Robotic Arm-Aided Non-Destructive Testing Using Eletromagnetic Acoustic Transducers for Thickness Measurement in Industrial Applications

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In the oil and gas industry, expediting inspections of critical components is imperative. Overcoming Nondestructive Testing (NDT) challenges is crucial for forecasting future demand, particularly in difficult-to-reach areas. Within the realm of robot manipulators, modern robots possess desirable qualities for constructing automated NDT systems capable of meeting the demanding specifications of the oil and gas sector. This study introduces an autonomous inspection using a robotic arm with 5 degrees of freedom to assess the effectiveness of nondestructive inspection via an electromagnetic acoustic transducer in plate metal thickness measurement. The enhanced inspection speed and anticipated operational limits for conducting the scan enhance the visualization of various thicknesses.
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The passage elucidates the functionality and significance of robotic arms equipped with 5 Degrees of Freedom (DoF), elucidating their capability to maneuver in diverse directions through interconnected joints. It delineates the utility of 5 DoF robotic arms in conducting nondestructive testing (NDT) via ultrasonic immersion inspection to identify flaws and defects in materials and structures.

Furthermore, it underscores the advancement of industrial robots in manipulating probes with heightened speed and precision compared to alternative NDT techniques. However, it emphasizes the necessity to optimize robotic trajectory to minimize inspection duration and investigates factors influencing the efficiency of robotic scanning motion, including those often overlooked in current methods. In NDT applications utilizing industrial robots, the conventional setup involves securing the specimen while the robot handles the ultrasonic probe and executes operations [1,2].

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The article delves into integrating a robotic arm with nondestructive testing utilizing electromagnetic acoustic transducers (EMAT) for thickness measurement in industrial contexts. It delves into the benefits of leveraging a robotic arm for NDT with EMAT technology, enabling non-contact and nondestructive inspection of materials.

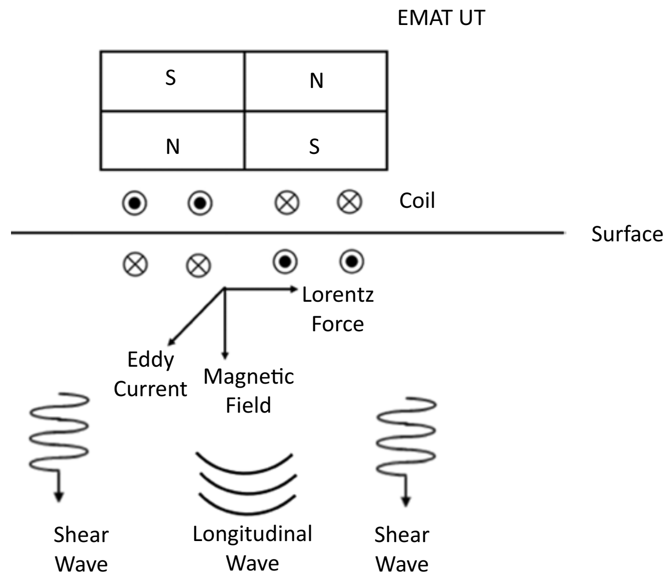
Materials and Methods

EMAT Theory and Automated Inspection

In an EMAT setup, a coil generates dynamic electromagnetic fields on the surface of a conductive material, while permanent magnets or electromagnets establish a biasing magnetic field [3,4]. The EMAT operates based on the interactions between these electromagnetic fields within the material, the resulting forces on the body due to the interactions between the electromagnetic and elastic fields, and the computation of the acoustic fields arising from these forces on the component [5-7]. Figure 1 illustrates the behavior of longitudinal and shear ultrasonic waves [3].

The Lorentz force directly impacts the ions within the material, inducing mechanical vibration and potentially generating an ultrasonic wave. When an external magnetic field is applied to a ferromagnetic material, a dimensional change occurs depending on the magnitude and direction

Figure 1. EMAT longitudinal (L-wave) and shear (S-wave) propagation [3].



of the field [6,7]. Magnetostriction, the property of ferromagnetic materials to deform in the presence of an external magnetic field, contributes to higher energy conversion efficiency in EMATs based on magnetostriction compared to those based on the Lorentz force [10,11].

The advantage of EMATs lies in their non-contact nature, allowing for continuous operation at high temperatures without requiring physical coupling, sample preparation, or active cooling of the transducer [12-14]. When measuring metal plate thickness, EMATs assess the time interval of the echo signal to determine the plate's thickness. Traditionally, the transit time between two consecutive echoes in an ultrasonic waveform is used as the time-interval value, with signal amplitude and signal-to-noise ratio (SNR) serving as critical indicators of measurement accuracy.

Inspecting defects in specimens with complex surface shapes using traditional manual ultrasonic testing (UT) methods is challenging due to the difficulty in manipulating the probe [15].

However, robotic scanning technology has garnered significant interest due to its enhanced repeatability and accuracy. Robot arms offer the advantage of accessing areas and inspecting geometries impractical for manual methods [16].

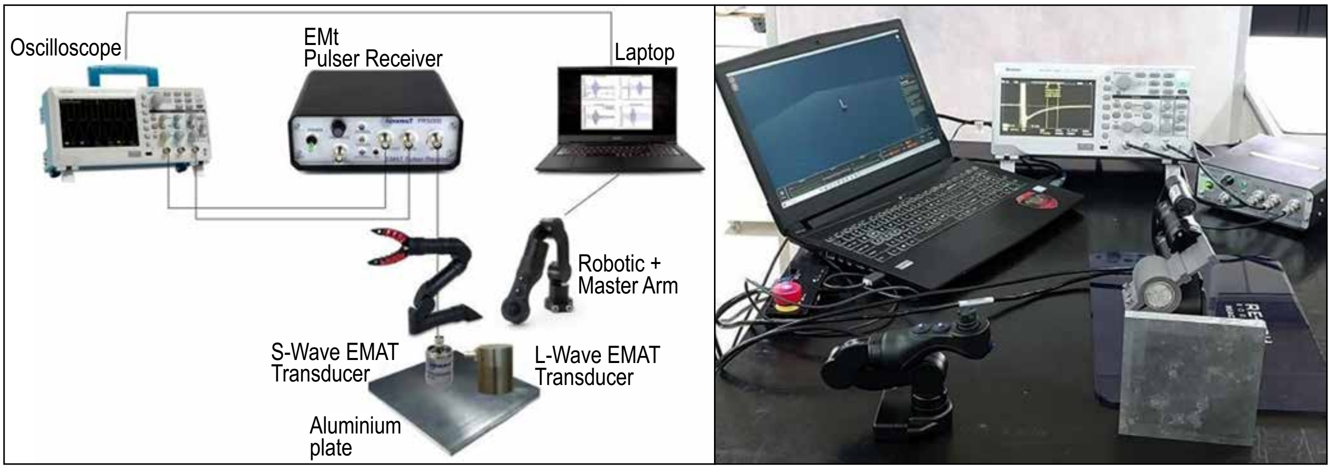
Hamidreza and colleagues [17] developed and evaluated a flexible robotic gripper incorporating embedded EMATs within a versatile lizard-inspired tube inspector (LTI) robot. The gripper affixed to a robotic manipulator, was assessed on pipes of varying outer diameters. The system effectively captured transmitted and received signals in the time domain, observing signal amplitude amplification with increased sample diameter.

Furthermore, EMATs were integrated into the robotic ultrasonic system to generate Lamb waves with satisfactory SNR for inspecting tubular components. The system's effectiveness in detecting cracks and corrosion was evaluated through experimental measurements of artificially induced defects.

Experimental Setup

The schematic depicted in Figure 2 illustrates the setup utilized for the nondestructive testing process. The Reach Robotics© Alpha 5 manipulator served as the platform for conducting the tests, employing two types of EMAT transducers from SONEMAT in its end effector: an S-wave 5 MHz center frequency HWS2225GC

Figure 2. Arrangement experimental.



and an L-wave 5 MHz center frequency LW155T. To accommodate each EMAT transducer, a custom gripper was designed with dimensions tailored to the specific requirements of the L-wave and S-wave transducers. The movement of the gripper was controlled using the master arm of the Alpha 5 manipulator.

The EMAT PR500 pulse generator system delivers a 400 V pulse adjusted at a 100 kHz Pulse Repetition Frequency (PRF) to the selected EMAT transducer. Subsequently, the output signal collected by the transducer is digitized by the Tektronix© TDS1102C oscilloscope, which boasts a sampling rate of 4 MS/s and a data length of 20000 samples. To minimize the influence of noise, the received signal undergoes 256-time averaging by the oscilloscope. Ultrasonic signals are collected via a laptop connected to the oscilloscope's USB port, utilizing a data acquisition system for waveform analysis with the designed EMAT. Additionally, the laptop facilitates communication with the robotic arm via the RS232 port of the master arm, allowing control over the position, speed, acceleration, and torque of the Alpha 5 manipulator.

To evaluate the inspection capacity of the EMAT transducer using the Alpha 5 manipulator, an aluminum testing plate measuring 100 x 100 x 10 mm is selected. A comparative analysis will be conducted between the results obtained from the manually performed experiment and those obtained through the described robotic arm experiment.

Figure 3 depicts the analysis flowchart outlining the utilization of EMAT with the robotic manipulator. In this setup, the liftoff distance varies from 0 to 1 mm, aiming to assess the ability to measure thickness without a signal amplifier in the pulser receiver system. One hundred thickness measurements are conducted using this experimental scheme to cover various regions of the aluminum specimen. Mean values and standard deviations are computed to evaluate material thickness.

Results and Discussion

Figure 4 displays the typical received signals of EMATs for L-Wave and S-Wave, respectively. The reflection peaks of the testing block, which will be utilized for thickness measurement, are distinctly visible. These peaks indicate thickness variation in the block and provide crucial information for inspection. Comparatively, when employing the robotic arm inspection technique, the amplitude intensity of the received signals is compatible with manually collected signals.

The utilization of the Alpha 5 robotic arm offers significant advantages in terms of signal intensity and reliability. The robotic arm ensures consistent

Figure 3. Fluxogram to perform EMAT analysis.

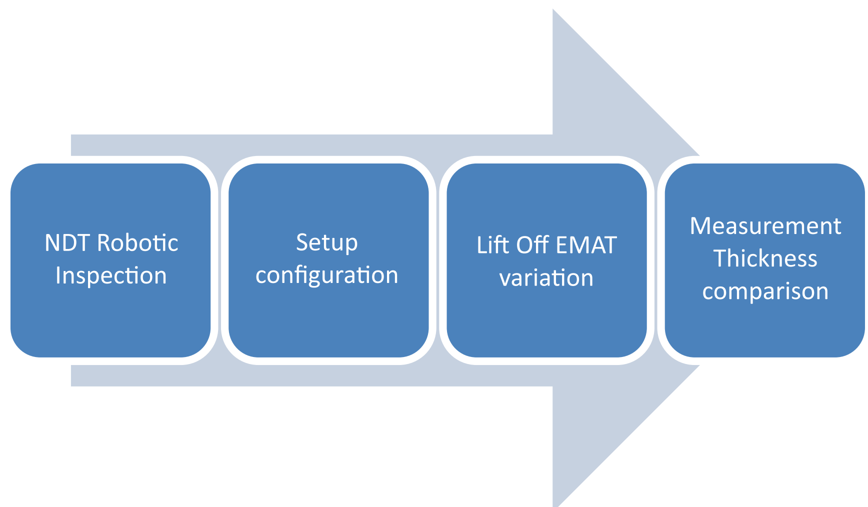
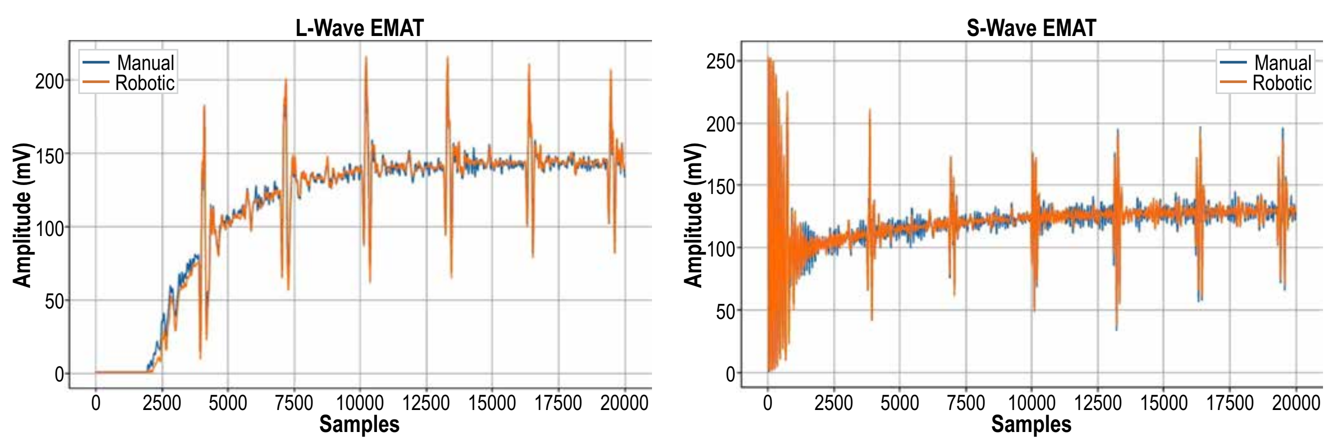


Figure 4. Signal collected comparison for Longitudinal and Shear Waves.



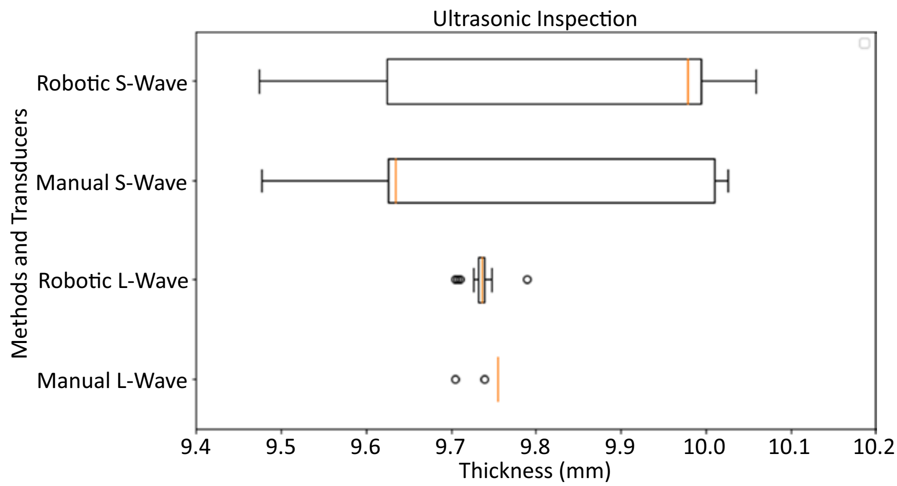
and precise application to the EMAT transducer, producing more robust and pronounced ultrasound signals. These higher signal amplitudes facilitate easier detection and analysis of reflection peaks, enabling more precise thickness measurements. Furthermore, robotic arm inspection with the Alpha 5 diminishes the likelihood of signal distortion or noise interference, leading to more reliable inspection results.

As a result, robotic measurement of plate thickness using EMAT has the potential to yield more accurate results than measurements performed by an operator using identical transducers. Figure 5 depicts a comparative boxplot of the actual thickness values, those obtained through manual measurements, and those achieved using Alpha 5. The boxplot illustrates that the robotic measurements are more tightly clustered around the actual thickness values, indicating higher accuracy.

The boxplot analysis, employing zero liftoff techniques, provides valuable insights into the suitability of the robotic signals for measuring the thickness of aluminum using nondestructive inspection techniques with EMAT transducers. It allows for observation of the average values and dispersion of the signals, offering crucial information about their effectiveness and reliability.

When examining the average values, we can assess whether they align with the desired

Figure 5. Boxplot for all thickness measurement experiments.



measurement accuracy for aluminum thickness. The boxplot analysis confirms that the average values obtained from the robotic signals fulfill this purpose. The robotic arm demonstrates excellent efficiency and successfully meets the high-speed inspection requirements to capture and measure the thickness of aluminum with the desired precision.

Furthermore, the dispersion of the signals, as depicted in the boxplot, provides an understanding of the variability or spread in the measurements. In the case of the robotic signals, the dispersion is also deemed appropriate for the proposed task, and this implies that the measurements obtained from the robotic arm inspection exhibit consistent and reliable results, as the dispersion falls within an acceptable range.

The analysis of thickness calculation and the corresponding error margin, expressed as a percentage, is presented in Table 1.

The Table 1 offers valuable insights into the thickness measurements obtained using the manual EMAT and robotic approaches. A notable observation is that the manual EMAT technique exhibits a higher error margin than the robotic approach, as evidenced by the error margins in the table. This difference is primarily attributed to the considerable variation in pressure applied during manual EMAT scanning.

Conclusion

This study utilized a 5-degree-of-freedom robot arm to conduct robotic ultrasonic inspection on an aluminum test plate. The outcomes of the robotic inspection were compared against those of manual and passive compliance-based inspection.

Table 1. Margin error % measurement.

Inspection Arrangement		0mm Liftoff		1mm Liftoff	
		Thickness ($\bar{X} \pm \sigma$)	Error margin	Thickness ($\bar{X} \pm \sigma$)	Error margin
Manual	L-Wave	9.57 ± 0.01	-4.3%	10.71 ± 3.33	+7.1%
	S- Wave	9.79 ± 0.70	-2.1%	10.31 ± 0.51	+3.1%
Robotic	L-Wave	9.77 ± 0.01	-2.3%	9.55 ± 0.01	-4.5%
	S- Wave	9.89 ± 0.70	-1.1%	9.79 ± 0.71	-2.1%

The versatility of the robot arm's movements enabled the inspection of complex geometries, while ultrasonic waves facilitated the detection of surface and subsurface discontinuities.

The experimental findings demonstrated satisfactory precision with real-time data collection using a sufficiently high sampling rate, and this facilitated thickness measurement using EMAT in the aluminum test plate. The advancement of path planning software tailored for NDT inspections is anticipated. Moreover, implementing automated metrology solutions is poised to enhance the accuracy of these inspections. The evaluation of integrating a soft robotic gripper end effector will also be a focus of this study.

Furthermore, a mechanism will be developed to ensure the synchronous acquisition of real-time positional data from the robot controller for discrete points with the corresponding ultrasonic flaw echo signals. This mechanism will ensure precise alignment and correlation between positional information and ultrasonic data during inspections.

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