Wireless Power Transfer based Tx-Rx Probe Frequency Feature Extraction for Non-destructive Testing and Evaluation

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Abstract: Wireless power transfer (WPT) based eddy current can be applied for metal defect detection because of its resonance point attainment and frequency splitting nature due to coupling effect. Of recent, it has started been applied for metal detection. However, metallic crack detection and characterization remain a great bared challenge. Therefore, an eddy-current influence from resonance WPT is proposed in this research to quantify the cracks in a metallic sample using splitting frequency features. Two coils for transmitter and receiver are configured based on resonance inductive power transfer to act as an eddy current probe. It then scanned an Aluminium sample over three cracks area after a vector network analyzer is connected to transmitter and receiver unit. The magnitudes of the transmission coefficient for the two coils configuration measured at every scan point for the crack evaluation. Point base-features are extracted from the data, and the principal components analysis (PCA) also mapped its extracted feature to spatial position for comparison. The results illustrated that the magnitudes of transmission coefficient (S12) depend on geometrical nature, conductivity, and permeability of the material. Also, the depth of each crack is inversely proportional to the deviation of frequency at the crack position from that of the non-crack point. Similarly, the PCA feature shows a linear dependency between crack depth and its principal component value.

Keyword: Inductive coupling, Principal components analysis, Metallic crack, Resonance frequency, Transmission coefficient.

1. INTRODUCTION

In metallic structures, it is essential to detect and quantify cracks for safeguarding healthy structure operational services. Cracks initiated due to fatigue or stress loading and its propagation through the structure lead to fracture. Failure to its early detection in structures like a rail line, pipelines, and aeroplane results in a fatal accident. To detect the crack, eddy current testing (ECT) probes are generally used to detect the presence of cracks in conducting metallic structures. It is based on the time-varying current passing through the exciter coil, which creates an electromagnetic field (EMF). Whenever an electrically conducting material is brought near to the probe, an eddy current is said to be induced in the material. The induced eddy current generates its field opposite to the field generated by the exciter coil. It then creates back EMF that causes impedance changes in a coil. For two coils probe, the coils impedance, a part of the effect by lift-off and separation between the two coils, varies according to the permeability, conductivity, surface and subsurface geometry of the material [1]. Generally, ECT is efficient on a sample made of conducting materials and less sensitive to complex geometric defect.

Many researchers have presented Eddy Current Testing (ECT) as one of the prominent and widely used Quantitative Non-Destructive Evaluation (QNDE) for assessing abnormalities in metallic structures [2-4]. Based on the coil-probe, the two common methods for eddy current inductive probe testing are single coil and pair of two coils [5]. They include absolute, differential, reflection, and hybrid probes. Both are on the same principle for detection and interaction of exciting magnetic field and the eddy-current-induced opposite magnetic field nature. In the single coil approach, change of coil impedance because of change in the magnetic field manifest the ECT conditions. It reduced the sensor size but has fewer features compared to two coils ECT. The two coils method employs a second coil to measure the superposition of the exciting field by transmitter (Tx) coil and the field created by the eddy currents known as receiver (Rx) coil. However, the

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[1] Created the first draft

features are still extracted from amplitudes (magnitudes) of peak rising and or descending points [6]. These features are prone to noise due to liftoff influence and direct linking-field signal among others.

WPT as an approach differs from other eddy current testing (ECT) approaches in terms of response to excitation. It possesses multiple resonance features, unlike ECT that uses non-resonance features which are susceptible to noise [5, 6]. Furthermore, it uses sweep frequency excitation to solve limited penetration depth and feature variation due to inherent defect parameters obsessed by single frequency ECT [7]. Similarly, it overcomes the problems of shorter testing time with less power in each frequency component by multiple-frequency ECT [8]. In comparison with pulse ECT, besides its measuring time reduction to a minimum and a broad spectrum of frequency components [4], still, suffers coupling variation and response-distortion due to materials heterogeneity. However, WPT resonance frequency has shifting and splitting features sensitive to coupling variation [9-11], which are good for scrutinizing crack information. When compared to RFID, it doesn’t require a calibration mechanism for any environmental application and the problem with fading of RF signal exhibit by RFID [12]. Currently, the ECT is facing challenges related to the development of probes that could investigate complex geometrical defect with high sensitivity and explore multiple features for different information on the material under test. As par geometrical defect detection, many solutions were found using a rotating probe, array probe and rotating field probes [5]. However, these inductive probes are complicated in structure and very expensive compared to the bobbing probe. Beside structural simplicity of the bobbing probe and it's low-cost [5]; still, it is only for axial defect detection [4, 5]. Another aspect to consider while modifying the ECT probe is the excitation strategy. Among different excitation solutions, inductive probe arrangement based on Tx and Rx coils near each other with a magnetic axis perpendicular to the specimen surface are considered promising architectures [5].

Based on the stated issues with ECT, low-cost and straightforward rectangular spiral coils based on Tx-Rx WPT are proposed for this experimental proof of concept. The rectangular spiral nature of these coils makes them have axial and radial edges to the scan axis, which is suitable for radial and axial perpendicular fields to the sample. Moreover, it has resonance frequency shifting and splitting behaviors that combined the advantages of NERSE, MFEC, and sweep frequency ECT. These make it have freedom of best features selection that are not affected by Tx and Rx gap and lift-off impact for crack QNDE. The present of its splitting frequency at resonance makes it have many features. Its multiple features have never been harnessed by ECT even though some of them are not affected by lift-off distance. Hence, this freedom for multiple features selection could give the best information related to the sample for QND&E. The remaining part of this paper is organized into wireless power transfer for eddy current in section 2, methodology in section 3 results and discussion in section 4 and conclusion in section 5.

2. WIRELESS POWER TRANSFER FOR EDDY CURRENT TESTING

Wireless power transfer (WPT) is a mean of interaction wirelessly through the time-varying electromagnetic field between two or more components. Therefore, it can be classified as electromagnetic radiation, electric (capacitive) coupling and magnetic (Inductive) coupling [13-15]. The electromagnetic radiation WPT uses a microwave to achieve long-distance wireless power transmission. However, its travel distance and omnidirectional energy radiation render it inefficient and harmful to living things. Contrary, the electric and magnetic couplings techniques in the near field are non-radiative. In the capacitive coupling mode, electric field energy is used for interaction between parallel metallic plates or electrodes. Its relatively low cost and weight, has a negligible eddy-current loss and excellent misalignment performance [16]. However, its low efficiency and power density and hazardous nature of electric fields to living things than magnetic fields make it less researchable than magnetic coupling type [13, 16]. The magnetic coupling techniques explore magnetic field advantages, and is further divided into inductive power transfer (IPT) and coupled magnetic resonance system (CMRS) [13]. CMRS is an emerging concept as a particular case of IPT with a high-quality factor because of its resonance nature. Its sometimes has additional relay coils that make it to efficiently transfer power up to 5 m length [17].

An inductive WPT is divided into loosely- and tightly-coupled systems based on the mutual coupling between the coils. For tightly coupled systems, the coupling factor is close to unity. Its common application is in a power transformer. On the other hand, the loosely-coupled systems have low coupling factor ranging from 0.01 and 0.5; depending on the application [18]. The weak coupling coefficient is because of the large distance between coupled coils (center-to-center) compared with the coil sizes in addition to the absence of high permeable magnetic path connecting them. Therefore, for improvement, its reduced power transfer efficiency is counterbalanced by adding resonance circuit. This resonance circuit enhances the power transfer between Tx and Rx coils [19], which is the key issue in this research.

For WPT application to NDT&E, the presence of conductive-material-sample (CMS) near the field generated by the primary coil varies the magnetic field linking Rx. The variation of magnetic field linking Rx is a result of direct and remote field linkage between Tx and Rx. The direct field has no information to the sample, whereas the remote field passes through the sample to Rx has information related to the sample's permeability, conductivity, and geometrical nature. Apart from the induced-eddy-current influence on the remote field, power transfer from Tx to Rx is also affected by electrical conductivity, magnetic permeability, the sample volume and inhomogeneity of the material near the probe. These factors manifest their influence on the defect signal features. Therefore, WPTEC approach has potential application to material crack detection and characterization.

The concept of WPT has mostly been applied to the different area of knowledge-discipline as either energy re-charging system or information transfer system [13, 18, 20-23]. Recently, it has started been applied to the different scenario for metal detection as presented in [24-28]. However, the area of metallic defect detection and characterization has never been studied. Therefore, this research proposed an experimental proof of concept for non-destructive testing and evaluation, particularly to cracks investigation in a metallic sample.

3. METHODOLOGY

Wireless power transfer approach ss applied to the probe of eddy current testing base on inductive power transfer. Two identical, rectangular coils for wireless power transfer approach are used to act as the sensor-probe for scanning the sample under test. The two coils were connected to vector network analyser (VNA -E5071B) through port1 and port 2 as shown in the system diagram in Fig. 1 at 4mm separation and 2mm lift-off. The sample was moved for 178 mm distance at each step of 2 mm interval. The captured VNA data signal for each scan point is transferred to the personal computer for numerical processing. Matlab numerical simulation software was used for the signal processing, feature extraction and projection via sample with crack. Finally, the experimental results are discussed for crack QNDE.

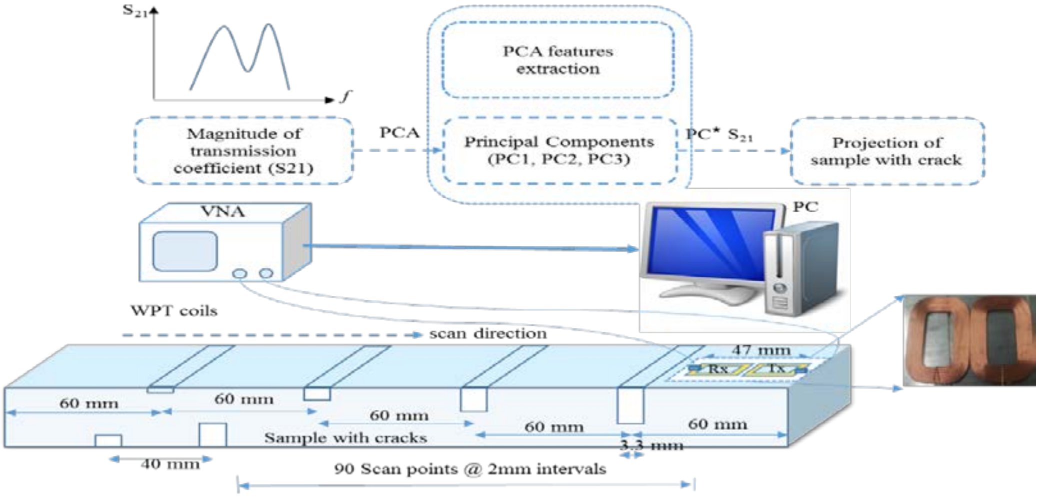


Fig. 1 WPT EC based system diagram

The probe is made up of two identical wire wound rectangular coils, one for Tx excitation coil and the other one for Rx sensing coil. Tx and Rx coils are configured as series-series resonance network as seen in Fig. 1. For testing purposes, an Aluminium sample with 300mm length by 50mm width by 10mm depth having four different artificial surface cracks is used. The cracks are 8mm, 6mm, 4mm, and 2mm depths and each having 3.3 mm width along the scan side is used. Non-crack and three crack points area measurements are carried out on the sample using a sweep frequency excitation ranging from 50 to 100 MHz at a step size of 31.25 kHz. The values of the magnitude of transmission coefficients S_{12} and S_{21} in dB are recorded and processed for feature extraction in a personal computer.

4. RESULTS AND DISCUSSION

The S_{12} data from VNA contained 1601 frequency points for 90 scan points at an interval of 2 mm each. Fig. 2 shows the plots of the magnitude of the transmission coefficient S_{12} against the frequency for a non-crack and three cracks points. From the values of S_{12} in Fig. 2, there are two resonance frequencies and their S_{12} magnitude as four features used for defect analysis. The 'M' shape or double resonances have rich information of the Tx-Rx probe-samples system relationship (lift-off and geometry), defect shape and depths due to a wide range of frequencies, material inhomogeneity [9-11, 29-31]. These multiple features extracted through PCA and point-based features using Matlab numerical simulation software for comparison.

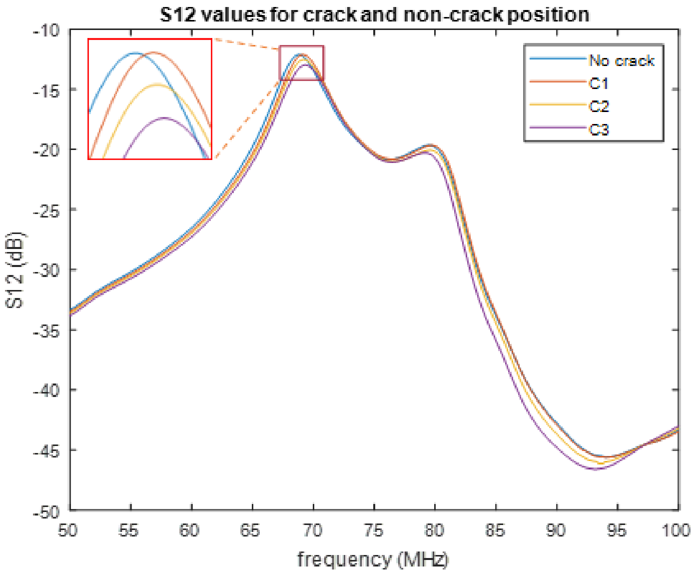
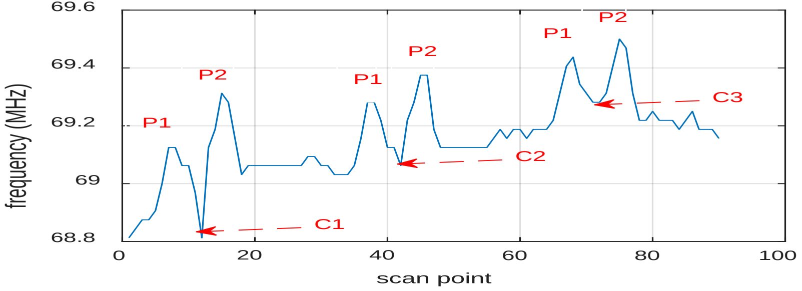


Fig. 2 S_{12} values for four selected scan points

A. POINT BASE FEATURE

Fig. 3 shows the two frequencies feature variation along the scan axis. For the first crack, the first frequency feature increased to a peak value, P1 as the Rx coil approached the crack position and dropped to a minimum value, C1 at the crack center and then raised to another peak value, P2 immediately after the crack position. These happened to the remaining two cracks, as seen in Fig. 3(a). Each of the points, P1, C1, C2, C3, and P2, corresponds to a scan point, and a frequency feature value.

(a) First frequency feature



(b) Second frequency feature

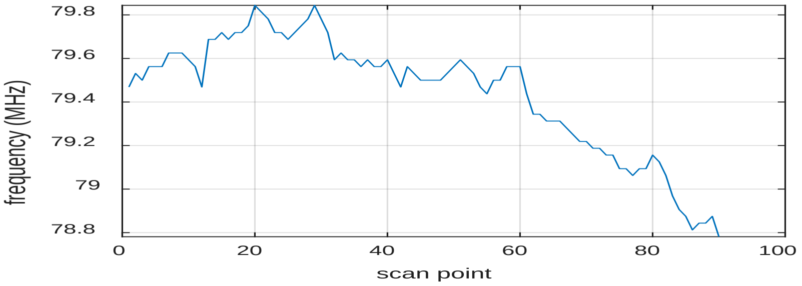
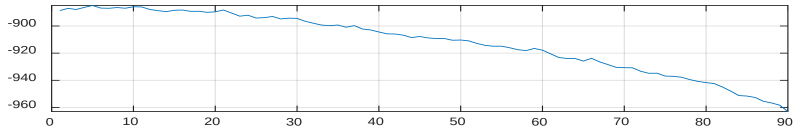


Fig. 3 Frequency features

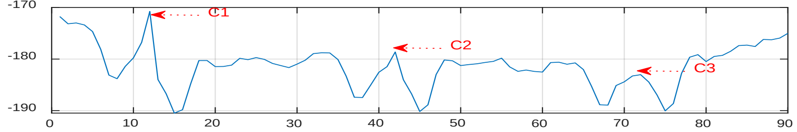
B. PRINCIPAL COMPONENTS ANALYSIS FEATURE

PCA is one of the statistical tools, which helps to extract principal components (dominant features) from a set of multivariable data. PCA is applied here for extracting the relevant features from WPTEC responses for comparison with the point base features. The S_{12} values were the input training data to PCA for features extraction. Three of the dominant features called principal components (PC) from PCA were selected. The original data, S_{12} were then multiplied by each of the three selected PC and obtained the feature via sample. Fig. 4 shows the PCA features via sample for the three selected PC. The second PC gives the best projection of crack centre position for the three cracks, C1,2,3. This PC2 projection corresponds to first frequency feature as seen in Fig. 3(a) above. It shows a similar pattern to frequency features for each crack but in reverse order, as seen in Fig. 4(b). The other two PCs show variations along the scan axis that are dominated by noise.

(a) PC1 projection



(b) PC2 projection



(c) PC3 projection

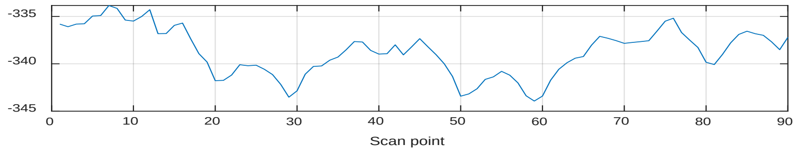


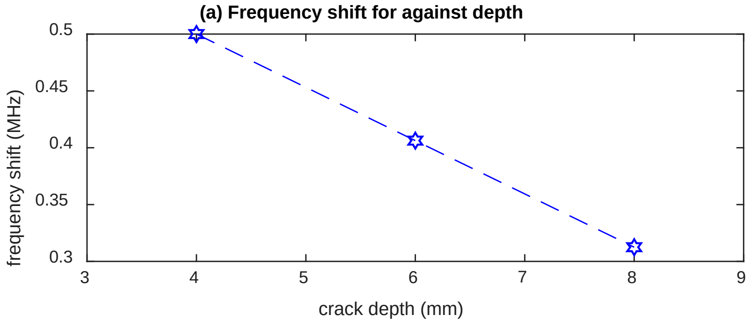
Fig. 4 PCA features via sample

C. RESULTS DISCUSSION

This study explored the feasibility of WPT for ECT based on frequency features. The samples presented in Fig. 1 has four surface cracks along the scan side, but only three cracks with 8 mm, 6 mm and 4 mm depths respectively were scanned in this investigation. Results from Fig. 2 shows that the two splitting frequencies shifted as the probe moved along the sample around the crack position. This is because of higher eddy current density at the cracks surrounding which causes probe sensitivity to crack morphology. This frequency shift is used to characterize the crack in this research.

The first frequency feature is more sensitive to Rx response due to a remote field. The width of the two peak values (P1 and P2) in each crack point is constant because all the cracks were of the same width as seen in Fig. 3 (a) and 4 (b). Similarly, the distance between C2 to C1 and C2 to C3 in Fig. 3 (a) and 4 (b) is 30 scan points (60 mm), which is the same as in the actual sample shown in Fig. 1. Therefore, C1, C2, and C3 show the centre position of the three cracks. Reference to Rx position, the cracks were at the 12th, 42nd, and 72nd scan point as indicated by C1, C2 and C3 in Fig. 3(a) and 5(b).

In comparison between both the features extracted, the crack dependency on frequency features and PC values deviations are similar and characterized the cracks. Fig. 5 shows the dependence of depth on frequency shift and PC deviation from the non-crack position. For the three cracks investigated, the frequency shift is inversely related to the depth. The deeper the crack, the less the eddy current density around it and the lower the frequency shift at its position as seen in Fig. 5(a). For the PCA features in Fig. 5(b), deeper cracks show higher PC coefficient deviation. All these were as a result of the variation of the remote field due to high eddy current influence immediately before and after the crack position.


(a) Frequency shift for against depth

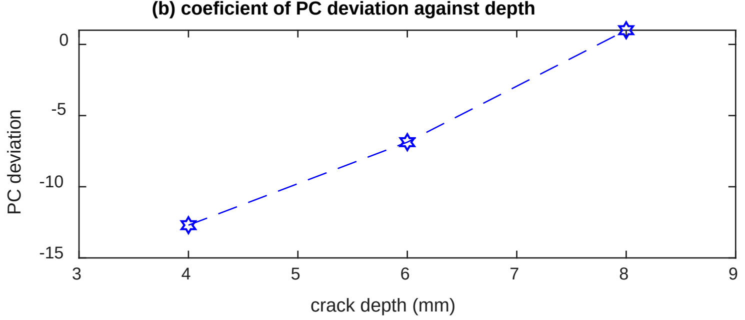

(b) coeficient of PC deviation against depth

Fig. 5 Frequency and PC deviations from no-crack position

5. CONCLUSION AND FUTURE WORK

In this research, an investigation of frequency features for cracks detection has been explored experimentally. We have shown that the PCA feature validates the resonance frequency shift before and after the crack through its second PC. The three cracks with 8, 6, and 4mm depth in a block of Aluminium sample were detected and quantified based on frequency features. Hence, the WPT approach is a useful tool for a probe to ECT investigation on material QNDE.

In the future works, the research will focus on crack orientation using different WPT resonance network topology and arrangement of multiple Tx and Rx coils. These can explore the potentials of WPT, especially for the testing complex and natural crack at very low frequency because of the skin depth issue.

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