Defect searching in ferromagnetic materials

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Abstract

In the present paper, theoretical and experimental work concerning defect searching in ferromagnetic materials is carried out. Key idea of this searching method is as follows: When the DC magnetic field is applied to the ferromagnetic materials, their magnetization vectors are aligned in a direction of the applied DC field. However, if there is a defect in the material, then alignment of magnetization vectors is distorted at the defect position. This disturbed magnetization vectors are detected by the moving search coils. Thus, it is possible to detect the defect in ferromagnetic materials in a quite simple manner.

1. INTRODUCTION

Defect searching in the ferromagnetic materials is of paramount importance because most of the structural materials in various artificial objects, e.g. car, train, escalator and elevator, are composed of iron or its compounds, i.e. ferromagnetic materials. Sometimes, the defect of structural materials leads to the serious accidents. In order to protect such tragic accidents, it is essentially required to exploit a reliable defect inspection device for the ferromagnetic materials. Therefore, various nondestructive testing methods, e.g. eddy current testing, electric potential method, ultrasonic wave imaging, and X-ray tomography, are currently used [1-3]. Even if any of these existing methods are applied to the defect searching in ferromagnetic materials, it is difficult to expect the reliable results because of their own magnetization vectors. In the present paper, the theoretical and experimental works concerning with the defect searching in ferromagnetic materials are carried out. Key idea of this searching method is as follows: When the DC magnetic field is applied to the ferromagnetic materials, their magnetization vectors are aligned in a direction of the applied DC field. However, if there is a defect in the material, then alignment of magnetization vectors is distorted at the defect position. This disturbed magnetization vectors are detected by the moving search coils. Thus, it is possible to detect the defect in ferromagnetic materials in a quite simple manner [4]. Based on the principle described above, a defect inspection device for the wire ropes suspending the elevator cages has been successfully realized and practically used for the daily maintenance work. This paper describes the optimal design and usefulness of our new device.

2. THEORETICAL BACKGROUND

As is well known, ferromagnetic materials are composed of magnetic domains. This leads to a following constitutive relationship:

\[ H = M + M_0 \]  \hspace{1cm} (1)

where \( H \), \( M \) and \( M_0 \) are the magnetic flux density, magnetic field intensity, ...
magnetization vector and permeability of air, respectively. Because of the existence of magnetic domains, alternating eddy currents flow between the domain walls when alternating magnetic field is applied to the ferromagnetic materials. Thereby, it is difficult to apply conventional eddy current testing (ECT) method to the ferromagnetic materials, because the input impedance of the ECT device is dominated by the domain structure of the materials. In order to overcome this difficulty, two representative methods may be considered. One is the DC magnetic field superposition in addition to the alternating magnetic fields in order to saturate the material, i.e., reducing into nonmagnetic material property \[1\]. The other is the DC magnetic field application to the materials in order to align the magnetization vector in a direction of the applied AC field. If there is a defect in the material, then the magnetization vector will not align at the defect position. This magnetic field distortion can be picked up by moving the search coils in a parallel direction to the applied AC magnetic field. When we introduce the permeability \( \mu \) into \(1\), it is modified to:

\[
\mathbf{H} = \mu_0 \mathbf{H} - \mathbf{M}(\mathbf{H} + \mathbf{M}(\mathbf{H})) = \mu_0 \mathbf{H} - \mathbf{M}(\mathbf{H})
\]

where the permeability \( \mu \) is defined by

\[
\mu = \mu_0 + \chi(\mathbf{H})
\]

Mathematically, the former method is based on the following fact:

\[
\text{lim}_{\mathbf{H} \to 0} (\chi(\mathbf{H}) - \text{lim}_{\mathbf{H} \to 0} \chi(\mathbf{H})) = \chi_0.
\]

Equation (1) means that the strong magnetic field application makes the ferromagnetic material property possible to reduce magnetic property. Thus, the ECT sensitivity can be enhanced. In the latter case, latter one has to measure the permeability discontinuity due to the defect. As shown in Fig.1, when a search coil moves from left to right sides, obviously a voltage is induced by the magnetic field distortion at the defect position. This magnetic field distortion may be regarded by the permeability difference at the defect position.

![Diagram](image)

**Figure 1. Principle of the DC magnetic field method.**

Then, this latter method is based on the quite simple principle even though the target is limited to the objects having flat surfaces. Further, taking the difference of induced voltages in the two aligned search coils along the target surface enhances the sensitivity of this DC magnetic field method. In order to satisfy the following condition:

\[
\mathbf{E}_L = 0,
\]

we introduce a vector potential \( \mathbf{A} \) defined by

\[
\mathbf{H} = \nabla \times \mathbf{A}.
\]

Combining (2), (6) with Maxwell's equation:

\[
\nabla \times \mathbf{E}_L = -\frac{\partial \mathbf{B}}{\partial t}.
\]
it is possible to obtain the following governing equation:

\( \nabla \times (J/\mu_0) = 0 \)

(8)

where \( J \) denotes a current density. The details of magnetic field distortion at the defect in Fig. 1 can be obtained by solving (8).

3. DETECT INSPECTION DEVICE FOR WIRE ROPE

3.1. Wire rope tester

We have exploited a defect inspection device for the wire rope suspending the elevator cage, because we have an urgent need of wire rope testing particularly used for the modern high speed elevators. Figure 2 shows a schematic diagram of the device. The left and right electromagnets make the magnetization vectors in the wire rope align along the rope. The two heads are located at the center to picking up the difference between the induced voltage, and the distance between these heads coincided with the strand pitch of wire.

![Diagram of a wire rope tester](image)

Figure 5. Schematic diagram of a wire rope tester. (W denotes the width of magnetic pole)

3.2. Experimental

We have carried out the experiments changing the width of magnetic poles. One has W-avg and the other has W-blk width of magnetic poles. The diameter of wire rope used in the both experiments is 1.6cm. The moving velocity of the wire was set to 30cm/s. Moreover, the wire rope has six defects located at different positions. The experimental results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Width</th>
<th>Defect 1</th>
<th>Defect 2</th>
<th>Defect 3</th>
<th>Defect 4</th>
<th>Defect 5</th>
<th>Defect 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-avg</td>
<td>13.0</td>
<td>6.8</td>
<td>12.0</td>
<td>8.0</td>
<td>6.5</td>
<td>0.0</td>
</tr>
<tr>
<td>W-blk</td>
<td>19.0</td>
<td>8.0</td>
<td>13.0</td>
<td>8.5</td>
<td>6.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Figure 3 shows an experimental recorder output signals, where upper and lower signals are the direct induced voltage difference and filtered output, respectively. Consideration of the results in Table 1 and Fig. 3 obviously shows that the tester equipping the wider magnetic pole has high sensitivity. This is because the wider magnetic pole provides the uniform magnetic field distribution in the wire rope cross section. This fact was confirmed by obtaining the MM solutions of (8). Figure 4 shows an example of magnetic
field distribution in the wire rope.

Figure 3. An experimental recorder output signals. The upper and lower signal are the direct induced voltage difference and filter's output, respectively.

Figure 4. Computed magnetic field distribution in wire rope. Two dimensional model and relative permittivity of wire rope was assumed to 100.

4. CONCLUSION

As shown above, we have succeeded in realizing one of the defect searching devices for the ferromagnetic materials. The exploited wire rope tester is practically used for the daily maintenance work of the elevator. Furthermore, it has been revealed that the optimum width of magnetic pole exists depending on the diameter of wire rope. According to our research, at least, the magnetic pole having the width $w = 6 - 7x$ (wire rope diameter) is required to get the reliable results.

5. REFERENCES