Numerical Modeling and Experimental Study of Motion Induced Remote Field Current Effect and its Application to Online Inspection And Quality Examination Of Rolling Metallic Strips

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ABSTRACT

Currently, rolled metallic strips and sheets are inspected off-line that is costly, time consuming and improper for quality control. A well designed online diagnostics and control system for metal rolling process may reduce largely the cost, improve the quality, and hence enhance the competitiveness of the products of the United States. The overall objective of the work to be presented in this paper is to study a new nondestructive measurement system for on-line diagnostics and control of metallic rolling process using motion-induced remote-field eddy-current (MIRFEC) effect. The system may potentially monitor in real time the rolled metallic strips/sheets for possible anomalies, inclusions, voids, bubbles, lamination, as well as measuring variations of its properties. The potential advantages of the MIRFEC system include simplicity, robustness, low cost, allowing high temperature, large lift-off and vibration, capable of working at high rolling speed, high reliability, quick and accurate signal classification and characterization that can used for real-time process control, or off-line data analysis.
Results from finite element modeling of the MIRFEC effect and experimental measurement data obtained from a prototype system will be presented.

1. INTRODUCTION

Modern industries, such as aerospace, demand high quality metallic products. Currently, rolled metal inspection is made off-line and limited to surface inspection. It is a highly manual procedure, allowing only a small portion of the product surface to be inspected. Manual inspection procedures involve periodic removal and unwrapping of heavy metal coils and the inspection is done by sampling only a certain points of the inspected products. Therefore, the quality of the inspected products is not guaranteed.

A research project named “On-line automatic surface inspection of hot rolled strip” [1], was carried out by American Iron and Steel Institute, 1101 Seventh Street, NW, Washington, DC 20036-4700. However, what can be expected from successful accomplishment of this project is an on-line surface inspection technology based on surface images obtained by area cameras. The technique is inherently unable to detect any non-surface defect. Some high quality aluminum plates, such as those used for aircraft structures, are inspected after rolling using ultrasonic technique in a huge water sink.

The objective of this research is to develop a novel on-line inspection and quality examination technology that is capable of through-wall inspection of metallic trips. It saves inspection time, eliminates manual work and provides a reliable control of the product quality. The proposed new technology is based upon a newly discovered physical phenomenon, the motion induced remote-field eddy-current (MIRFEC) effect [2] and the remote-field eddy-current (RFEC) technique capable of detecting deeply hidden corrosion and cracks in multi-layered aluminum structures [3], [4], [5]. A US Department of Commerce supported project named *On-line automatic full-coverage inspection and quality examination of rolling metallic strips and tubes using motion induced eddy current and remote field current effect* has been carried out by the authors since January of 1996. The project was supported through the Center for Advanced Technology Development of Iowa State University. Quite promising results have been obtained from both numerical modeling and experimental measurements in this project for validating the basic concepts of the proposed new technology. The purpose of this paper is to present these research results.

2. REMOTE FIELD EDDY CURRENT EFFECT

The RFEC effect was first observed in a specific situation where an alternating current was applied to a coil inside a metallic pipe, Figure 1. The phenomenon is characterized by a process where the energy released from the excitation coil traverses the tube/pipe wall twice before it reaches the pick-up coils/sensors, see the indirect energy coupling path in Figure 1. When the pick-up coils/sensors are located 2-3 diameters away from the excitation, the signal received by the pick-up coils/sensors is dominated by the energy coming from the indirect coupling path [6]-[8]. Now, this technique is used routinely for metallic tube inspection. It has a few distinguishing features, such as equal sensitivity to both OD and ID defects, independence of phase signals to lift-off, and approximately linear signal phase/thickness relationship.

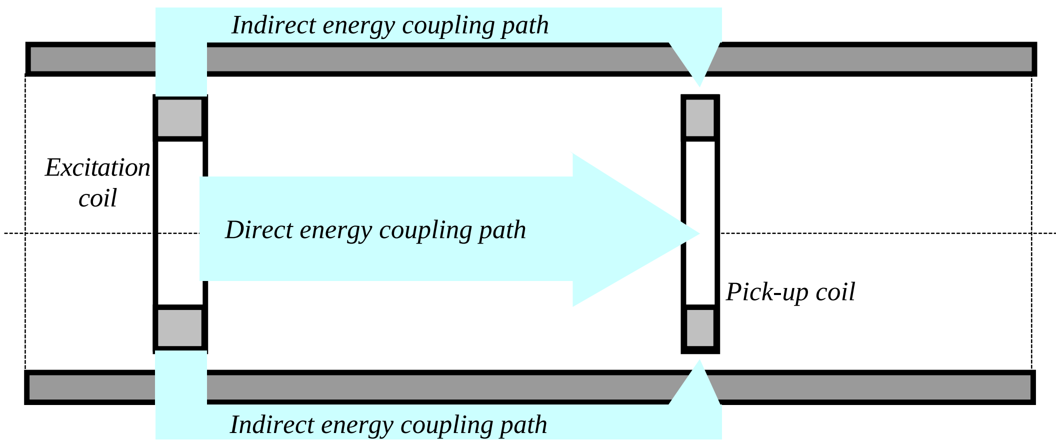


Figure 1. Schematic of a remote field eddy current probe inspecting a tube showing the two energy flow paths

3. REMOTE FIELD EDDY CURRENT TECHNIQUE DETECTING DEEPLY HIDDEN CORROSION/CRACK IN MULTI-LAYERED ALUMINUM STRUCTURES

Recently the RFEC technique has been extended to the inspection of flat geometry objects, see Figure 2, and is capable of detecting material discontinuity that is 0.5" below surface, 1% corrosion thinning that is 0.245" below surface, and a 0.031" long fastener hole crack that is 0.446" below surface [5].

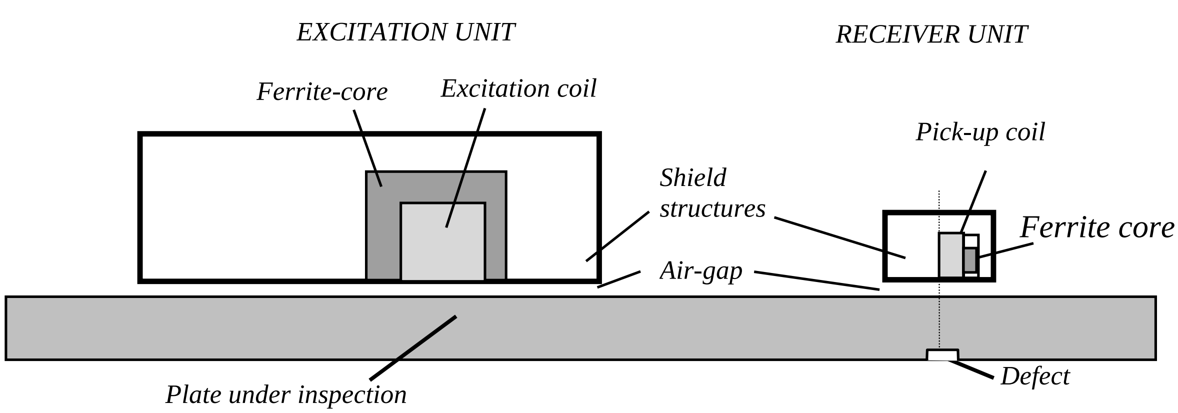


Figure 2. Prototype probe for inspecting metallic plates

4. MOTION INDUCED REMOTE FIELD EFFECT

When a pair of magnetic poles moves with a certain speed inside a conducting tube, a one-cycle current is induced according to Maxwell law. It has been shown [2] that the RFEC effect occurs in such case. In other words, the energy in vicinity of the poles is transmitted through the conducting tube wall twice, so that the electromagnetic signal measured from the pole side slightly away from the poles is closely related to the material property and its wall thickness. It is called the MIRFEC effect. In this paper the authors make use of the MIRFEC effect to the inspection of rolled metallic sheets.

5. OPERATING PRINCIPLE

A pair of magnets, permanent or electromagnetic, of opposite polarity is place on top of the moving metallic sheet that is in rolling process, see Figure 3. The motion generates currents in the metal. The motion induced eddy current can be very strong. For example, an aluminum strip, $\sigma = 3.0 \times 10^7$ $(1/\Omega.m)$, with a moving speed $V = 2$ m/s, passing through the magnetic field generated by a pair of magnetic poles with magnetic flux density, $B = 1.0$ T results in a current density of $|\boldsymbol{J}| = \boldsymbol{\sigma}|\boldsymbol{V} \times \boldsymbol{B}| = 6.0 \times 10^7$ $(ampere/m^2)$!!!

The motion induced eddy-current pattern in metallic strips is a function of the shape and relative location of the magnet pole pair. In other words, by variation of the shape and relative location of a magnet pair, the proposed technique can meet different requirements of defect detection and quality examination.

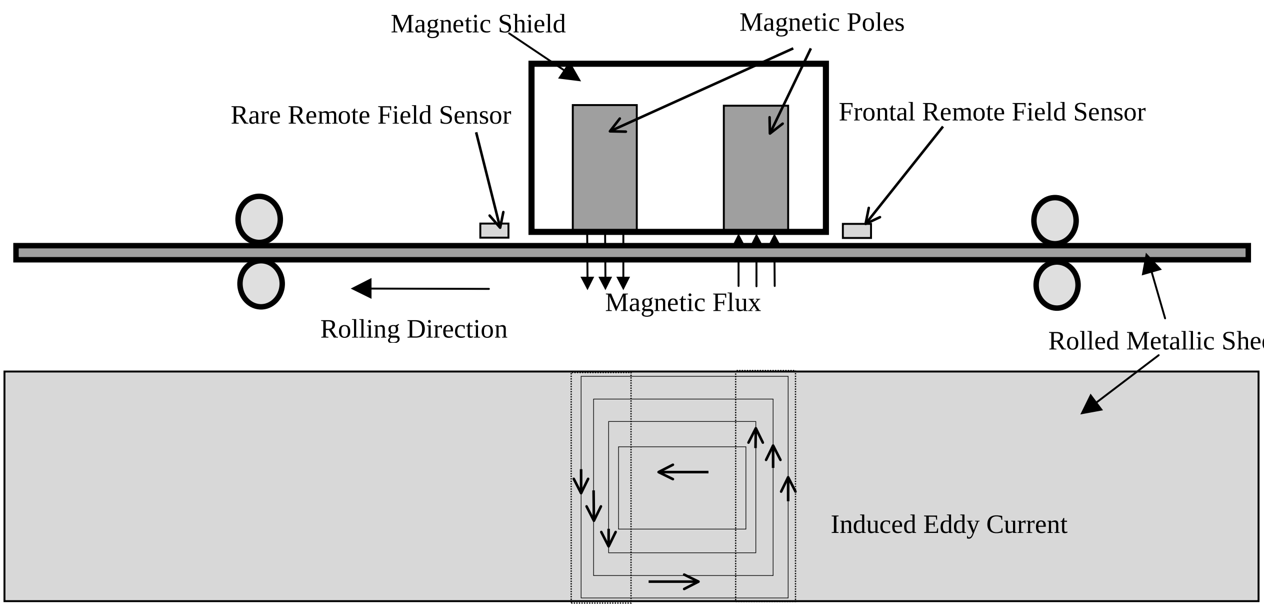


Figure 3. Fundamental idea showing the operating principle of the system

There are two kinds of signals available for defect inspection and metal product quality examination:

- Near field current signals which can be measured by a set of sensors placed between the two magnet poles. The signal reflects near side surface and sub-surface condition of a metallic strip.
- RFEC signals that can be obtained using a set of sensors placed at a certain distance away from the poles, either in front of or behind depending on some practical considerations of a specific situation. Since the RFEC technique is a through-wall inspection, it gives a signal from an anomaly or quality variation that is irrespective of its location in the strip wall.

6. FINITE ELEMENT MODELING

A 2D finite element code calculating transient electromagnetic procedures and considering velocity effect [8] was used to model the above-mentioned test set-up. Different probe designs working at different speeds are simulated. Different magnetic field components are calculated. Figures 4 - 7 show a set of typical calculation results obtained from design Model M-11 at velocity v = 5 m/s. A 10 mm thick aluminum sheet with conductivity of 3.0 10^7 s/m is assumed in the calculation. Due to page limitation only the vertical components B_y at front and rare sensor locations is given.

Comparing the data of the four plots it is not difficult to see that:

1. A defect on the backside of the aluminum sheet introduces significant change of the magnetic field at both front and rare sensor locations;
2. The signals on the rare sensor locations are about 5 - 6 times greater that those on the front sensor locations;
3. The signals at both locations are practically measurable.

7. EXPERIMENTAL VERIFICATION

A vertical lathe was used to generate the necessary speed for the sample under inspection. The schematic of the test set-up is shown in Figure 8. The MIRFEC probe prototype Model M11, **1**, with five rare coil sensors, **2**, are placed above the rotating aluminum sample, **3**, at a radius **R** from the rotation center. The linear velocity of the sample at the probe center is known as $V = 2\pi R*RPM/60\ [m/s]$, where RPM is number of rotations of the sample per minute. The sample is raise up from the chuck, **5,** by the support bars, **4**, to minimize the magnetic field interference from the ferromagnetic chuck. The magnet, **6**, generates flux ϕ, **7**, and hence, causes induced currents, **8**, in the moving sample, **3**. Any change in the sample's geometry alters the induced currents resulting a signal of $e = -Nd\phi_{rf}/dt$ in the sensors, where $N\phi_{rf}$ is the flux-link of a sensor coil in remote field region.

The actual sample, ***S***, used in the test is made of a piece of 36" wide aluminum plate with four saw-cuts of different depth, ***D1, D2, D3,*** and ***D4***, made on the lower side of the plate as shown in Figure 9. The center of the MIRFEC probe prototype M11 with five rare coil sensors is placed on top of the sample at a radius of 15" with an adjustable lift-off. Because the required outer diameter of the sample is 42" that is greater than the width of the material, 36", there are two straight edges, ***E1*** and ***E2***, on two sides of the sample and are very close to the sensors, #1 and #2. Notice also that there two through holes, ***H1*** and ***H2***, made very close to these two sensors and near the center points of the two edges. We are going to see signals from all the saw-cuts, as well as from the edges and holes. Note the measured signals represent the induced voltages in the sensor coils, instead of the flux densities. The induced voltages are proportional to the time derivative of B_y.

A 8-channel DT321 data acquisition system was used in conjunction with a Gateway-2000 Pentium II PC to condition and collect the signals from 3 of the 5 sensors as shown in Figure 10.

Typical experimentally signals measured from Sensor #3, which is placed right on top of the four saw-cuts, are shown in Figure 11. Signals from all saw-cuts, as well as from the holes, ***H1*** and ***H2***, and Edges ***E1*** and ***E2***, can be seen in Figure 11 A. Figure 11 B shows the signals from Sensor #3 when there is no excitation. The small signals seen there are due to the residual magnetism from the steel lathe.

We notice that in the Edge ***E1*** area the signals are complex, because ***E1***, ***H1***, and ***D3*** are very close. Their signals overlap each other. Similar situation happens in the Edge ***E2*** area with signals from ***H2*** and ***E2***. However, e can see clearer pictures in Figures 12A and 12B. Comparing to Sensor #3, Sensor #2 is closer to the edges and holes and is away from Saw-cut ***D3***. Therefore, clearer hole and edge signals are shown in Figure 12 A. Similarly, Sensor #4 is away from the edges and holes. Therefore, the those signals become less and Saw-cut ***D3*** signal is greater in the curves seen Figure 12 B.

Lift-off is considered a critical problem in rolling process, because it is very difficult to be accurately controlled. Therefore, we tested the sample under different lift-off distances. The results are shown in Figure 13. It can be seen that all signals we have seen in Figure 11, where the lift-off is 1.5 mm, can be also observed in Figure 13 A, where the lift-off = 3.0 mm, and Figure 13 B, where the lift-off = 6.35 mm. The differences among these figures are basically in their magnitudes only. Therefore, we believe that lift-off wouldn't be an critical issue in the proposed technique.

8. PROSPECTIVE

The limited FE simulation and experimental measurements have provided the feasibility and the positive aspects of the proposed technique. The probe is made only of magnets and magnetic shields and the system is a simplest data acquisition system. Therefore, we can surely to predict its possible good features, such as low cost, low power consumption (can be basically a passive device), robustness, standing high temperature, ease in operation, etc. We can also easily to predict that the inspection can go much deeper than the 3/8" aluminum sample, because

1. Much stronger magnetic field can be obtained by either using a higher ampere-turns excitation or simply using newly developed rare-earth permanent magnets.
2. The sensors are arbitrarily chosen coils. There is a big room for increasing their sensitivity, for example using a well-designed magnetic circuit, introducing a preamplifier, and/or using the newly developed highly sensitive magnetic sensor, such as MR and GMR, etc.
3. A better data acquisition system, specified signal processing algorithms and pattern recognition methods can be utilized to enhance the delectability of the system.

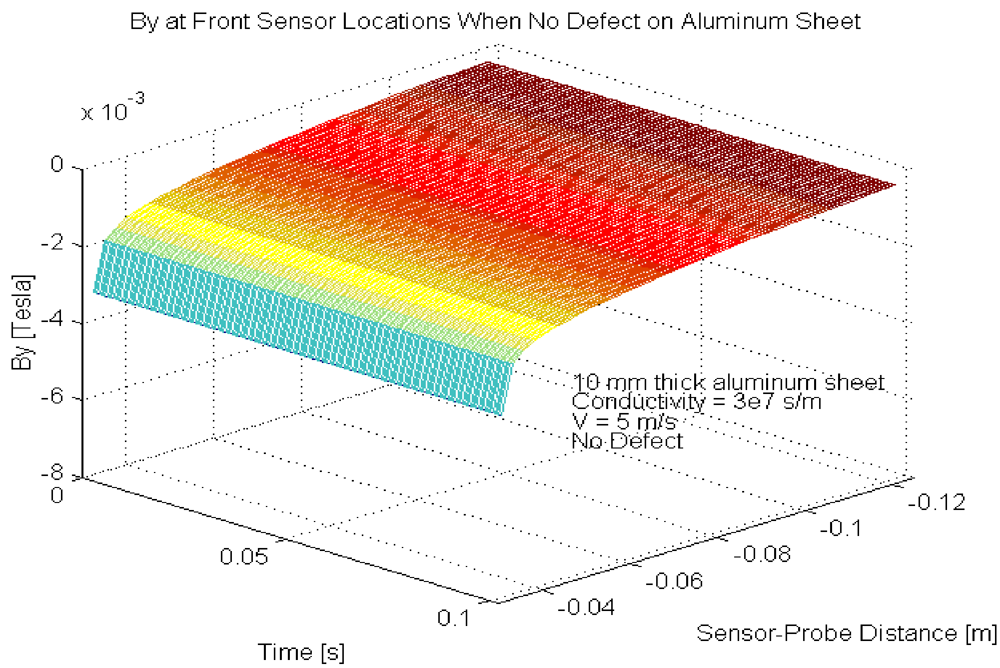


Figure 4. FEM Data of Model M11 No. 1:
B_y at front sensor locations when there is no defect on the sheet

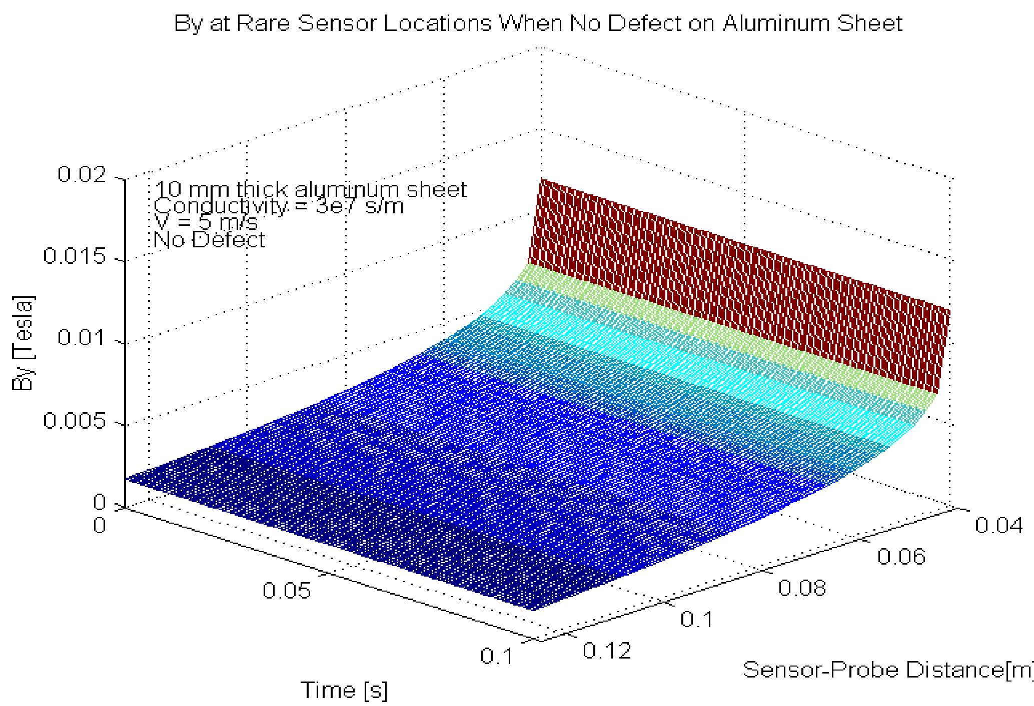


Figure 5. FEM Data of Model M11 No. 2:
B_y at rare sensor locations when there is no defect on the sheet

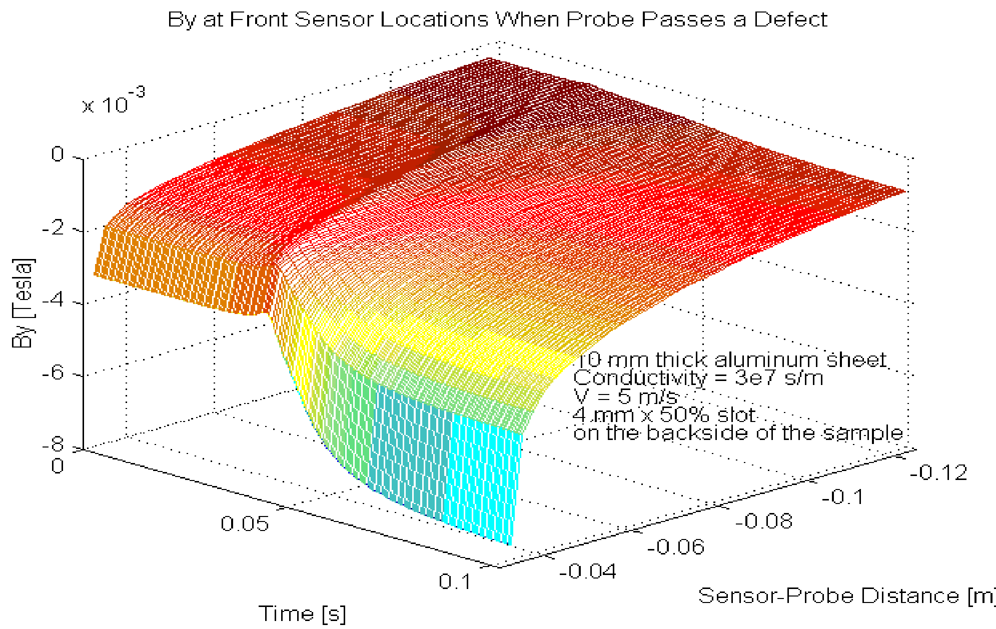


Figure 6. FEM Data of Model M11 No. 3:
B_y at front sensor locations when probe passes a 4 mm x 50% defect on the backside of the sheet

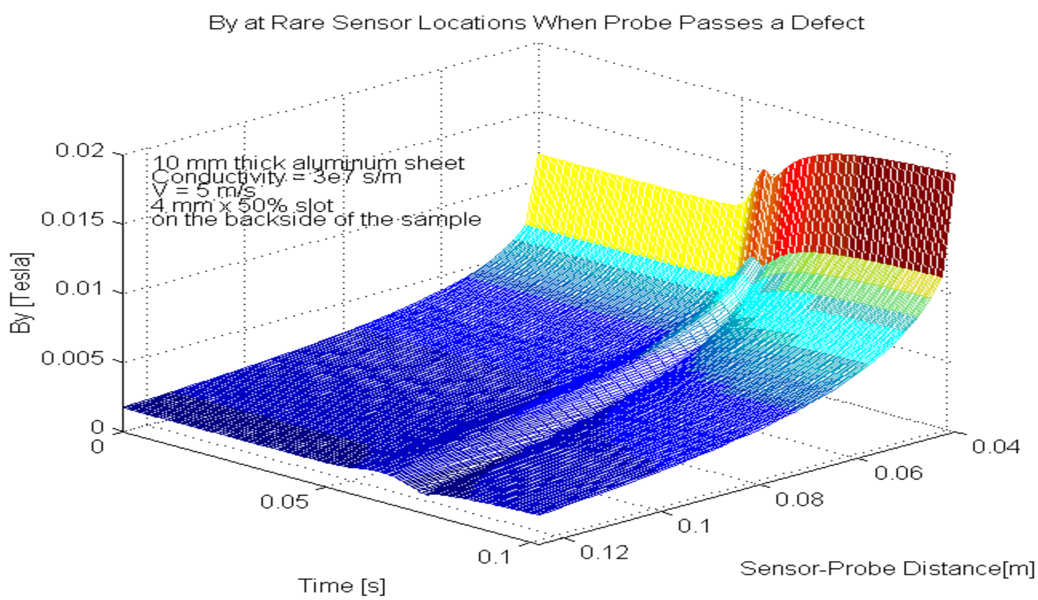


Figure 7. FEM Data of Model M11 No. 3:
B_y at rare sensor locations when probe passes a 4 mm x 50% defect on the backside of the sheet

A. Top view

B. A side view

C. A one cycle induced current in the moving aluminum plate

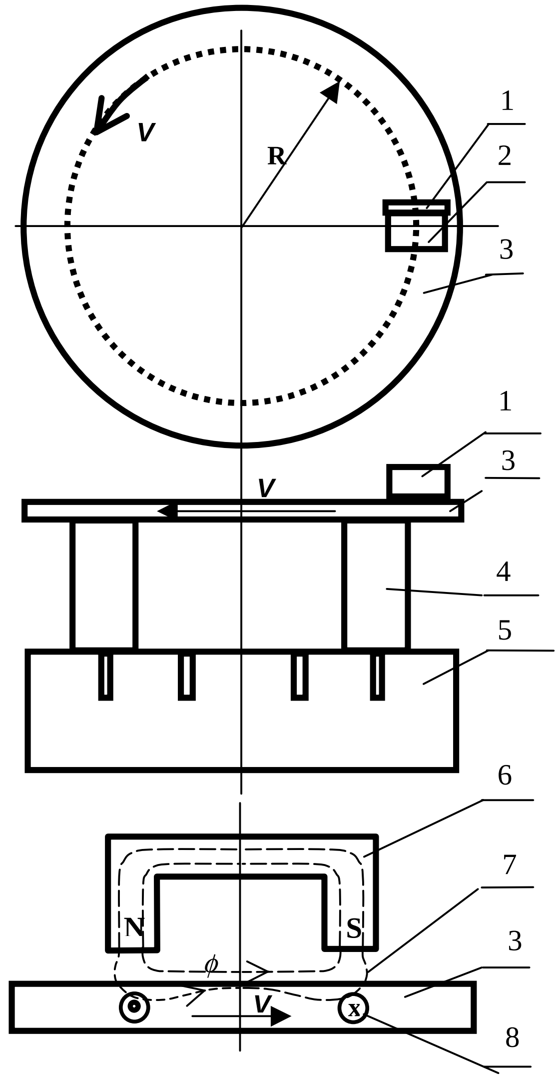


Figure 8. Schematic and principle of the test set-up used for verification

1. MIRF probe.
2. Five horizontally aligned coil sensors.
3. Aluminum sheet sample.
4. 4 Non-conducting and non-ferromagnetic support bars.
5. Lathe Chuck.
6. Magnetic of the MIRF probe.
7. Magnetic flux.
8. Induced current.

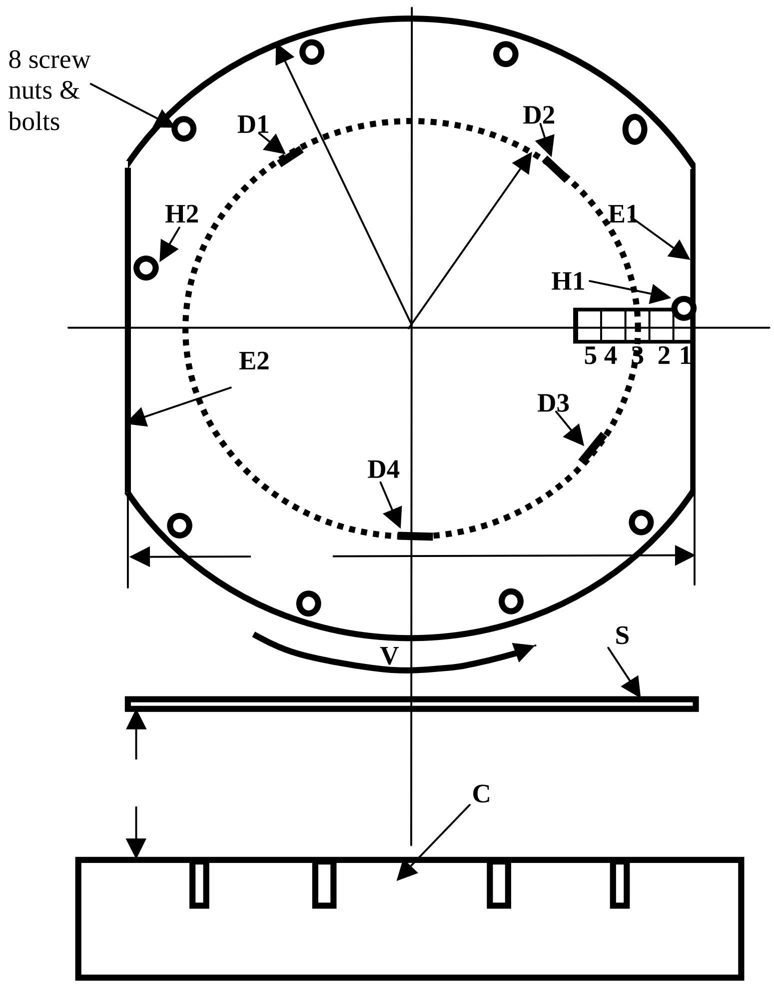


Figure 9. Arrangement of the key components in the test
P - Specimen, a $^{3}/_{8}$" thick aluminum plate. C - Chuck
D1, D2, D3, D4 – four 2" long 0.04" wide saw-cuts
with a depth of ¼", $^{1}/_{8}$", $^{1}/_{16}$" and ¼", respectively.
E1, E2 – two edges on the specimen.
H1, H2 – two through-holes near the edges.
1, 2, 3, 4, and 5 - five rare sensor coils of the probe.

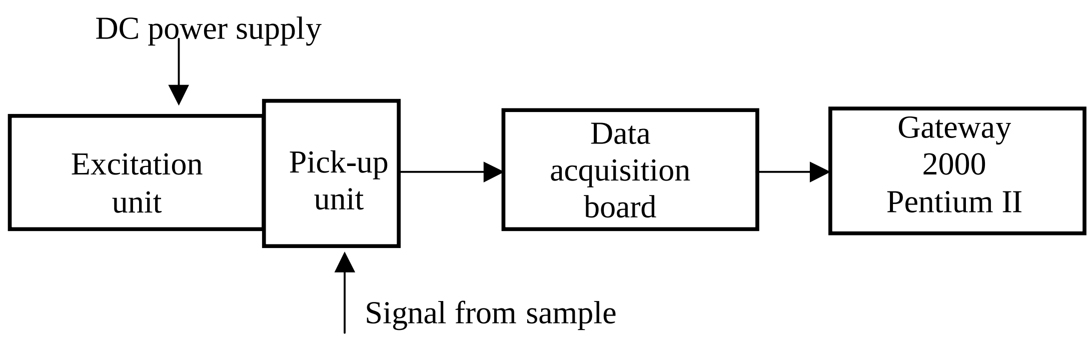
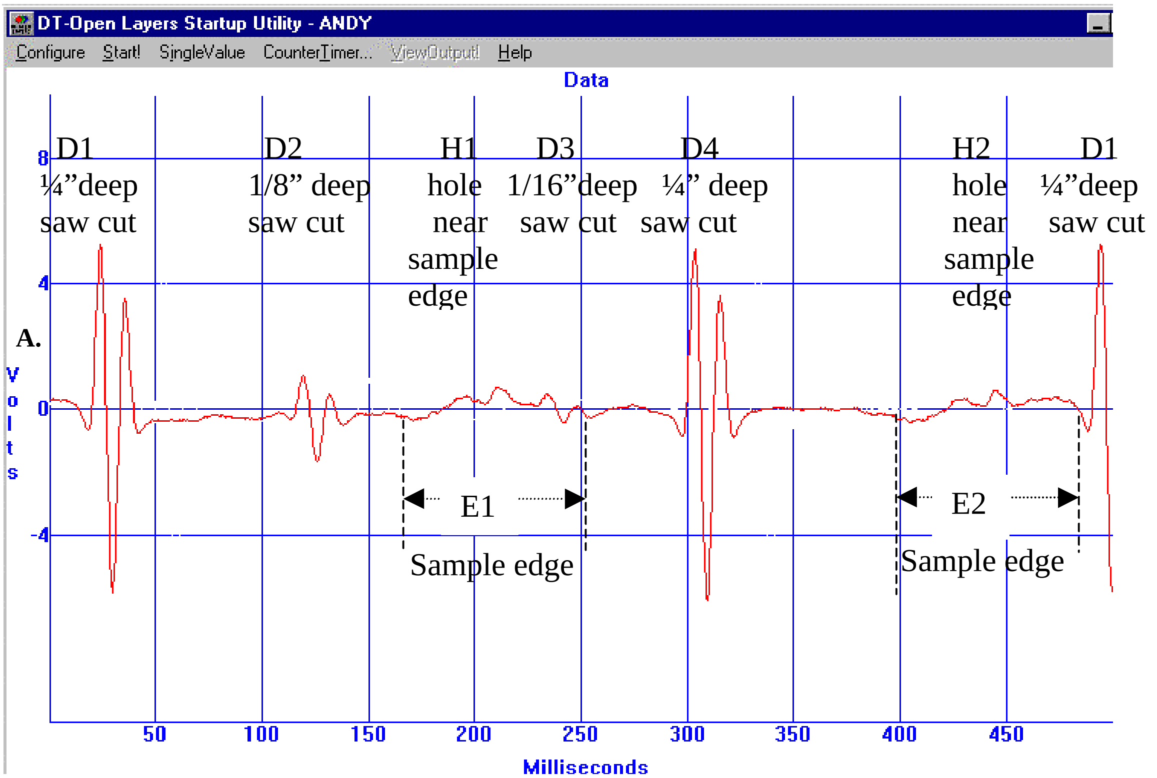


Figure 10. Diagram of data collecting



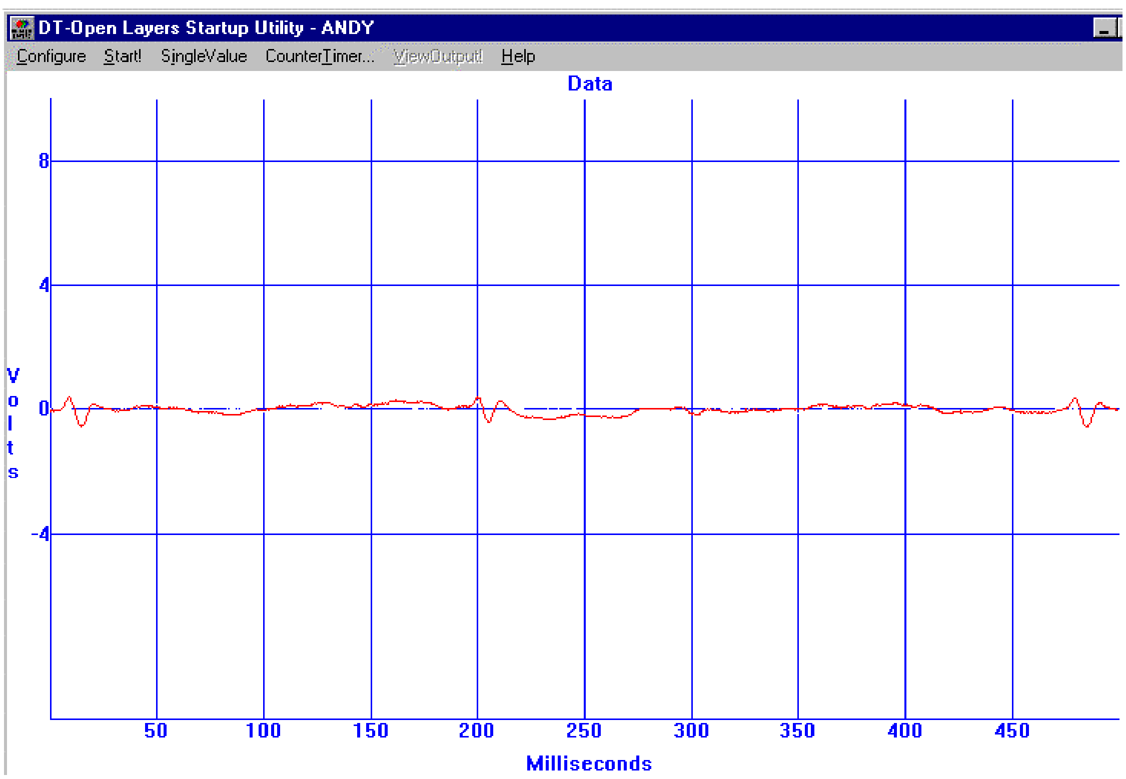


Figure 11. Typical test results obtained from Sensor #3 showing the feasibility of the proposed method
Speed = 4.87 m/s, Lift-off = 1.5 mm, Gain = 2
A. Excitation = 180 Ampere-turns; **B**. Excitation = 0 Ampere-turns.

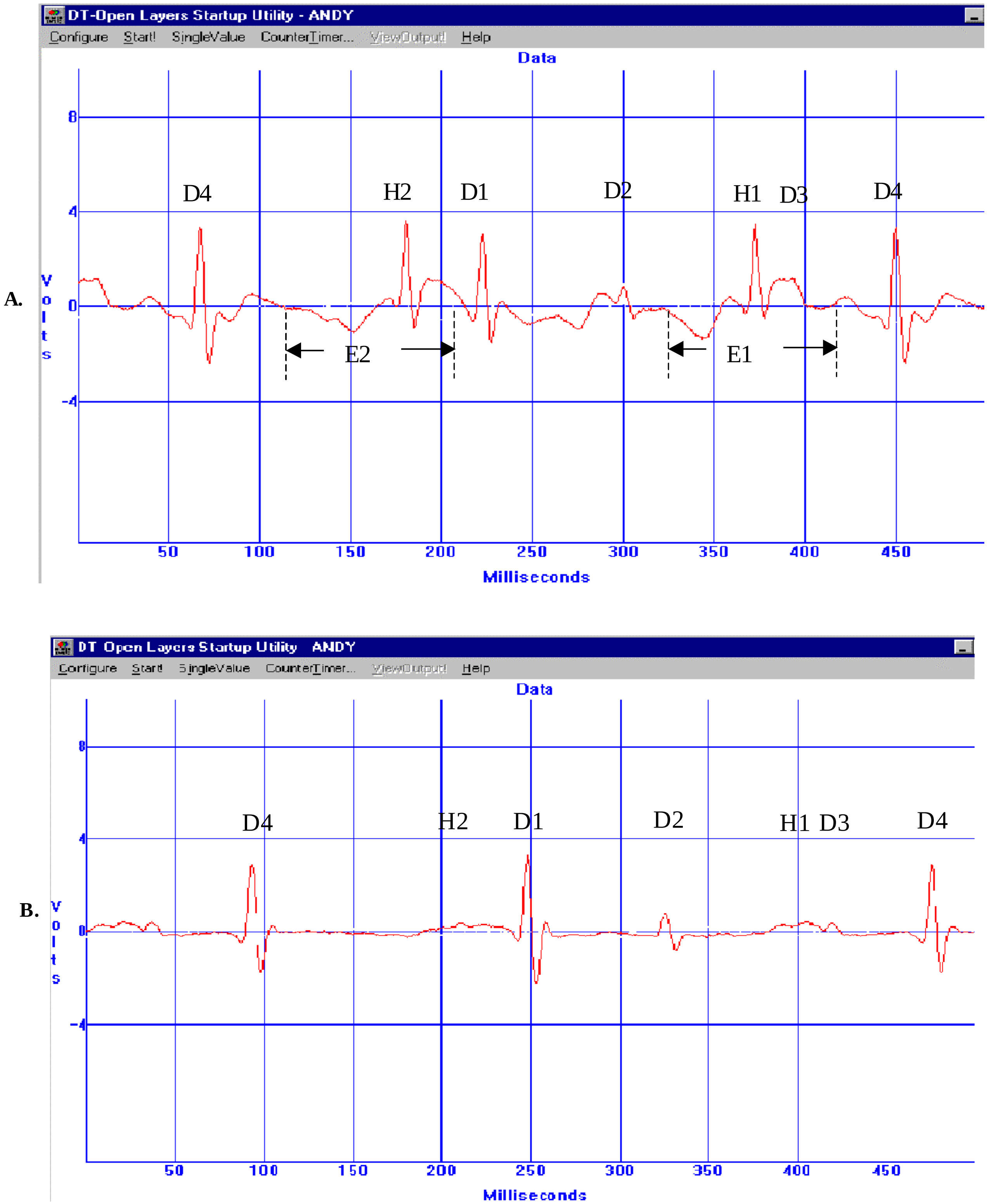


Figure 12. Typical test results from sensors slightly away from the defect
Speed = 4.87 m/s, Lift-off = 1.5 mm, Gain = 2, Excitation = 180 ampere-turns
A. Sensor #2, **B**. Sensor #4.

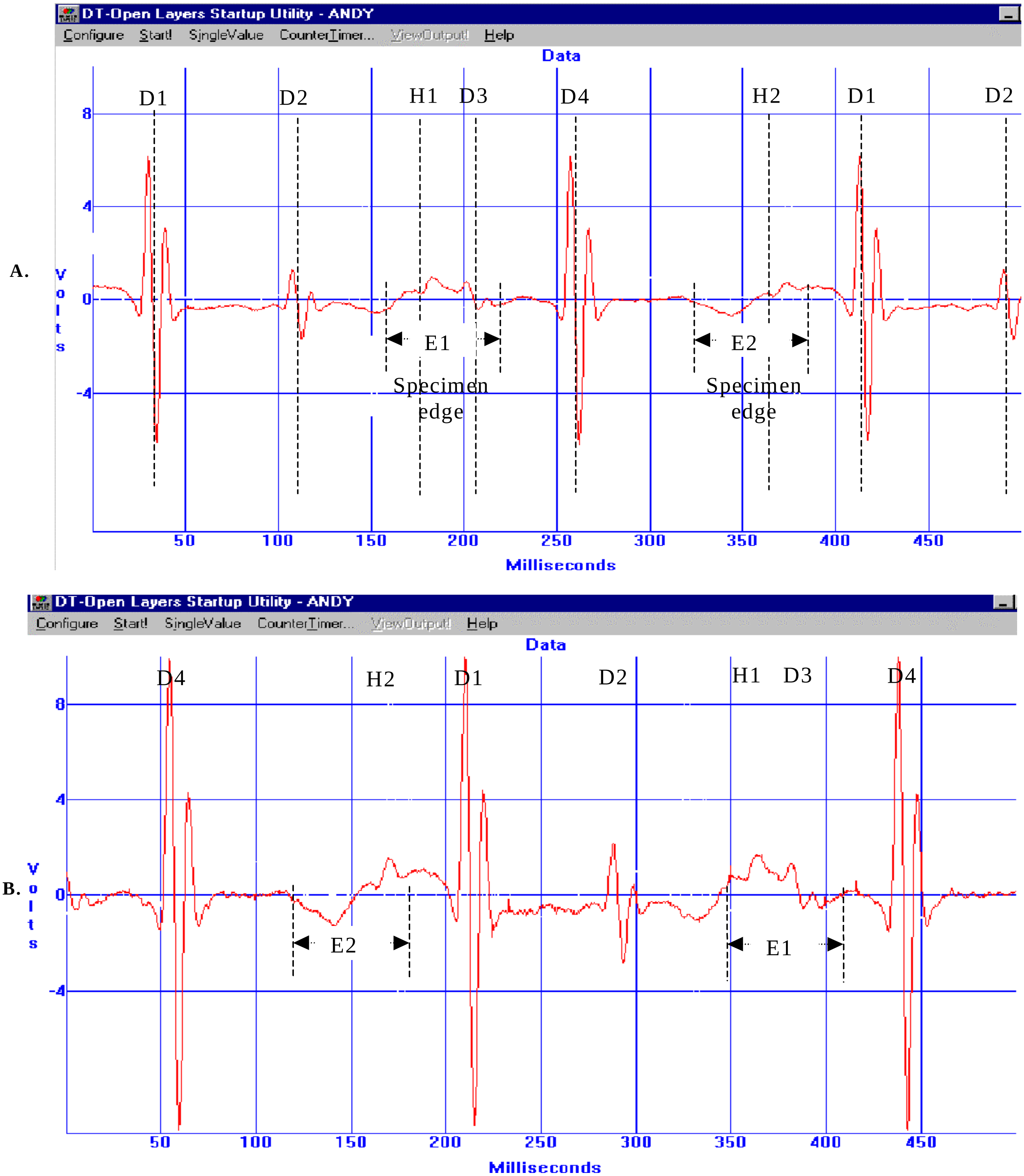


Figure 13. Typical test results from Sensor #3 at greater lift-off
Speed = 4.87 m/s, Excitation = 180 ampere-turns
A. Lift-off = 3 mm, Gain = 2, **B**. Lift-off at 6.35 mm, Gain = 4.

9. CONCLUSIONS

1. A novel non-destructive inspection system and method capable of on-line real-time monitoring and examining quality of rolled metallic strips is presented. The system/method is based on the motion induced remote-field eddy-current effect and capable of detecting flaws irrespective of their locations in a metallic strip under inspection.
2. The feasibility of the system/method has been verified using both finite element simulation and experimental measurements.
3. It can be predicted from the work done so far that the proposed system/method may have great prospective in possible future applications.

10. REFERENCES

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