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Image processing in eddy-current testing for extraction of orientations of defects

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Abstract. This paper presents an image processing method for eddy-current testing for the detection of the defects with a specific orientation. The method utilizes the fact that a line-shaped signal is, throught the Fourier transform, mapped onto a line passing through the origin and perpendicular to the orientation of the original signal. Hence, nonseparable fan filters is used to select the frequency components corresponding to the defects orientated in a specific direction. This approach enables more precise control of the extraction characteristics of signals compared to the iterative application of one-dimensional (1-D) filtering in the vertical and horizontal directions, in which the shape of the pass band is restricted to a geometry made from squares. The effectiveness of the proposed method is shown by a demonstration using a metallic sample with a defect aligned in a number of directions.

1. Introduction

Eddy-current testing (ECT) techniques are used for the inspection of versatile metallic objects, such as thin generator pipes in atomic power plants [1], wings of aeroplanes [2], and printed circuit boards (PCBs) [3]. The noncontact nature of ECT enables fast nondestructive inspection of delicate samples and the investigation of invisible parts by choosing appropriate excitation frequencies taking into account the skin effect.

The data processing of the derived ECT signals [4] also plays an important role in nondestructive testing for the recognition of the existence of defects. For example, in the case of PCBs, the inspection requires the discrimination of the defect-origined signal from other peaks, coming from the printed pattern, noise, the offset, and its variation. Moreover, the parameters of defect features, e.g., shape, length, depth, and conductivity, derived through image processing gives many useful informations. One such feature is the orientation of the defect, which can be used to classify defects, and in pre-processing of the Hough transform [5].

An iterative application of the wavelet transform in both the horizontal and vertical directions can be carried out in order to classify the defect direction [5–7]. This method has advantages in its simple procedure compared to intelligence-based nonlinear classification methods (e.g. neural networks), but since it requires making a two-dimensional (2-D) filter by the product of 1-D filters, the shape of the pass band in the frequency domain is restricted to a figure made from several squares. This fact means

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that the above method is unsatisfactory when the defect signal has a wide frequency distribution. An approach with more flexibility about amplitude characteristics is required. As a solution to this problem, this paper describes an image processing method using 2-D linear non-separable filters to achieve more precise discrimination of defects with respect to their orientations. Considering the relation between the signal in specific direction and its spectrum, fan filters have been adopted instead of separable processing using 1-D filters.

This paper is organized as follows. In Section 2, the inspection of metallic objects using an ECT probe is described. In Section 3, the concept and procedure of the proposed method is explained. Section 4 demonstrates the usefulness of the method through examples and possible improvements are discussed. Finally in Section 5, the whole study is summarized.

Inspection of a metallic object with an ECT probe. Relation between defect signals in various directions and their spectra.

2. Eddy-current testing of metallic objects

The test object is inspected as shown in Fig. 1 using an ECT probe [3] consisting of a meander type coil for the excitation of eddy-currents in the conductor and a solenoid coil for the detection of the tangential magnetic flux induced by eddy-currents. The probe output is constant when the conductor is uniform. But at any point where a nonuniform distribution of conductor exists, a disturbance of the eddy-currents is generated, and it is detected by the solenoid coil as change in the magnetic flux. This time, the probe produces a pair of positive and negative pulses (called here a 'defect peak'). Therefore, in the inspection of a uniform object, the resultant ECT image has a major change of amplitude only at those points where a defect exists.

Note also that the output of the ECT probe contains phase information, too, but here only the amplitude is used. In practice, the ECT signal contains many kinds of undesired components other than defect signals including noise, the offset and its variation. Approaches to remove them have been proposed (e.g. reference [8]).

Using a solenoid coil in this way, a high signal-to-noise ratio is achieved. If the defect is large enough compared to the minimum resolution of the probe, the shape of the defect can also be observed. In this study, our aim is the extraction of the defects based on their orientations. The method described in the next section achieves this by utilizing the nature of 2-D spectra.

Geometrical interpretation of (a) conventional and (b) proposed methods in the frequency domain.

Sample copper plate used in this study. Amplitude response of the fan filter used in this study.

3. Image processing method

The fundamental property made use of in the proposed method lies in the gradient of the spectra of lines in the ECT image. Assume a sinusoidal signal oscillating along a line extending in a direction θ in the spatial domain represented by x_1-x_2, that is,

$$f(x_1, x_2) = \sin\{\cos\theta x_1 + \sin\theta x_2\}. \quad (1)$$

After the transformation into the frequency domain, which consists of spatial parameters f_1 and f_2 (they corresponding to x_1 and x_2, respectively), the spectrum of $f(x_1, x_2)$ is expressed as follows:

$$F(\omega_1, \omega_2) = \delta(\cos\theta\omega_1 \pm \sin\theta\omega 2) \quad (2)$$

Since any signal can be expressed as the sum of plural sinusoids, these equations shows that when a defect has an orientation of θ (whether its intersect is zero or not), its spectrum is located on a line passing through the origin with an angle $90° + \theta$ (i.e., perpendicular to the defect orientation) (Fig. 2) [9]. Therefore, if iterative 2-D manipulations using 1-D separable filters are used, the shape of the pass band is restricted to a geometry made from squares (Fig. 3(a)). A method making use of the discrete wavelet transform (DWT) suffers form this drawback, if it is applied in both the horizontal and vertical directions separately. This approach satisfactory in the case when the support of the spectrum of the defect signal is sufficiently narrow, but usually, this condition is not satisfied for a defect.

Desired amplitude response of a fan filter.

Given the above nature of a spectrum of a signal with a specific direction, a more appropriate strategy for the extraction of a signal component with a specific orientation θ is the adoption of a fan filter with a center angle $\phi_c = \theta + 90°$ (Fig. 3(b)). The general desired response of a fan filter for this purpose is shown in Fig. 4. The transition bands of the filter are also kept to a fan-shape in an attempting to get a similar selectivity for each spatial frequency [10]. In this study, a discrete least square (LS) strategy is adopted as a 2-D filter design methods [11], because of its simplicity. To implement it, the following problem is solved:

$$\min \sum_{m_1,m_2} |H(e^{j2\pi f_1}, e^{j2\pi f_1}) - H_d(e^{j2\pi f_1}, e^{j2\pi f_1})|^2 \qquad (3)$$
$$f_1 = m_1/M, f_2 = m_2/M, \;\; m_1, m_2 \in \{0, 1, \cdots, M-1\}$$

where H and H_d are the designed and desired amplitude responses of the fan filter. This is carried out by the simple inverse discrete Fourier transform.

Results of proposed image processing. 1-D plots in the right of the images show cross section amplitude characteristics along the solid lines A–B in the 2-D images.

4. Examples and discussion

In this section, we investigate the effectiveness of the proposed method through sample images taken from a copper plate.

The ECT images are in fact derived from one sample shown in Fig. 5 by setting various scanning directions. Consequently, features other than the angle of the defect are kept almost the same in all images. Defect directions of 45°, 60°, and 90°, are used with the objective of identifying a defect with a direction of 45°. Hence the fan filter used here is designed with center angle $\phi_c = 45°$ ($\phi_{s1} = 38°, \phi_{p1} = 42°, \phi_{p2} = 48°, \phi_{s2} = 52°$). The derived amplitude response of a 10×10 fan filter is shown in Fig. 6(b).

The results of the proposed method applied to ECT images with different defect orientations are shown in Fig. 7. The signals of the defects in the undesired orientations ($\theta = 60°$, 90°) are considerably reduced after image processing. The amplitude of 45°-defect is also attenuated because of the degradation of the amplitude response of the fan filter due to its narrow transition band in the low frequency region, but still remains considerably larger than the other two examples, demonstrating the usefulness of the proposed method.

Since the signals are periodically extended for the filtering operation, leakage components are found in the corners of the images. However actual objects are assumed to be large enough so that we can ignore this effect.

The proposed method could also be used to eliminate undesired signals in ECT images. For example, steam generator tubes in general suffer from stress in certain directions, which results in cracks almost along a specific direction. If the spectrum of this direction is extracted, undesired components in other regions of the plane are suppressed. In addition, if the removal of the offset signal is required, the fan filter can be designed to implicitly attenuate the amplitude in the low frequency region (Note that its amplitude is reduced naturally).

5. Conclusions

In this paper, an ECT image processing approach which extracts the defects in a specific direction has been described. Based on the relation between the direction of a defect and its spectrum, fan filters are used to select the defects with the desired orientation. By using nonsperable 2-D filters, more precise discrimination of defects is achieved compared to the use of separable filters in which the shape of the pass band is restricted to a square. The effectiveness of the proposed method has been shown through an example, but it has been seen that it is affected by the degrading of the signal by the fan filter in low frequencies.

Future works in addition to the improvement of low frequency attenuation are applying the method to various types of defects with different features (length, width, depth). Moreover, we plan to apply the proposed method to the reduction of data points for the case when the two-pass scanning is needed in both the horizontal and vertical directions.

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