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Pulsed magnetic flux leakage techniques for crack detection and characterisation

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Abstract

Magnetic flux leakage (MFL) techniques have been widely used for non-intrusively inspecting steel installations by applying magnetization. In the situations where defects may take place on the near and far surfaces of the structure under inspection, current MFL techniques are unable to determine their approximate size. Consequently, an extra transducer may have to be included to provide the extra information required. This paper presents a new approach termed as pulsed magnetic flux leakage (PMFL) for crack detection and characterisation. The probe design and method are introduced. The signal features in time–frequency domains are investigated through theoretical simulations and experiments. The results show that the technique can potentially provide additional information about the defects. Lastly, potential applications are suggested.

Keywords: Magnetic flux leakage; Pulsed magnetic field; NDT&E; Defect detection and characterisation

1. Introduction

Magnetic flux leakage techniques are widely used for pipe and tank floor inspection [1–7]. This technique requires magnetisation of the specimen under test. The magnetisation generates magnetic flux flowing in the specimen in a certain direction, which is ideally perpendicular to the axis of the crack to be detected. The presence of any flaws will implement as an abrupt change of magnetic permeability to the flux in the specimen. The permeability of the flawed part is generally lower than flawless parts, providing high resistance to the flux and forcing it to take a different route. In cases where the other routes are magnetically saturated, some flux leaves the specimen to the surrounding space temporarily causing flux ‘leakage’. This leakage is readily detectable by a magnetic sensor located in the proximity of the specimen surface. The defect parameters that affect the distribution of the leakage flux are the ratio of depth of the defect to the thickness of the pipe wall, length, width, sharpness at the edges and sharpness at the maximum depth [2]. In practice, the magnetisation device is usually a permanent magnet or an electromagnet [8,9]. For dc inspection, Hall devices, magnetoresistives and SQUIDs [10] can be used to measure the leakage field. For ac measurements, pick-up coils are another alternative. The advantage of MFL techniques is its simplicity and low cost. The technique is more robust to the variation of magnetic properties in magnetic materials compared to eddy current techniques, which belong to electromagnetic NDT techniques as well. Like many electromagnetic techniques, MFL is also non-contact, which is a very useful feature for on-line dynamic inspection. Unlike eddy currents, however, MFL only works with magnetic materials.

Improvement in accuracy in NDT techniques is desired in many applications, such as pipe inspection where good accuracy in defect detection and characterisation can help reduce unnecessary costly pipe replacements. To meet this requirement, pulsed MFL technique is proposed in this paper. The technique potentially offers richer information about structural defects compared to the other MFL techniques. Our study on this proposed technique is presented in this paper. In the following sections, simulation and experiments on PMFL are reported, followed by conclusions and further work.

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2. Pulsed MFL

The dc MFL technique provides limited information on the defects detected in terms of location and sizing. Generally, it has to be ensured that only one type of defect is present and these defects can only happen on one side of the inspected structure to allow accurate inference of the defect size, because the technique only relies on one measurement feature, i.e. the magnetic field leakage intensity. In some implementations they are complemented with sensors of other modality to allow discrimination of near and far surface defects. With ac MFL, the inspection is generally sensitive to only one side of the sample depending on the excitation frequency chosen. With pulsed MFL, the probe is driven with a square waveform and the rich frequency components can provide information from different depths due to the skin effects. It is expected that we could inspect thicker samples for far side defects and at the same time has good sensitivity for near surface defects. In addition, we should also have additional information such as the location and size of defects. The development of the pulsed MFL system is an extension of our work on pulsed eddy current NDT systems [11,12].

To explore the potential of the technique, a probe was designed and built using a U-shaped ferrite yoke. Fig. 1 shows the dimensions of the probe in mm. A Hall device sensor from Honeywell's SS490 family [13] has been chosen and is positioned halfway between the yoke's poles to measure the magnetic field density normal to the sample surface. The Hall sensor has a sensitivity of 3.125 mV/G. A coil of wire is wound around the top horizontal part of the yoke and driven with a rectangular waveform for excitation. During operation, the excitation current is controlled to avoid the ferrite yoke getting magnetically saturated. Data acquisition is performed using a 14-bit digitisation at 100 kHz sampling rate.

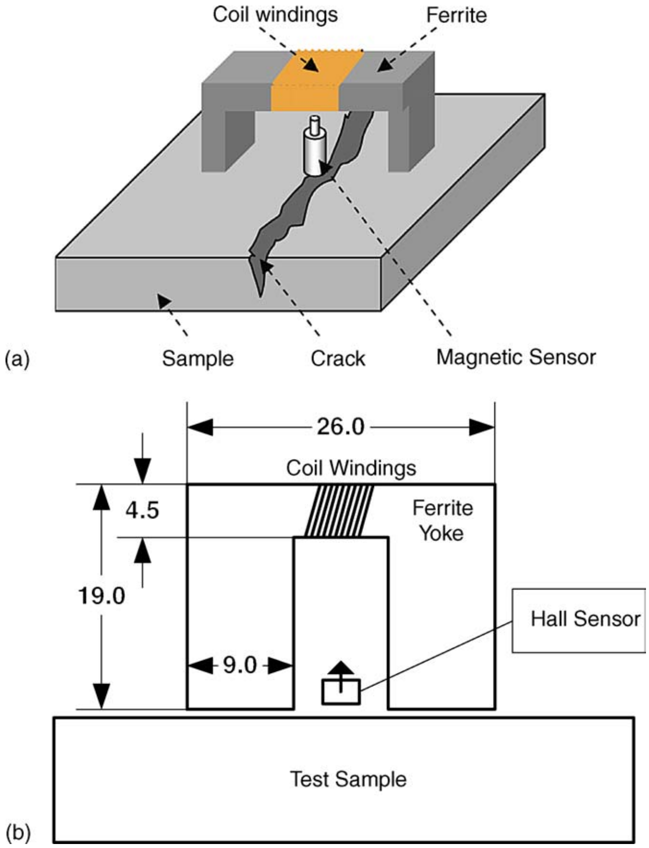

Fig. 1. (a) Illustration of the probe and a test ample and (b) pulsed MFL probe layout and dimensions.

3. Simulation

Finite element modelling (FEM) has been widely used for the study of electromagnetic NDT techniques, including MFL [4]. In this work, a FEM package called FEMLAB is used to study the effects of surface and sub-surface cracks on the magnetic field and to predict the system outputs. The package uses the finite difference method to perform transient analysis that is required for our purpose. Fig. 2 shows the meshed model used in the simulation. Finer meshes are created surrounding the slot to give more accurate results. The width of all the slots used in the simulation is 1 mm. In this article, the depth of the surface slots refers to the length of the slot from the surface to the bottom tip of the slot and in the simulation it is varied from 1 to 3 mm. The depth of sub-surface slots is the distance between the top surface of the sample to the top of the slots that always have an opening on the bottom surface of the sample. The sub-surface slots are located 0.5 and 1 mm below the surface in the simulation.

Fig. 3 shows the calculated normal magnetic field density above the right hand side edge of the each slot. Fig. 3a and b show the results from surface and sub-surface slots respectively. In the figures, time = 0 is when the excitation pulse starts rising. It is shown by the shapes of the signals that the

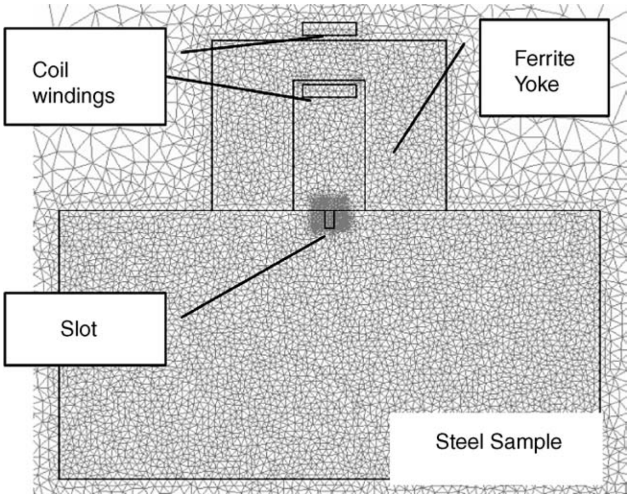

Fig. 2. FEM simulation.

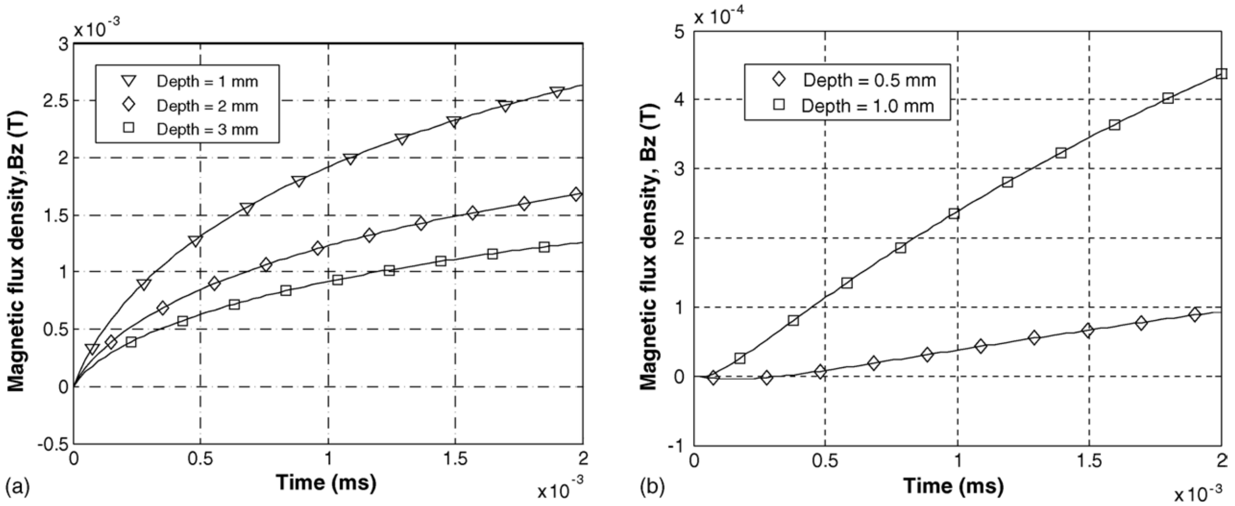

Fig. 3. FEM simulation results: (a) surface slots and (b) sub-surface cracks (symbols are for identification, not actual data points).

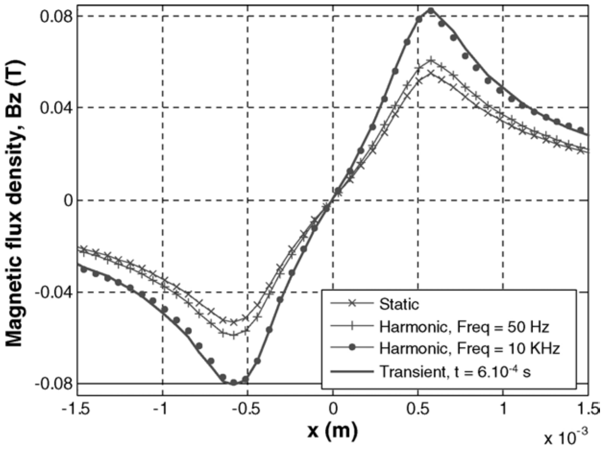

Fig. 4. Comparison of different excitations.

technique can potentially discriminate the depths of the slots detected and also the position of the defect by using temporal information of the signals.

Fig. 4 shows the plots of the calculated normal magnetic field against the distance x to the central major axis of a surface slot with different excitation waveforms. The surface slot's depth is 3 mm. The plots show that the transient performs slightly better than the 10 kHz frequency excitation and significantly better than both the dc and the low frequency excitations.

4. Experimental results

The experiments are designed to give us some initial results that illustrate the capabilities of the technique. The samples have surface slots with depths varying from 1 to 9 mm and sub-surface slots with location depths ranging from 0.5 to 7 mm. The width of the slots is approximately 1 mm. The coil is driven with a square waveform with a pulse width of 40 ms. The plots of signals shown in this section are: initial experiment results show that the highest signal peak amplitudes are obtained at different normal distances from the slot's central major axis depending whether the slot is on the top surface or on the bottom surface of the sample. When the slot is located below the surface, the measured field is more spread out due to field dispersion. Therefore, the positive peak to negative peak distance is larger than the slot width. This is illustrated by experimental results plotted in Fig. 5. The slots' width is approximately 3 mm. The depth of the surface slot is 3 mm and the buried slot is located 1 mm below the surface. The thickness of the sample is 10 mm. The results were obtained by manually scanning the probe over the slots with a 1 mm step and $x = 0$ being the central major axis of the slots. The probe is unmoved every time a measurement is taken. The signal amplitudes are taken for the plot. It is known that with MFL techniques, the polarity of the magnetic field

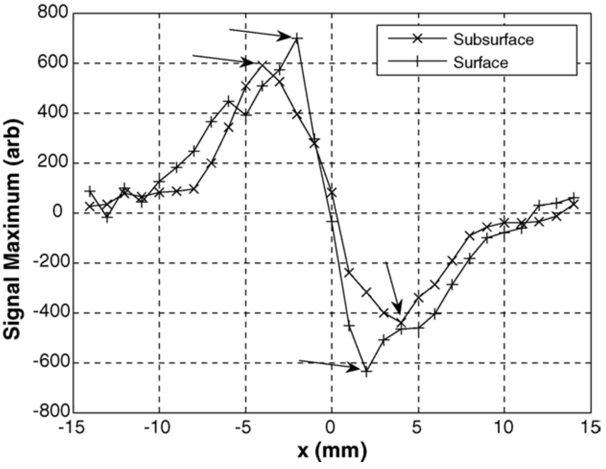

Fig. 5. Scanning results of sub-surface and surface slots.

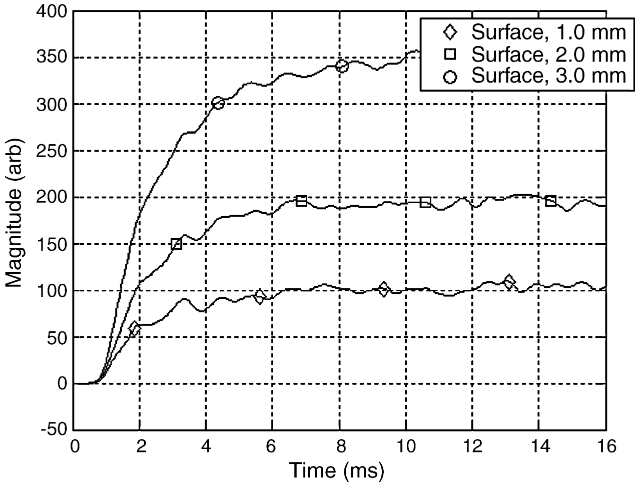

Fig. 6. Results with surface slots with depths of 1, 2 and 3 mm; the rising edge of the excitation pulse initiates at time = 1 ms (symbols are for identification, not actual data points).

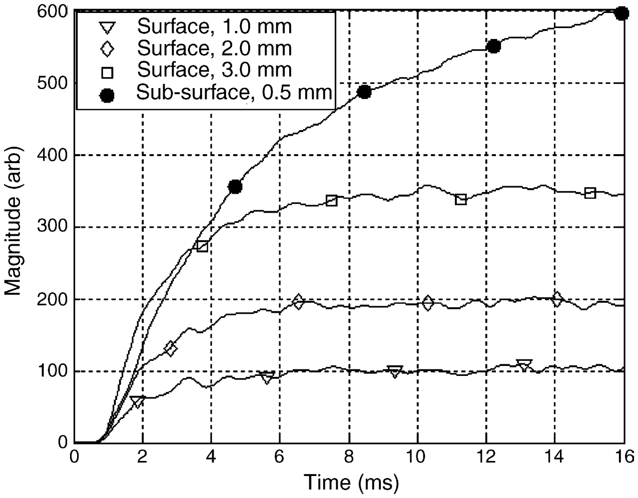

Fig. 7. Surface and sub-surface slot signals; the rising edge of the excitation pulse initiates at time = 1 ms (symbols are for identification, not actual data points).

changes if the sensor is scanned over a crack. The plots show that with the 1 mm scanning step used, the distances between the positive and negative peaks are 4 and 8 mm for the surface and sub-surface slots, respectively.

As can be seen in Fig. 5, the amplitude of the signal varies with the relative position of the probe to the slot axis. From now on, the output signals used are obtained when the probe is such positioned that the highest signal amplitude is measured. The positive peaks are taken with the assumption that the negative peaks have the same absolute amplitudes due to symmetry. Fig. 6 shows the resulting signals from surface slots with different depths. It shows that the technique is able to differentiate different depths of the inspected slots by using the amplitudes of the signals, provided that the location of the slot is known. It should be noted that all plots of the experimental signal output against time have been arranged so that the rising edge of the excitation pulse coincides with time = 1 ms.

Fig. 7 shows the comparison of the signals obtained for both surface and sub-surface slots. It clearly shows that the signal of the sub-surface has a different characteristic where it initially increases slowly and after some point in time increases at a faster rate. In other words, the inflexion points of sub-surface slot signals happen later than those of surface slot signals. These can be more clearly seen by taking the first derivative of the signals.

Experimentally it was found that the probe could not detect sub-surface slots 1 mm below the surface. To demonstrate the ability to discriminate surface and sub-surface and also to be able to discriminate the location depths of the sub-surface discontinuities, another probe with a bigger yoke having a horizontal length of 93 mm is used. The results are shown in Fig. 8, which demonstrates that again the inflexion points of the sub-surface slot signals happen later than the surface slot signals. The inflexion points for surface signals occurs at approximately the same time, while the inflexion point of the deeper-located sub-surface slot happen at a later time than in the case of a sub-surface slot that is closer to the surface. All these results indicate that the inflexion point can be used to discriminate the depth location of a detected slot.

Fig. 9 shows the frequency analysis of the signals. The plots support our statement that the temporal information, which is represented as phase in the frequency analysis, is useful for characterising the defects. The low frequency components, below 50 Hz, seem to discriminate not only between surface and sub-surface but also discriminate the distance of the sub-surface slots below the surface. Location discrimination seems to also be achievable using the frequencies around 200 Hz. It is, therefore, clear that determination of the slot's distance from the surface and the discrimination of which sur-

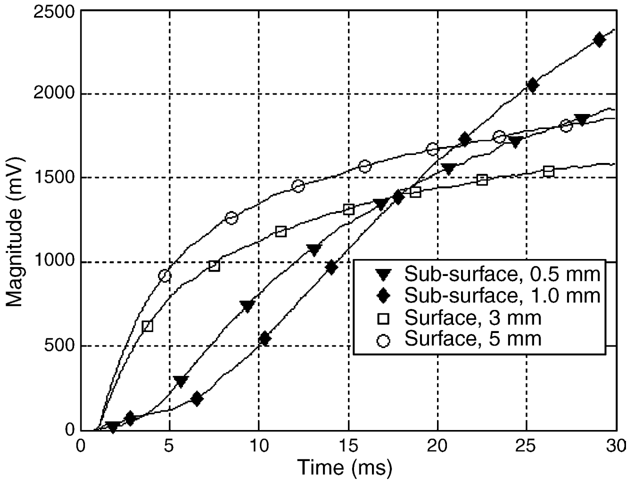

Fig. 8. Surface and sub-surface slot signals using a bigger-yoked probe; the rising edge of the excitation pulse initiates at time = 1 ms (symbols are for identification, not actual data points).

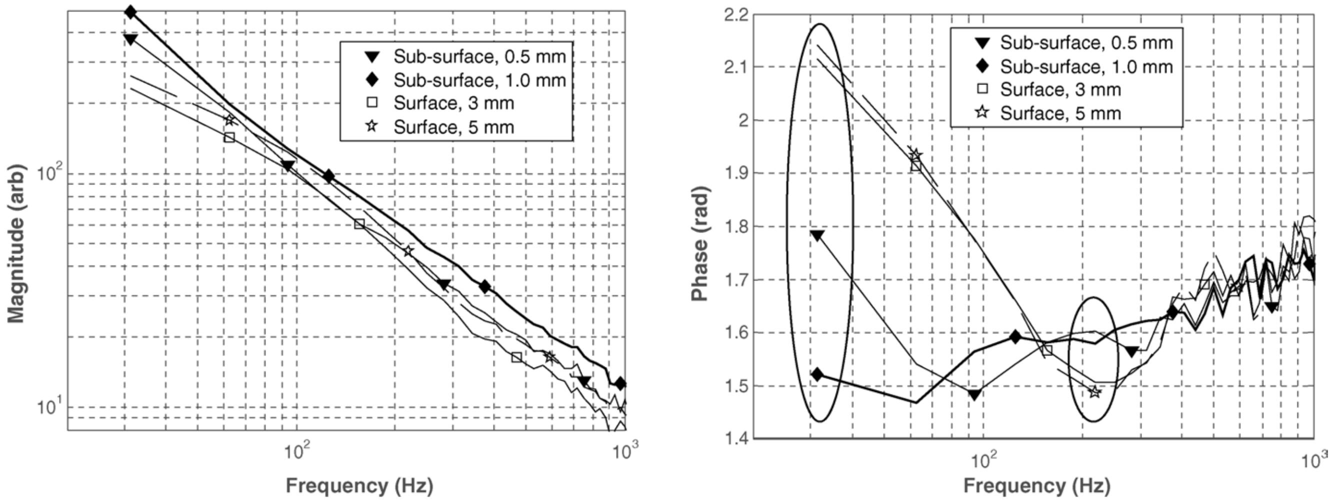

Fig. 9. Frequency analysis of the surface and sub-surface signals: (a) magnitude, (b) phase (symbols are for identification, not actual data points).

face the slot is located, can be achieved conveniently using the pulsed MFL technique.

5. Conclusions

A variant of pulsed MFL technique has been proposed and investigated. The numerical analysis and experimental studies has shown PMFL clearly has advantages in terms of defect location and sizing by using features in time–frequency domain, including the arrival time of the inflexion point, signal magnitude and phase variation of frequency components. It has been shown that the technique is able to discriminate cracks' locations in addition to give relative depths of the cracks. The probe design should be tailored to the application in hand as the dimension of the yoke determines the depth of penetration, where generally a larger yoke offers deeper penetration. The scanning results also show the potential of exploiting a linear array of magnetic sensors between the yoke poles for better understanding of the sample conditions. The simulation results show that the transient or pulsed MFL performs the best overall for both surface and sub-surface cracks inspection. The advantages of PMFL make it potentially suitable for many applications for ferromagnetic materials, including detection of cracks in ferromagnetic metal strips where defects can be present on both sides while access is limited to one side of the strip. For future work, the capabilities of the PMFL for corrosion detection/characterisation by using feature fusion techniques [14,15] will be investigated. The simulation technique will also be improved to explore the potential of this technique further.

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Dr. Ali Sophian received BE (Hons) degree in 1998 and PhD in 2004, both in electronics engineering from the University of Huddersfield, England. He is currently a research fellow at the School of Computing and Engineering, the University of Huddersfield. His research interest, includes eddy current NDT system design, signal processing and embedded systems. He has been working on electromagnetic NDT systems since he started his PhD project that was co-sponsored by the TWI Ltd.

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Dr. Sofiane Zairi obtained his BSc (Hons) in applied physics and semiconductors from the University of Monastir in 1996. He acquired his MSc in microelectronics from INSA of Lyon in 1997, France. Then, he has got his PhD in integrated sensors from the School of Centrale Lyon, France in 2001. Later on, he joined a post-doc project at the University of Strathclyde, Glasgow, UK. This project funded by the SHEFC council, where versatile cell library of microsystems, pertaining the realms of MOEMS and RF MEMS, has been fabricated. Dr. Zairi has shown a great interest to the fields of embedded microsystems, and software modelling using HDL and FEM-based analysis methods. He is currently a research assistant at the School of Computing & Engineering, at the University of Huddersfield.