Analysis and Sizing of Fatigue Cracks in Metallic Structures from Eddy Current Probe Signals

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Abstract
Detection and sizing of fatigue cracks in metal structures surfaces are of the most important applications of non-destructive testing. One of non-destructive methods for this purpose, is eddy current. In this technique, an eddy current is created on the surface of the workpiece, using an alternating current (AC) conductor coil. The presence of cracks leads to disruption of distribution of this current to collapse and thus the variation in the impedance of the coil. Detection and sizing the cracks from impedance variations of the coil, which is called a reverse problem, is important to estimate the life of the workpiece and its optimal use. In this paper, a phenomenon-based inverse model and an inverse algorithm based on the particle swarm optimization are proposed to detect the shape and depth of the cracks from impedance variations of the coil. The results obtained from the estimation of the shape of the cracks from the sizing data indicate that the proposed model is highly accurate in determining the shape and depth of the cracks.

Keywords: non-destructive testing, eddy current, particle swarm optimization, inversion.

1. Introduction
Metal surfaces are always exposed to cracks due to corrosion and fatigue. Since the amount of stress on the surface of metals is usually greater than within them, the cracks often occur on the surface of the metals and expand inside them [1].

It is important to detect and prevent the growth of these cracks in the early stages of their creation. Non-destructive testing techniques can be used for this purpose. These techniques evaluate workpiece without causing any damage to its physical and chemical structure. Different techniques have been presented for non-destructive testing, each of which has its own applications, disadvantages and advantages [2].

One of the important techniques of non-destructive testing for investigation and evaluation of metal structure surfaces is eddy current technique [4,3], which is widely used in the industry, due to the simplicity of its test system, low cost and safety. In this method, the metal under investigation is placed adjacent to an alternating current conductor coil, and eddy currents are induced in the metal body, based on Faraday and Ohm's law.

Induced currents variation their path in dealing with the cracks in workpiece, in comparison with the absence of the cracks, which in turn causes variations in the distribution of the magnetic field around the workpiece and hence the variation in the impedance of the coil. The location and dimensions of the cracks can be determined by sizing the variations in the impedance of the coil.

The determination of the shape and size of cracks from probe signals (variations in impedance of the coil) is called a reverse problem and its solution is of particular importance. The inverse problem solving is not usually possible in the closed form, and typically, for reversing, two types of phenomenon identification-based and non-phenomenon identification-based techniques are used for inversion.

Non-phenomenon identification based techniques are those that work using signal processing techniques. Two common methods in these techniques are the use of inverse curves and neural networks.

In the use of inverse curves, for the different cracks, the sensor output signals are generated initially by sizing or simulation. Then a characteristic of these signals, such as the signal peak, is plotted on a curve in terms of the quantitative scientific characteristic of the crack such as its depth. Developing inverse curves is possible only for special shapes and parameters (such as the depth of cracks in long cracks [5]), while the cracks do not have a particular shape in practice. So this method is useless in most cases. On the other hand, in the neural network based methods, the sensor output signal is entered into the neural network and the network, based on the training, maps this signal in the shape of a crack [6,8]. Neural network based inverse methods are fast and easy to use, but their generalization to all shapes of the crack is often unfeasible.

In phenomenon identification-based techniques, which are referred to as iterative direct problem solving algorithms, iteration of a direct problem solving is used to find the shape of the crack. The direct problem refers to a situation in which the shape and dimensions of the crack and coil are determined and the impedance of the coil (probe signal) is unknown.
In iterative direct problem solving techniques, at first one or several basic shapes are initially considered for the crack and then, the sensor output signal is simulated for this crack using the direct problem solving. By defining an error quantity, the error between the simulation signal and the probe signal is calculated based on the error, and using an optimization algorithm, the crack shape is variation in such a way that the error rate is reduced in the next step. The crack shape variation and calculating the error is repeated so that the error reaches its lowest value and the crack shape is obtained [9,10]. In spite of the fact that this method is slower than using inverse curves and neural network, different types of crack shapes can be estimated with a proper accuracy, using this technique.

In present study, a phenomenon identification-based inverse model and a particle swarm optimization algorithm are presented in an eddy current technique that can accurately estimate the shape of the cracks on metals surface from the impedance variations of the induction coil.

Figure 1. Schematic representation of eddy current technique in the investigation of a workpiece B- the crack cross section in the xoz plan.

2. Theory and Simulation of inductor response in the eddy current method

Fig. 1 shows the schematic representation of the eddy current method in the investigation of a flat metal workpiece. According to this figure, a crack of length 1 and arbitrary shape is assumed to be at the surface of the workpiece. The crack opening is very tiny and the distance between the surfaces is a thin layer of air and there is a thin layer of air in the distance between its surfaces. The x axis corresponds to the edge of the crack and the y axis is perpendicular to it. In eddy current is created at the surface of the workpiece, using an alternating current conductor coil. One can ignore the frequency of the current passing outside the metal. For the direct problem, the characteristics of coil and crack are known, and coil impedance variations are unknown. To solve this problem, the method presented in [11] is used. In this method, the following EFIE equation is assumed for the crack area:

\[ E_i(r) = (r) - \int_{S_{crack}} \sigma E_n(r')G(r,r') ds(r') \]  

(1)

where, \( E \) is the total electric field, the Radiant electric field (the field at the crack location and in the absence of it), \( \sigma \) is the metal conductivity and \( G \) is the Green's function of the problem. By solving this equation and determining the electric field in the crack area (\( E \)), the impedance variations of the coil are obtained from the following equation:

\[ \Delta z = -\frac{\sigma}{i\omega \varepsilon_0} \int_{S_{m}} E_i(r)E(r)ds(r) \]  

(2)

As is shown in equations (1) and (2), the variations in the impedance of the coil are a function of the crack shape as well as the shape of the inductor coil and the electrical profile of the workpiece.

Figure 2. iterative direct problem solving based inverse model and particle swarm optimization algorithm
Table 1. Inductor profile, workpiece and crack in two eddy current testing [11].

<table>
<thead>
<tr>
<th>Expt.1</th>
<th>Expt.2</th>
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<tbody>
<tr>
<td><strong>Coil parameters</strong></td>
<td><strong>Coil parameters</strong></td>
</tr>
<tr>
<td>Inner radius</td>
<td>6.15±0.05 mm</td>
</tr>
<tr>
<td>Outer radius</td>
<td>12.4±0.05 mm</td>
</tr>
<tr>
<td>Length</td>
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<tr>
<td>Lift-off</td>
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<td>Number of turns</td>
<td>3790</td>
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<tr>
<td>Frequency</td>
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<tr>
<td><strong>Conductor</strong></td>
<td><strong>Conductor</strong></td>
</tr>
<tr>
<td>Conductivity</td>
<td>30.6±0.02 MS/m</td>
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<tr>
<td>thickness</td>
<td>12.2±0.02 mm</td>
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<tr>
<td><strong>Flaw</strong></td>
<td><strong>Flaw</strong></td>
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<tr>
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<tr>
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</tr>
<tr>
<td>Depth</td>
<td>5.0±0.05 mm</td>
</tr>
<tr>
<td>Opening</td>
<td>0.28±0.01 mm</td>
</tr>
</tbody>
</table>

**Inverse model**

Simulation of inductor coil impedance variations for various crack shapes was presented in the previous section. But in practical applications, the important thing is to determine the shape of the crack from the variations in impedance (probe signal). Accordingly, in this section, an inverse model is presented, so that detects the shape of the crack by receiving the sized impedance variations.

Figure 2 illustrates the block diagram of the proposed model. In this method, which is based on iterative direct problem solving and particle swarm optimization algorithm [13-12], first, number M basic crack shapes are assumed, and the coil impedance is simulated for them, by the direct problem solving for each. Then the simulation data is compared with the sizing values and the error is obtained for each shape. If the error for a shape is less than the specified error, that shape is selected as the cracks profile. Otherwise, the crack shapes will be optimized and the process be repeated until a satisfactory result is obtained. In the above inverse process, the shape of each crack is considered as a vector $D = \{d_1, d_2, \ldots, d_{n-1}, d_n\}$, in which $d_k$ represents the depth of the crack in the length $X_k = \frac{(k-1)}{n-1}$ of the crack. The optimization of the cracks shape is done using particle swarm optimization algorithm, and the basis of the work is that, at each stage, each shape sets its cracks in the search space according to the best mode ever it has been in and the best mode in its entire adjacency.

To optimize the shape of the i-th crack in the step (n + 1), the corresponding equations are as follows:

$$V_{n+1} = wV_n + c_1r_1(p_{best,n} - D_n) + c_2r_2(g_{best} - D_n)$$

$$D_n + 1 = D_n + V_{n+1} \quad (3)$$

Where the vectors $D = (d_{i1}, d_{i2}, \ldots, d_{in})$ and $V = (vi1, vi2, \ldots, vin)$ are respectively the shape and rate of the i-th crack convergence. Also, $p_{best}$ and $g_{best}$ are the best solution for the i-th crack and the best solution among all the cracks, respectively.

The parameter $w$ is an inertia weight, which is usually chosen in the range [0,1], and $c_1$ and $c_2$ are acceleration constants, which are usually chosen 2 [13].
3. Sizing the model using sizing data

The sizing data are used to evaluate the inverse model provided. Sizing is performed for two different modes. Table 7 shows the profile of the inductor coil, the testing workpiece, and the crack for two modes. In each test, the coil moves along its opening and its impedance variations are sized. Figure 3 shows the results of sizing the impedance variations for the first test in the form of amplitude and phase. The sizing results for the second test are as follows: coil inductance and resistance variations in Fig. 4, which can be converted to the amplitude form and the impedance phase.

To evaluate the accuracy of the inverse model, the sizing data of each test is entered into the model as amplitude and phase. To estimate the crack shape, its profile is considered as a 9-element vector, representing the depth of the crack at 9 points of the crack length. 10 basic shapes are considered for the crack and the inversion is conducted. In Figs (5) and (6), the response of the inverse model with the actual shape of the crack is shown for each of the cracks. To determine the network error rate, the error parameter $E_t$ is defined as follows:

$$
E_t = \frac{1}{8} \sum_{k=1}^{8} \left(1 - \frac{f(k+1) + f(k)}{d(k+1) + d(k)}\right)
$$

(5)

Where $d(k)$ and $f(k)$ are the actual depth of the crack and the model response for the depth of the k-th element respectively. The general error in the estimation of the cracks in Figures (5) and (6) is 2.7 and 8.8 percent respectively, which indicates the high accuracy of the model in estimating the cracks shape.
Figure 5. The actual shape (-) and the inverse model response (...) for the first test.

Figure 6. The actual shape (-) and the inverse model response (...) for the second test.

Conclusion
In this study, a reverse model was introduced in the eddy current method to detect the cracks shape caused by fatigue at metal workpieces surfaces. The proposed model is based on phenomenon identification, in which the iterative direct problem solving and particle swarm optimization algorithm are used. The results obtained from applying the probe signals to the proposed model showed that the model is able to accurately detect the shape of the cracks. Although in this paper the results are presented for cracks in the non-magnetic metal surfaces, the proposed model can also be used for ferromagnetic metals, and the only difference is direct problem solving.

References