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A Review of Material Properties Estimation Using Eddy Current Testing and Capacitor Imaging

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Abstract: The non destructive testing applications based on inductive (eddy current testing) and capacitive sensors are widely used for imaging of material properties. The simple structure, safe to use, low cost, non contact application, good response at medium range frequency of the sensors make them preferable to be used in the industries. The aim of this study is to talk about the material properties estimation applications using eddy current testing and capacitive sensing. The basic operations of eddy current testing and capacitive sensing with example of application in the non destructive testing are discussed. Next, the recent advancements of eddy current testing and capacitive testing in imaging technique are presented in this paper. *Copyright © 2009 IFSA.*

Keywords: Material properties, Eddy current testing, Capacitor imaging, Non destructive testing

1. Introduction

A specimen under test using NDT (non destructive testing) is safe from destruction and alteration of its natural properties. The application of material properties estimation in non destructive testing has two purposes in general as following:

1) *Inspecting the material structure*. The inspection of material structure involves the measurement of material defect (cracks and corrosion), uniformity in terms of dimension or shape, thickness, material strength etc. Every solid object or component has the risk of damage and breaking during service, therefore testing at manufactures and during use to detect defects is often essential so that this problem and avoided. For example, during the process of casting a metal object, the metal may shrink as it

cools, and crack or introduce voids inside the structure. The performance of structures can be degraded; therefore, the detection plays an important role in quality control and its successful use in practical application. The categories of flaws may be defined broadly, for example bursts, fillet cracks, inclusions and laminations are commonly defects that can be found in wrought metals.

2) *The material properties studies.* The study of the material properties of the measurement mainly includes mechanical parameters (e.g. structural integrity) and electrical parameters (e.g. dielectric and conductivity).As discussed before; NDT is widely used in flaw and detection testing. However, applications of NDT go much deeper and are much broader in scope than the detection of gross effect. They concern all aspects of the characterization of solids, their microstructure, texture, morphology, chemical constituents, physical, electrical, dielectric and chemical properties, as well as their methods of preparation. There is concern for the most minute detail that may affect the future usefulness of the object or material, so that all properties need to be under control and all factors understood that may lead to undesired incident.

2. Material Properties Estimation Using Electromagnetic Technique

The electromagnetic methods are less popular compared to other inspection technique but are receiving a growing attention by the international scientific community [1]. Such methods are particularly effective in several applications, for example the detection of flaw on conductive materials [1-4] or less conductive material [3, 5], material characterization in terms of electrical properties and thickness [6], water content monitoring in a production line [7] and soil condition monitoring [8]. Of all magnetic methods, eddy current testing and capacitive-based sensing are possibly the most widespread methods for material properties estimation in terms of electric properties such as permittivity, conductivity and permeability using magnetic technique at medium-low frequency. All these material properties can be used to evaluate the condition of the material. For instance, it is possible to predict the mechanical state [9-12] or early stage of fatigue and cracks [13] of the material by determining the electrical properties such as conductivity, permeability etc Next section will discuss the application of eddy current testing and capacitive sensing in material properties estimation.

2.1 Eddy Current Testing

An inducting coil generates a time-varying magnetic field (most often AC at a given frequency), which induced eddy currents in the material under test (commonly conducting material). The density and spatial patterns of these eddy currents (and hence of the magnetic field that they produce) depends on the material properties (permittivity, conductivity and permeability) coil geometry and frequency [14]. Hence, it is possible in principle to estimate the material properties. Typically, the inducing coil is used also to detect the reaction magnetic field; the coil impedance variation is recorded and gives information on the material under test [1]. A separate inductive sensing/pick-up coil can also be utilized to detect the reaction magnetic field [4].

Recent applications demonstrate the use of other type of magnetic sensor to measure the reaction of magnetic field such as Giant Magneto resistance Magnetometer (GMR), Hall, squid, etc. A pulsed eddy current system is also available to measure the thickness, electrical and permeability of conducting material with the use of improved GMR sensor. The use of GMR-sensors opens the possibility of spatial resolution improvement by reducing transmitter coil size. More, a multi array probe system could be considered with a common transmitter enabling faster processing [15-18]. The use of the GMR technology as magnetic sensor looks promising for the following reasons [19, 20]:

– -the high sensitivity in a large frequency range and low noise provides the capability of detecting deeply embedded flaws as well as surface breaking flaws.
– -the collective manufacturing process facilitates the making of large array probe.

Although inductive pick-up coils show decreasing sensitivity at lower frequencies they can successfully be used for sensitive low frequency eddy current testing and there are several means for increasing the sensitivity of inductive pick-up coils:
- larger coil diameter (limited by the desired lateral resolution)
- increased number of turns.
- Well compensated differential arrangements of pick-up coils for optimal usage of the dynamic range of the read out electronics.
- Shielding from external electromagnetic noise sources.

The inductive pickup coils have some clear advantages in comparison with magnetic field sensor:
- very good linearity, very small hysteresis and no saturation even at quite large excitation levels.
- High flexibility in sensor configuration
- Easy adaptation to available eddy current electronics
- Lower cost and simple to construct.

Advantages of eddy current testing are instantaneous results, sensitive to a range of physical properties, contact between inspection coil and specimen not required, equipment small and self-contained and the sensor/probe can be miniaturized to observe flaws even at µm resolution. One major limitation of eddy current testing based on alternating input signal applied into the excitation coil is that the eddy currents are concentrated close to the surface (the so-called skin effect), especially at high frequency and conducting material [15]. The magnetic field of the eddy current is counteracting the exciting magnetic field thus lowering the eddy current density with increasing depth. On the other hand the eddy current test system cannot be used at low frequency due to limited sensitivity. Consequently, the ECT system is not able to estimate deep defects. However, some of the methods to increase effective penetration depth [21]: decrease of exciting frequency, increase of exciting field strength, selecting deep penetrating field trajectories, changing material's properties and increasing sensor sensitivity at lower frequency.

2.2 Capacitive Based-sensing

Capacitance-based sensing system is based on measurement of changes in the dielectric constant between the sensing plates. By passing the material near or through plates of a capacitor the electrostatic field changes and so, the capacitance value measured across the plates. With modern electronics it is possible to measure very small capacitance changes. Another popular type of capacitive-based sensor is interdigital sensor. It shares the same basic principle with parallel capacitor. Fig. 1 shows operating principle of interdigital sensor similar to that of parallel plate capacitor.

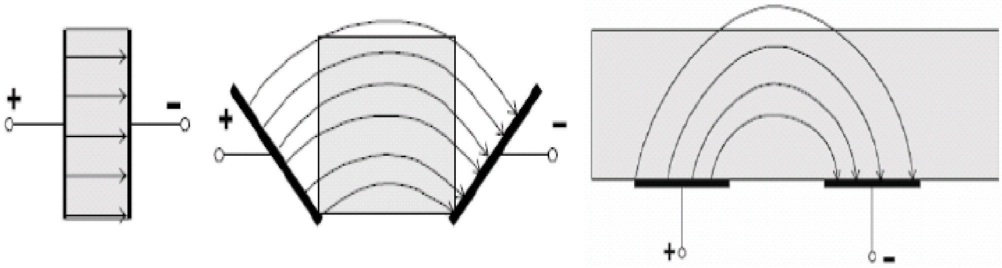


Fig. 1. Operating principle of an interdigital sensor.

The interdigital sensors have been applied in many areas such as bridge structure testing [3], study of relationship between dielectric properties of insulating material with age and absorption of water [22], moisture content measurement in pulp [23], measurement of fat to protein content in milk [24], estimation of fat content in pork meat [25], inspection of the quality of saxophone reed [26], detection of gases [27], detection of humidity [28], detection of affinity binding of molecular structures for nano-scaled application [29], dielectric properties estimation of agricultural product [30] etc.

Capacitive-based sensing or interdigital sensor offer many advantages. The broad distribution of the electric field allows relatively large area of coverage (compared to the size of the sensor) with a single sensor [3]. Moreover, capacitive sensors are immune to noise caused by lighting, or audible noise and insensitive to the color, shape, surface and texture of the object [31]. In addition, the interdigital sensor has one side access to the material leaving the other side open to environment which can allow absorption of gas, moisture, or chemicals which can change electrical properties of the material under test [27].

3. Imaging in Nondestructive Testing

Systems that provide pictorial information certainly offer the user global information that can be interpreted rapidly [18]. There are many different types of non-destructive testing that are applying imaging technique in the industries. The images can be obtained directly (as with a camera) or indirectly. Direct imaging refers to the visualizing and recording of live scenes which may be invisible to the human eyes, such as infrared or x-ray imaging. The most common utilized recording devices in direct imaging are high performance charge-coupled device (CCD) cameras. Innovative examples of direct imaging include particle imaging velocimetry (PIV), measurement of pH and temperature profiles by fluorescence imaging and micro scale imaging of shear stress in fluids. The other broad of imaging technology is indirect imaging, measurements are made around or ever the surface boundary of the measurement and these data are inverted by a mathematical algorithms. Amongst the common indirect imaging technique in NDT are ultrasound, x-rays, eddy current testing and capacitive sensing imaging.

Ultrasound imaging is one of the most widely used techniques in civil, aerospace and medical applications. Normally, a coupling medium between the sensor and material is required either using a water-bath or a contact approach. However, the use of water gel as couplant may not always be suitable for certain inspection situation, e.g. where the material absorbs water, or where surface contamination or damage would result, therefore, there has been increase interest in using air as coupling medium [32]. The use of x-rays has always been a popular technique for difficult materials, but x-rays systems use ionizing radiation and so require proper screening to protect the users [32]. Moreover, x-rays systems are comparatively expensive compared to other imaging system. The next section will focus on the applications of eddy current and capacitive imaging for non-destructive testing.

3.1 Eddy Current Imaging

The conventional eddy current testing is well established for the detection of flaws and defects of surface or near surface in electrically conductive material since its introduction has been mainly used to detect flaws with little success in providing quantitative results [33]. A decision to reject or disregard a component is generally made when a flaw signal is detected above some predetermined threshold values. More complex applications often demand new inspection methods, as the detection or measurement of material properties estimation may not accurate enough, thus imaging technique must be applied. In an imaging problem, the aim is to produce a spatial map of the material properties from the measured data [33].

Imaging technique using electromagnetic sensors are mainly used for biological and non-biological properties estimation, and flaw/defect detection. In the case of eddy current imaging, by maximizing the oscillating magnetic field generated by the excitation coil, the creation of a maximized induced eddy current within the material under test is made possible. The imaging technique in can fall into categories as discussed before i.e. indirect method and indirect method.

3.1.1. Indirect Technique of Eddy Current Imaging

The intensity of Eddy currents induced in the material is related to the properties of material. This can be measured from the impedance change of the coil. The EC coil (probe) is instrumented with an impedance-measuring device. The impedance measurement can be an absolute measurement or, more commonly, a differential measurement from a balanced bridge network [34]. Raster scanning is used to produce images of the impedance or impedance changes over a 2-D surface of the object. Acquired images are complex valued since the impedance change consists of a resistive and reactive component [34].

Indirect type of eddy current imaging system usually involves less equipment and smaller and simpler structure as compared to direct technique. Furthermore, the total cost of the system can be significantly reduced. However, the images quality and system performances depend on the algorithms use to reconstruct the image and the computation power, respectively. The next section will discuss few important examples of indirect technique of eddy current imaging.

3.1.1.1. Imaging based on ECT for Biological Tissues

Measuring the magnetic field of the induced currents in a conducting body provides a means to image the electrical conductivity of biological tissues. In general, the system uses magnetic excitation to induce currents inside the body and measures the resulting magnetic field. This type of system usually operates between 10 kHz to 20 MHz and the concept has been applied for decades and commonly known as eddy current testing (ECT) or induced magnetic measurement technique. Most of the applications are in the field of geophysical inspection, non destructive testing (NDT), salt content measurement in sea water and impurity measurement in semiconductor.

It was reported that, in 1968, Tarjan and McFee introduced the application of measurement of induced magnetic field to determine the electrical resistivity of the human torso and head [35, 36] first. Later, after the discovery of tomography method in 1980 [37], induced magnetic field measurement has evolved into novel imaging system of mutual inductance imaging [38] and followed by magnetic induction tomography (MIT) [39]. For both mutual inductance and magnetic induction tomography systems, the main features are [40]:

1. Operate at high frequency (between 1 MHz and 20 MHz).
2. Employs multiple sensing channels.
3. Thick biological bodies are of main interest.
4. The displacement currents in the conducting body are not negligible.
5. The propagation effects should be taken into account.
6. The stray capacitances are effective in the measurement.
7. Both the theory and the experimental work are more complicated than the low-frequency studies.

A low operational frequency imaging system (between 10 kHz and 1 MHz) which the main objective is to visualize near surface of biological body [40, 41] employs a single channel to collect data with a scanning mechanism. It was constructed to overcome the limitation of conventional inspection systems for biological tissue where low-current sinusoidal current has to be applied via electrodes attached to the body surface. The use of current injection from the surface electrode affects the performance of the imaging system. A low-frequency driven contactless induced magnetic field measurement system has the following advantages:

1. No physical contact between the body and the measurement system, therefore the risk of contaminations can be avoided.
2. Current can be coupled into the biological tissues avoiding screening effect of the superficial insulating layer.
3. The number of measurement can be increased by simply shifting the transmitter and receiver coil array.

Fig. 2 shows the basic mechanics of an induced magnetic field measurement imaging system which usually operates at low-frequency. A coil system is assumed nearby the upper surface of a conductive body (biological tissues). The transmitter coil is driven by a low-frequency sinusoidal wave to provide alternating magnetic field. When a conductive body is brought near these coils, induced current in the body are proportional to the conductivity distribution. These currents create secondary magnetic field and electromotive force (emf) induced in a receiver coil is measured.

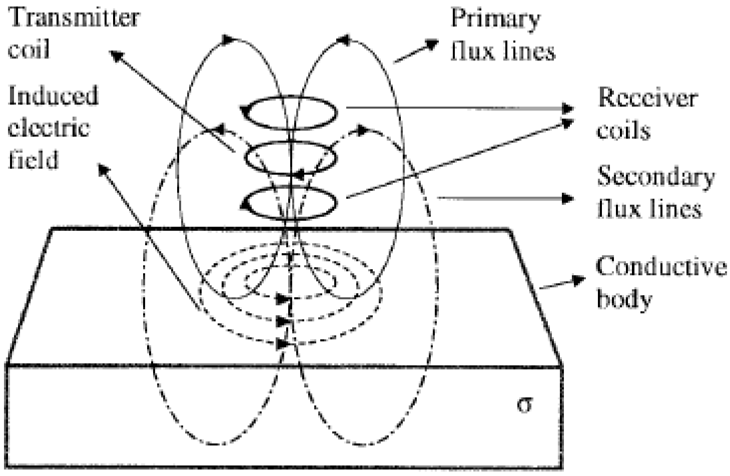


Fig. 2. General principles of data collection in the induced magnetic field measurement imaging.

Forward problem (i.e. the calculation of measurement for a given material property such as conductivity distribution) is solved by relating the system parameter such as the relation of magnetic flux density to induced currents. A set of sensitivity matrix which relates to the perturbation in measurements to the conductivity perturbation is calculated. The sensitivity map is used in the inverse problem solution. Inverse problem (i.e. the calculation of the unknown material properties using the measurements) is solved using image reconstruction algorithm such as Newton Raphson method.

The application of induced magnetic measurement imaging for visualizing spatio-temporal conductivity changes in biological tissues by magnetic coupling (i.e. contactless measurement) has been demonstrate [41]. It is observed that is it possible to identify conductivity perturbation at 2 cm depth. However, the resolution is inversely proportion with the depth of conducting perturbation. A couple of years later, improvisation [40] to the technique using different coil designs and an effective data acquisition was employed. The outcomes of the experiment were very promising in proving necessary conducting information for electromagnetic source imaging of the human brain for future applications.

3.1.1.2. Eddy Current Imaging for Printed Circuit Inspection (PCB)

Eddy current imaging technique has significantly increased the ability to detect flaw in PCB [42-46]. In general, the process of obtaining the images was done by placing the sensor near the PCB at a fixed distance or lift-off, then the sensor was moved in x and y direction to cover the PCB areas while the output of the sensor is recorded, all the recorded data then plotted on a surface chart representing the image of the PCB.

A new structure of a single pick up coils made of solenoid coil was developed and used for imaging of the defects of PCB, the new coil is lower sensitiveness non-uniformity of magnetic field accompanying the investigated signal [43], furthermore, the tangential component of magnetic field which only appears in specific areas-together with defects or at conductor's boundaries. To generate an image of the electromagnetic properties of the PCB board a single probe (coil system) scans the PCB surface point by point at a certain resolution. The resultant output signal is displayed correspondingly to the probe position. Within one complete scan, an image may be recorded. The solenoid coil tested the tangential component of the magnetic flux delivers smaller output voltage but pickup less noise and the final quality of composed images is much higher. The advantage of this single probe scanning is a high quality of imaging due to the constant probe characteristics [47]. The main drawback is time consuming imaging process.

The application of eddy current has been improved using three solenoid pick up coils with the purpose to increase the speed of the inspection process [44]. Information about the defects was translated from amplitude or a phase signal provided the inspection, this research made use the amplitude signal in the visualization process. The image processing method was improved by using three steps: removal of a noise and an offset component coming from non-uniformity of geometrical conditions, calculation of threshold and visualization of data obtained as surface chart. A final image defects are visible as spots not corresponding to soldering iron as shown in Fig. 3. However, the detection of defects relies on the comparison between spots. Kacprzk et.al. [44] suggested that the extraction of the soldering point spots using phase characteristic and a new filter which can analyze the shape of the signal. This was accomplished using image processing technique such as wavelet-based [42-46].

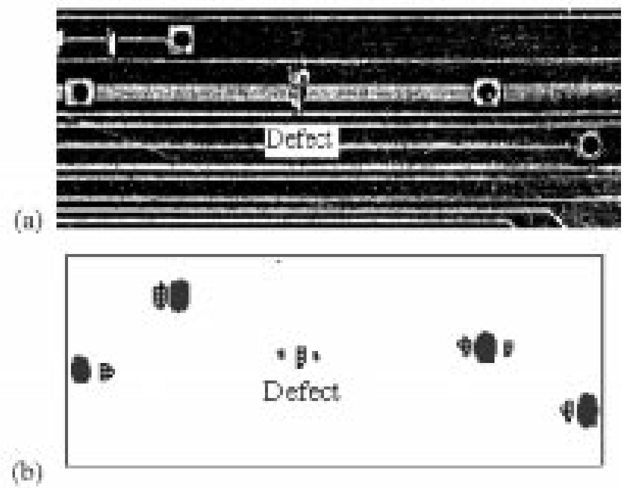


Fig. 3. Inspection results: PCB model (a), image using amplitude data (b).

Major improvement has been achieved [48, 49] where high-density double-layer PCB inspection based on ECT imaging was accomplished. The tangential component of magnetic flux which occurred due to defects of soldering iron was detected using a Spin-valve giant magnetoresistor (SV-GMR) sensors array with effective area of 100 μm × 93 μm. It has been shown that the identification of defects on both top- and bottom-layer of the high density PCB was possible either from top- or bottom scanning [49]. A high-density double-layer PCB with a dimension of 5 mm × 5 mm, as shown in Fig. 4(a) was used as a model. The PCB conductors parallel to the direction are the top-layer conductor, and the others are the bottom-layer conductor. The disconnection and partial defects are also allocated on both the top and the bottom layer of the PCB model. Two-dimensional (2-D) images reconstructed from the ECT signal obtained from scanning over the top layer of the PCB model in the *x* and *y* directions are shown in Fig. 4(b) and (c), respectively. The numerical gradient technique is a simple image processing technique used to eliminate signal offset and enhance the signal at the defect points. The 2-D images show that the probe is capable of inspecting the defect clearly, although the defect points are allocated on a bottom-layer PCB conductor. In the final report of the research, the usage of the sensor matrix was proposed for improving inspection time.

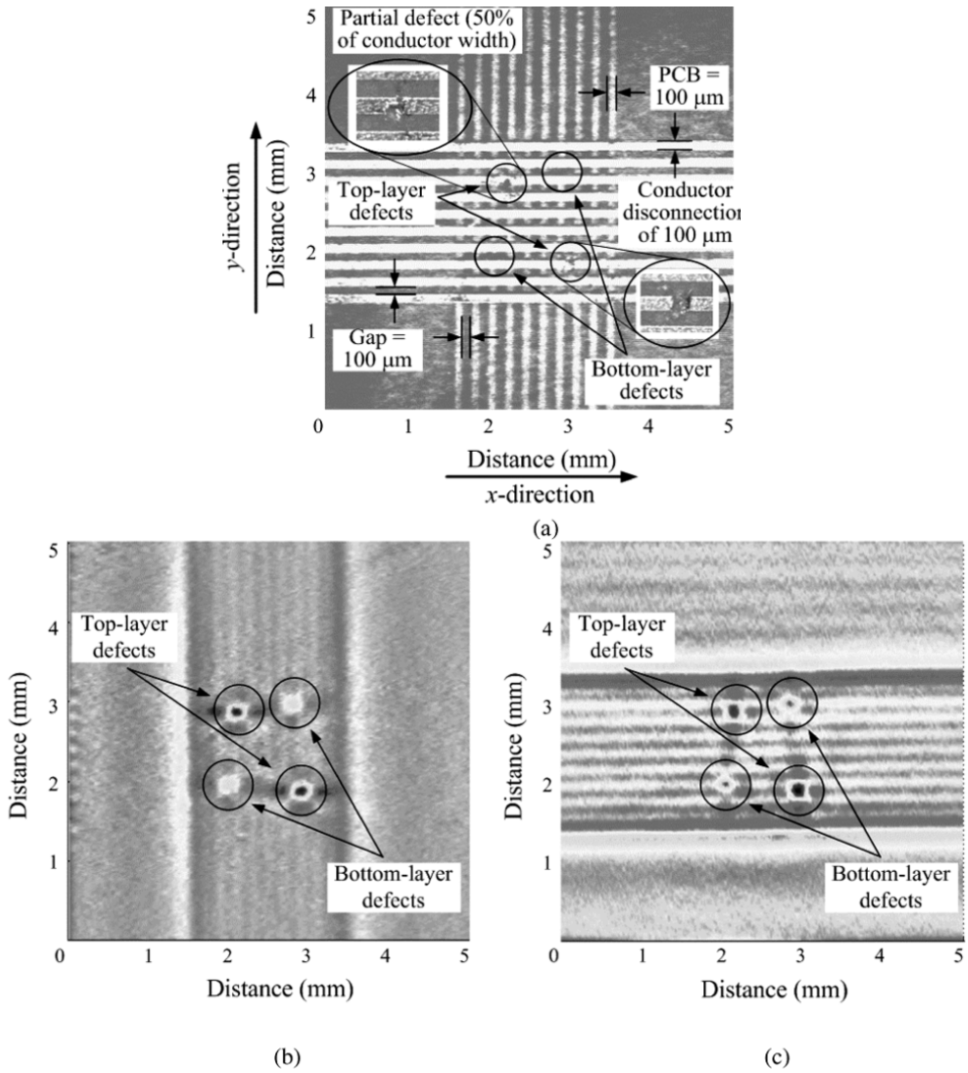


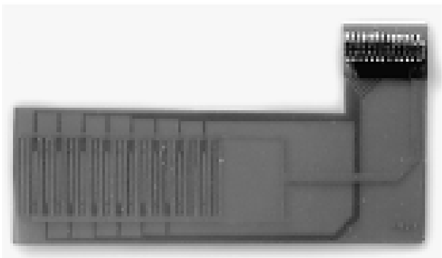
Fig. 4. High-density double-layer PCB model with defect points (100-μm disconnection length) and its inspection results obtained from the proposed probe: (a) High-density double-layer PCB model; (b) x-direction scanning; and (c) y-direction scanning.

Advantages of this method compares to other PCB inspection methods are:
1. The system performance is not limited to visible or surface defects where optical method cannot detect the invisible flaw.
2. This system can be applied to many different kind of PCB as compared to flying probe method where different kind of flying probe is required for each type of PCB1 [43]. This will significantly reduce the time and efforts to complete the inspection.
3. The use of array of magnetic sensor such as spin-valve giant magnetoresistance (SV-GMR) offer high-spatial resolution and high sensitivity to low magnetic field.

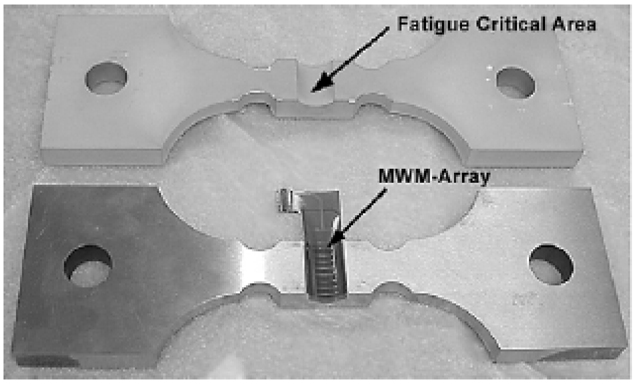
Disadvantages and issue regarding to eddy current imaging for printed circuit board inspection are:
1. A reference or standard measurement is required before the inspection can be performed.
2. The measured signal across the sensing coil is a combination of signals due to defects superimposed with noise signals.
3. When magnetic sensor array is employed, long inspection time is unavoidable. Furthermore, magnetic sensor such as SV-GMR requires external power supply to operate.

3.1.1.3. Eddy Current Imaging in Metal Component Flaws

Early stages fatigue cracks and damage can be detected by measuring the changes of electrical conductivity or, in the case of ferromagnetic materials, magnetic permeability. Linear MWM-Arrays [50, 51] were developed to test the condition of a custom-designed high-strength steel specimen. The design of the sensor is shown in Fig. 5(a) while Fig. 5(b) shows the fatigue-critical cavity where the MWM-Array was mounted on high-strength steel specimens.



(a)



(b)

Fig. 5. Design of MWW-Array and the testing procedure.

Fig. 6(b) shows MWM-Array measured permeability images for the Type 304 stainless steel specimen which was never fatigue tested and was still fully austenitic after a full anneal heat treatment and, thus, nonmagnetic (μ = 1). The other specimen (tested to 88 % of fatigue life) was in a similar fully austenitic condition prior to the fatigue test. Fatigue damage region in the image shown in Fig. 6 (c) is well defined by the higher magnetic permeability as measured by the MWM-Array. The main advantage of this system is both permanently mounted and scanning MWM-Arrays can detect short cracks (significantly less than 250 µm in length at the surface) formed in steel components. Furthermore, MWM provides the capability for continuous on-line monitoring of crack initiation and growth during fatigue tests of steel specimens and components.

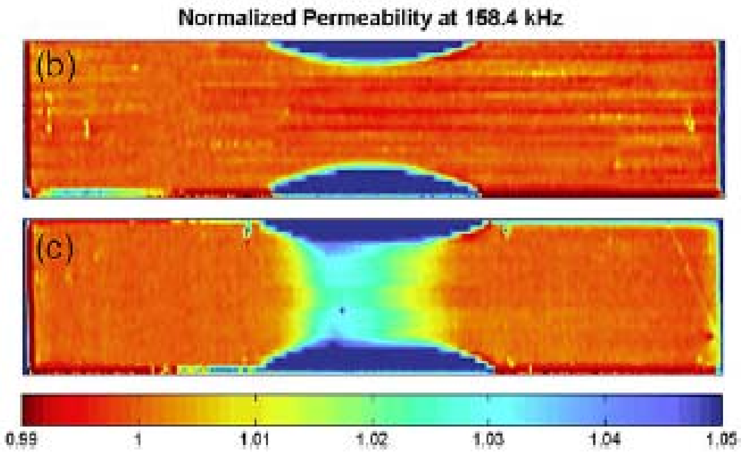


Fig. 6. The images generated by MWM-Array.

3.1.1.4. Eddy Current Imaging for Buried Landmine

The process to discriminate between harmful buried landmine and harmless clutters is difficult to achieve using conventional method such as handheld metal detector. A unique design of inductive array sensors which incorporates a single drive with multiple sense elements was developed to detect landmine and unexploded ordnance [52]. The drive winding creates a shaped magnetic pattern that concentrates the field energy into longer wavelength spatial modes with "focused" penetration into the ground and the multiple sensor arrays placed at different positions within the drive provide different "views" of buried objects and clutter as shown in Fig. 7.

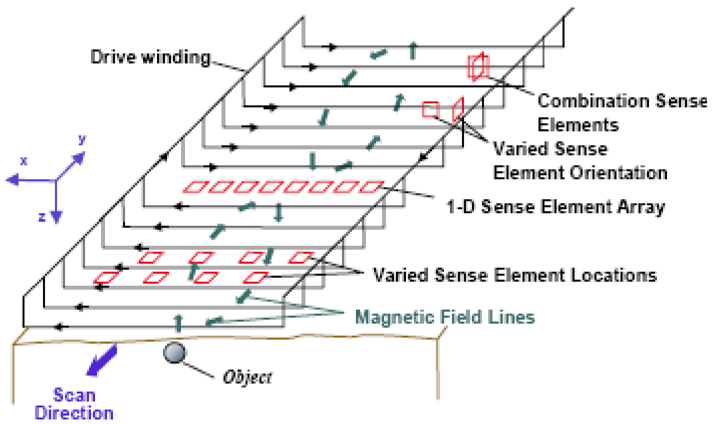


Fig. 7. Schematic for a distributed drive winding with multiple sense elements.

The modeling of the interaction of drive winding with the object was established using Braunisch et al [53] for distributions of conducting and permeable bodies of generic geometry. The resulting images provide a basis for spatial filtering and signal processing. Figs. 8, 9, and 10 show the images of object for single object with different diameter and at different depth, different orientation of hidden object and multiple objects at different depth and distance, respectively.

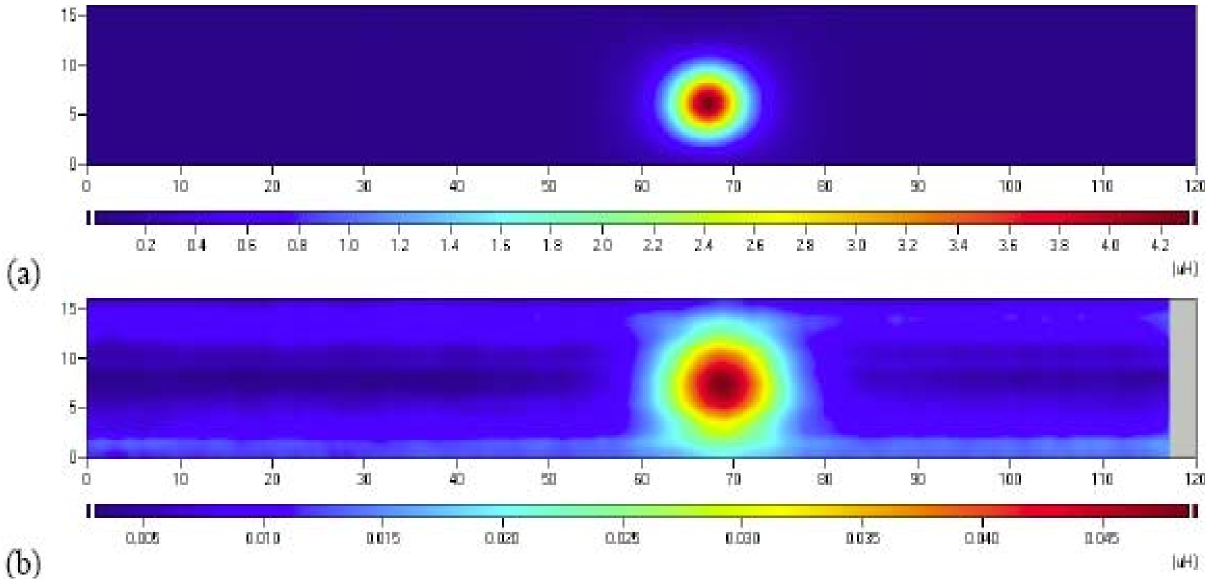


Fig. 8. Array magnitude response over (a) a 12.7 cm diameter aluminum sphere at a depth of 5 cm and (b) a 6.4 cm diameter aluminum sphere at a depth of 20 cm.

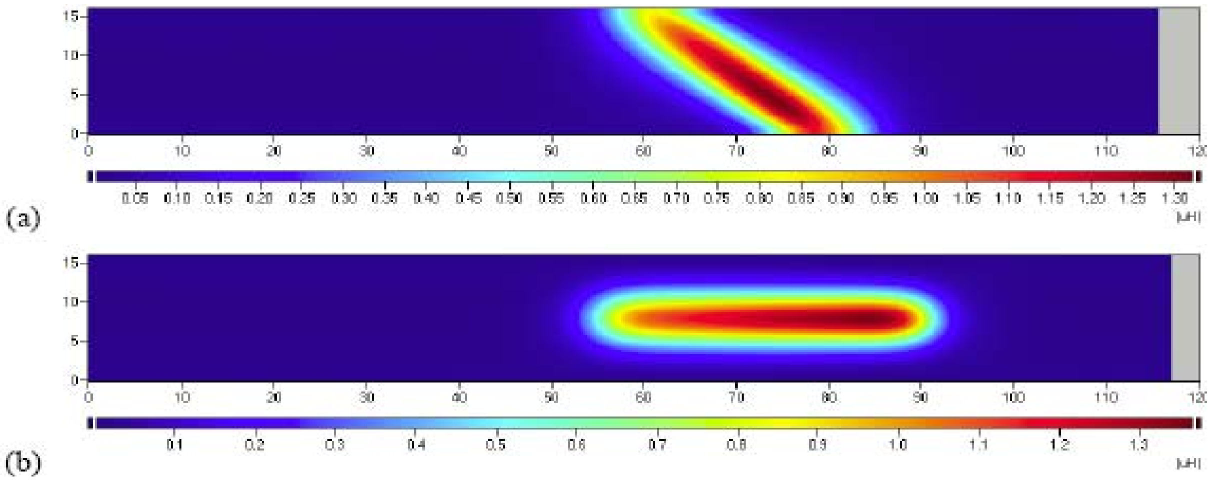


Fig. 9. Array magnitude response over a 91 cm long 3.8 cm diameter pipe at a depth of 10 cm oriented (a) at 45 degrees to the sense element array and (b) perpendicular to the sense element array.

From Fig. 8 the smaller but deeper sphere provides a larger spatial image than the larger but shallower sphere. Thus, the image has to be rescaled using certain method such as magnitude scaling before it can differentiate the object properties. Alternatively, if the depth is known, then the image size directly reflects the object size. Different orientation of objects can also be easily visualized as shown in Fig. 9. It is found that the spatial width of the images increases with object depth and size. It is shown that in Fig. 10, at shallow depths and with large separation distances, the response of each bomblet is distinct. For deeper depths and smaller separation distances, the interactions between the objects become more apparent and the diffusion of the magnetic field response leads to an overlap of the effective response and a "single" object response. This problem can be overcome by using higher resolution of sensor array.

Apart from the information of shape and orientation of objects retrieved from the images, a grid method was employed for converting the measurement data into physical properties. This patented method uses a database of responses, generated prior to data acquisition that relates the sensor response to variations in object material properties (conductivity, permeability and permittivity), size, depth, orientation, etc. over the range of interest [52].

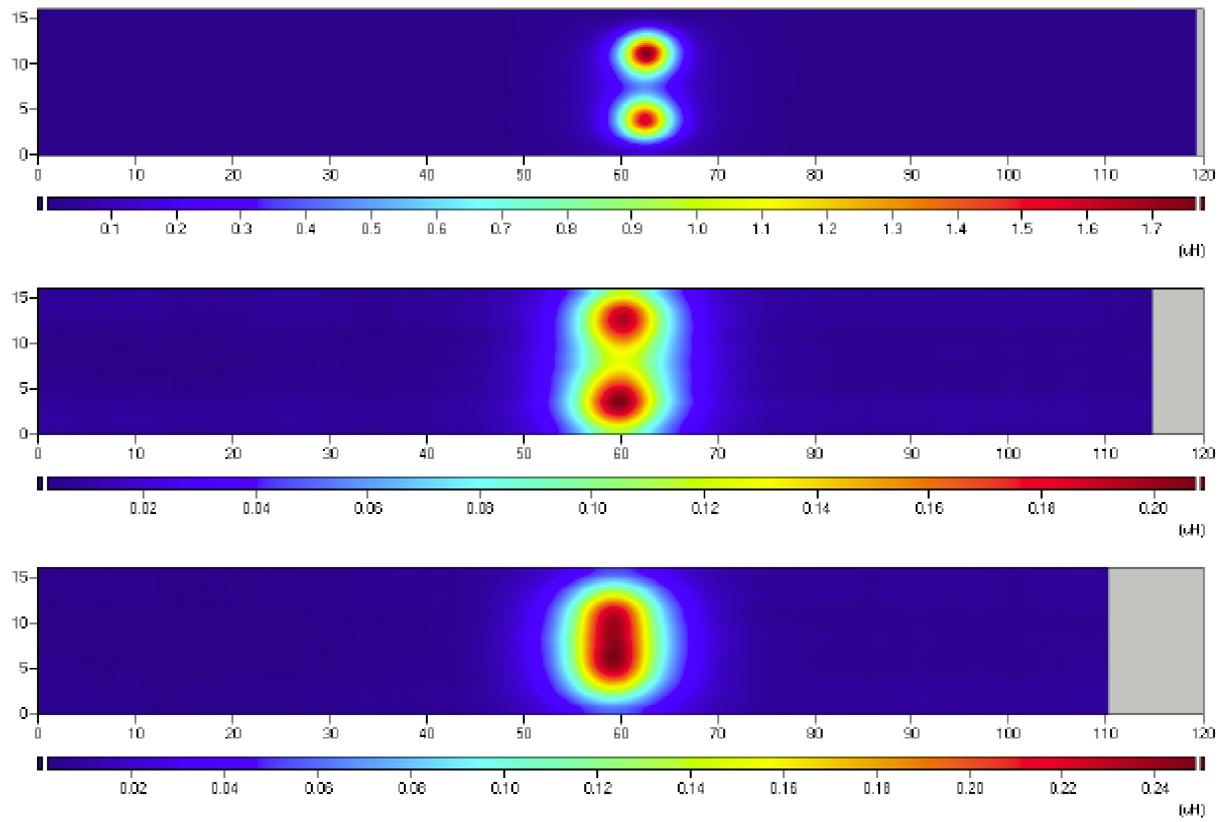


Fig. 10. Response of two BLU-26 bomblets oriented parallel to the sensor array (top) 20.3 cm apart and 3.8 cm deep (middle) 20.3 cm apart and 11.4 cm deep (bottom) 10.2 cm apart and 11.4 cm deep.

3.1.1.5. Stripe Sensor Tomography

Tomographic imaging using meander like structure sensor has been successfully applied for imaging particularly in the field of magnetic resonance imaging [54]. An array of meander sensor sensors was applied as shown in Fig. 11 below. It was proven that principally there is no difference between the two-dimensional tomographic stripe sensor with X-ray tomography by using Radon transform [54].

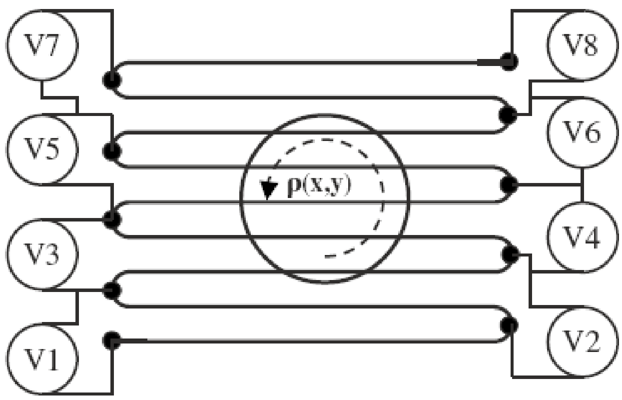


Fig. 11. Stripe sensor array tomographic imaging.

By creating a meander like loop array and detecting voltages at sequential nodes in the array, signals are obtained without the requirement for linear translation of the sample. The sample used in this research consists of two circular coils, separated by a distance slightly larger than the thickness of the sensor as shown in Fig. 12. The coils are driven in phase with 100 mA ac electric current at 11 kHz from an audio power amplifier. Fig. 13 shows the two-dimensional image of the loops through standard filtered back-projection image reconstruction. The image was obtained from linear scanning motion of the array of meander sensors with different angle orientation. However, the image spatial resolution is a limited along both x and y axes by the line-thickness of the sensor.

Fig. 12. Two loop sources.

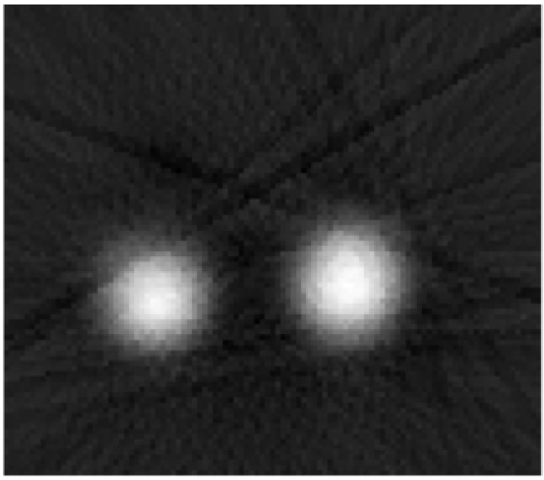


Fig. 13. Reconstructed images of the two loop sources.

This research aims the sensors to be miniaturized into submicron scale where it could be performed without the need for high power-radio frequency excitation as needed by the conventional Nuclear Magnetic Imaging (NMR) technique.

3.1.1.6. Transient Eddy-current Imaging

The previous sections discuss the application of eddy current testing based on single continuous waveform. Another version of eddy current imaging is based on pulsed input or alternatively called as the transient eddy-current method. In the transient eddy-current method an eddy-current pulse is generated at the surface of a structure and propagates down into the structure over the course of a few milliseconds [55]. The magnetic field measured at the surface will be modified by any changes in the propagation path of the pulse, such as caused by flaws, electrical properties changes, edges or interfaces. This pulsed excitation is equivalent to superimposing a range of frequencies simultaneously in one spatial location, which can improve the efficiency of eddy current testing because all of the necessary information is collected in a single scan [56]. Moreover, the introduction of magnetic sensor arrays provides increased depth of sensitivity over conventional eddy-current sensing coils.

In the application of detecting defects in multi-layer air-frame structure [56], images can be obtained as shown in Fig. 14. In Fig. 14, green is no change in transient signal (material without defects); red to white represent material loss; light and dark blue indicate positive material – or a material loss above the reference layer.

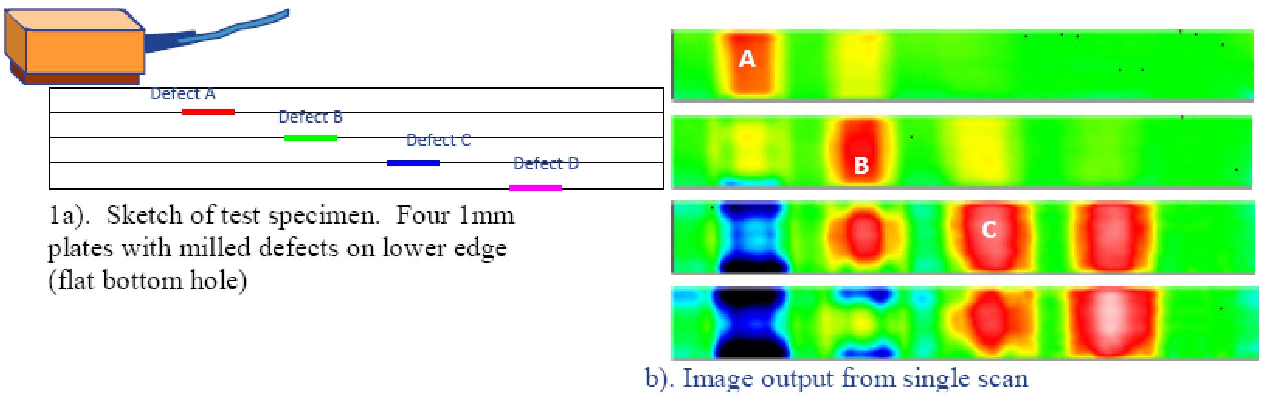


Fig. 14. Images of multi-layer air frame produced by transient eddy current imaging.

Transient eddy current method has several advantages over single and multi-frequency Eddy-Current (EC) methods that give comparable results but the main advantage is simpler and less expensive instrumentation. The primary disadvantage is that quantitative models for the interpretation of PEC measurements are not readily available [57].

3.1.2. Indirect Technique of Eddy Current Imaging

The indirect technique of eddy current imaging technique usually involves the application of more complicated system where additional devices are required for the system to operate. It can be observed that in both direct and indirect eddy current imaging techniques that the requirement of image processing is very important. The next section will discuss the application of magneto-optic eddy current and thermo-inductive imaging.

3.1.2.1. Magneto-optic Eddy Current Imaging

In some cases, testing over large area is highly required and it would be advantages if the testing can be done in considerably fast time. For example, in the case of testing of aircraft's skins. It is essential these skins are regularly tested for flaws or defects, conventional method such as eddy current probe usually requires the paint of the skin to be strip off due to unwanted lift-off and repaint again after the testing was finished.

Magneto-optic eddy current imaging (MOI) reduces the testing time and is more sensitive than conventional eddy current technique [58]. A prototype of an eddy current imager dedicated to the high speed inspection of aeronautic riveted lap joints is demonstrated [59]. The system is capable of providing high resolution images of the complex magnetic field distribution at the surface of the inspected structure. The system aims to detect and characterize buried defects in riveted lap joints. Fig. 15 shows the representation of the system. The eddy current on the material under investigation is excited using a specific current inductor carrying a standard sine wave input with adjustable frequency. A linear Magneto optic (MO) sensor by Faraday effect [58] is used to sense the variation of magnetic field distribution at the surface of the material. Magneto-optic eddy current operates based on the combination of principal of magneto-optic imaging and eddy current induction. By inducing eddy current on the material under test (usually conducting material) by using sheet current in an induction coil, perturbations in the eddy current flow are communicated to the magneto-optic sensor [60]. A beam of polarized light is directed to the MO sensor as shown in Fig. 15. Thus by imaging the reflected polarized light through the MO thin film, defects can be imaged [61].

An MOI system is capable of detecting fatigue cracks and corrosion in the aluminum aircraft skins by inducing eddy currents in the frequency range from 1.5 to 100 kHz. The frequency is adjusted to high for imaging small and tight surface cracks near the rivets, where as a low adjusted frequency, it can provide visualization of subsurface cracks and corrosion in the conducting material.

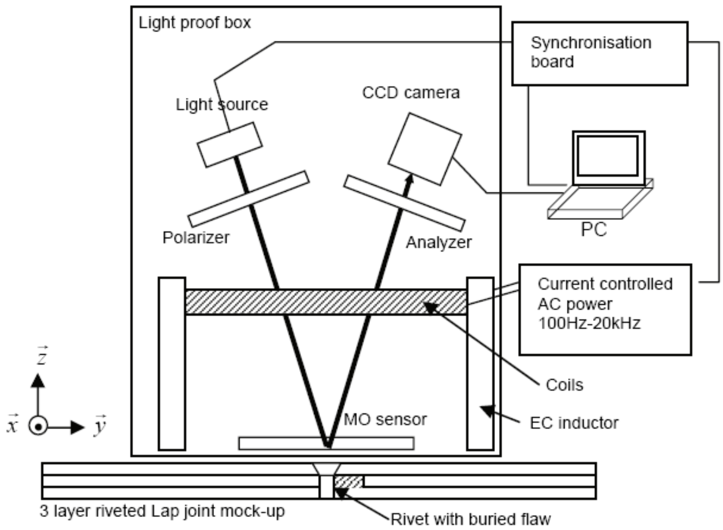


Fig. 15. Schematic presentation of the eddy current imager.

Fig. 16 shows the riveted lap joint mock up used to test the performance of the system. The mock up is constituted of three identical 3 mm thick plates made of aluminum based alloy, featured by a 20 MS/m electrical conductivity and a unity relative magnetic permeability. The plates are fastened by 6 mm diameter head aluminum rivets. The notches representing the simulated flaws are circled as shown in Fig. 17.

Fig. 17 shows how the signal processing method based on the principal the results of the inspection using a principal component analysis (PCA) allows 3 mm and 6 mm deep buried flaws (notches) placed next to the rivets to be correctly detected and localized. The implementation of the system to real lap joints with additional flaws such as fatigue crack and corrosion and a better classification scheme is still under consideration.

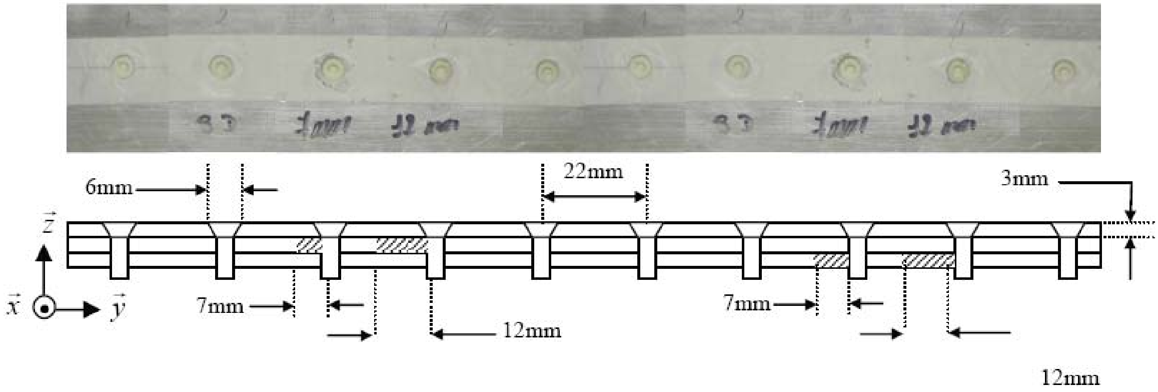


Fig. 16. Laboratory made lap joint mock-up with sound and flawed rivets. Reconstituted photograph (top view), and schematic representation (side view).

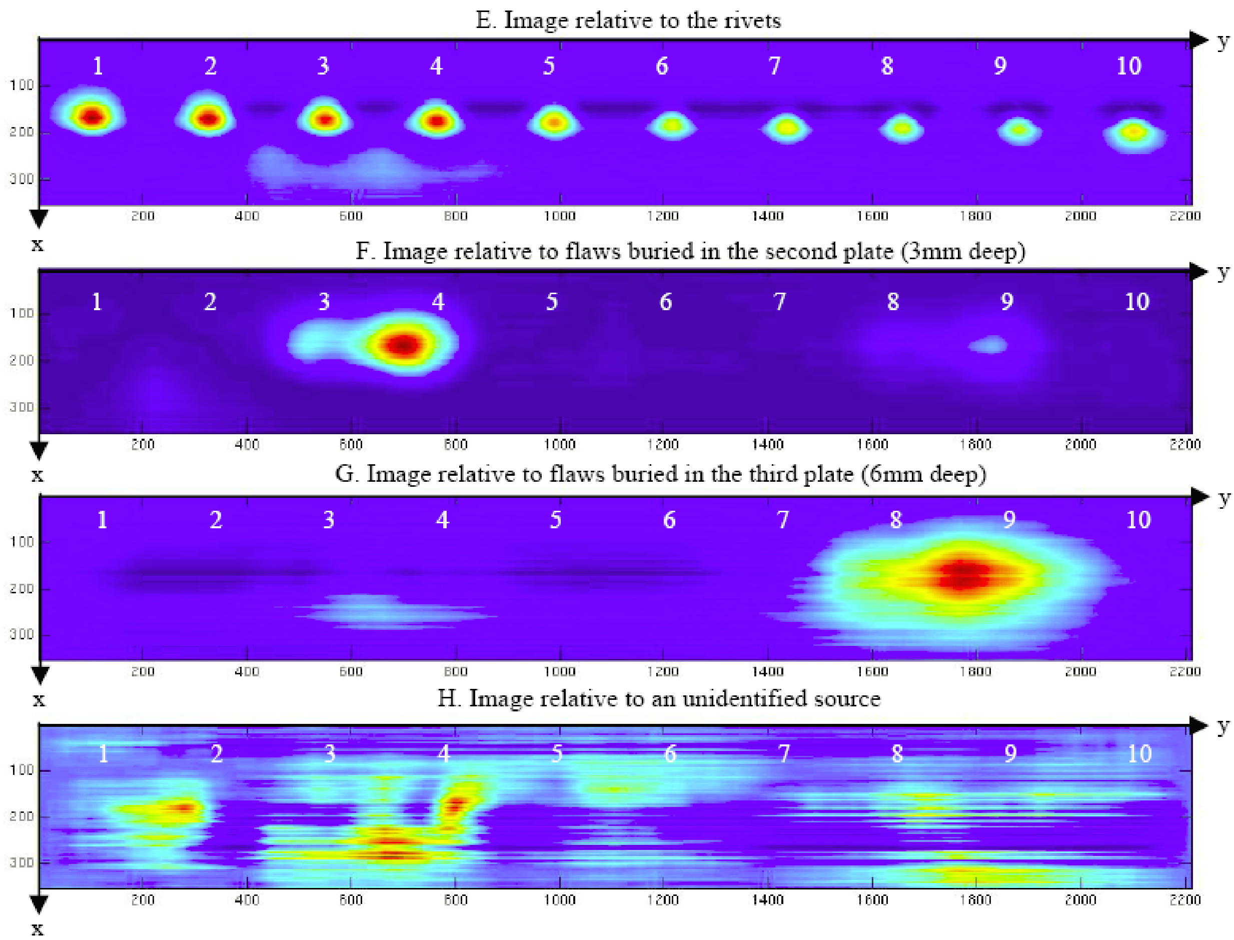


Fig. 17. Images obtained after signal processing for the detection of the buried flaws. Colors are arbitrary and the sampling step is 100 μm along the x and y axes.

The performance of the system mainly depends on the properties of the MO thin film. Thus, the MO thin film should be analyzed according to its MO properties and be chosen carefully to obtain MO images of high resolution. The MO thin films should meet the following requirements to assure the validity of the detection [61]:

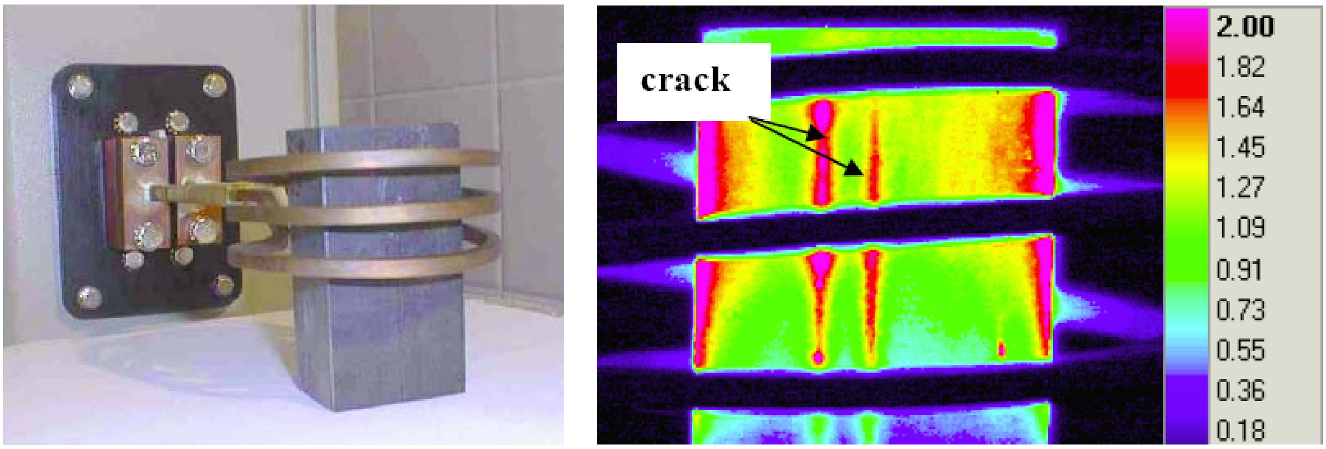
(1) High MO rotation ratio to enhance the contrast of the MO image.
(2) High temperature stability to maintain the reliability of the testing process.
(3) Approximately linear MO response curves to gain succinct adjustment.

Anti reflection is required on the surface of the thin film to reduce the strong reflectivity on the thin film. The reflected light can also affect the extinction ratio and Faraday rotation [61]. Other interference such as the change of the sending light, the change of YIG's magnetic domain and some other noises can be eliminated by using special image processing technique such as Adaptive filtering, Gray scale manipulation, Binary conversion [61]. Therefore, the magnetic domains (background) and to the defect signature can be suppressed and enhanced, respectively.

This system can be employed to large area with reducing the inspection time, moreover the lift-off factors has a negligible effect to the system. However, the cost, big size and complexity of the system make it become less popular and immobility. In addition, the current MOI system lacks the capability of providing a quantitative measure of the defects [62]. Moreover, the differences in flaw morphologies due to structural edge effects, excitation frequencies, and intensities, particularly for small defects, often make the interpretation of MO images subjective and inconsistent from inspector to inspector [62].

3.1.2.2. Thermo-Inductive Technique Imaging

Thermo-inductive probing is a thermo-graphic non-destructive testing method to detect shallow surface cracks in metallic materials [63]. An induction coil which carries high frequency current usually placed around or near the material to induced eddy current on the surface of the material. The heat dissipation due to the eddy current and the resistance of the material causes local heating [63]. The infrared emission from the material surface is detected by suitable recording/visualizing devices such as thermography camera. Anomalies in the surface heating correspond to in-homogeneities in the material. The technique can be used for the inspection and detection of macroscopic cracks in materials where eddy currents can be induced, whereby metals are particularly well suited. Fig. 18 shows the images obtained using thermo-inductive method.



(a) Inductive heating of a steel work-piece inserted into the induction coil.

(b) Infrared image of the heated steel.

Fig. 18. Experimental setup and results of the thermo-inductive system.

A Thermo-Induction method usually utilizes a thermography camera with a detector array to monitor induction heated areas. Temperature patterns and their time dependence responding to the coded excitation allow for fast imaging of defects in larger areas without the need of slow point-by-point mapping which usually employed in conventional single probe eddy-current imaging [64].

The signal contrast from cracks with this technique is optimal if the inductive excitation is in that way that the eddy currents are perpendicular to the crack orientation [65]. Other difficulty is to interpret the flaw in unknown material due to the prior knowledge from experiment demonstrate that in magnetic materials the flaw is visible by higher temperatures and in non-magnetic materials by lower temperatures [63]. Moreover, a structure of excitation coil with high power is needed to produce enough eddy current at the surface of the material under test. The requirement of expensive equipment such as CCD camera obviously increased the maintenance cost of the system.

3.2. Capacitive Imaging

In the case where eddy current generation is discourage: the presence of a pickup coil minimizes the magnetic field component and the estimation of dielectric properties of material, thus, capacitive sensing method is employed. Capacitive sensing system tries to maximize the electric filed component and hence induces an electrostatic field in the material between the probes which can be used for imaging. Moreover, magnetic techniques such as eddy current testing and potential drop method are limited to conducting material. The imaging technique based on capacitive sensing in nondestructive testing is mainly concerned about indirect method. Therefore, the next section will discuss the important application of capacitive imaging in non destructive testing which employing planar capacitive electrodes.

3.2.1. Capacitive Imaging of Material and Structure

An imaging system based on capacitive sensing was established for imaging a wide range of materials which consist of carbon composite materials, Perspex and metals [66]. The technique used a set of planar metallic electrodes, which are fixed from each other at a certain distance and placed above the surface of the object to be imaged as shown in Fig. 19. An ac voltage is applied to one electrode, and signal detected on others. An alternating electrostatic field is established, with field lines passing through the object, whereby charge is then induced on the surface of the second electrode. The coupled charges than detected using standard technique of charge amplifier, processed and outputted as DC voltage level [66].

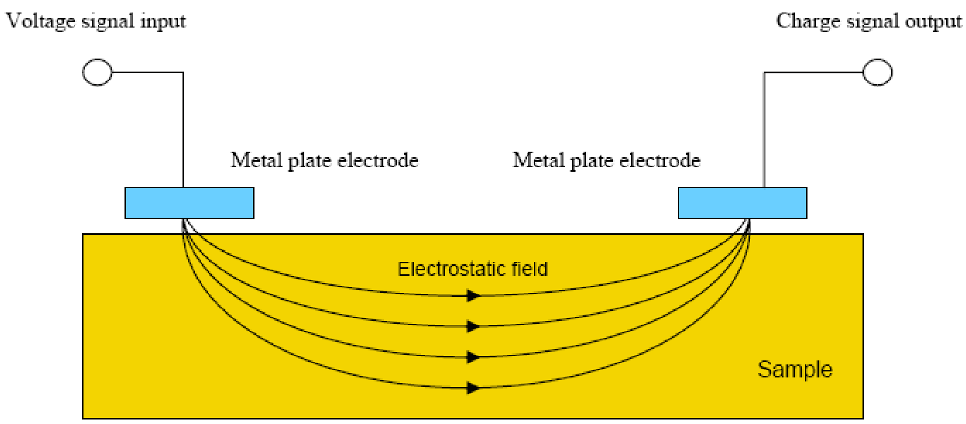


Fig. 19. Schematic diagram of the capacitive imaging system.

The output signal of the system is the function of electrostatic field pattern establish between the electrodes, thus any presence of sample between the electrodes will affect the electrostatic field and consequently change the output. Electrostatic (capacitive) imaging was performed using a two-axis scanning system, where the electrodes were scanned at a constant separation over the surface of the sample, keeping the air gap as constant as possible [66]. The resolution of the image was determined by the step size of the scan, which in this case it was set to 2 mm.

Fig. 20 (a) and 20 (b) show the images for thin aluminum plate and Perspex, respectively. From Fig. 20 (a), the aluminum plate with 0.075 mm thickness was placed above two aluminum blocks distanced at 10 mm. The image shows that the area where the thin aluminum plate suspended over the air has lower amplitude compare to the area where the two aluminum blocks touched the aluminum plate. The approach seems to have distinguished between air and metal on the far side of a thin metal wall.

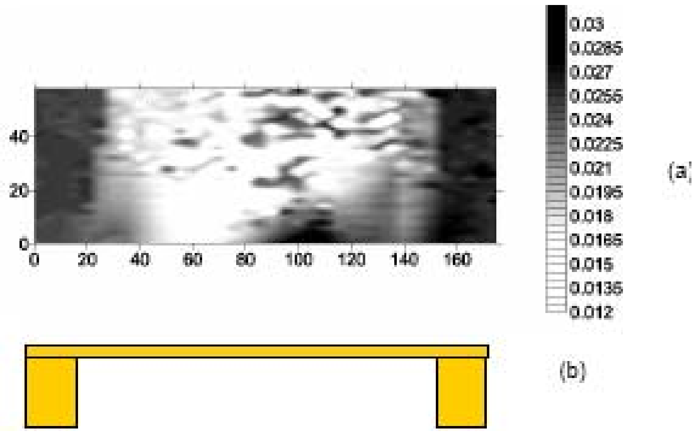


Fig. 20. (a) Electrostatic image of a 0.075 mm thick aluminium metal plate, suspended above an air gap; (b) side view of sample.

The system was also tested for material with lower electrical conductivity and the result is shown in Fig. 21. The image surface of Plexiglas sample that has a side-drilled hole of 10 mm (Fig. 21 (b)) was obtained by scan over the surface of the Plexiglas. The hole can be easily detected by the system due to the different properties of air and Plexiglas. However, the image shows that the hole is extended more than the nominal 10 mm hole diameter of the cylindrical hole. This is because of the width (10 mm) of the electrodes, which caused lateral "smearing" of the image [66].

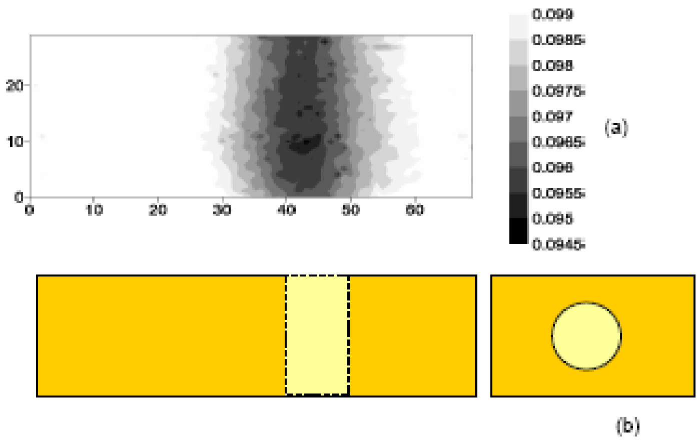


Fig. 21. (a) Electrostatic image of a Perspex plate containing a side-drilled hole of 10 mm diameter. (b) Diagram of the Plexiglas sample as viewed from the top surface (left) and the side (right).

It is shown that this system can provide images of materials with high and low electrical conductivity as the electric field distribution is capable of penetrating large distances into conducting and insulating materials.

3.2.2. Capacitive Imaging of Buried Landmine

An imaging system based on five-element capacitive array was used to visualize and detect low-metal content landmine buried in a laboratory sandbox [52]. Fig. 22 shows a schematic of the sensor array and images for an M14 landmine buried at several depths. The system has limited capability to detect landmine at depth between 1cm to 3cm when the liftoff (distance between the sensor and the land surface) was set for 2cm. The total depth of sensitivity is approximately 5 cm below the sensor, which is consistent with the approximation that dielectric sensors have a depth of sensitivity of roughly one-quarter of a wavelength, which is 20 cm for this capacitive sensor [52].

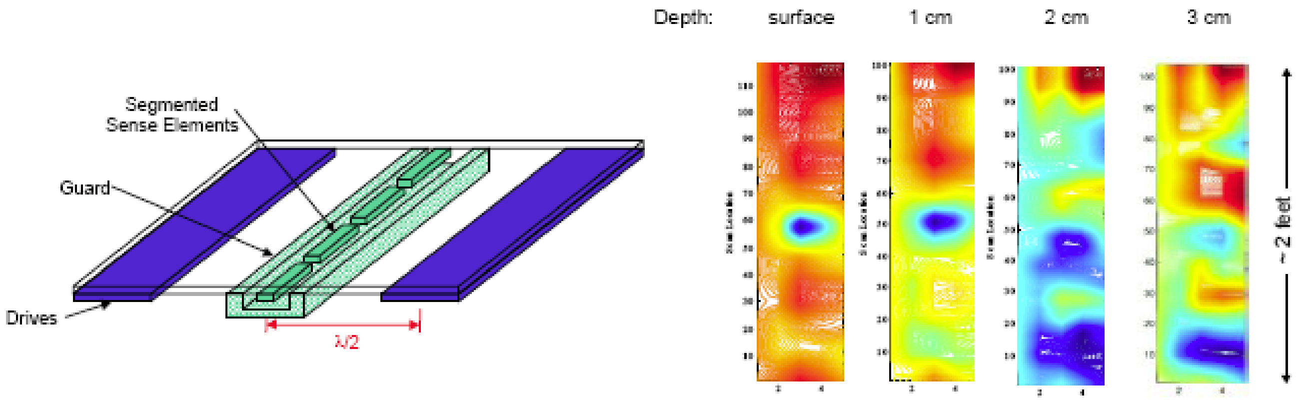


Fig. 22. A capacitive sensor array (on the left) and scan images of a capacitive sensing array over an M14 landmine buried at several depths (on the right).

3.2.3. Micro-capacitive Tomography

A micro-tomography sensors based on silicon integrated circuit technology [67] has been developed for use with electrodes as small as 10 µm wide and planar arrays of electrode were considered. Series of finite element simulations and experiments were conducted to identify the optimum geometries of electrode for micro-scale applications. From the simulation three parameters regarding of the sensing design were investigated:

1) Electrode length and particle radius-increasing the length of the electrodes, as the particle size increases, would increase the standing capacitance of the sensor and make it difficult to compare results directly.
2) Liftoff of particle/material: the capacitance decreases in a uniform way as the liftoff increases
3) Electrode spacing: smaller electrode spacing the greater the sensitivity of the sensor but the sensitivity of the sensor rapidly decrease with height.

Image reconstruction algorithm has been achieved using planar arrays consist of 12 electrodes, 5 mm long, 5 mm wide with 5 mm spacing and back projection algorithm. Block of Tufnol ($\varepsilon_r = 5$), arranged in four layers above the sensor was used as material under test. Fig. 23 shows the reconstructed image of holes in the first layer of Tufnol above sensor one. Due to the low penetration depth of the sensor, image reconstruction of features within the second, third, and fourth layer of Tufnol failed to produce discernible image of the features. In summary, the use of more sophisticated image reconstruction algorithm combined with accurate measurement system and thinner layer of dielectric (material under test) should allow image reconstruction of feature that are not in direct contact with sensor surface.

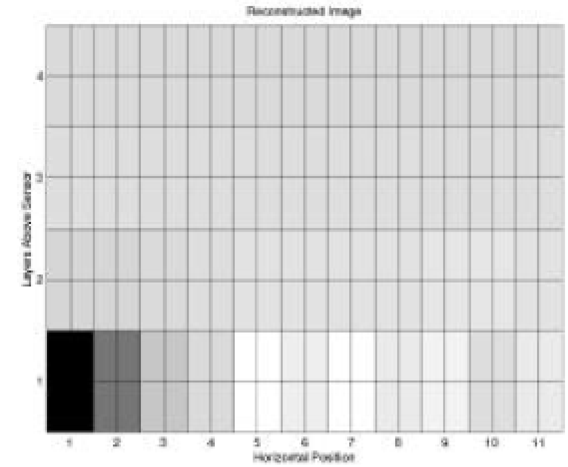


Fig. 23. Reconstructed Image of Hole above Electrode One.

A micro planar capacitive imaging system presents two main challenges as compared to macro planar capacitive imaging system [68], firstly, micro planar capacitive imaging system, both sensors and measurement circuitry will be integrated onto the same piece of silicon, as it is not practical to implement a macro-tomography system with discrete circuitry. Secondly, the magnitude of stray capacitance on a PCB track would be several times greater than any sensor capacitance, and would entirely swamp any capacitance being measured.

4. Conclusions

Imaging techniques based on eddy current testing and capacitive sensing (interdigital sensor) are successfully applied in many fields. It is shown that both eddy current testing and capacitive sensor systems can be relatively low in cost, simple structure, can produce instant response (output). Therefore, the possibility to design a low cost imaging system based on the combination of both systems looks very promising. The combined imaging system can enhance the capability of visualizing property estimation of material ranging from different properties.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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