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Study of Acoustic Characterization for Reinforcing Steel Using Ultrasonic Waves

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Abstract – *The reuse of reinforcing steel bars in construction is a common practice to reduce material costs. However, bending and re-straightening processes may cause changes in mechanical properties and internal defects that are difficult to detect visually. Conventional material evaluation often relies on Destructive Testing (DT), which damages the specimen. Therefore, an accurate evaluation method is needed without damaging the material. This study aims to design and develop a portable and cost-effective Non-Destructive Testing (NDT) device to analyze the serviceability characteristics of reinforcing steel bars using the Ultrasonic Testing (UT) method based on Time of Flight (ToF). The analyzed parameters include ToF and signal amplitude. Tests were conducted on straight, bent, and re-straightening reinforcing bars with a length of 1 m and diameters of 12 mm and 14 mm. The results showed that the ultrasonic wave velocity in straight reinforcing bars was 4973.66 m/s (12 mm) and 4975.37 m/s (14 mm). In bent reinforcing bars, the velocity decreased to 4394.56 m/s (12 mm) and 4216.24 m/s (14 mm). In re-straightened reinforcing bars, the velocity increased to 4774.35 m/s (12 mm) and 4495.96 m/s (14 mm). These results indicate that the straightening process can partially restore the acoustic characteristics of reinforcing bars, making them closer to those of straight reinforcing bars. However, residual deformation still remains in the material.*

Keywords: *Non-destructive testing, Reinforcing steel, Time of flight, Ultrasonic testing*

I. Introduction

In the construction industry, high material costs are often one of the main challenges in project implementation. This condition encourages the reuse of reinforcing steel bars from previous projects as an alternative to reduce construction costs, particularly in small- to medium-scale projects. In practice, reused reinforcing steel bars are often considered suitable for reuse based solely on visual inspection. However, the reuse of materials that have undergone deformation may result in a reduction in material quality and reliability if further evaluation is not performed [1].

Reinforcing steel bars are commonly subjected to bending and re-straightening processes, which may alter their mechanical properties, induce residual stresses, reduce elongation, and increase corrosion susceptibility [2]. These deformation-induced changes can affect the load-bearing capacity of the reinforcement and consequently influence structural reliability. In addition to internal cracks, the re-straightening process may cause microstructural changes, residual stresses, and a reduction in the material's ability to absorb loads before failure [3]. Such changes can adversely affect structural resistance to loading and fatigue. Therefore, an evaluation method capable of accurately detecting material degradation and potential internal defects without damaging the tested material is required [1].

Ultrasonic Testing (UT) has been increasingly employed as a non-destructive approach for evaluating the internal condition of metallic and structural materials without inducing additional damage. Recent studies have demonstrated the effectiveness of ultrasonic and guided-wave techniques for assessing reinforcing steel, including the detection of rebar–concrete debonding, pitting corrosion, corrosion-induced degradation, and residual-strength deterioration [3]-[11]. These studies indicate that changes in material and structural conditions can modify ultrasonic-wave characteristics, such as propagation velocity, attenuation, amplitude, and time- and frequency-domain features. In reinforcing steel, these acoustic parameters are particularly relevant because bending-induced deformation, residual stresses, microstructural changes, and internal defects may alter the propagation behavior of ultrasonic waves. Consequently, ultrasonic-based characterization provides a promising approach for identifying material-condition changes that may not be readily detected through conventional visual inspection.

Despite these advances, most existing ultrasonic NDT studies on reinforcing steel have primarily focused on

corrosion detection, rebar–concrete debonding, structural degradation, or residual-strength assessment [7]-[15]. Relatively limited attention has been devoted to the acoustic characterization of reinforcing steel subjected to bending and subsequent re-straightening, particularly using a portable and low-cost ultrasonic measurement platform. Furthermore, several existing approaches rely on sophisticated signal-processing algorithms, numerical models, or high-performance ultrasonic instrumentation, which may increase implementation complexity for routine field inspection. Therefore, there remains a need for a cost-effective ultrasonic system capable of quantitatively determining whether bending and re-straightening processes produce measurable changes in the ToF and received-signal amplitude of reinforcing steel.

Therefore, this study focuses on the design of a microcontroller-based ultrasonic testing device to evaluate the characteristics of reinforcing steel bars using a non-destructive approach. The developed system is designed as an alternative to commercial UT instruments by offering a more portable size and lower cost, making it more suitable for field applications. The ultrasonic-based NDT method was selected because it is capable of detecting the internal condition of materials through wave analysis without causing damage. This capability is particularly important because changes in mechanical properties and the possibility of internal defects caused by the bending and straightening processes of reused reinforcing steel bars are difficult to identify through visual inspection. Therefore, the developed system is expected to assist in the material qualification process to ensure the safety and reliability of building structures.

II. Research Method

A. Non-Destructive Test (NDT) – Ultrasonic Test (UT)

NDT is a testing method used to evaluate material properties, internal structures, and the presence of defects in a component without causing damage or affecting its functionality. Therefore, the tested object can still be used after the inspection process is completed [4]. The main advantage of NDT is its ability to inspect components directly without causing damage, making it suitable for routine inspection and condition monitoring. However, this method also has several limitations, including the need for trained operators, potentially expensive equipment, and result interpretation that may be influenced by the inspector's experience [7].

UT method in this study uses the direct transmission method with two transducers that function as a transmitter and a receiver at both ends of the test material. The ultrasonic wave generated by the transmitting transducer propagates directly through the material and is received by the receiving transducer. During the propagation process, the wave characteristics are influenced by the elastic properties, density, and internal condition of the material. Deformation, microstructural changes, or internal defects may cause changes in wave propagation velocity, ToF, and the amplitude of the received signal. Therefore, the direct transmission method is used to evaluate material characteristics through the analysis of ToF and ultrasonic wave amplitude [8].

In this study, the ToF was obtained from the time difference between the transmitted signal and the received signal. The ToF value was used to calculate the ultrasonic wave propagation velocity. The relationship between wave propagation velocity, propagation distance, and travel time is expressed using Equation (1).

$$s = v \times ToF \tag{1}$$

where s denotes the propagation distance, v represents the ultrasonic wave velocity, and ToF denotes the wave travel time. In reinforcing steel bars, the velocity of longitudinal ultrasonic waves is taken as 5960 m/s [9].

B. System Design

The developed material testing system consists of a power supply, a DC–DC converter, an STM32 microcontroller, an AD9850 Direct Digital Synthesis (DDS) signal generator module, a power amplifier circuit, ultrasonic transmitter and receiver sensors, a low-pass filter (LPF) circuit, and an oscilloscope for data acquisition. The system block diagram is shown in Fig. 1.

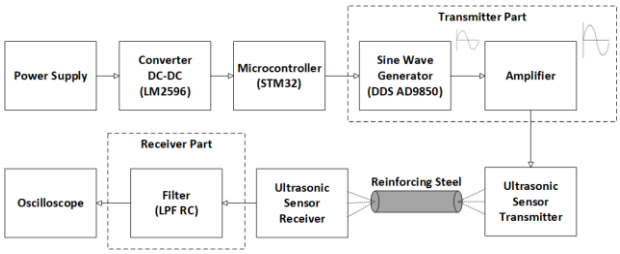


Fig. 1. Block Diagram

On the transmitter side, the STM32 microcontroller controls the AD9850 module to generate a sinusoidal signal at a predetermined frequency of 10 kHz. The generated signal is then amplified by a power amplifier circuit to provide sufficient amplitude for propagation through the steel reinforcing bar specimen. The ultrasonic wave is subsequently transmitted into the material by the transmitting sensor. On the receiver side, the transmitted wave resulting from its interaction with the internal structure of the material is received by the ultrasonic receiving sensor. The received signal is then passed through an RC LPF circuit to reduce noise before being displayed on the oscilloscope. The time difference between the trigger signal and the received signal is used for ToF analysis to identify changes in the material characteristics.

The testing process begins when the prototype is supplied with power. The system then initializes the AD9850 module, generates the ultrasonic wave, and transmits the signal to the test material. After the received

signal is detected, the oscilloscope is used to observe the waveform and determine the time difference between the trigger signal and the received signal. This value is then used for the analysis of the acoustic characteristics of the material. The testing system can be seen in Fig. 2.

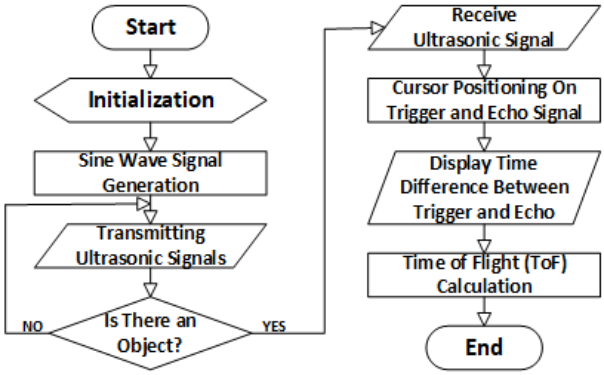


Fig. 2. Flowchart

Based on Fig. 2, the system begins by initializing the signal generator settings, after which the signal is generated and transmitted to the ultrasonic transmitting sensor. If no object is present, the system continuously transmits the signal through the ultrasonic transmitting sensor. If an object is present, the ultrasonic receiving sensor receives the signal, which is then displayed on the oscilloscope. Next, the cursors are positioned on the trigger signal and the received signal to determine the time difference (ToF). After obtaining the time difference, the ToF is calculated, and the propagation distance is determined.



Fig. 3. External view of Prototype

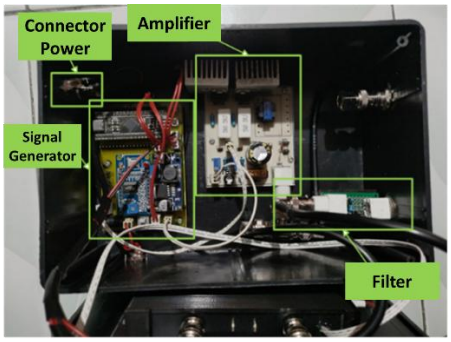


Fig. 4. Internal view of Prototype

The realized ultrasonic NDT prototype is shown in Fig. 3 and Fig. 4. Fig. 3 presents the external appearance of the prototype, while Fig. 4 shows the arrangement of the internal electronic modules and circuits used in the system.

C. *Amplifier Circuit Design*

The amplifier circuit was designed to amplify the sinusoidal signal generated by the signal generator before it is transmitted to the test material. Amplitude amplification is required to ensure that the ultrasonic wave has sufficient energy to propagate through the reinforcing steel bar and be properly received by the receiving sensor. The amplifier was developed using a Class AB push-pull configuration with the IRF510 MOSFET as the active amplifying element. To increase the output voltage according to the system requirements, a center-tapped transformer (CT) was used as the main amplifying element.

The input signal had an amplitude of 1 Vpp at a frequency of 10 kHz. Based on the IRF510 datasheet, the gate-source threshold voltage ranges from 2–4 V, while the maximum drain-source voltage is 100 V. To ensure continuous operation in the active region and achieve linear amplification, the gate voltage was set to 4 V. This DC bias voltage was generated using a voltage-divider circuit.

In the push-pull configuration with a 12 V power supply, one side of the transformer primary winding is pulled to ground when one of the MOSFETs is turned on. This condition produces a peak-to-peak voltage of 24 Vpp on the primary side. To achieve the target output voltage of 50 Vpp, the transformer turns ratio was calculated based on the ratio of the number of secondary turns to the number of primary turns, resulting in a ratio of approximately 2:1. Based on these calculation results, a CT transformer with a turns ratio close to 2:1 was selected.

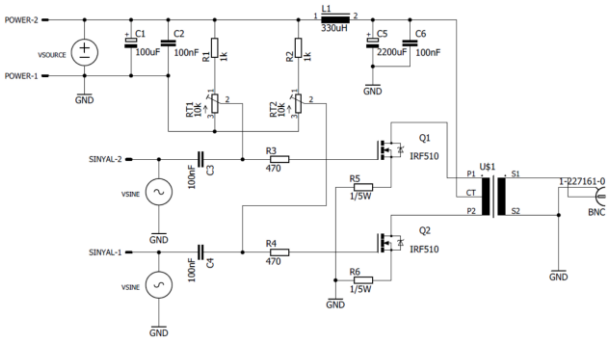


Fig. 5. Amplifier circuit schematic

To ensure stable circuit operation, several supporting components were used in the input and power supply sections. A coupling capacitor was installed at the input to block the DC component from the biasing circuit so that only the AC signal was passed to the amplification stage. A gate resistor was used to suppress high-frequency oscillations, while an RF choke functioned to prevent high-frequency signals from returning to the

power supply. In addition, a decoupling capacitor was used together with the inductance of the power supply line to form an LC filter that functions to reduce interference and maintain voltage stability during the amplification process. The amplifier design can be seen in the schematic shown in Fig. 5.

D. Data Acquisition Procedure

Data acquisition was performed after the system successfully generated a single-cycle burst-mode sinusoidal signal. Next, the ultrasonic transmitting sensor and the receiving sensor were positioned at both ends of the reinforcing steel bar so that the ultrasonic wave could propagate directly through the material. The trigger signal and the received signal were then displayed on the oscilloscope for analysis. The ToF value was obtained from the time difference between the beginning of the trigger signal and the beginning of the received signal.

The experiments were conducted on straight (new), bent, and re-straightened steel reinforcing bars with a length of 1 m and diameters of 12 mm and 14 mm. For the straight specimens, the ultrasonic sensors were positioned at both ends of the material. Measurements were carried out from two different positions: the side close to the bending point and the side far from the bending point. The measured time differences were subsequently processed to calculate the ultrasonic wave propagation velocity and to compare the acoustic characteristics of the different material conditions. The data acquisition setups are illustrated in Figs. 6, 7, and 8.

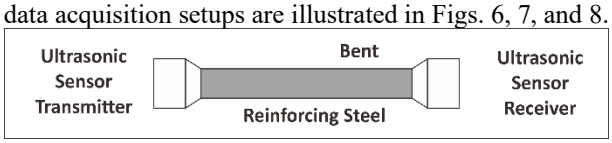


Fig. 6. Straight Reinforcing Steel Data Collection

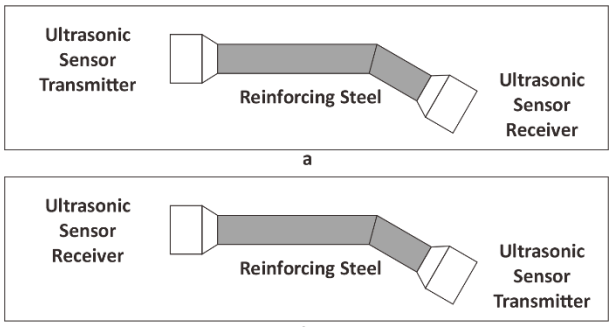


Fig. 7. Bent Reinforcing Steel Data Collection (a) Far from Bend (b) Near from Bend

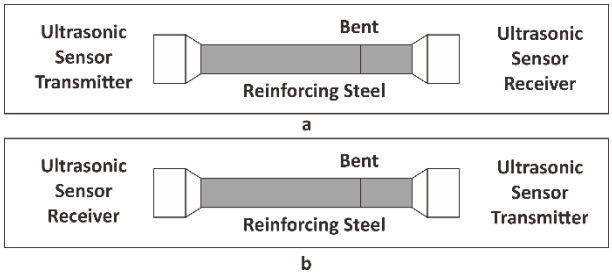


Fig. 8. Re-straightened Reinforcing Steel Data Collection (a) Far from Bend (b) Near from Bend

III. Result and Analysis

A. Amplifier Testing

The amplifier was tested using a sinusoidal signal generated by the signal generator with an input amplitude of 1 Vpp. Two input signals with phase angles of 0° and 180° were applied in accordance with the push-pull configuration. A commercially available center-tapped (CT) transformer was used in the amplifier circuit. The amplifier gain characteristics are illustrated in Fig. 9.

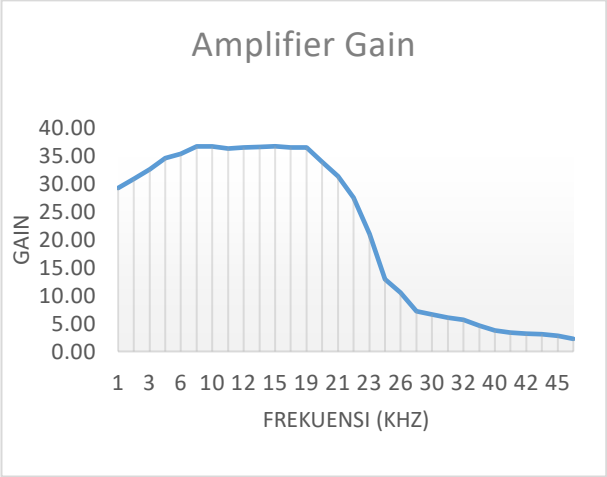


Fig. 9. Amplifier Gain Graph

The test results show that the amplifier circuit was capable of amplifying the input signal from 1 Vpp to approximately 2–36 times its original amplitude, depending on the operating frequency. In the frequency range of 1–10 kHz, the gain increased gradually from 29.20 to 36.60 times. Between 10–19 kHz, the gain remained relatively stable at approximately 36 times. However, in the frequency range of 20–50 kHz, the gain decreased progressively from 33.86 to 2.25 times.

Based on Fig. 9, a reduction in gain is observed because the amplifier was specifically designed to operate at a frequency of 10 kHz. This decrease in gain is mainly attributed to the transformer characteristics, particularly the ferrite core used in the transformer. The ferrite core is characterized by parameters such as flux density and operating frequency, which are closely related. As the operating frequency increases, the magnetic flux density decreases. In the amplifier design, the flux density was determined based on the initial design frequency. Therefore, when the operating frequency exceeds the design frequency, the transformer efficiency decreases, resulting in a reduction in amplifier gain [12].

Although the initial design target was to produce an output voltage of 50 Vpp, the test results showed that the maximum amplification achieved was only approximately 36 Vpp. This was due to the use of an EE-

19 center-tapped (CT) transformer, which was the only type of CT transformer commercially available. The core size and capability of the EE-19 transformer limited the voltage step-up process, preventing the target output of 50 Vpp from being achieved. Nevertheless, the 36 Vpp output amplitude was still sufficient to generate an ultrasonic wave that could propagate through the reinforcing steel bar and be properly received by the receiving sensor, allowing the system to be used for ultrasonic testing.

B. Results of Bent Reinforcing Steel

Each measurement was repeated 15 times, and the average value was used for analysis. The tests were carried out using two measurement configurations. The averaged results obtained from the bent reinforcing steel bar specimens are summarized in Table I.

TABLE I
AVERAGE MEASUREMENT RESULTS OF BENT SPECIMENS

Condition			Amplitude Received (mVpp)	Time Difference (us)	Velocity (m/s)
12 mm	Straight		135.07	201.07	4973.66
	30°	Trigger Far	124.93	205.73	4861.39
		Trigger Near	136.27	204.40	4893.07
	60°	Trigger Far	129.47	207.07	4829.53
		Trigger Near	134.27	206.40	4845.94
	90°	Trigger Far	117.33	228.13	4394.56
		Trigger Near	122.13	225.33	4448.72
14 mm	Straight		94.13	201.07	4975.37
	30°	Trigger Far	78.40	212.27	4731.72
		Trigger Near	88.53	211.73	4743.34
	60°	Trigger Far	87.60	215.47	4651.56
		Trigger Near	88.13	214.93	4666.05
	90°	Trigger Far	84.67	237.20	4216.24
		Trigger Near	88.80	232.93	4298.66

Based on the test results in Table I, the position of the ultrasonic trigger sensor affects the ToF value and the amplitude of the received signal, where placing the trigger sensor farther from the bend tends to produce a larger time difference than placing it closer to the bend. These results indicate that the presence of a bend affects the ultrasonic wave propagation characteristics within the material. The difference in amplitude indicates the attenuation of ultrasonic wave energy due to changes in the material geometry at the bent region.

The velocity column table is obtained based on calculations using Equation (1), showing that the ultrasonic wave propagation velocity in bent reinforcing steel bars was lower than that in straight reinforcing steel bars. The decrease in velocity calculated from the ToF indicates that the bending process causes material deformation, resulting in the reinforcing steel bar undergoing stretching or elongation. The greater the bending angle, the greater the ToF value obtained and the smaller the amplitude of the received signal, indicating changes in the acoustic characteristics due to deformation in the reinforcing steel bar material. Representative ultrasonic waveforms obtained from the bent reinforcing bar specimens are shown in Figs. 10 and 11.

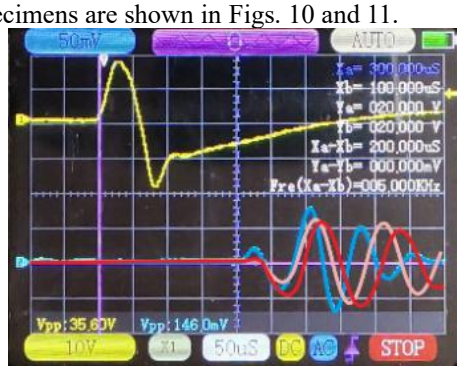


Fig. 10. Ultrasonic waveform of bent reinforcing steel bent 90°, 12 mm

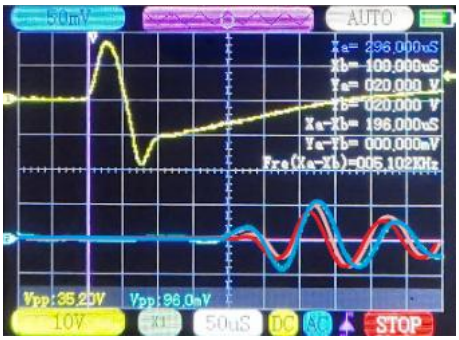


Fig. 11. Ultrasonic waveform of bent reinforcing steel bent 90°, 14 mm

Figs. 10 and 11 show the comparison of ultrasonic signals in straight reinforcing steel bars and bent reinforcing steel bars. The yellow signal represents the trigger signal. A difference in the arrival time of the received signal can be observed under each condition. The received signal of the straight reinforcing steel bar (blue) arrived first, whereas the bent reinforcing steel bar with the sensor positioned near the bend (red) experienced a slight delay. The bent reinforcing steel bar with the sensor positioned farther from the bend (pink) showed the latest arrival time. The difference in the received signal arrival time resulted in a larger ToF value in the bent reinforcing steel bar, indicating that deformation caused by bending affects the propagation of ultrasonic waves within the material.

C. Results of Re-straightened Reinforcing Steel

Each measurement was repeated 15 times, and the average value was used. The tests were carried out using two measurement configurations. The averaged results

obtained from the re-straightened reinforcing steel bar specimens are summarized in Table II.

Based on the test results in Table II, the position of the ultrasonic trigger sensor affects the ToF value and the amplitude of the received signal, where placing the trigger sensor farther from the bend tends to produce a larger time difference than placing it closer to the bend. These results indicate that the straightening process still affects the ultrasonic wave propagation characteristics within the material, even though the physical shape of the reinforcing steel bar has returned to a condition close to straight. The difference in amplitude indicates that the deformation and straightening processes cause changes in the material characteristics, resulting in the attenuation of ultrasonic wave energy as it propagates through the reinforcing steel bar.

TABLE II
AVERAGE MEASUREMENT RESULTS OF RE-STRAIGHTENED SPECIMENS

Condition			Amplitude Received (mVpp)	Time Difference (us)	Velocity (m/s)
12 mm	Straight		135.07	201.07	4973.66
	30°	Trigger Far	112.40	205.73	4861.57
		Trigger Near	118.67	203.87	4905.58
	60°	Trigger Far	119.47	208.40	4798.89
		Trigger Near	124.80	207.20	4826.54
	90°	Trigger Far	122.93	209.47	4774.35
		Trigger Near	125.20	208.40	4798.83
14 mm	Straight		94.13	201.07	4975.37
	30°	Trigger Far	85.33	203.60	4911.86
		Trigger Near	87.20	202.80	4931.40
	60°	Trigger Far	85.07	209.60	4771.52
		Trigger Near	92.27	208.13	4805.23
	90°	Trigger Far	72.27	223.20	4495.96
		Trigger Near	70.53	214.67	4676.43

The velocity column table is obtained based on calculations using Eq. (1), showing that the ultrasonic wave propagation velocity in re-straightened reinforcing steel bars was lower than that in straight reinforcing steel bars. The decrease in velocity calculated from the ToF indicates that the straightening process still leaves residual deformation, causing the reinforcing steel bar to undergo stretching or elongation. However, the velocity obtained was higher than that of the bent reinforcing steel bar, indicating that the acoustic characteristics of the re-straightened reinforcing steel bar tend to approach those of the straight reinforcing steel bar. Nevertheless, the lower amplitude of the received signal indicates that changes in the material structure due to deformation still affect the propagation of ultrasonic waves within the material. Representative ultrasonic waveforms obtained from the re-straightened reinforcing bar specimens are shown in Figs. 12 and 13.

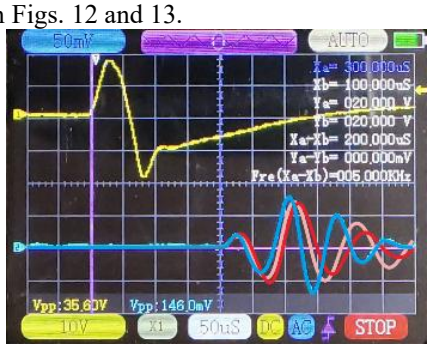


Fig. 12. Ultrasonic waveform of re-straightened reinforcing steel bent 90°, 12 mm

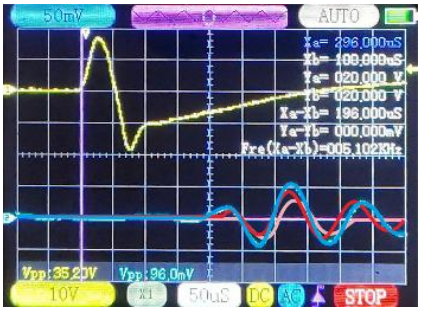


Fig. 13. Ultrasonic waveform of re-straightened reinforcing steel bent 90°, 14 mm

Figs. 12 and 13 show the comparison of ultrasonic signals in straight reinforcing steel bars and re-straightened reinforcing steel bars. It can be observed that the arrival time of the received signal in the straight reinforcing steel bar (blue) remains the earliest. Meanwhile, the re-straightened reinforcing steel bar with the sensor positioned near the bend (red) and farther from the bend (pink) shows arrival times that are relatively close to those of the straight reinforcing steel bar, although they still experience a slight delay. This indicates that the straightening process is able to reduce the effect of deformation, causing the ultrasonic wave propagation characteristics to tend to approach those of a new reinforcing steel bar. However, residual deformation still remains in the material, resulting in a slightly larger ToF value and a lower received signal amplitude compared to the straight reinforcing steel bar.

D. Acoustic Characteristic Analysis

Based on Table I, the ultrasonic wave propagation velocity in the straight reinforcing steel bar used as the reference was 4973.66 m/s (12 mm) and 4975.37 m/s (14 mm). In the bent reinforcing steel bar, the velocities at bending angles of 30°, 60°, and 90° were 4861.39 m/s, 4829.53 m/s, and 4394.56 m/s for the 12 mm diameter, and 4731.72 m/s, 4651.56 m/s, and 4216.24 m/s for the 14 mm diameter, respectively. These results indicate that the greater the bending angle, the lower the wave propagation velocity due to the increasing material

deformation. This deformation is caused by the bending process, which causes the reinforcing steel bar to undergo stretching or elongation, thereby affecting the ultrasonic wave propagation characteristics within the material.

Based on Table II, the ultrasonic wave propagation velocity in the straight reinforcing steel bar used as the reference was 4973.66 m/s (12 mm) and 4975.37 m/s (14 mm). In the re-straightened reinforcing steel bar, the velocities at bending angles of 30°, 60°, and 90° were 4861.57 m/s, 4798.89 m/s, and 4774.35 m/s for the 12 mm diameter, and 4911.86 m/s, 4771.52 m/s, and 4495.96 m/s for the 14 mm diameter, respectively. These values were still lower than those of the straight reinforcing steel bar but higher than those of the bent reinforcing steel bar at the same bending angles. This indicates that the straightening process is able to reduce the effect of deformation, causing the ultrasonic wave propagation characteristics to tend to approach those of the straight reinforcing steel bar. Nevertheless, residual deformation still remains in the material, causing the wave propagation velocity not to fully recover.

IV. Conclusion

The testing of bent reinforcing steel bars showed a decrease in ultrasonic wave propagation velocity due to material deformation caused by the bending process. At a diameter of 12 mm, the velocity decreased from 4973.66 m/s for straight reinforcing steel to 4861.39 m/s, 4829.53 m/s, and 4394.56 m/s at bending angles of 30°, 60°, and 90°, respectively. Meanwhile, at a diameter of 14 mm, the velocity decreased from 4975.37 m/s to 4731.72 m/s, 4651.56 m/s, and 4216.24 m/s, respectively. These results indicate that the greater the bending angle, the lower the wave propagation velocity.

The testing of straightened reinforcing steel bars showed higher ultrasonic wave propagation velocities than those of bent reinforcing steel bars, but they were still lower than those of straight reinforcing steel bars. At a 12 mm diameter, the velocities were 4861.57 m/s, 4798.89 m/s, and 4774.35 m/s, respectively, while at a 14 mm diameter, they were 4911.86 m/s, 4771.52 m/s, and 4495.96 m/s for bending angles of 30°, 60°, and 90°, respectively. These results indicate that the straightening process is able to reduce the effect of deformation, although residual deformation still remains in the material.

The developed ultrasonic-based NDT system is capable of evaluating acoustic characteristics through the ToF, wave propagation velocity, and received signal amplitude parameters. Therefore, it has the potential to serve as a practical and cost-effective non-destructive testing solution for field inspection.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper. The research was conducted independently within the academic environment of Politeknik Elektronika Negeri Surabaya, and no financial, commercial, or personal relationships influenced the study design, data analysis, interpretation of results, or decision to publish this work.

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