Simulation and Design of Applied Electromagnetic Systems
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Defect searching in ferromagnetic materials

Y.Oohira[a], Y.Hirama[a], S.Hayano[b] and Y.Saito[b]

[a]R & D Hitachi Building Systems Engineering and Service,
16-23 Nakagawa, Adachi-ku, Tokyo 120, Japan
[b]Coll. of Engng., Hosei Univ., Koganei, Tokyo 184, Japan

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 distorted 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. Thereby, 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 distorted 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 optimum 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:

$$B = \mu_0 H + \mathbf{M}, \qquad (1)$$

where B, H, **M** and μ_0 are the magnetic flux density, magnetic field intensity, magnetization vector and permeability of air, respectively. Because of existence of magnetic domains, anomalous 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 DC field, if there is a defect in the material, then the magnetization vector could 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 DC magnetic field. When we introduce the permeabilty μ into (1), (1) is modified to

$$B = \mu_0\{1+[M/(\mu_0 H)]\}H = \mu H, \tag{2}$$

where the permeability μ is defined by

$$\mu = \mu_0\{1+[M/(\mu_0 H)]\}. \tag{3}$$

Mathematically, former method is based on the following fact:

$$\lim_{H\to\infty} \langle\mu\rangle = \lim_{H\to\infty} \langle\mu_0\{1+[M/(\mu_0 H)]\}\rangle = \mu_0. \tag{4}$$

Equation (4) means that the strong magnetic field application makes the ferromagnetic material property possible to reduce nonmagnetic property. Thus, the ECT sensibility can be enhanced. On the other side, 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.

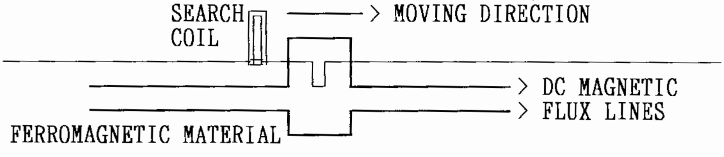

Figure 1. Principle of the DC magnetic field method.

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

$$\nabla\cdot B = 0, \tag{5}$$

we introduce a vector potential A defined by

$$\nabla\times A = B. \tag{6}$$

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

$$\nabla\times H = J, \tag{7}$$

it is possible to obtain a following governing equation:

$$\nabla\times(1/\mu)\nabla\times A = J, \qquad (8)$$

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. DEFECT INSPECTION DEVICE FOR WIRE ROPES

3.1. Wire rope tester

We have exploited a defect inspection device for the wire ropes 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 makes 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 voltages, and the distance between these heads coincides with the strand pitch of wire.

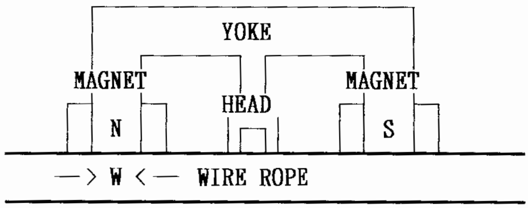

Figure 2. Schematic diagram of a wire rope tester.
(W denotes the width of magnetic pole)

3.2. Experimental

We have carried out the experiments changing the width of magnetic poles. One has W=4cm and the other has W=8cm width of magnetic poles. The diameter of wire rope used in the both experiments is 1.2cm. The moving velocity of the wire was set to 30m/s. Moreover, the wire rope has six defects located at the different positions. The experimental results are summarized in Table 1.

Table 1 : Experimental results of the exploited wire rope testers.

	OUTPUT PEAK VOLTAGE [mV]					
WIDTH	DEFECT 1	DEFECT 2	DEFECT 3	DEFECT 4	DEFECT 5	DEFECT 6
W=4cm	15.5	6.5	12.0	8.0	6.5	0.0
W=8cm	19.0	9.0	13.0	8.5	6.0	5.0

Figure 3 shows an experimental recorder output signals, where upper and lower signals are the direct induced voltage difference and filtered outputs, respectively. Consideration of the results in Table 1 and Fig. 3 obviously shows that the tester equipping the wider magnetic pole has high sensibility. 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 FEM solutions of (8). Figure 4 shows an example of magnetic field distribution in the wire rope.

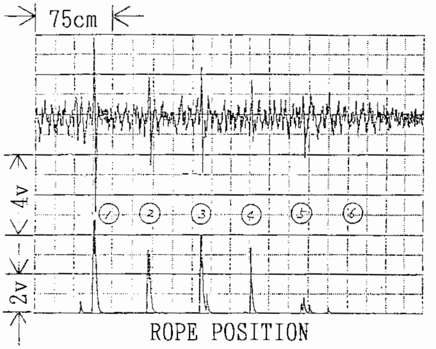

Figure 3. An experimental recorder output signals. The upper and lower signal are the direct induced voltage difference and filtered outputs, respectively.

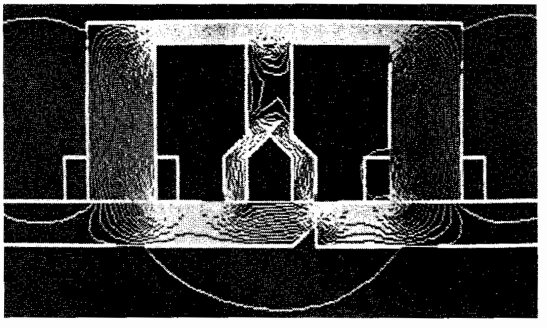

Figure 4. Computed magnetic field distribution in wire rope. Two dimensional model and relative permeability of wire rope was assumed to 100.

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 = 6～7×(wire rope diameter) is required to get the reliable results.

5. REFERENCES

1 Y.Hirama et al, The method for Eddy Current Sensor added to Magnetic Bias, Paper on Technical Meeting of Magnetics in IEEJ, MAG-92-73, Feb.(1992) pp.143-148.

2 T.Doi et al, Inverse Analysis of Defect Identification based on the Electric Potential Method, Proc. of 2nd Japan-Hungary Joint Seminar, Published by Hokkaido University, (1992).

3 H.Saotome et al, Crack Identification in Metallic Materials, IEEE Trans. Magn. to be published.

4 W.Lord et al, The generated reaction field method of detecting defects in steel bars, J. of Mater Evaluation, 29(2),(1971) pp.21-27.