTEK, Serpong, Tangerang, Indonesia, from May to December 2025.

2.2. Materials and Equipment

The probe was constructed using a lead zirconate titanate (PZT) piezoelectric crystal with a nominal frequency of 2 MHz, a diameter of 2.8 mm, and a thickness of 0.7 mm. The construction materials included tungsten oxide powder, acrylic material, copper cable, Araldite epoxy adhesive, a stainless-steel tube, an iron pipe for the probe housing, and polyvinyl chloride (PVC). The epoxy-based mixture containing tungsten oxide powder was used as the damping material behind the piezoelectric element.

The principal equipment comprised a Krautkramer USL 32 ultrasonic testing instrument, an oscilloscope, electrical soldering equipment, and a steel calibration block [32], [33]. A BNC-type connection was used to connect the probe to the ultrasonic instrument. Oil was used as the couplant during calibration. The materials and equipment were selected to support probe fabrication, signal acquisition, frequency measurement, and calibration.

Table 1. Materials and equipment used in probe fabrication and testing

Category	Material or equipment	Function
Active element	PZT piezoelectric crystal, 2 MHz	Converts electrical energy into ultrasonic waves and receives reflected signals
Damping material	Tungsten oxide powder and epoxy	Damps residual vibration behind the crystal
Housing and insulation	Stainless-steel tube, iron pipe, acrylic, and PVC	Supports and encloses the probe components
Electrical connection	Copper cable and BNC connector	Connects the piezoelectric element to the testing instrument
Ultrasonic instrument	Krautkramer USL 32	Generates, receives, and displays ultrasonic signals
Signal measurement	Oscilloscope	Displays the signal waveform and supports frequency analysis
Calibration medium	Steel calibration block and oil couplant	Provides reference reflectors and acoustic coupling

2.3. Fabrication of the 2 MHz Normal Probe

The normal probe was designed to transmit ultrasonic waves approximately perpendicular to the surface of the test material. A single PZT crystal with a diameter of 2.8 mm and a thickness of 0.7 mm was used as the active element. The structural configuration and principal components of the fabricated 2 MHz normal ultrasonic probe are illustrated in Figure 1.

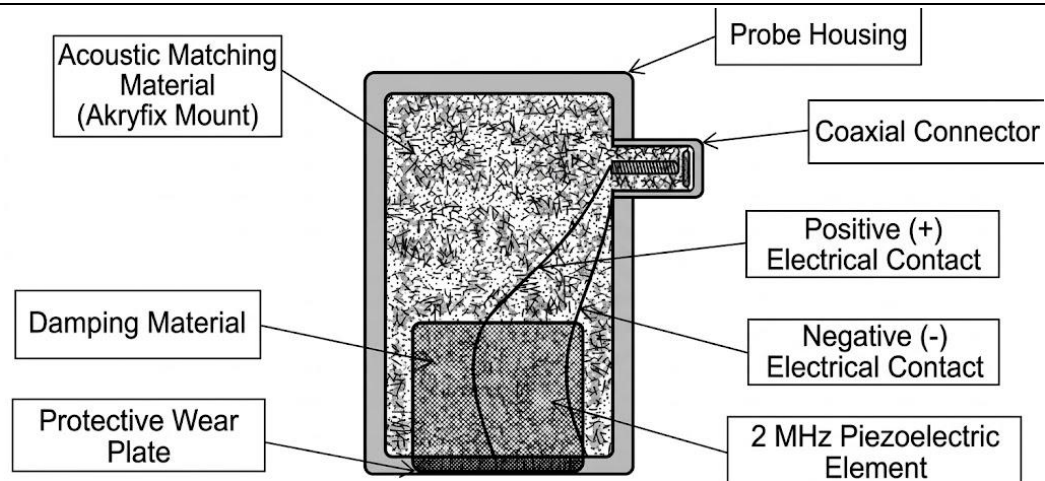


Figure 1. Cross-sectional configuration of the 2 MHz normal ultrasonic probe

First, the probe housing was prepared from a metal pipe, which was machined to accommodate the crystal and other components. The electrical leads were then soldered to the positive and negative surfaces of the piezoelectric element.

Next, the damping mixture was prepared from epoxy adhesive and tungsten oxide powder and positioned behind the crystal to reduce residual vibration. The crystal and damping assembly were placed inside the housing, after which the assembly was cast and secured. The probe housing was then reassembled and finished to produce a complete probe. Finally, the fabricated probe was connected to the ultrasonic testing instrument and oscilloscope for characterization and calibration. The fabrication process of the 2 MHz normal ultrasonic probe involved machining the probe housing, preparing the piezoelectric element and its electrical connections, and assembling the crystal with the backing material. The main fabrication stages are presented in Figure 2.

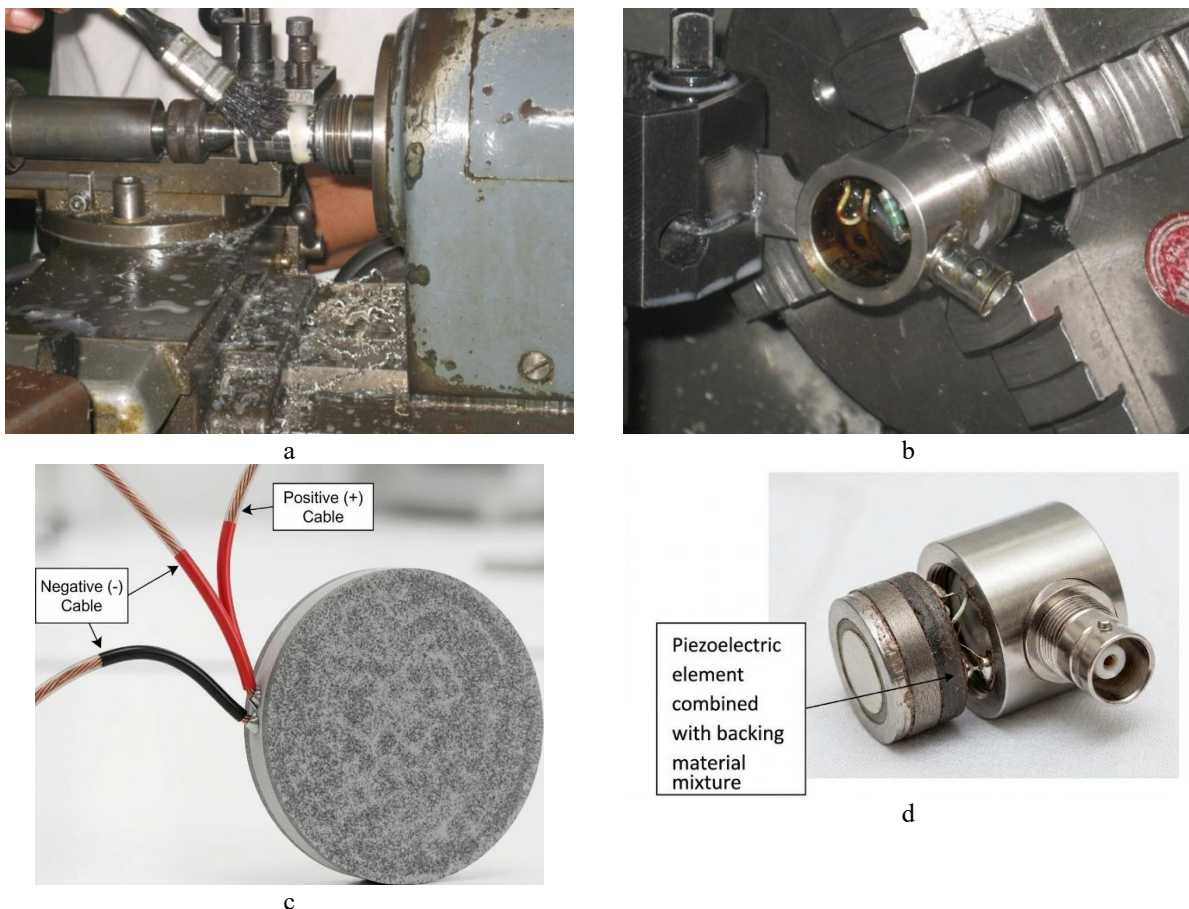


Figure 2. Fabrication stages of the 2 MHz normal ultrasonic probe

2.4. Frequency Characterization

The actual operating frequency of the fabricated probe was evaluated using an oscilloscope. The ultrasonic signal processed by the testing instrument was transferred to the oscilloscope, where a segment of the high-frequency waveform was selected for analysis. The waveform was then processed using the Fast Fourier Transform (FFT) function to obtain its frequency spectrum. The dominant frequency component, identified by its highest amplitude, was used to represent the actual frequency of the fabricated probe.

2.5. Near-Field Estimation

The near-field distance was estimated from the active crystal diameter and the nominal operating frequency. The theoretical near-field distance was calculated using the relationship between the effective diameter of the piezoelectric element, the ultrasonic frequency, and the longitudinal-wave velocity in the relevant medium. The calculated value was used to characterize the region close to the probe in which the acoustic intensity fluctuates. This parameter was considered when interpreting echo amplitudes because measurements within the near field may be affected by variations in the sound field.

2.6. Calibration Block and DAC Procedure

Calibration was performed using a steel reference block and an ultrasonic testing instrument. The thesis describes a rectangular calibration block measuring 200 mm in length, 50 mm in width, and 160 mm in height. A diagonal reference line was marked on the block, and holes with a diameter of 10 mm were positioned at 15 mm intervals along the line. The reference block was used to assess the response of the probe to reflectors at different positions.

For calibration, the probe was coupled to the steel block using oil and connected to the Krautkramer USL 32 instrument through a BNC cable. The instrument range was adjusted so that the reference echoes appeared at their expected positions on the display [34], [35]. This study employs a calibration configuration involving a 50 mm calibration block and a 100 mm test ring, with reference indications interpreted at nominal distances of 100 mm and 95 mm.

The distance–amplitude correction procedure involved recording the maximum echo response from the reference reflectors at their respective distances. The resulting distance and amplitude responses were used to construct the DAC representation. This procedure enabled the response of the probe to be examined as a function of reflector distance and provided a reference for comparing the fabricated probe with the commercial probe.

2.7. Comparative Ultrasonic Testing

The fabricated probe was compared with a commercial probe using the calibration setup described above. The comparison considered echo responses at nominal depths of 100 mm and 95 mm, the percentage of full-screen height (% screen), and the instrument gain setting in decibels (dB). The same reference depths and display parameters were used as reported in the thesis to allow the two probes' responses to be compared.

The comparison was interpreted descriptively by examining the recorded echo amplitudes and gain settings. The measurements were used to assess whether the fabricated probe could produce recognizable ultrasonic indications and support thickness or reflector-location measurements under the tested conditions. Because the source document does not clearly report replicate counts or statistical uncertainty, the comparison is treated as an experimental characterization rather than a statistically generalizable performance assessment.

2.8. Data Analysis

The data analysis consisted of frequency-spectrum interpretation, near-field estimation, calibration-distance verification, DAC construction, and descriptive comparison of echo responses. The dominant frequency obtained from the FFT spectrum was used to characterize the probe's operating frequency. The near-field distance was estimated from the probe's design parameters and the wave-propagation relationship applied in the thesis. Calibration results were assessed by comparing the displayed echo positions with the reference distances, while the comparative test was summarized using echo height and gain values. No inferential statistical analysis is claimed because the thesis does not provide a documented replicate structure or sufficient data for such an analysis.

3. RESULTS AND DISCUSSION

3.1. Near-Field Distance and Beam Divergence Angle

The near field is the region in which wave intensity fluctuates between minimum and maximum values. Therefore, this region is not recommended for measurements. The near-field distance can be determined from

the diameter and frequency of the crystal. The designed crystal has a diameter of 2.8 mm and a frequency of 2 MHz. Based on the calculation, the near-field distance is 0.98 mm.

The beam divergence angle obtained from the calculation is approximately 2° .

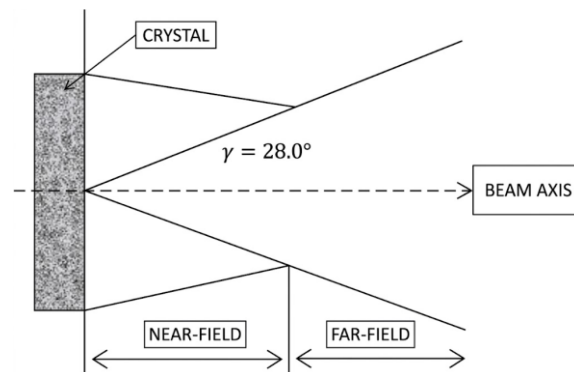


Figure 3. Measurement of the near-field angle.

3.2. Fabrication of the DAC (Distance Amplitude Correction) Block

To construct a DAC diagram, the calibration block must represent different flaw depths while maintaining the same flaw dimensions, in accordance with ASME Article 5. The recommended dimensions of the calibration block are presented in Figure 4.

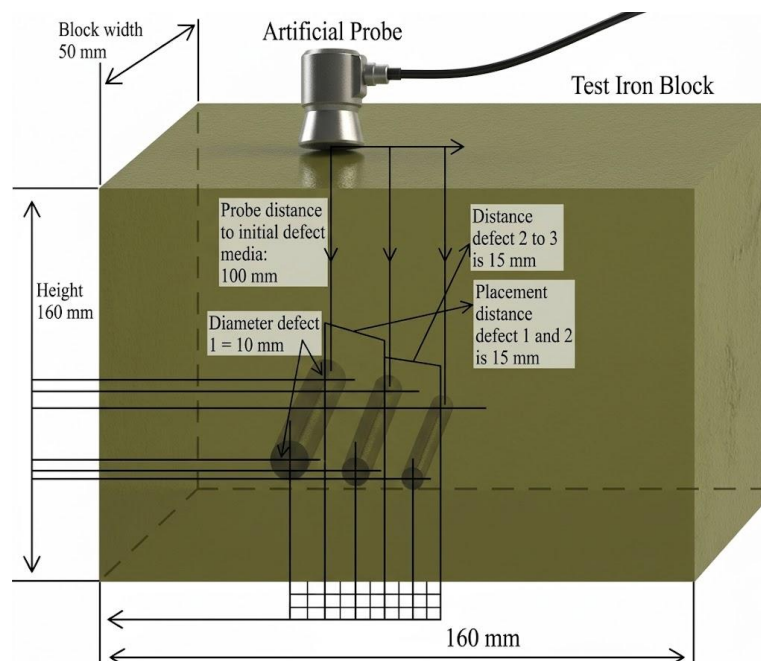


Figure 4. Calibration using the DAC block.



Figure 5. Schematic of the DAC calibration block.

Based on the requirements illustrated in Figure 5, a rectangular calibration block was fabricated with a length of 200 mm, a width of 50 mm, and a height of 160 mm. Holes with a diameter of 10 mm were made along a diagonal line at intervals of 15 mm from the right side. The actual shape of the fabricated DAC calibration block is shown in Figure 6.



Figure 6. Actual DAC calibration block.

Calibration was performed using a calibration block with a thickness of 50 mm and a test range of 100 mm. Two echo pulses were observed: the first at a scale distance of 100 mm and the second at 95 mm. These pulse positions represented depths of 100 mm and 95 mm, respectively.



Figure 7. Ultrasonic testing equipment.

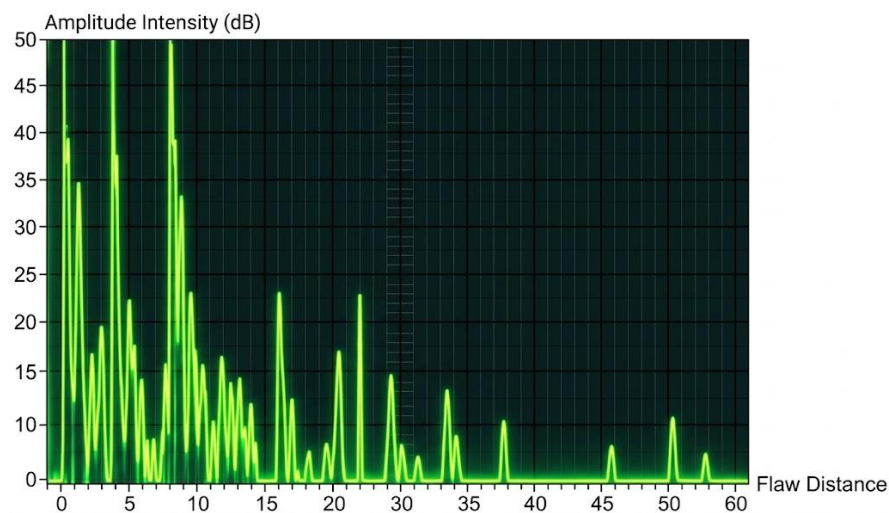


Figure 8. Echo-pulse display during calibration of the fabricated probe using the ultrasonic testing instrument.

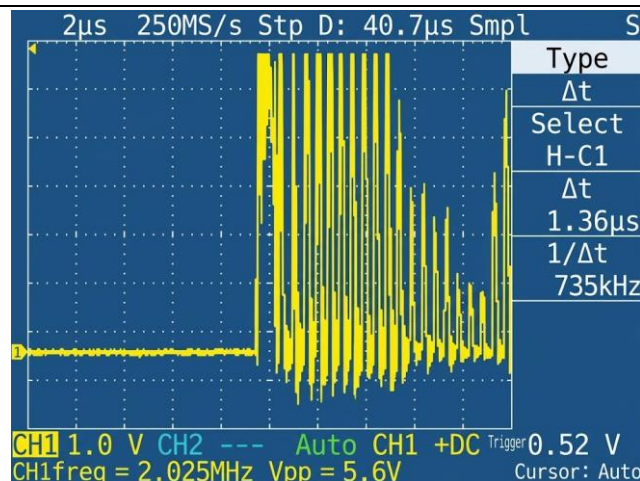


Figure 9. High-frequency wave spectrum.

3.3. Ultrasonic Field Distribution

The ultrasonic field emitted by the probe produces different pressure levels across the beam. When the probe is moved toward a flaw, only a small portion of the wave is reflected, resulting in a low-intensity pulse on the monitor. The highest wave intensity occurs at the center of the beam, as illustrated in Figure 4.8b. As the beam center moves away from the flaw, the intensity decreases until it reaches 0%.



Figure 10a. Sound beam at 10% intensity.

As the radial distance from the beam center increases, the wave pressure decreases. This reduction can be observed using an oscilloscope. When the probe is moved toward the flaw from the 10% position, the echo pulse increases until it reaches its maximum height of 100%. If the probe continues to move, the echo pulse decreases again to 10%. An oscilloscope is required to determine the percentage of the ultrasonic wave reaching the flaw.

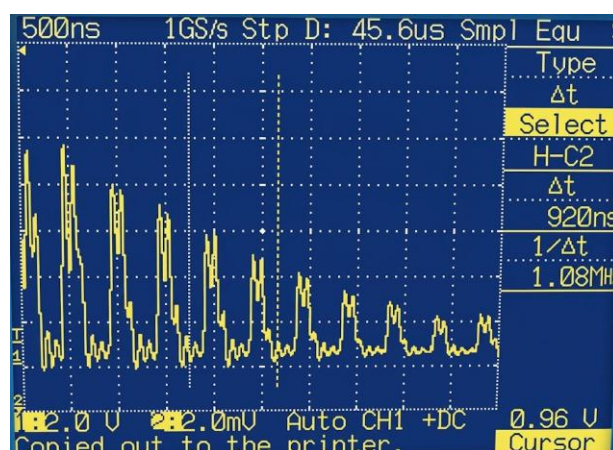


Figure 10b. Oscilloscope display at 10%.

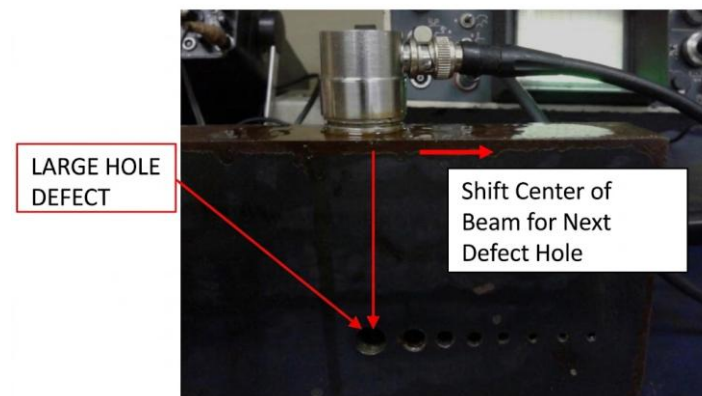


Figure 11a. Maximum echo when the flaw is positioned at the beam center.

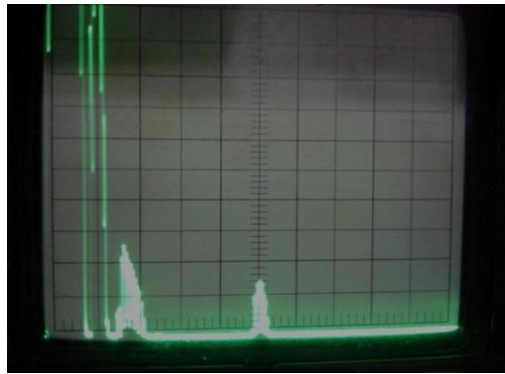


Figure 11b. Ultrasonic instrument display showing the movement of the beam center relative to the flaw hole.

3.4. Calibration Results

The fabricated probe was calibrated using a block thickness of 50 mm, a test range of 15 mm, and a calibration factor of 20 mm per division. The first pulse appeared at division 2.5, corresponding to a distance of 100 mm, while the second pulse appeared at division 5.0, corresponding to a distance of 95 mm.

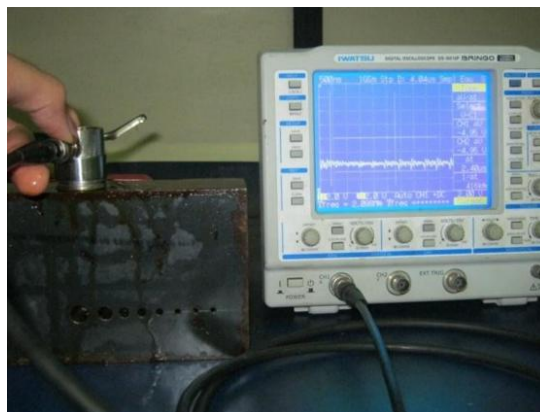


Figure 12. Calibration of the fabricated probe.

At 100% DAC, the fabricated probe indicated 40 dB, whereas the factory-made probe indicated 34 dB. The difference was attributed in the thesis to the presence of a pulse in the near-field region, which reduced the energy. Nevertheless, the fabricated probe could be used to determine the thickness and detect flaws in metallic materials.

3.5. DAC (Distance Amplitude Correction) Diagram Results

The DAC diagram is used to determine the size of flaws beneath a material's surface. The fabricated probe was able to detect a flaw with a diameter of 3 mm in steel, which was reported as consistent with ASME Article 4.



Figure 13. Echo pulse at a flaw depth of 100 mm.



Figure 14. Comparison between (A) the factory-made probe and (B) the fabricated probe.

Table 2. Comparison of the factory-made and fabricated probes

Probe type	Depth (mm)	Screen height (%)	Intensity (dB)
Factory-made probe	100	80	34
Factory-made probe	95	32	34
Fabricated probe	100	80	40
Fabricated probe	95	41	40

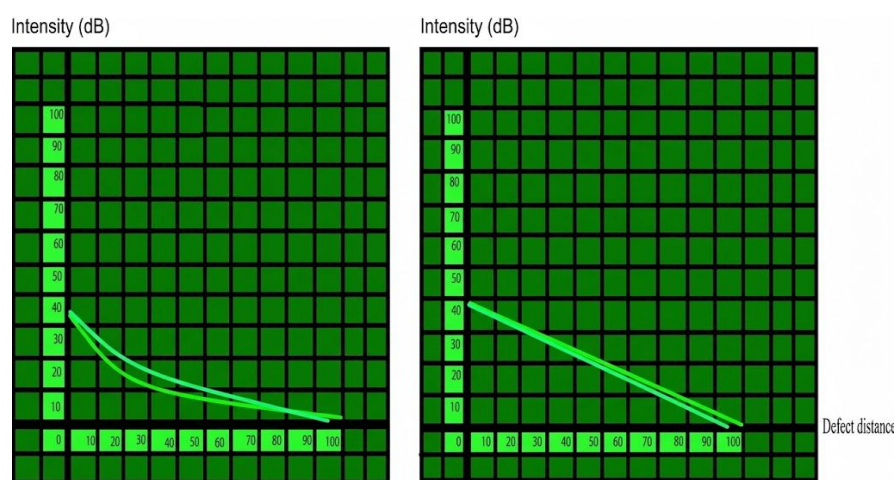


Figure 15. Comparison of the factory-made and fabricated probes.

The DAC graphs for the factory-made and fabricated probes showed a difference of 6 dB. This indicates that the factory-made probe had better resolution and sensitivity than the fabricated probe. According to the thesis, this difference was caused by an imperfect weight ratio between the epoxy and tungsten oxide powder used in fabricating the probe.

The thesis recommends mixing one part epoxy with two parts tungsten oxide powder, with a greater proportion of tungsten oxide powder. This composition is intended to dampen vibrations in the upper part of the crystal so that vibrations are transmitted primarily through the lower crystal surface facing the test material.

4.6 Ultrasonic Field Size of the Fabricated Probe

When a flaw approaches the beam-center region, the echo pulse increases in height. The maximum pulse height occurs when the flaw is directly beneath the beam center. The probe is then moved until the pulse height reaches 10%, and marks are made on the test block to determine the beam width.

Measurements using the oscilloscope showed that the fabricated probe had a beam width of 30 mm at a depth of 200 mm. This result indicates that the fabricated probe has relatively low resolution.

4.7 Frequency Spectrum Measurement of the Fabricated Probe

The frequency spectrum of the fabricated probe was measured using an oscilloscope. The emitted waveform was displayed as a complete waveform and then converted into FFT (Fast Fourier Transform) format to determine the actual frequency.

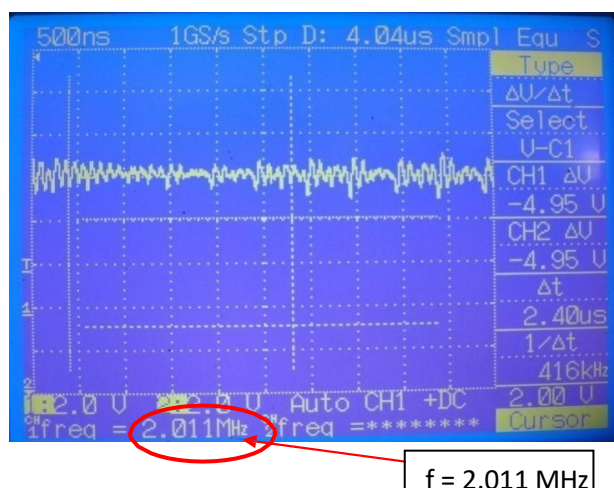


Figure 16a. Complete waveform displayed on the oscilloscope.

The measured frequency of the fabricated probe was 2.011 MHz.

The findings demonstrate the feasibility of fabricating a 2 MHz normal-incidence ultrasonic probe using a PZT piezoelectric element and an epoxy-based damping material containing tungsten oxide powder. The measured operating frequency of 2.011 MHz was close to the nominal frequency of 2 MHz, indicating that the fabricated probe operated within the intended frequency range. The probe also produced recognizable echo responses from reference reflectors at depths of 95 and 100 mm and detected a 3 mm-diameter steel reflector under the experimental conditions. However, the results reveal several performance limitations that require critical consideration. First, the fabricated probe exhibited an indicated gain of 40 dB, compared with 34 dB for the commercial probe, representing a 6 dB difference. Although the screen height at 100 mm was identical for both probes (80%), the fabricated probe required a higher indicated gain to obtain that response. This result suggests that the fabricated probe may have lower sensitivity under the tested configuration, although a definitive conclusion requires controlled measurements of gain, signal-to-noise ratio, and repeatability. At 95 mm, the fabricated probe produced a screen height of 41%, compared with 32% for the commercial probe, indicating that the response pattern was not uniformly better for either probe at both reference depths. Furthermore, the measured beam width of 30 mm at a depth of 200 mm suggests a relatively broad acoustic field and potentially limited lateral resolution. These findings indicate that the fabricated probe was operational, but its performance should not be considered equivalent to that of a commercial probe without additional quantitative validation. The near-field calculation also requires verification because the results section reports 0.98 mm, whereas the introduction reports approximately 1.96 mm.

The present findings are consistent with previous studies demonstrating that ultrasonic transducer performance depends on the active element, backing material, acoustic field, and calibration procedure. Hidayat and Setianto [36], in a study published in *Journal of Science: Advanced Materials and Devices*, demonstrated

that the tungsten-to-epoxy ratio affects the porosity, acoustic impedance, and attenuation characteristics of tungsten-epoxy composites. Their findings support the present observation that the composition of the damping material is an important fabrication parameter. However, the present study evaluated a fabricated probe through frequency measurement, calibration, and echo response, whereas Hidayat and Setianto focused on the material properties of the backing composite. Similarly, Barakat and El-Wakil [37] investigated polyvinyl acetate composites as backing materials for ultrasonic transducers, highlighting the importance of selecting suitable backing materials for transducer construction.

These studies support the interpretation that improvements in the fabricated probe should include systematic optimization of the damping composition rather than relying solely on the nominal frequency of the PZT element. The calibration findings can also be compared with Würschig [24], who demonstrated that reference-defect characteristics and their acoustic reflection profiles influence the evaluation and repeatability of ultrasonic testing systems. This supports the use of reference reflectors and DAC analysis in the present study, while emphasizing that measured amplitudes must be interpreted in relation to reflector characteristics and measurement conditions. In addition, Lei et al. [22] investigated probability-of-detection modelling for phased-array ultrasonic testing and showed that inspection performance can vary with defect characteristics, focusing conditions, and other experimental parameters. Although their work used a simulation-based phased-array approach rather than a conventional normal probe, it reinforces the importance of evaluating detection performance under defined and repeatable conditions. Dupont-Marillia et al. [38] likewise demonstrated that ultrasonic probe configuration involves trade-offs between reflected amplitude and spatial resolution when inspecting large steel forgings. Their findings are relevant to the present result of a 30 mm beam width at a depth of 200 mm, because a detectable echo does not necessarily indicate high spatial resolution. Collectively, these studies support the importance of integrating material selection, acoustic characterization, reference-based calibration, and resolution assessment when evaluating a fabricated ultrasonic probe.

The novelty of this study lies in the integrated experimental characterization of a conventionally fabricated 2 MHz normal-incidence ultrasonic probe using a PZT element, with particular attention to its actual operating frequency, near-field characteristics, calibration response, DAC performance, and comparison with a commercial probe. Unlike studies focusing primarily on advanced phased-array configurations, numerical simulations, or the acoustic properties of backing materials, this investigation brings together probe fabrication and practical ultrasonic measurements within a single experimental framework. The measured frequency of 2.011 MHz, the echo responses at 95 and 100 mm, the comparison of screen heights and gain settings, and the measured beam width provide configuration-specific evidence of the probe's operating characteristics. The study therefore contributes practical information on the feasibility and limitations of fabricating a normal ultrasonic probe using accessible materials. Its novelty should be understood as an integrated experimental assessment and comparative characterization, rather than the introduction of a fundamentally new ultrasonic testing principle.

The findings have practical implications for the development and preliminary evaluation of ultrasonic probes for non-destructive testing of metallic materials. The measured frequency indicates that the fabricated probe can operate close to its intended nominal frequency, while the recognizable echo responses demonstrate its potential for detecting reference reflectors under the tested conditions. Nevertheless, the 6 dB difference in gain settings and the relatively broad measured beam indicate that further optimization is necessary before the probe can be considered a reliable alternative to a commercial device. Future fabrication efforts should prioritize controlling the tungsten oxide-epoxy composition, improving the consistency of the backing material, and optimizing the assembly of the PZT element and probe housing. These improvements should be accompanied by standardized calibration, repeated measurements, and quantitative assessments of signal-to-noise ratio, bandwidth, beam profile, and defect-detection capability. Previous research on tungsten-epoxy composites indicates that their acoustic properties depend on the composition and physical structure of the backing material, supporting the need for systematic material optimization [39], [40], [41]. In practical applications, the fabricated probe may serve as an experimental prototype or an educational and research instrument, provided that its limitations are clearly documented and its performance is verified before use in safety-critical inspections.

The findings should be generalized cautiously because the investigation was conducted using a specific probe design, a nominal frequency of 2 MHz, a particular calibration block, and reference reflectors at specified depths. The results demonstrate the behavior of this fabricated probe under the reported experimental conditions, but they do not establish that other probes fabricated using the same general approach will produce equivalent performance. In addition, the available results do not document sufficient replicate measurements, uncertainty estimates, or statistical analyses to determine the repeatability and reliability of the observed differences between the fabricated and commercial probes. The reported 3 mm-diameter flaw detection should therefore be interpreted as a result obtained under the experimental configuration rather than as a universal minimum detectable flaw size. The inconsistency between the reported near-field values of 0.98 and 1.96 mm should also be resolved before drawing conclusions about the acoustic field. Furthermore, the comparison of gain settings alone is insufficient to establish sensitivity differences without a clearly defined calibration procedure and consistent measurement conditions. These limitations are consistent with the broader ultrasonic testing literature,

which emphasizes that detection capability depends on defect characteristics, measurement conditions, and the repeatability of the inspection procedure [22], [24]. Future studies should therefore include multiple probe specimens, repeated calibration and detection trials, uncertainty analysis, and comparison across different reflector sizes and depths. Such work would provide a stronger basis for assessing the reproducibility, reliability, and potential industrial applicability of the fabricated probe.

4. CONCLUSION

This study successfully fabricated and characterized a normal-incidence ultrasonic probe with a nominal frequency of 2 MHz using a PZT crystal with a diameter of 2.8 mm and a thickness of 0.7 mm. The fabricated probe achieved a measured frequency of 2.011 MHz, demonstrated echo responses from reference reflectors at depths of 95 and 100 mm, and detected a 3 mm diameter steel reflector under the tested conditions. At a 100% DAC reference level, the probe produced an 80% screen-height response at a gain of 40 dB, compared with 34 dB for the commercial probe, indicating that further sensitivity and performance evaluation is necessary before concluding equivalence. The findings demonstrate the feasibility of fabricating a functional 2 MHz ultrasonic probe, although its beam characteristics and response consistency require further optimization. The practical implication is that the fabricated probe may serve as a prototype for ultrasonic testing research and educational applications after standardized calibration and performance validation. Its development also provides a basis for investigating how backing-material composition and probe construction influence ultrasonic response. Future research should investigate different epoxy-to-tungsten oxide ratios and backing configurations to optimize damping, bandwidth, beam profile, and sensitivity. Further studies should also include repeated measurements, uncertainty analysis, signal-to-noise ratio evaluation, and testing on multiple reference blocks to establish the reliability and generalizability of the probe's detection performance.

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