Effective Nondestructive Imaging of Defects in Engineering Components

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Abstract
Imaging of defects in engineering components is gaining importance and wider acceptability. Imaging enables automation of measurement process by the use of sensor, enhanced detection and characterisation of defects. Further, it helps in assessing incremental damage in a critical region by performing periodic imaging and comparing. Raster-scan based single sensor imaging and line-scan based array sensor imaging are increasingly employed and ultrasonic, eddy current, magnetic flux leakage and microwave techniques have exploited these modalities. This paper discusses some recent trends in effective NDE imaging of defects and highlights image fusion modalities for high probability detection and enhanced characterisation of defects by combining images of same regions by different NDE sensors.

Keywords: Eddy current, microwave, ultrasonic, magnetic flux leakage, imaging, sensor arrays

1. Introduction

Non Destructive Evaluation has become an integral part of manufacturing quality and structural integrity assessment of engineering components. As a result, high probability of detection and enhanced characterisation of defects are very important. This requires scanning of NDT probe over object surface, data acquisition and interpretation of several probe line-scan signals using a computer. By this way, NDE images can be generated. NDE imaging is possible by scanning a single probe in a raster-manner or by linear scanning of array of probes or by electronic scanning of a stationary linear or 2-D array probe. The image format provides comfortable interpretation of NDE data enabling discern irregularities within an image. By imaging, process automation is possible as computers perform the probe scanning, data acquisition, and data interpretation. Imaging enables documentation and storage of NDE data. Further, availability of image data allows application of image processing techniques. Furthermore, imaging helps assessment of incremental damage in a critical region by performing periodic imaging of the same region and comparing the resulting images.

When the main objective of imaging is reliable detection of small defects and characterisation of defects, usually smaller size probes with focusing possibility are employed. However, this increases the time for imaging and storage requirements for computers. In this regard, several novel approaches such as coarse scan screening followed by fine scan imaging of a suspected region etc. are followed [1]. More recently, multi-sensor fusion concepts are also being exploited. This paper discusses the advances in ultrasonic, eddy current (EC), magnetic flux leakage (MFL), and microwave imaging techniques that enabled effective imaging of defects.

2. Eddy Current Imaging

Eddy current imaging is used for detection of corrosion and cracks in multi-layer structures of aircrafts, dovetail regions of aero engines, heat exchanger tubes, and other critical engineering components. Small size pick-up coils and solid state sensors are being used for reception.
Depending upon the geometry of the component, in order to reduce the inspection time, for imaging either single sensor or arrays are employed [2]. One interesting application of eddy current imaging is the location of centreline of stainless steel welds in reactor vessel of fast reactors to scan the ultrasonic transducers at desired skip distances for inspection of welds and heat-affected zones. An eddy current probe that can withstand $250^\circ$C has been developed. This probe can detect the presence of delta ferrite (magnetic phase), that is intentionally formed to prevent hot cracking of austenitic stainless steel welds, and produces a large impedance change even at a lift-off of 10 mm. Typical raster-scanning of EC probe is shown in Figure 1. The EC images of weld region in different weld orientation angles (WOA) from 0 to 75 degrees to the probe scanning axis, in steps of 15 degrees are also shown in Figure 1. In all the images, a distinct peak is observed in the images at the center of the weld. The locus of maximum of each line-scan represents the centerline of the weld [3].

In order to automatically detect a weld in the imaged region and to orient the raster-scan window perpendicular to the weld centerline, characteristic features viz. maximum signal amplitude (MSP) and full-width at half maximum (FWHM) have been chosen from line-scan signals. It has been observed that the MSP increases continuously as the probe approaches the weld from one end and then continuously decreases as it moves away from the center of the weld. For a particular weld width, the MSP varies directly with the weld orientation; maximum amplitude when WOA is $90^\circ$ and minimum amplitude when WOA is $\approx 0^\circ$ as shown in Figure 1. The FWHM of the signal depends on the weld width. Although width of weld is around 15 mm, the FWHM varies with weld orientation. As can be observed from Figure 1, FWHM decreases with WOA. FWHM obtains a value of nearly 15 mm (but greater) as the WOA tends to $90^\circ$ and increases for lower angles and reaches a maximum of 47 mm when the WOA is $\approx 0^\circ$. Thus, with certain threshold WSP and FWHM can be used for automated detection and centerline determination of welds. An imaging scheme has been developed for quick identification of weld and this has been successfully validated by performing a series of experiments on stainless steel weld specimens. The scheme consists of the following steps:

- Coarse raster-scan imaging of 100x100 mm$^2$ region in 5 mm scan interval both across and along the weld direction.
- Noise suppression and formation of a binary image based on maximum signal amplitude threshold and identification of weld.
- If the weld is about the center of the scan window, fine scan imaging of 75 x 25 mm$^2$ region in 1 mm and 5 mm scan intervals, respectively in X and Y-direction.
• Confirmation of weld presence using MSP and FHWM parameters.
• Determining the WOA and weld centerline. If WOA is not 90° and the weld centerline is not in the middle, determination of new raster-scan window.
• Display of 3-D image of weld region.

Carbon-Carbon composites are coated with Silicon carbide (SiC) and measurement of coating thickness and assessment of uniformity of coating are very important. Evaluation of SiC thickness by EC technique is influenced by variations due to probe lift, substrate thickness, surface roughness, and the errors associated with the inspection personnel [4]. For accurate measurement of coating thickness using 5 mm diameter absolute probe coil, radial basis function based neural network has been developed. The centres of the hidden node activation functions have been optimised by K-means clustering algorithm. The maximum error in evaluation of coating thickness has been found to be ±2.4 µm. The uniformity of coating has been assessed by images formatted using the radial basis function network output. Figure 2 shows the images of thickness profile for uncoated and specimens coated with 11.87µm, 16.30 µm and 29.54 µm thicknesses.

For detection of small metallic particle in non-conducting cellulose boards, EC probe consisting of 8 array coils has been developed and successfully employed in production line. The measurement system consisting of multiplexer, data acquisition, software, and display modules produces on-line images of the scanned region. The inspection process has been automated.

Image processing techniques applicable to EC images are different, as compared to ultrasonic or optical images because of larger pixel size and image blur due to convolution of probe footprint with defect. Image restoration is possible and several image processing techniques (time-based, frequency-based and wavelet-based) have been developed for image deconvolution, enhancement, and delineation of desired information in images and for determination of input features to artificial intelligence schemes for off-line or on-line testing [1]. Imaging by mechanical scanning of EC probe is slow and influenced by material variations and lift-off. For quick and automated EC testing of SS plates and welds, an intelligent imaging scheme, which synergistically combines artificial neural network and image processing techniques, has been developed to quickly obtain defect’s 3-D image with accurate length, width, depth, and orientation [5,6].

![Figure 2 Assessment of uniformity of SiC coating on C-C composite using EC imaging.](image-url)
3. Sampling Phased Array Ultrasonic Imaging

Ultrasonic sampling phased array (SPA) technique is gaining popularity in NDE for imaging defects in components, especially, thick-wall cladded weld seams, composite structures, thick plates, and pressurised components. SPA technique makes use of propagation of elementary waves (Huygens principle) generated by individual elements of the sensor array and involves reconstruction of sector image by synthetic composition of elementary wavelets by fast numerical computation for any arbitrary individual angel or physically possible focus depth. This is in contrast to the conventional phased array (CPA) technique which electronically steers the sound beam by delay controls. Typical application of delay law for conventional and sampling phased array is shown in Figure 3. In SPA technique, ultrasonic transducer with maximal beam spread is used and due to smaller aperture size of the phased array elements, synthetic focusing through SPA technique is well suited. SPA technique has a few distinct advantages over the CPA technique, concerning reduced dead-zone, quantitative high speed 3-D imaging of defects, improved spatial resolution and signal-to-noise and real-time reconstruction of sector-scans with automatic focusing at each pixel, which enhances the lateral and depth resolution of the image. The lateral and depth resolutions for SPA are superior to CPA technique [7].

Extensive studies have been carried out to resolve closely spaced defects in 25 mm thick stainless steel plates. Figure 4 shows the SPA system used for the studies. Pairs of side drilled holes of different diameters and inter-hole spacing have been introduced and sector scans have been acquired using both SPA and CPA techniques. It has been observed that the masking types and closely spaced angulated types of defects near to the scanning surface or back-wall surface could be clearly resolved using the SPA technique as shows in Figure 4, in contrast to the CPA technique [8]. This is attributed to better near-surface detectability and simultaneous focusing capability of the SPA technique at all the depths.
4. Magnetic Flux Leakage Array Imaging

For NDE of stationary steel track ropes used for transportation of coal through buckets, a flexible GMR sensor array capable of detecting leakage magnetic flux has been designed and developed with possibility for imaging localized flaw (LF) and loss of metallic cross-sectional area (LMA) type defects (refer Figure 5). The track rope has 8 layers of stranded wires of different diameters. During the operation of the rope system, the outer Z-wire is prone wire breakage and formation of cracks, corrosion and martensitic embrittlement. For detection of magnetic flux leakage from defects on top side surface of outer wire, Giant-Magneto Resistive (GMR) sensors (hysteresis < 2% unit) have been used. In order to identify the number of GMR sensor elements and to determine their locations, 3-D finite element modeling has been performed using COMSOL 3.4 Multiphysics software package. The flexible GMR sensor array has been kept at the middle of the magnetizing coils to measure the axial component (along the scan direction) of leakage flux from defects [9]. Figure 5 shows the MFL images of circumferential LF simulated by an EDM notch of 5.5 x 2.0 x 2.0 mm$^3$ size (length x width x depth) and that of axial LMA notch of 33.5x14.2x4.9 mm$^3$ size. Both types of flaws are readily detected while the images of circumferential notches have been found to be sharp and localized as compared to that of the axial notches. To further enhance the resolution and detection capability of the sensor, tandem sensor with a angular shift has been developed. Eigen value based approach has shown promise for image enhancement [10].

![Magnetic Flux Leakage Array Imaging](image.png)

Figure 5 Photograph of the track rope system, typical track rope damage, flexible GMR sensor array probe developed and the images produced by the array sensor.

5. Microwave GPR Imaging

Ground penetrating radar (GPR) is often used to describe microwave inspection systems for non-destructively locating utility lines below ground and steel rebars in concrete decks and pavements. GPR is a pulse-echo method and involves measurement of microwave energy (1 to 3 GHz) reflected when the pulse encounters an interface between dissimilar materials (materials with different dielectric constants). Cylindrical targets (rebars, pipes etc.,) in concrete structures will appear as a hyperbolic pattern in GPR images due to the conical radiation pattern of the microwave antenna. The shape of the hyperbolic pattern depends on depth, size and shape of the target. Only the targets that are perpendicular to the scanning direction of the polarized antenna are detected.

GPR imaging has been used to facilitate drilling holes for installation of scaffolding and other additional structural elements. Figure 1 shows the typical B-scan images of 1 m thick concrete
wall with rebars, obtaining by scanning 1.6 GHz antenna in horizontal as well as vertical directions to detect vertical rebars and vertical scanning to detect horizontal rebars as shown Figure 6. It also shows the mapped image of the inner rebar structure identified. The correct location for drilling the hole without interfering the rebars is also shown in Figure 1. 2D and 3D imaging have been performed by scanning the antenna over a grid layout on the concrete surface structure. Accurate estimation of rebar diameter using GPR technique is challenging. For this, a novel non-linear curve fitting method has been proposed. The error in diameter estimation has been found to be around 10% for large rebars (diameter > 65 mm) while the error has been found to be less than 35% for rebar in the diameter range of 13 mm to 65 mm.

Figure 6 Mapping of rebar location in a 1 m thick concrete wall to identify the location for drilling a hole.

6. Image Fusion

Image fusion is finding applications in NDE and this can be performed in spatial, frequency and wavelet domains. Image fusion ensures that all the salient information present in the source image be transferred into the fused image [11]. Four different image fusion methodologies have been applied to combine multifrequency and multi-sensor eddy current images having noise surface roughness variations in stainless steel plates having sub-surface defects. These include wavelet, spatial frequency, Bayesian and Dempster-Schafer based image fusion methodologies and their performance has been compared using metrics such as Signal-to-Noise Ratio (SNR), Root Mean Square Error (RMSE), Percentage Fit Error (PFE) and Mean Absolute Error (MAE). Improved performance is indicated by higher SNR value and lower MAE, RMSE and PFE values [12]. EC images of subsurface defects (2x1x0.5 mm$^3$, 2x1x1 mm$^3$, 5x1x0.5 mm$^3$, 5x1x1 mm$^3$) obtained by raster scanning of EC probes of 5 mm and 10 mm diameters, after the addition of Gaussian noise of 0.1 standard deviation simulating surface roughness are shown in Figure 7.

The results of the image fusion methodologies are given shown in Figure 8. As can be seen, there is an overall improvement in the quality of the images and all four defects are clearly brought out by the four fusion methodologies. The comparative performance by the methodologies for single probe and two probe image fusion are also shown in Figure 8. As can be noted, multi-sensor fusion performed better as compared to single sensor fusion and Dempster-Shafer methodology appears better for multi-sensor fusion.
Figure 7 Eddy current images of four defects at 75 kHz (left) and 300 kHz (right).

Figure 8 Fused images by a) wavelet methodology and comparative performance of various methodologies for b) one probe two-frequencies and c) two-probes two frequencies.

7. Conclusions

NDE image format provides comfortable interpretation of data enabling discern irregularities within an image by comparing different regions. Further, imaging helps assessment of incremental damage in a critical region by performing periodic imaging of the same region and comparing the resulting images. Imaging with EC, MFL, GPR and ultrasonic modalities have been discussed. For effective imaging of defects, it is essential to use proper sensor and scan plan to cover the entire component. Array sensors and intelligence imaging schemes are enabling faster inspection and reliable detection of defects in the scanned region. Image processing techniques enable noise elimination and enhancement of defect information. Image fusion is expected to enhance POD and defect sizing.

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References


