

## Eigen Vector based Approach for Enhancement of Non-destructive Evaluation Images of Defects

### EXECUTIVE SUMMARY

Eigen vector based approach is developed for enhancement of non-destructive evaluation (NDE) images of defects in carbon steel plates. Eddy current and magnetic flux leakage (MLF) images obtained by raster scanning of eddy current (EC) coil and giant magneto-resistive (GMR) sensor, respectively are influenced by variations in magnetic permeability, surface roughness and lift-off. These variations produce incoherent noise as compared to systematic impedance change or leakage flux variations produced by defects. Eigen pairs of image covariance matrix are determined and the significant Eigen pairs that have the maximum information of defects are utilized to suppress noise due to disturbing variables and to reconstruct images. This approach has resulted in a significant improvement in signal to noise ratio (SNR) and looks attractive for reliable detection of shallow fatigue cracks as well as deep-surface defects in carbon steels.

### OUTLINE

Non-destructive evaluation (NDE) is used for detection and imaging of defects in materials. In ferromagnetic materials such as carbon steel, impedance change in eddy current probe due to defects and permeability variations are usually of same phase angle and this makes even the multi-frequency methods inadequate to suppress the noise due to permeability variations. The impedance changes due to the permeability variations are incoherent whereas the impedance changes due to defects extend spatially depending on the foot-print of the eddy current probe used. Similarly, the magnetic leakage flux from deep-surface defects is feeble and contains undesirable and incoherent noise from variations in magnetic permeability, surface roughness and stress. Utilising the incoherent nature of noise, an innovative approach based on Eigen value and Eigen vector (Eigen pair) has been developed. In this approach, the energy packing property of the Eigen values is effectively utilized to suppress incoherent noise and to reconstruct images. This approach involves determination of Eigen pairs of image covariance matrix and reconstruction of images after considering the significant Eigen pairs having the maximum information of the defects. The insignificant Eigen pairs mostly represent the incoherent noise due to permeability variations are ignored in the reconstruction during the inverse transform. The performance of the approach is assessed on eddy current images of surface defects in 25 mm thick carbon steel plate and on MFL images of deep-surface defects in 12 mm thick carbon steel plates.

A carbon steel plate (thickness 25 mm) consisting of a 2.5 mm diameter hole is used in the studies. Using a 3.5 mm diameter surface absolute eddy current probe, images of 2.5 mm diameter hole (depth 0.25 mm) and a notch (length 10 mm, width 0.5 mm, and depth 0.5 mm) are obtained at an excitation frequency of 50 kHz. Using a C-core electromagnet (4A current) and high-sensitive GMR sensor, MFL images of notches (length 15 mm, width 0.5 mm) located at 3.1 mm, 6.3 mm and 8.6 mm below the surface of 12 mm thick carbon steel plates are obtained. The EC and MFL images are used for validation of the approach.

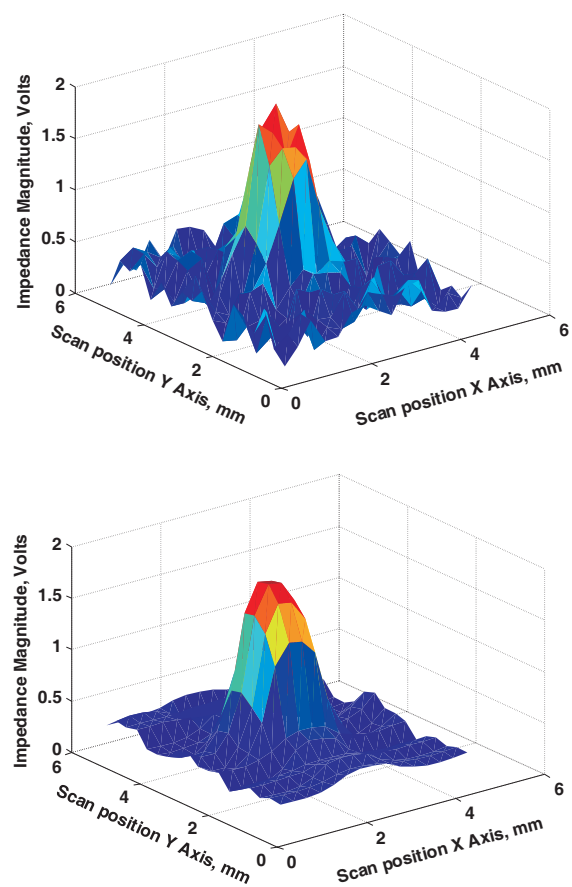


Fig. 1: Raw eddy current image of a 0.25 mm deep hole in carbon steel plate (up) and the image after reconstruction after taking the most significant Eigen value (down)

### ADDITIONAL INFORMATION ON THE VALIDATION OF THE APPROACH

Typical EC raw image of 0.25 mm deep hole and the reconstructed image are shown in Fig. 1. The MFL images of deep-surface notch located at 8.6 mm below surface and that of 1.1 mm deep surface-breaking notch are shown in Fig. 2 along with the reconstructed images by the Eigen vector approach. As can be observed, there is a significant enhancement in the quality of EC and MFL images after processing. The quality of reconstruction has been assessed by determining an empirical parameter called, noise reduction factor (NRF) which is ratio of average noise amplitude in a defect-free region in a raw image to that of the same region in reconstructed image. The NRF is found to be high when the most significant Eigen pair is used for reconstruction. However, when more Eigen pairs are included in the reconstruction, NRF is found to decrease. This is due to the fact that the smaller Eigen pairs which contain the incoherent noise information of magnetic permeability variations contribute to the reconstruction process resulting in image degradation.

■ GENERAL EXPLANATION RELATED TO THE DESCRIPTION

A significant improvement in signal-to-noise ratio (SNR) is observed after processing, as given in Table 1. This approach is very attractive for processing NDE images affected by incoherent noise due to local variations in material properties, coupling etc. and particularly useful for processing images from regions in operating components for detection of very shallow and incipient fatigue cracks that disturb structural integrity.

Notches	SNR		
	Raw	Processed	Enhancement factor
Near-side notch (1.1 mm deep)	2.04	6.25	3.06
Far-side notch located below 3.1 mm surface	9.45	15.92	1.68
Far-side notch located below 6.3 mm surface	6.85	11.13	1.64
Far-side notch located below 8.6 mm surface	3.52	5.64	1.60

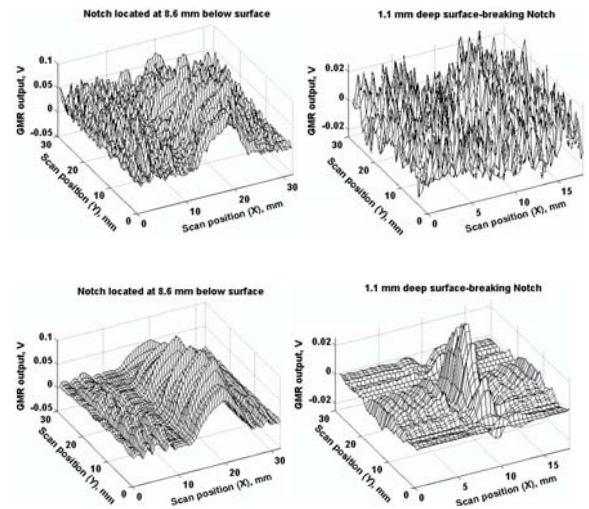


Fig. 2 : Raw (top) and processed (bottom) MFL images of a notch located 8.6 mm below surface and a 1.1 mm deep surface-breaking notch in carbon steel plates

■ BRIEF DESCRIPTION OF THEORETICAL BACKGROUND

Eigen values are a special set of scalars associated with a linear system of equations (i.e., a matrix) that are sometimes also known as characteristic roots or characteristic values. Eigen values and Eigen vectors are determined by Eigen decomposition of a square matrix and represent the energy content of a system. The Eigen vectors of image covariance matrix form an orthonormal set of vectors which are used as kernels to transform the original image matrix to variance domain where the significant Eigen values and the associated Eigen vectors point in the direction of maximum variance of the image data set. This transformation is popularly known as Karhunen Loeve Transform (KLT). It is a linear transform used to represent a dataset with a new set of basis functions such that the greatest variance by any projection of the data set lies on the principal axis and is also invertible. The basis vectors unlike other linear transforms (cosine or sine transforms) are derived from the original data set itself. Forward and inverse KLT necessary for this approach is implemented using MATLAB software. In the proposed approach, the energy packing property of the Eigen values is effectively utilized to reconstruct images free from noise due to permeability variations. In NDE, so far this kind of approach has been predominantly used to arrive at an optimal set of features from a set of signals for quantification using artificial intelligent schemes. However, the proposed approach is developed and applied to suppress noise due to magnetic permeability variations in eddy current and flux leakage images of defects.

■ ACHIEVEMENT

Eigen value based approach has been able to suppress incoherent noise due to magnetic permeability variations in eddy current and MFL images of defects. This approach has enabled reliable detection of deep-surface notch located at 8.6 mm below surface. This approach can also be applied to other ferromagnetic materials and also to other types of NDE images. This approach looks very attractive for detection of feeble signal producing defects such as shallow fatigue cracks as well as deep-surface defects in ferromagnetic steels. Further, the reconstructed images can be used as input images for artificial intelligent schemes for quantitative characterization of defects.

■ PUBLICATIONS ARISING OUT OF THIS STUDY AND RELATED WORK

1. P. Kalyanasundaram, S. Thirunavakkarasu, B.P.C. Rao, T. Jayakumar and Baldev Raj, *J. of Research in NDE*, **18** (2007) 13.
2. B.P.C. Rao, S. Thirunavakkarasu, K. Krishna Nand, T. Jayakumar, P. Kalyanasundaram and Baldev Raj, *Non Destructive Testing and Evaluation*, **23** (2007) 35.

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