Crack Detection in Aircraft Fastener Holes Using Flat Geometry Remote Field Eddy Current Technique and Super Sensitive Eddy Current System

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Abstract: The Flat Geometry Remote Field Eddy Current (FG RFEC) Technique has unique advantages in aircraft non-destructive inspection (NDI) including deep penetration, high sensitivity, portability, low price, etc. The technique has recently been recognized by aircraft NDI professional societies. Currently the FG RFEC technique is capable of detecting deeply hidden cracks and corrosion. This paper will introduce the recent progress made in the R&D of the FG RFEC technique in aircraft crack detection.

Introduction

An increasingly significant safety impact comes from the aging of currently in-service airplanes. One of the most important issues affecting the possibility of extending the life of aging airplanes is cracking. Therefore, a good non-destructive inspection (NDI) technique for aircraft crack inspection is essential to ensure the safety of aging airplanes.

Aircraft components often suffer from fatigue cracking because of their particular working environment. Conventional NDI techniques are incapable of detecting inner layer fatigue cracks from the aircraft exterior. Therefore, inspecting inaccessible areas of an aircraft component usually requires the removal of obstructions or disassembly prior to inspecting the desired component.

An airplane is inspected every given flight-hours or given landing cycles. Majority of the time, such an inspection is unnecessary since cracking may not be present. Such an inspection is also costly, because the direct cost spent on the inspection consists of a couple of percent of the total cost. The costs of other related work, including the teardown, replacement, and parking costs, are dominating.

Therefore, there is a great demand for advanced NDI techniques for aircraft fatigue damage detection. The major requirements for such a new NDI technique include:

A. Detect inner layer cracks from outside aircraft skin through multi-layered structures. The number of layers can be up to five.
B. Deep penetration to cover possible aircraft thickness which can be up to 5-10 centimeters of aluminum alloy, titanium alloy, composite or a combination of them.
C. Sensitivity to small-sized inner layer cracks with and without presence of fasteners of different materials, aluminum, steel, stainless steel, titanium, etc.
D. Reliability of detection without human factors involved.
E. High-speed and large-area inspection, considering all the above A-D requirements.
F. Discriminate noises from different factors, such as edge effect, thickness variations and possible sealant/gaps between layers, etc.
G. Low cost.
H. Portability and convenience in use.

There are quite a number of aircraft NDI techniques including conventional and emerging techniques. However, until now there is no single one that meets all the above requirements. Examples of other NDI techniques include:

A. Ultrasonic techniques (UT), including guided wave UT, which are incapable of penetrating through multiple layer structures and restricted to first layer and upper surface of second layer inspection.
B. X-ray techniques involve heavy equipment, protecting operators from radiation, and are relatively expensive and have low sensitivity to small cracks.
C. Most eddy current (EC) techniques and their alternatives have limited potential to further increase their penetration depth in metallic structures because of the skin-depth effect.
D. The Super-conducting Quantum Interface Device (SQUID) is capable of penetrating relatively deep. However, the system is quite heavy, large, expensive and has high noise problems. These issues restrict its practical applications.

Among current emerging aircraft NDI techniques, the FG RFEC and SSEC system has shown great promise in becoming a good candidate for expected aircraft NDI needs in the near future.

1. FG RFEC and SSEC System [1-3]

The original Remote Field Eddy Current (RFEC) technique has been used in the NDI of conducting tubing for years. The RFEC technique is characterized by its features of deep penetration and the linear relation of its signal phase to the total wall thickness under inspection. The signal phase to wall thickness relation is independent of probe lift-off and the location of a flaw in respect to the wall thickness.

IMTT has expanded the applications of the RFEC technique to the inspections of conducting objects of flat or nearly flat geometries with the help of specially designed probes called FG RFEC probes, see Figure 1. The probe blocks the direct coupling path, and the electromagnetic energy released from the drive unit is forced by the FG RFEC probe to go along the indirect coupling path. Therefore, the entire signal received by the pickup unit has passed the wall twice and carries the whole information about the wall condition. The signal can be extremely weak, but is very clean without noise coming from the driving unit.

A Super Sensitive Eddy Current (SSEC) system is a modified version of a conventional eddy-scope. The SSEC system has comparatively high gain and low noise level, and brings the weak pickup signal to a level that is readable on a computer screen.

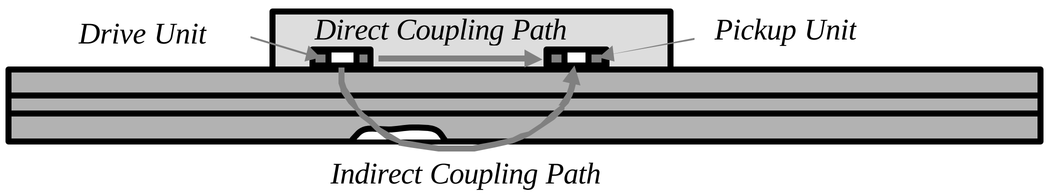

Figure 1.Simplified drawing of an FG RFEC probe and the energy coupling paths.

The current version of the SSEC system consists of a piece of software and a Printed Circuit Board (PCB) that are installed/inserted into a regular personal or industrial computer, see the left picture in Figure 2. It utilizes the fundamental features of a computer as the base of an SSEC system. Figure 2 right is the second version of the system where the system becomes a small box and can be connected to a customer preferred computer through a universal serial port (USB). This version will be available soon.

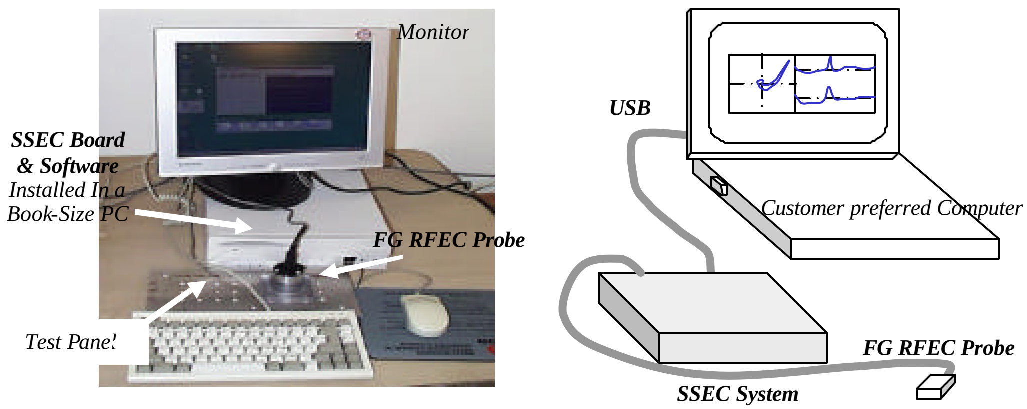

Figure 2. Current (left) and next (right) versions of an SSEC system.

2. Fastener hole crack detection: Raster Scan versus Rotational Scan

For the purpose of accurate and fast detection of fastener hole cracks, a series of rotational RFEC probes with accompanying software have been developed.

Traditionally, a raster scan mode is used for crack detection. In such a mode a probe moves in the X and Y directions over the entire area of interest. The raster scan mode has a disadvantage as inner-layer crack signals are submerged by the fastener signals/noises, which may be tens or hundreds times greater than the crack signals, see Figure 3. A rotational probe with a centered excitation coil and an off-set differential sensor, Figure 4, may minimize the noise if the probe is rotating right at the fastener center because of the geometric symmetry, Figure 3. When the probe rotation center coincides with the fastener center, we should have a zero signal from the differential sensor when there is a non-crack. A signal appears in the differential sensor only when it passes a crack.

However, to have a rotational FG RFEC probe work with high sensitivity the probe must be centered well with the center of the fastener under inspection.

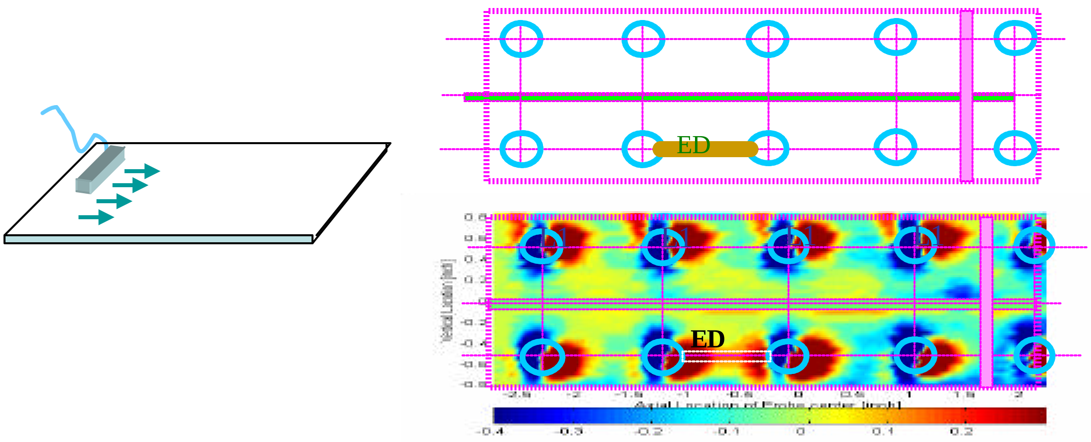

Figure 3. Raster scan – inner layer crack signals are submerged by strong fastener signals.

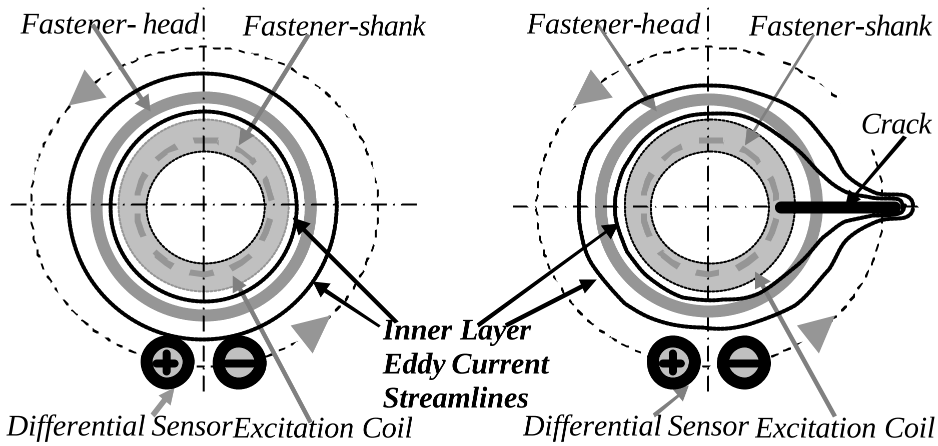

Figure 4. Rotating probe minimizes noises from fastener because of geometrical symmetry. No-crack case (left) and with an inner layer

3. Inspection of Raised-Head Fasteners [4]

One application of a rotational FG RFEC probe in aircraft crack detection is the inspection of raised-head fasteners, see Figure 5.

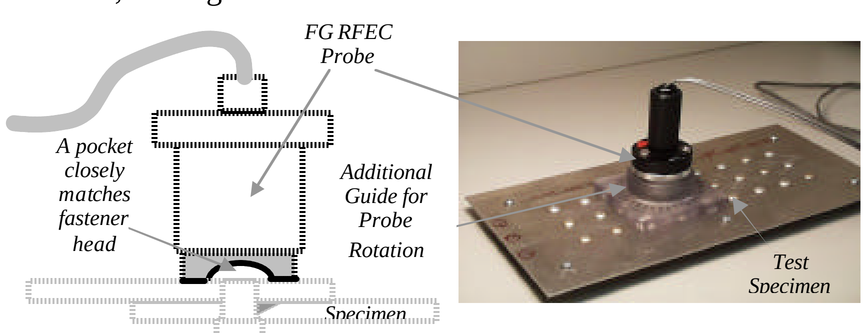

Figure 5. Rotational FG RFEC probe applied to raised-head fastener.

Raised-head fasteners are often used in helicopter structures. They are also seen on non-aerodynamic surfaces of conventional airplanes. The round fastener head can work as a guide for the probe rotation if a pocket that closely matches the outer diameter of the fastener head is made on an FG RFEC probe head.

The IMTT FG RFEC probe for inspection of raised-head fasteners has been extensively tested on different panels provided by the Airworthiness Assurance NDI Validation Center (AANC), Federal Aviation Administration (FAA) of the United States.

So far the probe has the best Probability Of Detection (POD) record in the detection of inner-layer cracks for two layer, 1.0mm + 1.0mm, aircraft aluminum structures. The following is a brief of the POD study report:

Results from Blind POD Tests at FAA AANC

OEM Target: Detection of 0.100" long cracks

- 1st layer crack detection in buttonhead (bucked) rivets - 90% POD number was 0.064" with 0 false calls.
- 1st layer crack detection in Cherrymax blind rivets - RFEC probe detected 100% of the flaws producing 0 false calls.
- 2nd layer crack detection in buttonhead (placed) rivets - 90% POD number was 0.047" with 5 false calls from 210 fasteners inspected.
- 2nd layer crack detection in Cherrymax blind rivets - RFEC probe detected 100% of the flaws while producing 3 false calls.

Currently, the probes with different pocket diameters are in the process of being produced. The probes, together with an SSEC system, will be available in the marketplace soon.

We are also working on the detection of fastener-hole cracks at much thicker structures.

4. Inspection of flush-head fasteners

Studies have shown that the probe signal varied significantly when the location of a rotating FG RFEC probe moves around a flush-head fastener center. A surprising phenomenon observed is that the minimum value of a probe signal is not necessarily the geometrical center of the fastener under inspection. The situation becomes even worse when there is a crack in the fastener hole. Figure 6 shows two typical test results of this observation.

4.1 Auto-centering System

A centering process is critical to the accurate inspection of flush-head fasteners. Visual observation is not accurate for detecting cracks in flush-head fastener holes detection, especially for inner layer crack detection. Furthermore, it has been noticed that the signal/electric center, where we see the minimum of signal magnitude at a no-crack case, may not always be the geometrical center of the fastener.

An auto-centering system, Figure 7, is used to help find the electric center of the fastener under inspection and to place a rotational FG RFEC probe precisely at the center. Three motors are used in an auto-centering device, one is for probe rotation, the other two are for moving the probe in X and Y directions. At each (x, y) position, the probe working with the SSEC system, collects the detected signal and sends the data to the PC.

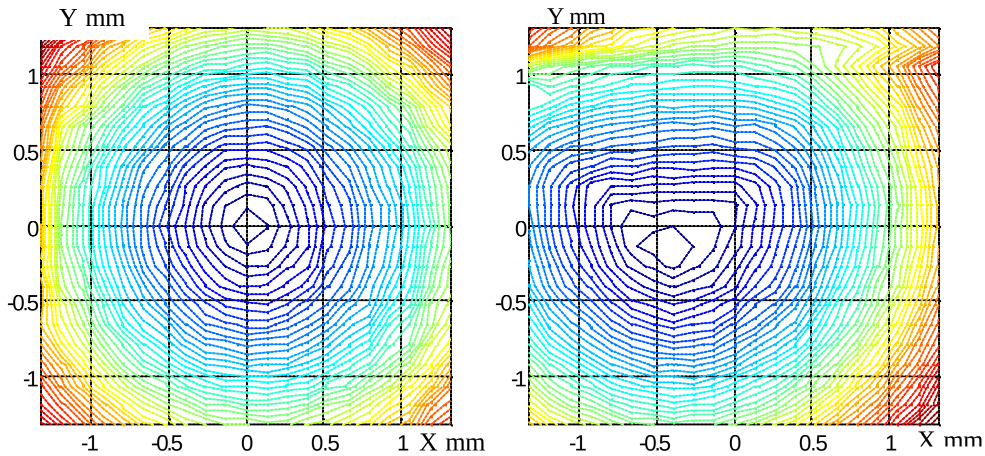

Figure 6. Signal variation around the center of the fastener under inspection. No-crack case (left) and the case with an 2nd layer crack, 2.62 mm long triangle shape, in fastener hole (right) of a two layer, 1.6 mm + 1.6 mm, aluminum structure.

A piece of built-in software processes the data and then provides a command to the controller telling it the necessary information regarding the next step of probe movement. When the probe has already reached the electric center, the intelligent software pops up an inspection report on the PC screen: "No-Crack", "Crack Found", "Significant S/N Ratio", and other information related to the detection.

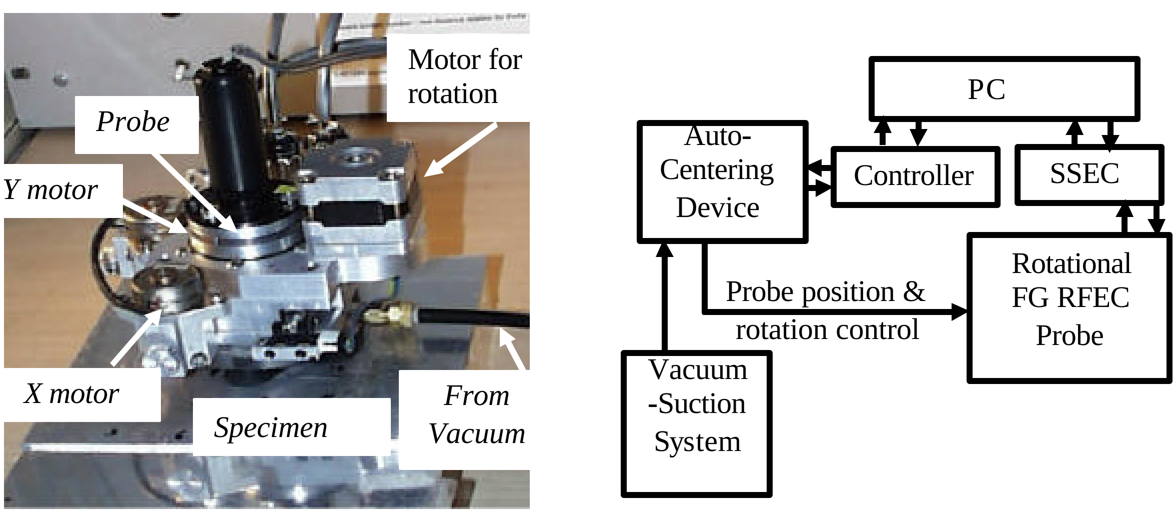

Figure 7. Auto-Centering Device (left) and Auto-centering system – A Block Diagram (right).

4.2 Example 1: Detecting EDM Notches In A "Very Conductive" Alodined Fastener Panel Provided By Boeing Commercial Airplanes

With the help of an auto-centering system the accuracy, reliability, repeatability and inspection speed have all improved greatly in the inspection of flush-head fasteners. See typical test results in *4.3 Example 2*.

A significant issue arose recently in detecting cracks in aircraft fastener holes. In 1985 The Boeing Company changed fastener surface treatment technology. Instead of using the previous anodized fasteners with non-conductive surfaces, alodined fasteners are now used in aircraft structures. Recently The Boeing Company has noticed that the crack signals detected from alodined fasteners using a number of conventional and emerging eddy current technologies can be much smaller than those detected from anodized fasteners. The crack signals may be lower than signals detected from no-crack anodized fasteners.

There is an urgent demand for aircraft crack detection to find new approaches that are not influenced by the electric conditions of fasteners. The investigation to date shows that the FG RFEC and SSEC technique can be one of the candidate techniques for solving this issue.

Our test shows that:

A. The signals detected from no-crack alodined and anodized fastener holes using the FG RFEC technique are approximately identical;
B. The signals detected from cracked fastener holes with alodined fasteners are generally smaller in average than those detected from anodized fasteners.
C. The FG RFEC & SSEC technique gives very high S/N ratio detection in both cases. Using this technique an operator should be able to find an inner layer crack no less than the currently given threshold, 5.08 mm in crack length, with a S/N ratio higher than the currently given value, 3, in a two-layer, 2 mm + 1 mm, aluminum structure.

Figure 8 shows test results obtained from a "very conductive" alodined fastener using the auto-centering rotating FG RFEC & SSEC technique compared with signals obtained from no-EDM fastener holes. The panel is provided by Boeing Commercial Airplanes. Among five fasteners detected there was a 5.08 mm long EDM notch made in the hole of the third fastener. Each fastener was inspected five times as shown in Figure 8.

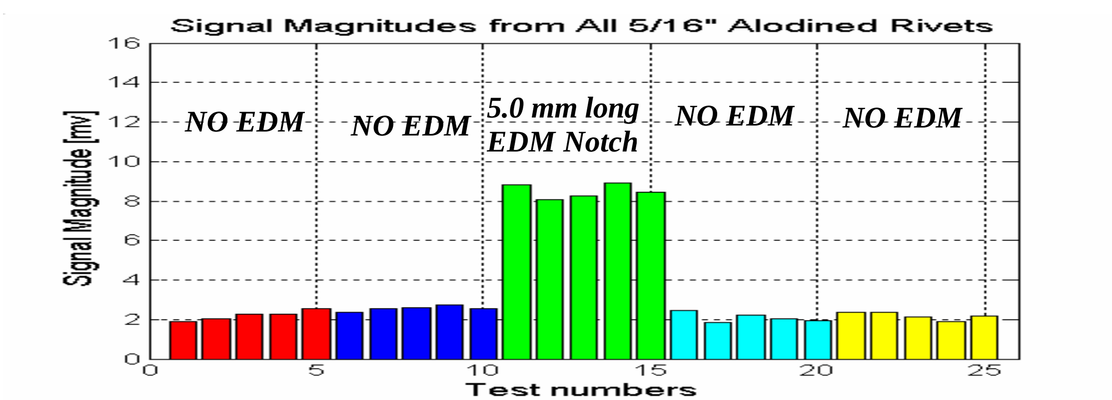

Figure 8. Signal from a 5 mm long inner layer EDM notch in a hole where a 'very conductive' fastener was installed.

4.3 Example 2: Detecting 2nd layer fatigue cracks on a piece of specimen taken from the skin of a retired Boeing 727: FAA ANCC Panel AC400 4R 660 – 680.

The auto-centering system has been applied in detecting fatigue cracks on a piece of aircraft skin taken from a retired Boeing 727. Typical test results are shown in Figures 9 and 10. The results indicate that the auto-centering FG RFEC and SSEC system is capable of detecting 1.83 mm long 2nd layer fatigue cracks in aircraft structures[1], while the best record in detectible crack length for other eddy current techniques is around 2.54 mm.

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[1] A POD study will be carried out to verify the reliability of the results.

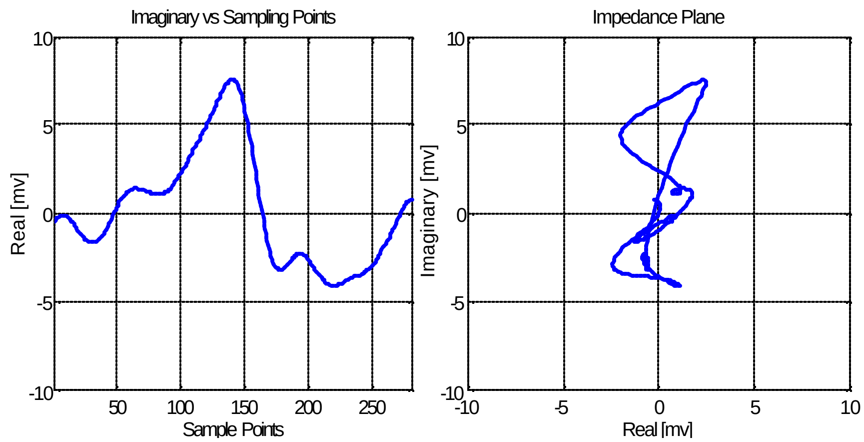

Figure 9. Crack signals detected from Fastener No. 667. The microscope observation by AANC indicates there are four cracks in the fastener hole. The lengths are: 1.83mm, 1.29mm, 1.29mm and 1.07mm.

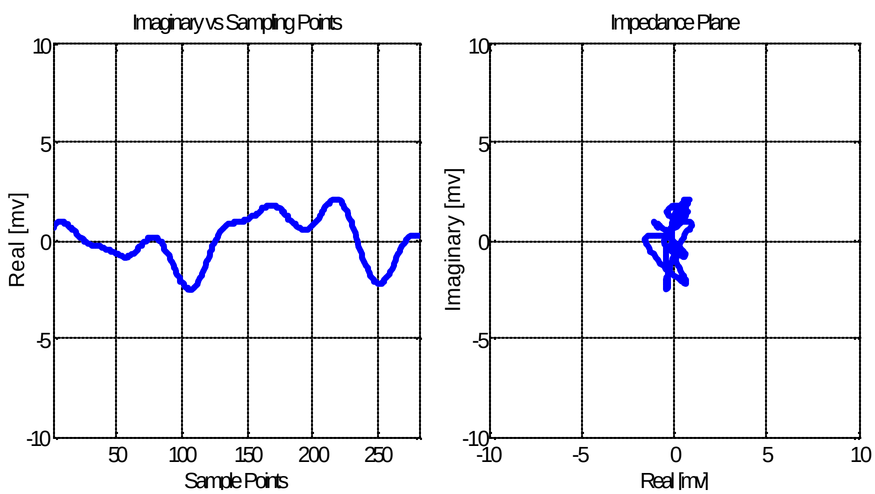

Figure 10. Signals obtained from Fastener No. 000. a non-cracked fastener hole.

5. References

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[2]. Yushi Sun, US Patent 6,002,251, "Electromagnetic-Field-Focusing Remote-Field Eddy-Current Probe System and Method for Inspecting Anomalies in Conducting Plates", Issue date: 12/14/1999.

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