AN INVERSION PROCEDURE FOR SIZING SURFACE CRACKS IN METALS, USING AN OPEN-ENDED WAVEGUIDE PROBE

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1. Introduction

Fatigue and stress crack detection in metallic structures is of utmost importance to the in-service inspections of metallic components. Beside the crack detection, the prediction of the crack size leads to a better estimation of the useful life of the metal in service. Currently, there are several prominent nondestructive testing (NDT) techniques for detecting and sizing surface cracks in metals each of which possesses certain limitations and disadvantages, including the potential drop technique, the eddy current technique, and the surface magnetic field measurement technique.

In the last decade, a great deal of attention has been given to the microwave non-destructive testing (MNDT) of materials. Yeh and Zoughi have demonstrated the potential use of MNDT for detection and sizing of surface-breaking cracks in metals [1]. In their work, the metal surface is scanned by an open-ended waveguide while its standing-wave characteristics is monitored using a slotted guide and a diode detector. The crack detection and sizing in this technique is done by analyzing the detector signal at different crack positions beneath the open-ended waveguide aperture.

Recently, an efficient modeling has been presented to predict the output signal of the open-ended waveguide probe when scanning an arbitrary-shape crack in metal [2],[3]. This modeling uses a discretization algorithm and reduces the crack to a series of rectangular waveguides. Then, the Generalized Scattering Matrix technique is applied to analyze the system of the waveguides and calculate the detector signal.

The paper aims to study the output signal of an open-ended waveguide probe when scanning elliptical-shape cracks of various sizes. The results will explore the possibility of inverting the probe output signal into crack dimensions. The structure of the paper is organized as follows. First, the modeling of the probe-crack interaction is briefly described. Then, several simulation results are presented to study the trends of the output signal associated with elliptical-shape cracks with various depths and openings.

2. Theoretical modeling

An open-ended rectangular waveguide probe with dimensions $a \times b$ interrogated with an arbitrary-shape crack in metal is depicted in Fig. 1. The crack has an opening width of w and its length, l, extends along the broad dimension of the waveguide probe. The crack width is assumed to be uniform while its depth can vary arbitrarily. Also, the waveguide probe is assumed to be in contact with the metal surface, and its flange is so large that the incident wave does not leak out of the probe-crack structure.

Assuming that the crack opening mouth is rectangular, the crack is segmented into N rectangular waveguides such that the wall of the waveguide series follows the crack shape, Fig. 1. Including the waveguide probe, a system of N+1 consecutive rectangular waveguides is realized, Fig. 2. It is noted that the last waveguide in the system is short-circuited, representing the crack bottom.

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The waveguide system (Fig. 2) described above consists of several waveguide junctions, separated by appropriate number of uniform waveguide sections. To obtain the dominant mode reflection coefficient at the waveguide probe, the Generalized Scattering Matrix technique [4] is used. A detailed description of the solution technique can be found in [3].

3. Simulation results

Based on the theoretical modeling technique presented in the previous section, several tests have been carried out. For brevity, only the results of two cases are presented here. In all of the simulations, the probe dimensions are a = 10.67 mm and b = 4.32 mm, and the operating frequency is 24 GHz. Also, the detector is positioned inside the exciting waveguide at a distance of 9.45 cm far from the metal surface. The crack is assumed to have a semi-elliptical shape, approximating a real fatigue crack.

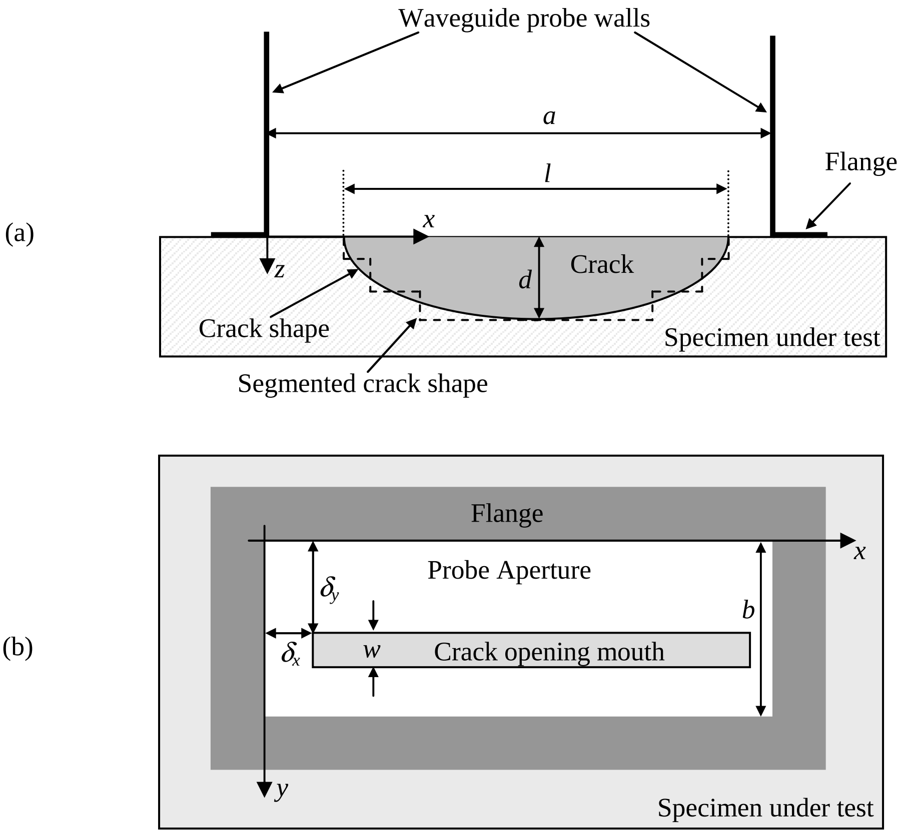


Fig. 1. Geometry of a surface crack and a waveguide probe: (a) side view; (b) plan view.

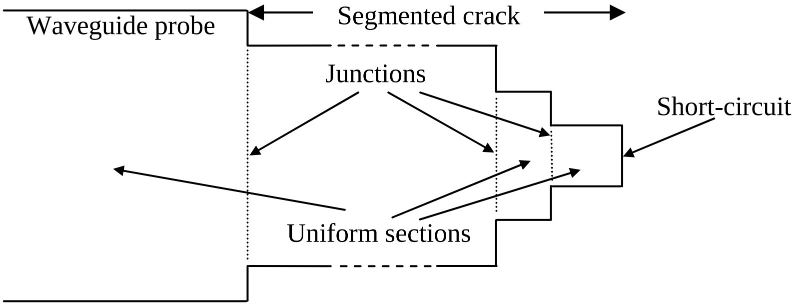


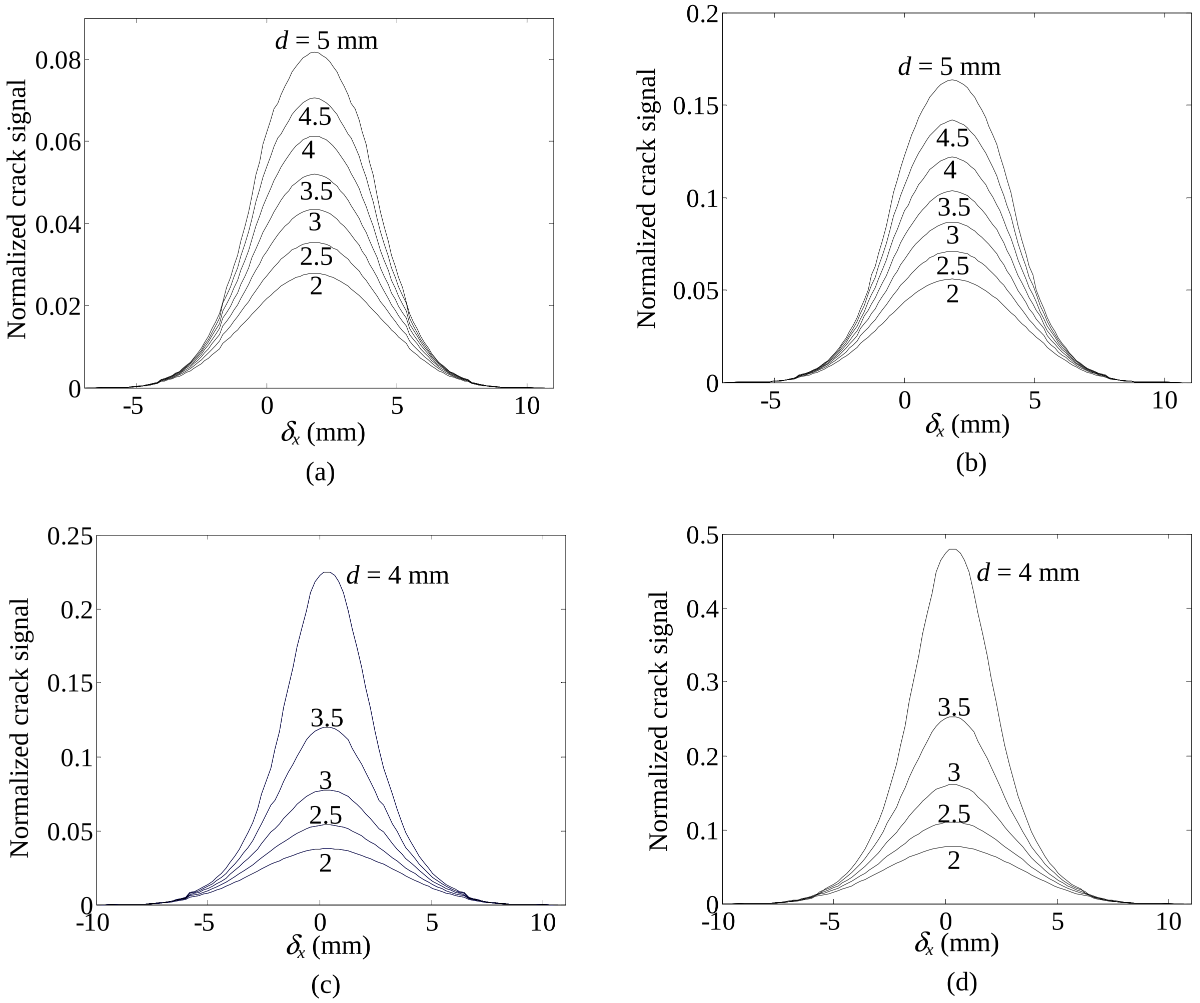
Fig. 2. Waveguide system representing the probe and the segmented crack.

In the first set of simulations, the probe scans the crack along its length (along the *x*-direction with respect to Fig.1) while the crack is at the middle of the small dimension of the probe, i.e. $\delta_y = (b - w)/2$. The normalized crack signals, V_{N}, versus δ_x are plotted in Fig.3 for different crack sizes. It is noted that the normalized crack signal is obtained by subtracting the probe output signal, V, from its value in the absence of a crack, V_0, and normalizing it to V_0, i.e.,

$$V_{\mathrm{N}} = \frac{V - V_0}{V_0} \tag{1}$$

As seen in Fig.3, the length of signal due to the crack equals $a + l$, and hence, the crack length can be easily estimated from the *x*-direction scan. Also, Fig.3 shows that the level of the signal at the middle increases as the depth and width of the crack increases.

In the next set of simulations, the variations of the detector signal is calculated for the case which the crack lies in the center of the probe aperture, i.e., $\delta_x = (a - l)/2$ and $\delta_y = (b - w)/2$. The normalized crack signals versus the crack width are plotted in Fig. 4 for two different crack lengths. This figure shows that when the crack is in the center of the probe aperture, the crack signal varies linearly with respect to the crack width variations. This linearity has already been confirmed through experimental results [5]. Fig. 4 also reveals that the slope of the variations is dependent to the width and length of the crack.



(a) (b) (c) (d)

Fig.3. Normalized crack signal versus δ_x: (a) l = 7 mm and w = 0.1 mm; (b) l = 7 mm and w = 0.2 mm; (c) l = 10 mm and w = 0.1 mm; (d) l = 10 mm and w = 0.2 mm.

The proposed inversion procedure establishes a 2-dimensional scan of the crack from which the crack length can be easily estimated. Then with *a priori* information of the crack width, the depth of the crack is estimated using the inversion curves which can be calculated for the approximated length and width of the crack. For instance, two inversion curves for l = 7 mm and the crack widths of w = 50 μm and w = 75 μm are depicted in Fig. 5.

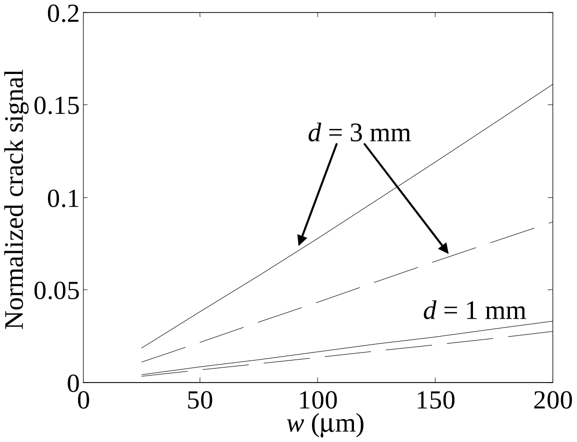


Fig.4. Variations of normalized crack signal versus w for various values of d; l = 10 mm (solid lines) and l = 7 mm (dashed lines)

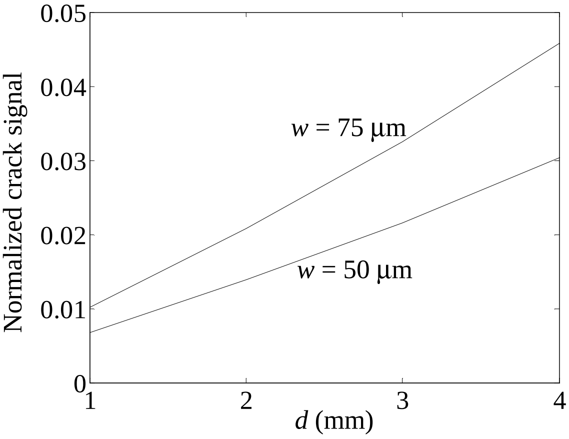


Fig.5. Variations of normalized crack signal versus d for various values of w; $\delta_x = (a-l)/2$, $\delta_y = (b-w)/2$ and l = 7 mm.

4. Conclusion

Output signals of an open-ended waveguide probe in response to elliptical surface crack of various dimensions have been studied. It has been shown that the crack length can be easily determined from the results of a one-dimensional scan along the crack edge. It has also been shown that the magnitude of the signal at the crack center increases as its depth or width increases. In fact, the crack signal can be inverted to the crack depth provided that its width is known as *a priori* information

Acknowledgement

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