Eddy Current Thermography: Advances in NDT Fusion Technology for Future Industrial Application

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Abstract. Fusion of NDT techniques has proven to increase the capability and reliability of defect detection thus improve inspection results. It can also provide solution for the limitations posed by a single NDT technique in acquiring the intended information and so achieving the required inspection efficiency. Eddy current thermography is an emerging technology in advanced NDT, which provides and alternative solution to the demand by the current industry. The technology combines the well-established eddy current testing with thermography inspection to provide a fast and efficient method for defect detection and characterization over a relatively large area. This paper provides an insight to eddy current thermography system development and its potential for industrial application. Results from 3D FEM simulation and qualitative experimental investigations of eddy current thermography in defect detection on conductive samples are also presented. The work demonstrates the effectiveness of NDT technique fusion in providing comprehensive and reliable defect assessment.

Introduction

Fusion of NDT techniques can provide complementary information in testing of materials or components. This will results in better inspection capability and possibility of more information can be acquired in a single test compared to the results from an individual technique. Consequently, the reliability of defect detection within a particular test can be increased by combination of several NDT techniques, especially when the methods are particularly sensitive to different types of defects and material parameters. In general, fusion can be achieved via combinations of NDT techniques; association of NDT data for complementary results; or incorporation of different excitation modes to provide a technique for improved inspection capabilities.

A combination of Pulsed Eddy Current (PEC) and Electromagnetic Acoustic Transducer (EMAT) has been proposed for the testing of surface defects in rail tracks. The fusion of these two techniques has demonstrated the capacity to accurately characterise surface-breaking defects with depths of up to 20mm. PEC is more sensitive to shallower surface cracks, discriminating defects up to 5mm deep, while the EMAT is more sensitive to surface-breaking defects between 2.5mm and 15mm deep [1]. Both techniques show good accuracy and the integration of the results enable more reliable depth measurement. One example of a system fusion study in NDT is an investigation funded by the US government into the feasibility of using multiple inspection techniques for assessing pipe wall conditions in natural gas pipelines [2]. The techniques considered for fusion in the study are Magnetic Flux Leakage (MFL), Ultrasonic (UT), thermal imaging and Acoustic Emission (AE). Fusion of MFL with thermal imaging shows the poorest results in the test due to limitations of both techniques in the identification of defect edges. On the other hand, UT and MFL produced the best fusion results because these techniques give the most quantitative NDT information relating to the geometry and location of defects.

Active thermography is another example of NDT technique fusion, which utilizes different modes of excitation for thermal stimulation in defect detection by thermographic images. Heating of the material under inspection can be accomplished via the application of sonic or ultrasonic energy
using a device such as an ultrasonic welding horn; this is known as vibrothermography, thermosonics or sonic infrared (IR) [3]. The applied excitation vibrates the material under inspection and leads the crack faces to rub against each other, the mechanical energy is converted to heat and the generated heat is detected at the material surface. Disadvantages include the need for contact between the test piece and the ultrasonic welding horn and the unreliability of this contact, which leads to the vibration spectrum produced being highly variable from contact to contact [3]. An alternative to heat lamp or sonic excitation is found in eddy current heating, where the part under inspection is heated by an inductively-generated current flow [4-6]. This technique, also known as induction thermography [7], tone burst eddy current thermography [8], and thermo-inductive [9] inspection, uses induced eddy currents to heat the material being tested [4, 5, 10, 11] and defect detection is based on the changes of the induced eddy current flow revealed by the thermal distribution captured by an infrared (IR) camera. Thermographic data and images can then be immediately assessed to provide an indication of major faults and the data can be further analysed to provide quantitative information of defects inside the inspected sample. This technique is able to detect hidden, subsurface defects even in complex components, in line with other thermographic NDT techniques such as sonic [12] and laser spot thermography [13].

![Diagram of eddy current thermography](image)

**Fig 1: The concept of eddy current thermography**

Eddy current thermography involves the application of a high frequency (typically 50–500 kHz) electromagnetic wave to the material under inspection. For pulsed thermography [8, 10] this is simply switched on for a short period (typically 20ms–2s), in contrast to lock-in techniques [14], where the amplitude of the high frequency is modulated by a low frequency lock-in signal. Fig. 1 shows the concept of eddy current thermography. The induced eddy currents are converted to heat through ohmic heating, according to Joule's Law. Both direct heating and diffused heating contribute to defect detection; defects such as cracks, voids or delaminations which are within the range of the eddy current distribution disturb the current flow and thus change the temperature distribution. Defects which do not directly interact with the induced eddy currents may interact with the heat generated at the surface as it propagates through the material (as with traditional heat lamp techniques). Thus, eddy current thermography has many potential advantages over heat lamp and sonic excitation (the change in temperature of the coil itself is very small), there is a little chance of damage to the material under inspection, as heating is limited to a few °C and for near-surface defects, direct interaction with eddy currents can improve detectability [15].

Although NDT technique fusion have shown the capacity for improving defect characterisation and inspection reliability, special attention should be given to the complexity of the integrative system and the possibility of having redundancy of information, which can provide more problems than solutions. Therefore, evaluation and initial investigations are required should fusion of NDT techniques be used to overcome the limitations of individual NDT techniques. This is where numerical simulation investigations can be used to their full potential in providing the initial results and evaluating the proposed NDT fusion technology. In this paper, the development of an eddy current thermography system is detailed initially; including excitation hardware, coil design and camera selection. The subsequent following section provide results from 3D FEM simulations and experimental qualitative investigations of eddy current thermography on defect detection. The final
section concludes the paper with a discussion of the work and the potential of eddy current thermography as a NDT fusion technology for future industrial application.

**Eddy current thermography system**

A typical system setup of the eddy current thermography system consists of an induction heating control box which supplies power to the work head. The work head contains a transformer coupled resonant circuit, including two capacitors and the excitation coil itself. The excitation frequency is dictated by the values of the capacitors, the inductance of the coil and the load of the circuit, i.e. the material, volume and proximity of the sample under inspection. A PC which is linked to the IR camera stores the thermal images captured by the camera for subsequent analysis. Fig. 2 shows an example of the system setup for an eddy current thermography system.

![Fig 2: System setup for eddy current thermography system](image)

The excitation subsystem for our system is based around a commercial induction heating system, the Easyheat 224 from Ambrell, shown in Fig. 3a. The Easyheat has a maximum excitation power of 2.4 kW, maximum current of 480A and an excitation frequency range of 150 kHz – 400 kHz.

![Fig 3: a) The EasyHeat 224 induction heating system; and b) Coils designed according to application](image)

In practice, the inductance of the coil has been found to be roughly proportional to the length of tube to construct the coil; a shorter coil operates at a higher frequency and a longer coil operates at a lower frequency. If the coil inductance is not within a certain range, the circuit will not resonate and the induction heater will not work. In our work, the excitation coils are constructed from 6.35mm hollow high-conductivity copper tube. Water is pumped through the coil during operation to aid in cooling. The coils design depends upon optimum defect detection capability, which is based on the type and geometry of the tested sample. In many cases, new coils need to be designed and fabricated to fulfil the inspection needs. Fig. 3b shows some of the coils that have been fabricated for different purposes and applications. One of the major factors influencing coil design is the induction of optimally uniform eddy currents in the object under inspection which will cut across, rather than divert around the expected defects.
Qualitative investigation by eddy current thermography

**3D FEM simulation on eddy current thermography.** Fig. 4 shows the 3D FEM simulation results of the interaction between uniform eddy currents with a defect in a conductive sample. The simulations for eddy current thermography for our work were conducted using COMSOL via the multiphysics application. The eddy current flow for the result is visualised by the streamline plot (Fig. 4a).

![Streamline plot of eddy current flow](image)

**Fig 4: Simulation results for conductive sample after 100ms of heating of a) eddy current, and b) resultant heat distribution**

In the presence of the defect, eddy currents will divert to complete their closed loop path, which leaves a unique eddy current distribution based on the defect geometry that can provide useful information about a defect. One notable observation from the streamline plot is that the presence of the defect causes an obvious diversion of the eddy currents around the tip of the defect. The streamline plot also illustrates the large influence that sample geometry has on eddy current distribution; where the eddy current loops encounter a sample edge an area of higher current density is formed, e.g. at the sample edge, under the coil. Thus, defects with the same geometry and orientation, but different position under the sample under inspection can interact with the induced eddy currents in different ways and cause very different heat distributions. Fig. 4b shows the resultant heat distribution for the defect, viewed from the top of the sample for surface heating distribution. It can be seen from the top view that for both samples, there are hotter areas directly under the induction coil, plus a build-up of heat at the edges of the sample. In addition to this, the defect exhibits a characteristic heat build-up at the tips of the defect and cooler areas at either side of the defect. Through the graphical results provided by the simulations, the heat distribution due to the presence of a defect was observed, and provides support for the experimental results. These results provide the visualisation of temperature distribution underlying phenomena due to the presence of a defect inside investigated sample.

**Eddy current thermography experimental investigations.** The evaluation of defects in industrial components can be assisted by the use of an artificial crack produced inside a ready-made sample. For example, the use of a Trueflaw sample which has a crack produced by the thermal fatigue cracking mechanism can provide a more realistic test defect. Work on the investigation of a crack inside a Trueflaw sample has been conducted using the eddy current thermography technique. These true parameters of the crack can be used to assess the technique’s performance for defect characterisation. Fig. 5 shows an example of eddy current thermography results on the Trueflaw sample. From the figure, it can be seen that the crack in the sample can be detected and a good definition of the crack shape can be observed from the thermal image. The Trueflaw sample investigation results can provide the reference for defect quantification applied to other industrial components, e.g. welded sample, turbine blades. Preventive maintenance on welded samples and
turbine blades, which are critical components in power generation industries, is an important factor in cost and safety issues within those industries.

From fig. 5, in the early stages (100ms), only heat generated at the tip reaches the surface. As the heating period increases to 300ms, heating at the tip of the defect are joined at the surface by a small amount of diffused heat from the bottom of the defect, hence the build up of heat which surrounds the defect. The result shows that a good definition of the defect tip edges can be obtained in the early stage of the heating period, where eddy current heating is dominant and there is less contribution from diffused heat. These observations confirm the results presented by the numerical simulations presented in the earlier section of this paper, where the eddy current follows the path of least resistance which forms the dedicated heating distribution with a particular defect.

Fig. 6a shows a welded carbon steel sample having a longitudinal surface crack. The indication of the crack was clearly visible under the eddy current thermography technique (Fig. 6b). The investigation on the welded sample provides the means to evaluate the eddy current thermography technique for defect detection, where the pattern of heating is dependent on the eddy current distribution resulting from its interaction with a defect. The employment of the IR camera with the eddy current thermography technique provided the high spatial resolution required to perform the visualisation technique for possible defect characterisation through the mapping of eddy current distribution.

Conclusions

The advantages and applications of eddy current thermography testing as NDT technique fusion have been outlined in this paper along with results from 3D FEM numerical simulations and experimental investigation on conductive sample. The simulations have provided an understanding of the fundamental behaviour of eddy current heating and heat diffusion in the presence of a defect. The qualitative investigations on the conductive samples provide the means to evaluate the eddy
current thermography technique for defect detection through the mapping and visualisation of eddy current distribution by the use of an IR camera. Good agreement was shown between the results from the simulation and experiment in terms of heating patterns, supported by the graphic visualisation of the heating mechanism provided by the simulations. The work has shown the effectiveness of the eddy current thermography technique, resulted from NDT technique fusion, to be applied on industrial components for an alternative NDT technique in industrial applications. Future work will focus on the characterisation and evaluation of defects for quantitative information.

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References
