IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 12, Issue 6, Ver. I (Nov.- Dec. 2017), PP 41-50
www.iosrjournals.org

Development and application of wireless eddy current system for nondestructive testing

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Abstract: *In this research, a wireless communication between the sensor and main unit was developed for nondestructive eddy current inspection technique. Such wireless probe aims at being inserted into different parts of the targeted structure such as aircrafts for internal and external inspections without sacrificing Nondestructive Inspection (NDI) capabilities when compared to a conventional cable-wired probe. The new wireless probe interface can generate various types of activation signals that are synchronized wirelessly with the main unit, and also, it can process the received signal at the probe and send it back wirelessly to the main unit. The aim of developing the wireless sensor was particularly the applications in aircraft inspections. Aircrafts usually experience frequent maintenance on structure and engine. Many inspections are undertaken to identify critical flaws which could cause failure of engine or structure. Nondestructive inspection (NDI) plays an important role in these tests. Conventionally, a NDI probe is placed on the testing structures and is connected to a NDI main unit through cable, but the use of cable may cause problems such as foreign object damage (FOD) and limitations of maneuverability. The cables are also non-repairable and expensive. Running cables through tight and hazardous areas adds to the difficulty of the task for the technician. On the other hand, wireless NDI has the advantage of safety, economic benefits, and maneuverability. Experiments on the detection of different defects and test set up were carried out and compared to wired NDI system to evaluate the wirelessly transmitted eddy current (EC) signals. Experimental results showed that the eddy current signals can be wirelessly communicated with main unit, the wireless prototype can detect defects of various sizes under various environments. The wireless signal distortion still need to be improved when compared to wired signals.*

Keywords: *Aerospace, Aircraft Inspection, Eddy Current Testing, Nondestructive Testing and Evaluation (NDT &E), Wireless Sensor*

Date of Submission: 13 -11-2017 Date of acceptance: 30-11-2017

I. Introduction

Eddy current technique has been widely used for electromagnetic material characterization and inspection of the parts and structures. In eddy current inspection technique, the oscillating magnetic field in the probe induces the eddy current in the conducting parts when the probe is brought into the close proximity to the part. The flow of eddy current in the part and changes in the electromagnetic parameters (impedance) can be used for testing and inspection of the materials. Eddy current inspection is one of the promising method for aircraft structure and engine inspections [1]–[4]. The inspection result signals are transmitting to the main processing unit using wires and cables. However, in field application, especially in aircraft structure and engine inspection [5], this can incur significant limitation in maneuverability, possible disconnection and increasing the cost and time of inspection [6]. Reliable wireless transmission of the signal for structural health monitoring and nondestructive testing applications can increase the flexibility of inspection and reduce the cost and time of testing [7]. Wireless eddy current probe has been studied [8]–[10] for use in inspection of the aircraft engine and structure. The purpose of previous studies was to inspect the complex structure of the aircraft with more maneuverability as well as insert the probe in the jet engine for the internal inspection without external cabling. The benefits of doing the inspection wirelessly are mostly on safety of inspection process, reduction of expenses and prevention of using long wires. The cables are non-repairable and thus can only be used for a few inspections before they become damaged and therefore must be replaced. However, procuring and replacement of the cables are expensive. Furthermore, the use of cables is detrimental to inspection efficiency as they have a tendency to get in the way during actual inspections. Running cables through tight and hazardous areas, a common occurrence during an inspection in aircrafts, also adds to the difficulty of the task for the technician. In wireless NDI, a reliable and accurate communication between the probe and main unit is critical to obtain consistent inspection results.

Reid et al. (2004, 2006) presented the prototype wireless eddy current probe for on-wing and engine inspection of the aircraft. In their project's first phase, notches down to 0.254 mm (0.010) were detected using 2 MHz eddy current probe and a dual-frequency phase modulated wireless analog communication system [8]. For the second phase of their project, it was tried to improve the performance of phase one with a digital wireless eddy current probe system [9].

In this paper, new development of wireless eddy current probe is described and the experimental study for its applicability for inspection with respect to different testing conditions is presented. The results of experiments on test specimens are compared to the wired EC tester. To develop the first prototype of the wireless eddy current system, it was tried to modify the current existing NDI equipment used by aerospace industry to realize the seamless wireless communication between NDI host controller and probe instead of purchasing new equipment. This would be a two-part device: one part would connect to the host controller, while the other part would connect to the NDI probe. The two parts together would serve the same function as a cable by transmitting and receiving signals between the host controller and probe but doing so wirelessly. The experiments for testing the system were considered in a way that patterns of detectable signal should be captured by the wireless system and that such pattern can be considered as the change in the sample or defect properties.

The phase I of this study which is presented here includes the technical study of the eddy current NDT system, identification and adaption of suitable wireless technology, design, and test of prototype circuit. This circuit would contain the proper components and design to accomplish the objective of two-way communication between NDI Controller and NDI Probe that the standard cable communication performed. Pending the successful completion of Phase I work, the study will continue to improve upon the breadboard prototype by turning it into a functional product capable of making an NDI tool wireless. This would be a packaged device which would be capable of initial field testing. Feedback from field testing would allow for improvements to be made to the design which will be presented subsequently.

II. Identify Suitable Technology

To realize wireless NDI, first an appropriate wireless technology has to be selected so that it can wirelessly transmit data from a transducer to the main unit. Accuracy, data rate and communication distance range are the most important factors for wireless NDI communication. If the NDI equipment is communicating using digital signals, its communication baud rate will weigh heavily on the communication speed of the wireless technology selected. If the NDI equipment communicates using analog signals, then the typical signals communicated between controller and probe will need to have a frequency analysis performed. For digital communication, faster speed is superior. They provide more accuracy in communicating signal amplitude and phase. For comparison, Bluetooth has a typical data rate of 2.1 Mbit/s; whereas, ZigBee can be up to 0.9 Mbit/s. Considering these factors, UWB communication is the most promising technique. UWB meets or exceeds all specifications and allows for the highest data rates, as 500 Mbits/sec.

III. Prototype System Design

For the first part of the work, EC NDI method has been considered for evaluation of wireless connection and inspection. NORTEC 2000D+ Eddy Current system was considered since it is mostly used for aircraft inspection. It is an Eddy current test system which offers a frequency range of 50 Hz to 12 MHz and its characteristics include single or dual frequency operation, which make it ideal for numerous aerospace NDT applications [11]. The goal is to design a prototype for this system to transfer and receive the signals wirelessly for inspection. The preliminary communication range requirement for wireless communication is 0.3-1.5 m (1-5 ft). The eddy current probe used for this project is a 200 KHz-1 MHz absolute probe. A functional block diagram of the designed prototype for wireless ET system is presented in Fig. 1. The instrument adapter and probe adapter are expanded into three stages: an interface circuit, a controller, and a transceiver. Using this topology, the phase and amplitude changes can be sent from the probe wirelessly to the instrument very quickly.

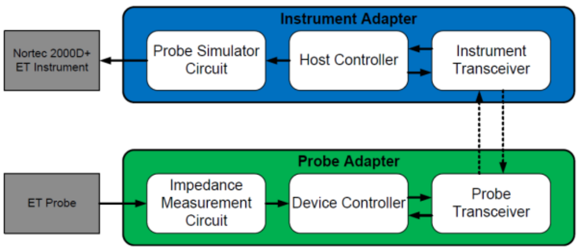


FIGURE 1. Wireless ET System Block Diagram

IV. Design Probe Adapter

The probe adapter is connected to the ET probe. The impedance measurement circuit in the probe adapter would be the interface to the ET probe, which allows the amplitude change and phase change of the signal sent in digital format which is more suitable for wireless communication through the ET probe, to be collected via hardware.

V. Design Instrument Adapter

The instrument adapter is connected to the NORTEC 2000D+ ET Instrument. The instrument transceiver receives communication data from the probe transceiver.

The probe transceiver communicates wirelessly with the instrument transceiver to make the data ready for the host controller to interpret. The host controller analyzes the data received from instrument transceiver and sets the value of the real and reactive components in the probe simulator circuit. The probe simulator circuit simulates the ET probe such that the NORTEC 2000D+ ET Instrument does not know that the ET probe is not physically connected anymore.

VI. Experimental Setup And Test Results

After calibration, flaws were easily detected with the impedance measurement circuit. In addition to a pre-cracked steel barrel, the 4-Notch eddy current standard test block, with 0.254, 0.508,0.762 and 1.016 mm (0.01, 0.02, 0.03 and 0.04 inches) depth slots, and conductivity sample, with the range of materials including; FE (Ferrite, MN60 (ui=6000)), TI (Ti 6-4), 304 SST, CU/NI(90-10 CuNi), MAG (Magnesium , 97Mg-3Al-1Zn or AZ31B-H24), 7075 AL (Al7075-T6), and 1100 AL(Al1100-H14) were used to evaluate the wireless system (Fig. 2). For calibration block, the impedance measurement was able to determine slot sizes from 0.254 mm to 1.016 mm (0.01” to 0.04”) in depth.

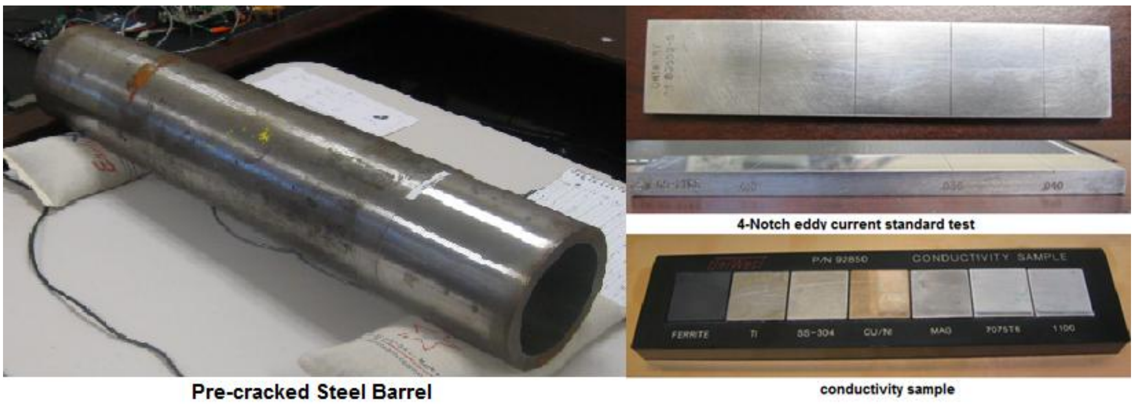


FIGURE 2. Pre-slot steel barrel (Left) and the 4-Notch EC standard test block and conductivity sample (Right)

In the case of notch sample, when the probe was not pressed to a metal, the amplitude voltage level was maxed out to 3.4 V, which is the lift off voltage. When the probe was pressed to steel, the amplitude voltage level dropped to ~2.0V. Finally, as the probe passed over the 0.508, 0.762 and 1.016 mm (0.04”, 0.03”, and 0.02”) slots, voltage levels dropped from 2.0V to ~1.1V, ~1.25V, and ~1.4V, respectively (Fig. 3).

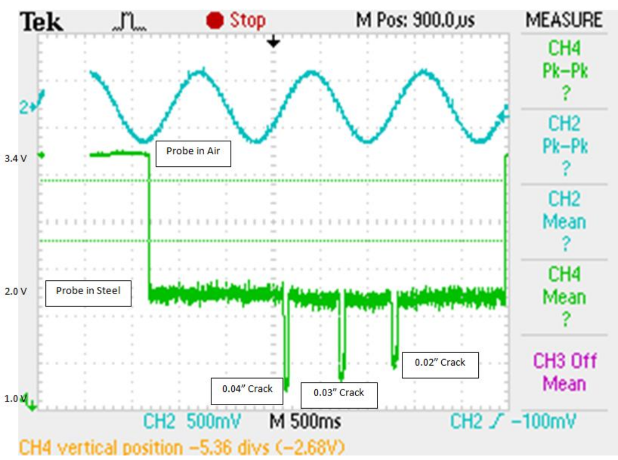


FIGURE 3. Probe Simulator Circuit I/O Signal Diagram

The signals in Fig. 4 have been detected right after "Impedance measurement circuit" of probe adapter to evaluate the appropriate signals for implementation of wireless transmission.

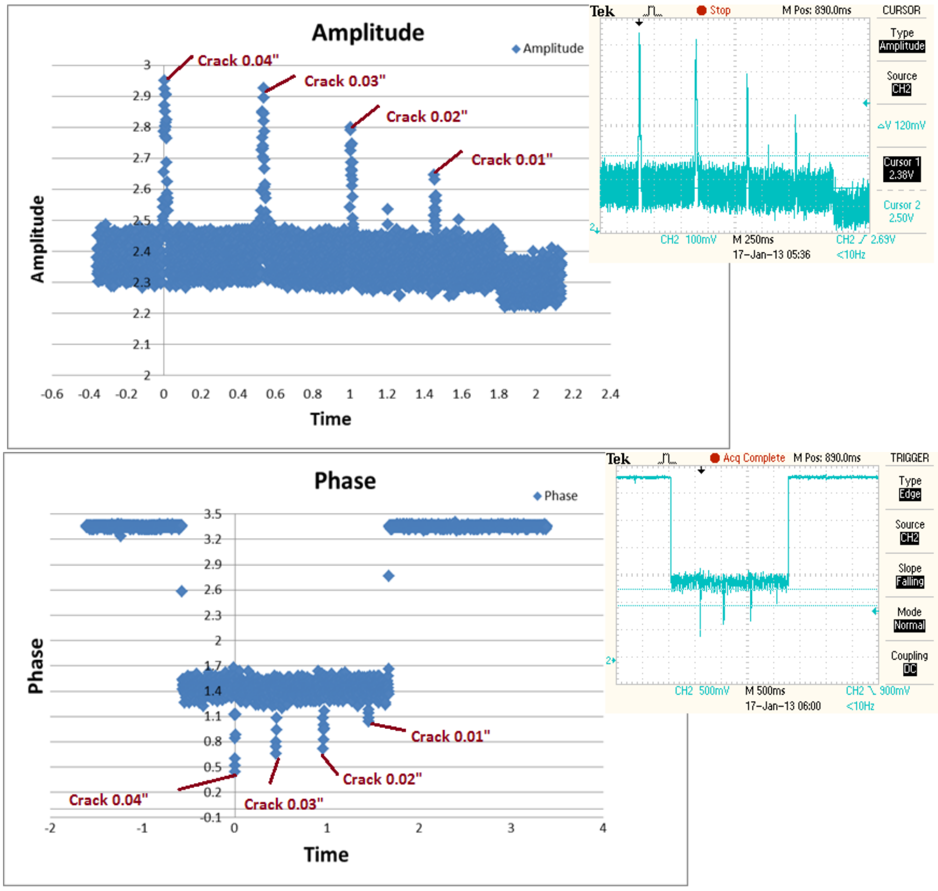


FIGURE 4. Amplitude (Top) and phase (Bottom) change signals detected with the impedance measurement circuit using 4-Notch eddy current standard test block

For evaluation of the whole EC signal, experiments with wired sensor were first conducted and such wired results were used as the baseline for future comparisons. In such wired tests, the probe is directly cable-connected to the main unit (as in a conventional eddy current test). Wired baseline results were then compared to wireless sensor test results. Fig. 5 shows the basic experimental setup for wireless testing.

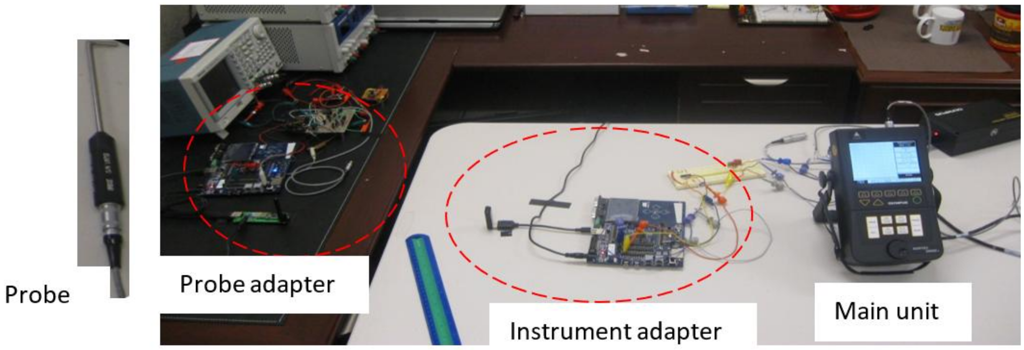
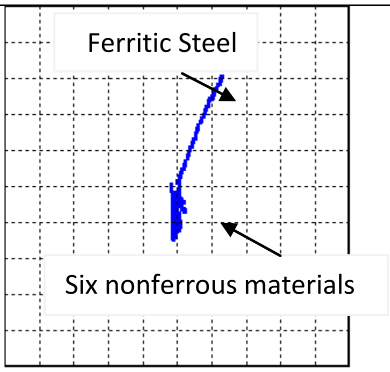
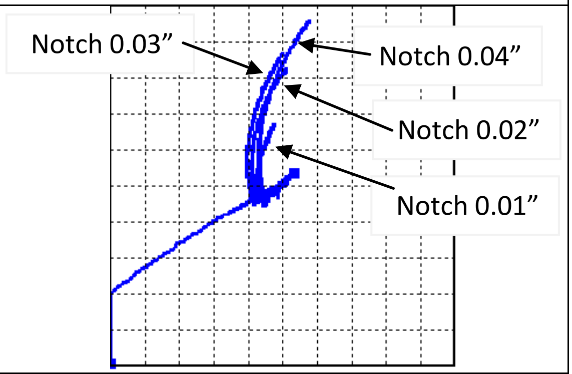
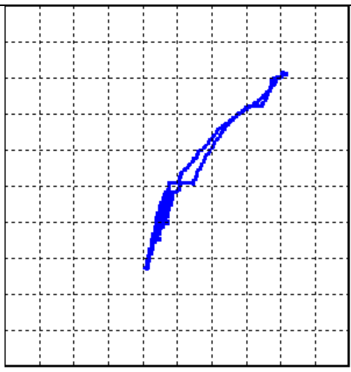
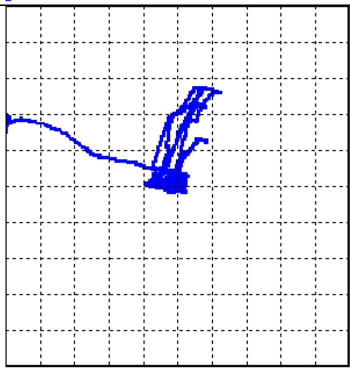
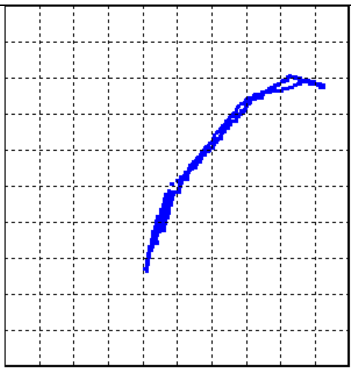
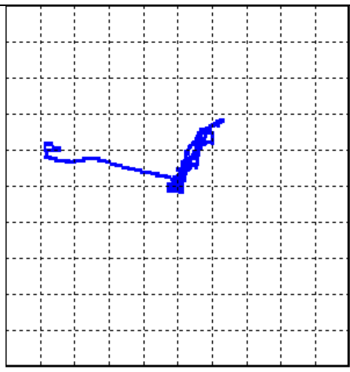
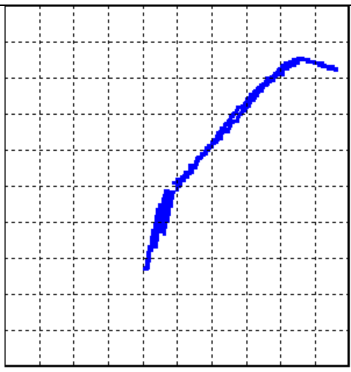
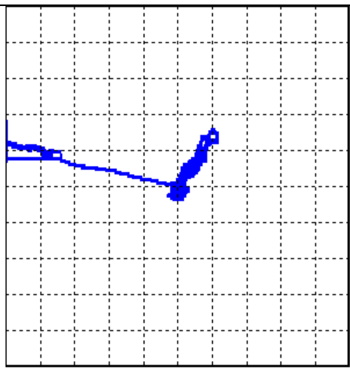


FIGURE 5. Basic wireless experimental system setup

VII. Wireless Testing At Various Distances

One of the important factors in wireless transmission of data is communication distance. The capability of performing the tests over distance is one of the major benefits of EC wireless inspection. The probe can be placed at desired location either manually or using a robot and data interpretation can be done at main unit location where might be more convenient or safer. Such distance should be large enough for reliable transmission and should also be short enough to avoid undesired interference. For this reason, wireless tests were carried out at various distances (0.3m, 0.6m and 1.5 m (1 ft, 2 ft and 5 ft)) between the probe transceiver and instrument transceiver to evaluate the effect of the distance in the transmitted signal. Table 1 compares the results of wired tests to wireless tests.

Table 1. Wired and wireless test results at various distance

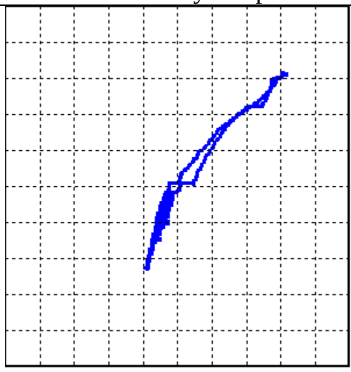
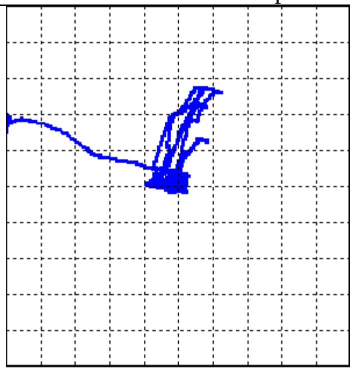
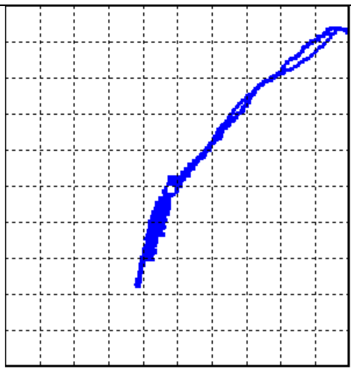
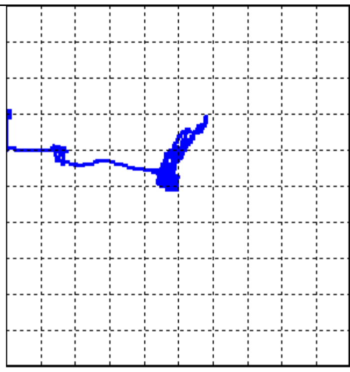
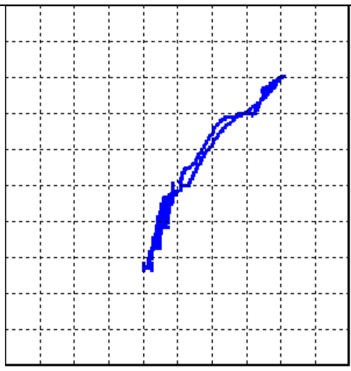
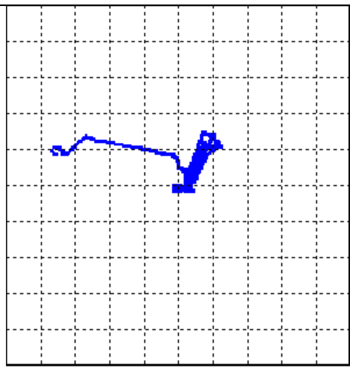
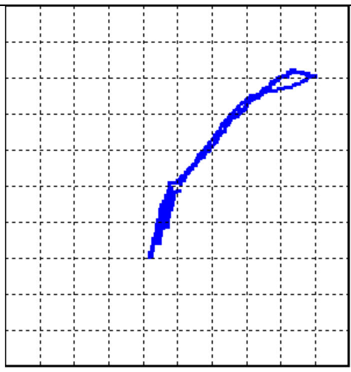
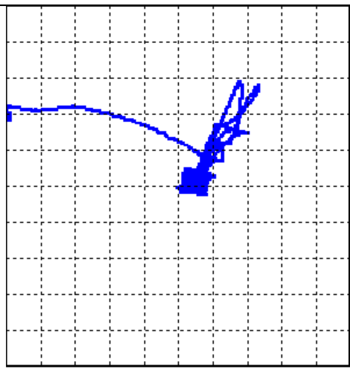
Wired /wireless	Conductivity sample	Steel slots/notch sample
Wired		
Wireless at 0.3 m(1 ft)		
Wireless at 0.6 m (2 ft)		
Wireless at 1.5 m (5 ft)		

Results show that wired signals generally agree with wireless signals and the distance between probe transceiver and instrument transceiver does not have significant influence on wireless signals.

VIII. Wireless Testing With Various Blocking Obstacles

Because of its induction nature, the wireless transmitted signal may be interfered by surrounding structures. So, this issue needs to be tested considering possible blocking obstacles. It is also can be considered as the safety feature of wireless EC testing for the cases which have a blocking part in the structure like metal parts or non-metal walls. Wireless tests were carried out with various blocking obstacles in between the probe and instrument transceiver. These obstacles include plastic plates, Aluminum plates, carbon fiber composite plates and glass fiber composite plates. Table 2 summarizes the results of wireless tests with various obstacles.

Table 2. Wireless test results with various blocking obstacles

Wired/wireless	Conductivity sample	Steel slots/notch sample
Wireless at 0.3 m (1 ft) without Obstacle		
Aluminum Plate		
Composite Plate		
Plastic Plate		

Wireless tests were also carried out with aluminum cans covering both the probe and instrument transceiver antennas (Fig. 6), and with person standing in between probe and instrument transceivers. For this round of tests, the distance between probe and instrument transceivers was 1.5 m (5 ft).

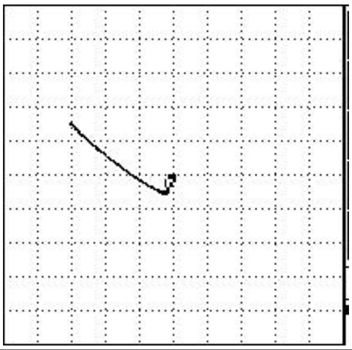
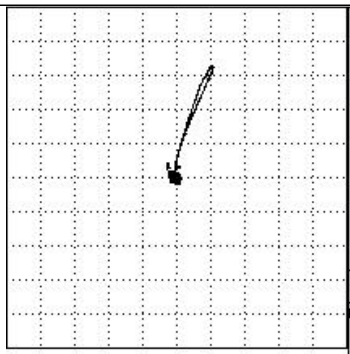
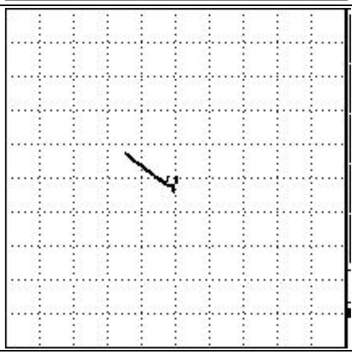
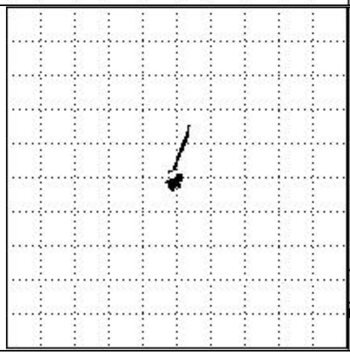
FIGURE 6. Picture of aluminum can which is covering instrument transceiver antenna

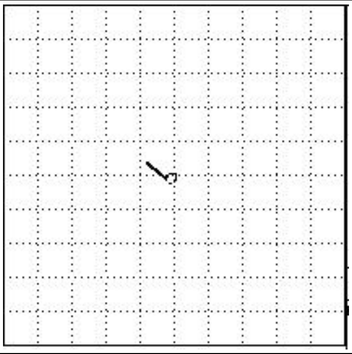
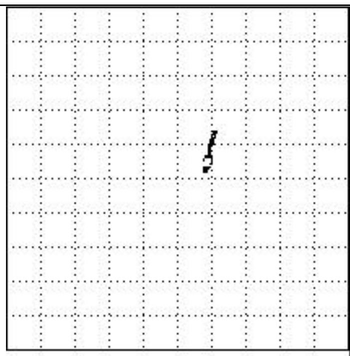
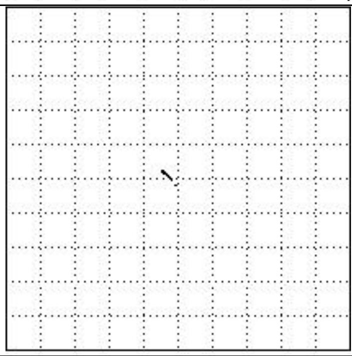
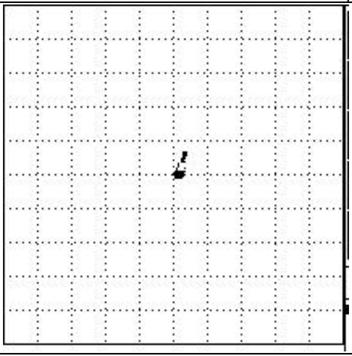
The testing results show that obstacles, especially metal parts, does not exert interferences on wireless signals, and this is due to the UWB wireless communication technique in our research.

IX. Wireless Testing With Covering Papers

Coating and painting of the structures are also an important factor in EC testing which may require to be evaluated or considered in EC inspection. Layers of printing paper were used to cover steel crack/notch sample to simulate non-conductive coating. Table 3 compares the 0.762 mm (0.03”) notch wired test results to wireless results.

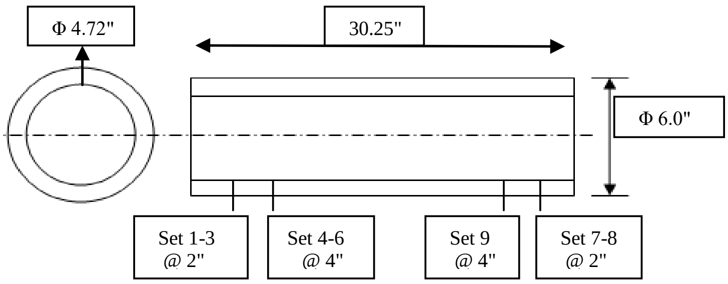
Table 3. Wired and wireless test results with covering printing papers

# of paper layers	Wired testing on 0.03” notch	Wireless testing on 0.03” notch
0		
2		

4		
6		

X. Wireless Testing On Steel Cylinders

Wireless tests were further carried out on steel cylinder as shown in Fig. 7. The cylinder has a total of nine sets of slots on its inner surface. Table 4 summarizes the notch dimensions. Since the probe was placed inside the cylinder during inspections (Fig. 8), such operations also simulate tests in an enclosed metal space. Table 5 summarizes testing results of notch set 4, 5 and 6.



(a) (b)

FIGURE 7. Test cylinder (a) picture and (b) dimensions with notch location

Table 4. Steel cylinder notch dimensions

Data	Length (mm/inches)	Width (mm/inches)	Depth (mm/inches)
set1	0.0508/0.002	0.1016/0.004	0.025/0.001
set2	0.254/0.01	0.1016/0.004	0.127/0.005
set3	0.508/0.02	0.1016/0.004	0.254/0.01
set4	0.508/0.02	0.1016/0.004	0.508/0.02
set5	1.016/0.04	0.1016/0.004	0.508/0.02
set6	2.54/0.1	0.1016/0.004	0.508/0.02
set7	6.35/0.25	0.1016/0.004	1.016/0.04
set8	12.7/0.5	0.1016/0.004	1.016/0.04
set9	25.4/1	0.1016/0.004	1.016/0.04

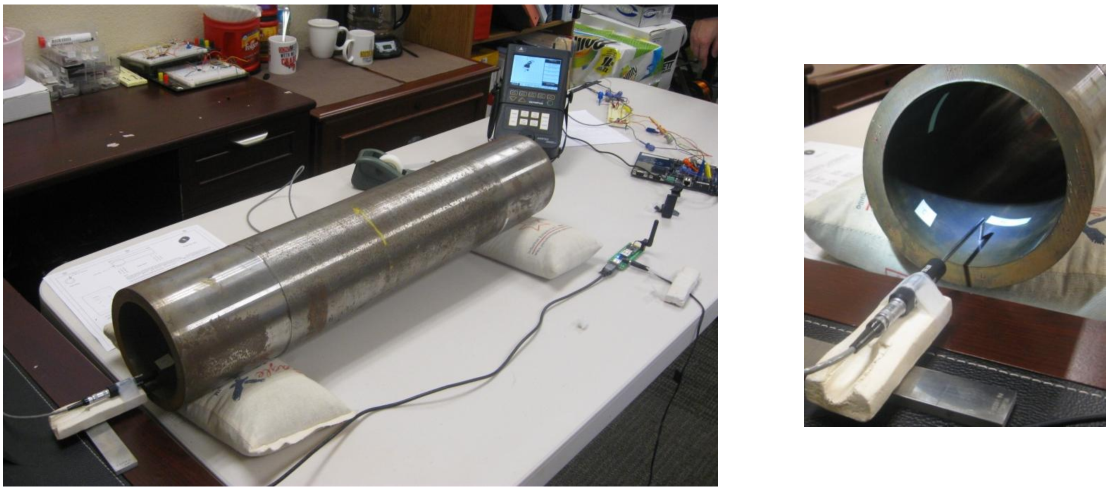
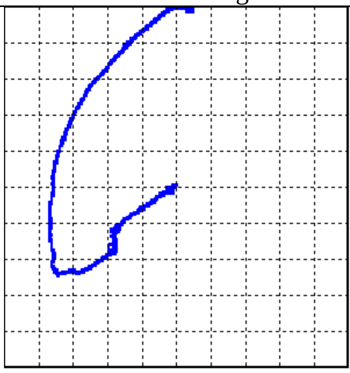
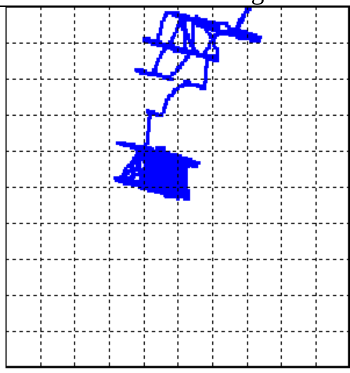
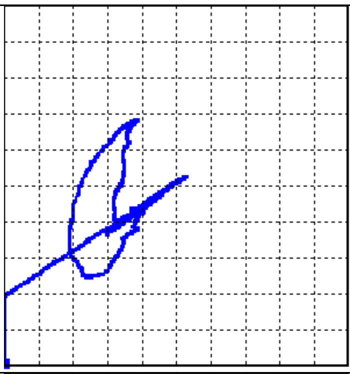
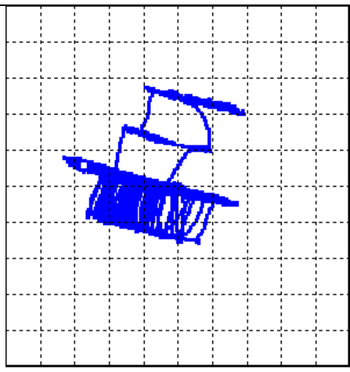
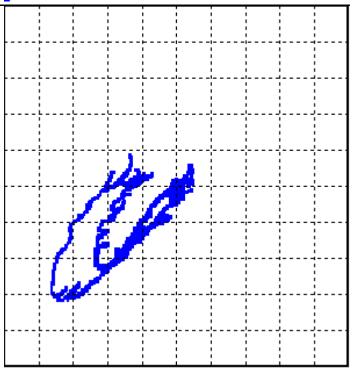
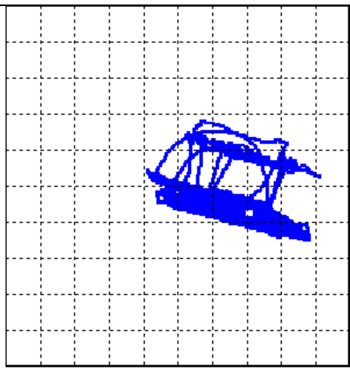


FIGURE 8. Steel cylinder wireless testing setup

Table 5. Steel cylinder wired and wireless testing results

Notch	Wired testing	Wireless testing
Notch set 6		
Notch set 5		
Notch set 4		

The results show that wireless signal amplitude increases as notch size become larger. But the wireless signals again showed distortion when compared to wired signals, such as the phase shift and the digitizing effects.

XI. Conclusion

The main advantages of wireless NDI probes are safety, economic benefits and maneuverability however, accurate wireless transmission of the data is very important. Considering these factors, UWB communication is the most promising technology. Wireless communication is realized between the adapter transceiver and instrument transceiver. The wireless signals reacts well to various materials and defects, but experiences distortion when compared wired signals and need to be further calibrated and improved. This is verified by tests on conductivity sample, steel crack/notch sample and steel cylinder. The distance between the adapter transceiver and instrument transceiver does not have influence on wireless communication. The obstacles between the adapter transceiver and instrument transceiver do not have influence on wireless communication. The wireless system can work in enclosed metal space. This is verified by putting aluminum can on the transceiver antennas and by putting the probe inside the steel cylinder. By the end of phase I study the prototype system for wireless eddy current system was designed and set up. The wireless signal could be sent and received with the related designed modules and transmitted signal is captured for different testing conditions. The next future step of this study would be completion of the work to achieve a functional product capable of making an NDI tool wireless.

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