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Multiple cracks detection and visualization using magnetic flux leakage and eddy current pulsed thermography

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ABSTRACT

This paper investigates two non-destructive evaluation methods, magnetic flux leakage (MFL) and eddy current pulsed thermography (ECPT), for both artificial and natural multiple cracks (MC) detection and visualization. The detection capability and characteristics of MC visualization are verified and compared through simulations and experiments. Results show that, MFL testing reflects the surface shapes and orientations of MC by 3D magnetic field imaging. However, it is unable to evaluate the depth of artificial MC and detailed surface shapes of natural MC due to limitations of sensor array spatial resolution. ECPT shows more capability in MC visualization in detail from thermal images. The obtained thermal image sequences from ECPT demonstrate rich transient and pattern information to evaluate MC geometrical features. After discussion of the two methods with the probability of detection (POD) analysis, a promising new sensing structure which potentially combines both advantages of them is proposed to enhance the NDE performance for MC evaluation.

1. Introduction

Ferromagnetic materials [1–6] are broadly used for constructed facilities such as pipeline [1], railway [3], wind power structures and gearbox [4] etc. Along with material aging and degradation [6,7] of in-service structures induced by fatigue [4,6], corrosion [7] and harsh environmental conditions, structural damage and geometrical discontinuity of key components occur which significantly reduce the device performance. For example, some serious defects especially complex-shaped multiple cracks (MC) caused by rolling contact fatigue (RCF) [4,6–8], as shown in Fig. 1 [6–7], reduce the mechanical strength and durability of component which can result in the sudden operational failure or structural fracture and potentially lead to catastrophic consequences. Non-destructive evaluation (NDE) [1–5] effectively provides qualitative and quantitative information in detecting and characterizing structural safety issues at early stages. Hence critical damage to facilities can be prevented if maintained in a timely manner. However, the detection and characterization of MC, especially on the surface and subsurface such as those induced by RCF are always challenging for NDE to identify their complex geometrical features, such as crack surface shapes, number of clustered smaller cracks, depths and orientations under specimen surface.

To detect and identify surface and sub-surface multiple cracks in metal, electromagnetic NDE (ENDE) techniques including eddy current (EC) testing [9–11], magnetic flux leakage (MFL) [1–3] and alternating current field measurement (ACFM) [12] own many advantages compared with other NDE methods. For example, traditional ultrasonic testing (UT) [8,13] which is sensitive to internal defect cannot identify near surface damages and need coupling medium during application. ENDE shows competitive properties in defect evaluation such as simple probe structure, high sensitivity to surface defects, rapid measurement, no need for surface preparation, low cost, no coupling required and non-contact implementations. MC have been investigated in previous studies using ENDE [14–16]. Wijerathna et al. [15] interpreted leakage flux in the presence of multiple defects and recovered the profile of a cluster of defects from MFL signals using a Gaussian process model. Ravan et al. [16] estimated multiple narrow-opening cracks using the Canny edge detection algorithm on MFL signals, such as defect number, location, orientation, length and an inverse model to estimate defect depth. Nakasumi et al. [9] analyzed the shape of MC separately based on an inverse model using an improved function and verified by numerical modelling on two adjacent semi-elliptical surface cracks using MFL. Rebican et al. [10] reconstructed the shape of MC based on a stochastic method from EC signals, which

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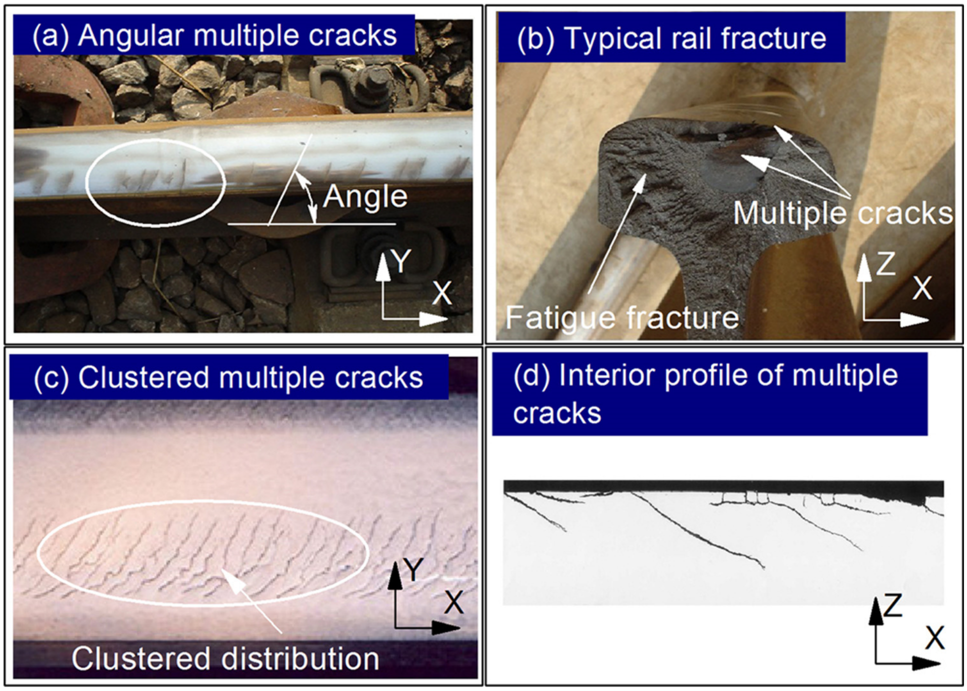

Fig. 1. The geometrical profile and features of multiple cracks from rolling contact fatigue [6–7].

can obtain the size, number and locations of cracks by inverse modeling. Cheng and Miya [11] proposed a two-step algorithm to identify and reconstruct parallel cracks using separation stage for cracks number, location and length identification and a reconstruction stage for cracks profile recognition based on EC. Yusa et al. [17] evaluated quantitative profile of natural cracks from EC signals and consider signals interfere effect of closely-located MC. Ghajar [14] proposed potential drop technique to evaluate MC on material surface and analyzed crack interactions in terms of depth and distance using simulation. Nicholson et al. [12] linked ACFM signals to complex shaped RCF cracks and discussed the sizing of clustered cracks using ACFM. However, current detection is inadequate to visualize defect shape of natural MC and identify their accurate details like defect depths and orientations.

To obtain more accurate surface shape and orientation of MC with different depths and spatial interval distances, new sensing techniques for the visualization of defects with high-resolution images and rich time-frequency-spatial information are required for quantitative NDE (QNDE). MFL testing [1–3,5] can be effectively utilized to image defects from the leakage magnetic field using sensor arrays. Li et al. [1] simulated the spatial leakage magnetic field distribution and obtained magnetic imaging result of irregular crack using full coverage scanning with an anisotropic magnetic resistor sensor. Huang et al. [19] obtained more accurate description of 3D defect geometry with different orientations through spatial magnetic flux modeling and edge leakage flux analysis. Sophian et al. [20] both proposed pulsed excitation to MFL named PMFL to provide richer time-frequency information for defect depth identification using the arrival time of inflexion point and phase variation of frequency component. Tang et al. [21] studied spatial magnetic field sensing for PMFL with simulation to provide comprehensive position information about the defect particularly crack shape and orientation. Wang et al. [22] extracted signal amplitudes of magnetic sensor array to image cracks over a large area using PMFL based scanning inspection. He et al. [23] proposed pulsed eddy current (PEC) [24,25] imaging and 3D magnetic field measurement [26] for defect evaluation. Tian et al. [27] and Wilson et al. [28] both proposed PEC thermography technique for imaging MC from RCF using infrared (IR) camera based on inductive heating and heat diffusion.

The eddy current pulsed thermography (ECPT) [27–31] technique, an emerging NDE method combining PEC and induction thermography, is rapidly developing and represents potential advances for complex MC characterization and material properties evaluation. Wilson et al. [29] modeled eddy current stimulated thermography with transient eddy current and heat propagation around simple slot and notches for quantitative characterization of defects. Pan et al. [30] and Cheng et al. [31] investigated the principal component analysis (PCA) and independent component analysis (ICA) on transient thermal image sequences for defects identification and characterization. Gao et al. [32–34] proposed a non-negative pattern separation model for ECPT to extract spatial and time patterns on automatic quantification of defects without prior knowledge. Tian et al. [4] proposed a statistical method based on single channel blind source separation to extract details of gear fatigue from transient thermal distribution and patterns of ECPT. Ren et al. [35] extracted divergence value to evaluate impact damage defects based on transient thermal patterns analysis. He et al. [36] proposed an eddy current step heating thermography to detect subsurface defects and employed two features to measure defect depth. Bai et al. [37] compared PCA and ICA in ECPT image sequences processing to enhance temperature contrast between defect and defect-free area and verified in natural sample testing. Li et al. [38] conducted state detections of structural material in power electronics using ECPT and compared heating performance of different induction coils. Peng et al. [39] investigated ECPT using Helmholtz-coil-types and different orientations of induction coil to analyze MC in time-spatial domains based on transient thermal image sequences. Recently, He et al. [40] proposed lateral heat conduction for detection of parallel and rail tread oblique cracks detection using ECPT. Lahiri et al. [41] reported on defect detection by combining MFL and infrared thermal imaging. Mahendran and Philip [42] proposed a direct visualization of defect in morphologies based on MFL.

The aim of this paper is to investigate recently developed 3D MFL and ECPT for detection and visualization of MC, to compare char-