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Optimum Design of the Non-Destructive Testing System to Maximize the Magnetic Flux Leakages

G.S. Park[1], P.W. Jang[2] and Y.W. Rho[3]

[1]Dept. Electrical Engineering, Korea Maritime Univ., Pusan 606-791, Korea
[2]Dept. Physics, Chongju Univ., Chungbook 360-764, Korea
[3]KOGAS R&D Center, Ildong 638-1, Ansan city, Kyunggi-do, Korea

Abstract

This paper describes the design method of the magnetic system to maximize the magnetic flux leakage (MFL) in non-destructive testing (NDT) system. The defect signals in MFL type NDT system mainly depends on the change of the magnetic leakage flux in the region of defect. The characteristics of the B-H curves are analyzed and the design method to define the operating point in B-H curves for the maximum leakage is performed. The computed MFL signal by nonlinear finite element method is verified by measurement using Hall sensors mounted on the 6 legs PIG in the 8 inches test tube with defects. The rhombic defects could be successfully composed from the defect signals.

1. Introduction

The magnetic flux leakage (MFL) type non-destructive testing (NDT) method is widely used to detect the corrosion and defect of the gas pipeline. In the system, the object pipeline is magnetically saturated by the magnetic system with permanent magnet and yokes. The Hall sensors detect the leakage fields in the region of the defect. So, the sensitivity of the sensor system depends on the operating point in the magnetic saturation curves of the object and the distribution of the magnetic field on the Hall sensor.

To increase the ability of the sensing system, it is necessary to increase the change of the magnetic leakage flux in the region of defect. In this paper, the optimal design method of the magnetic system with permanent magnet and yokes are described. In case the operating point in the magnetic saturation curves of the object is too small, the object will not be saturated in the defect region, so the defect signals are decreased. In case it is too big, the change of the magnetic flux in the defect region will be small, so the sensitivity of the sensor signal is decreased. The operating point of the magnetic system is optimized so as to maximize the change of the magnetic flux in the region of the defect signals. The computed MFL signal by nonlinear finite element method is verified by measurements. For the measurement, we made 8 inches diameter gas pipe with several types of artificial defects and MFL PIG with 6 legs. In each leg, magnetizing yoke and magnet were equipped with 3 sets of Hall sensors to detect the MFL signals. The rhombic defects could be successfully composed from the defect signals.

2. Optimal Operating Points in Saturation Curves

Fig. 1 shows the conventional cross section of the gas pipeline with defect. In the figure, Φ_a is the magnetic leakage flux under the region without defect and Φ_c is the magnetic leakage flux under the region with defect. The Hall sensor measures the leakage flux Φ_c so as to detect the defects. Not only the magnitude of Φ_c but the ratio Φ_c/Φ_a defines the sensitivity of the sensor system. Fig. 2 shows the magnetic saturation curves of the object. In the region with defect, the magnetic field is increased a little because of the defect depth during the measurements. The ratio Φ_c/Φ_a is defined with respect to the operating point in the saturation curves because of the non-linearity of the magnetic systems. In Fig. 2, B_q-B_p is proportional to the leakage flux. So, we can define the leakage parameter λ that is proportional to Φ_c/Φ_a.

$$\lambda = \frac{B_{q2} - B_{p2}}{B_{q1} - B_{p1}} \tag{1}$$

In Fig 3, there are three cases of the λ. In case the operating point is too small as in Fig. 3(a), the magnitude of Φ_c is small and so does λ. In case it is too big as in Fig. 3(c), the magnitude of Φ_c is big. But the change of leakage flux Φ_c/Φ_a is small and so does λ. The optimum case is in Fig. 3(b). In this case, the operating point of the object is about to being saturated and the small defect will saturate the object so that the λ value is big. So, the design of the magnetic system with permanent magnet and the yoke could be optimized to set the operating point in the region with high λ.

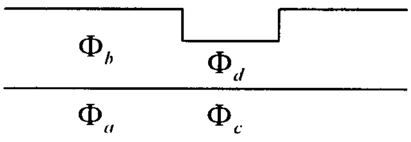


Fig. 1 The gas pipeline with defect.

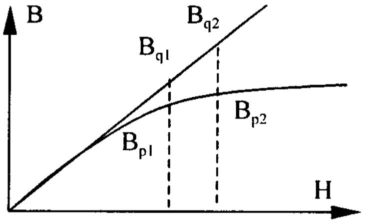
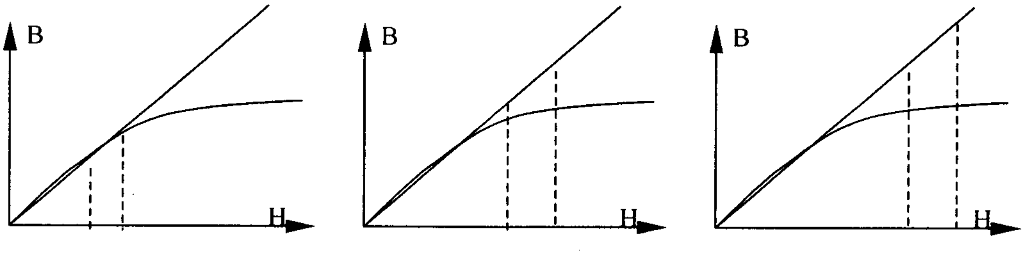


Fig. 2 The magnetic saturation curves.



(a) Case I (b) Case II (c) Case III

Fig. 3 Three cases of the operating point and λ.

3. Finite Element Analysis

In MFL type NDT, the Hall sensor detects the leakage field around the defect in the testing object. The field source is mainly the magnet assembled in the PIG. So it is highly nonlinear system with permanent magnet. In this case, we cannot use $B = \mu H$ relation anymore. The Maxwell equation in this nonlinear permanent magnet system would be as follows.

$$\nabla \times H = J \tag{2}$$

$$B = \mu_0 (H + M) \tag{3}$$

$$B = \nabla \times A \tag{4}$$

So, the system equation is as follows,

$$H = vB - v_r M \tag{5}$$

$$\nabla \times (v \nabla \times A) = J + v_r \nabla \times M \tag{6}$$

$$-(\nabla \cdot v \nabla) A = J + v_r \nabla \times M \tag{7}$$

In this equation, susceptibility is not a constant so that (7) need to be solved iteratively. In case the testing object with defect is under saturated, the magnitude of the magnetic leakage field will be small. In case the object is over saturated, the change of the magnetic field around the defect will be small. So the sensitivity of the NDT depends on the operating point in the saturation curve of the testing object.

Fig. 4 shows typical flux distribution of the MFL type NDT in PIG. If we want to detect the depth α defect sensitively, the magnet size should be designed so as the operating point of the B-H curve to be *p Bs* where *Bs* is the saturation point of the magnet and p is the saturation factor. In the figure, the length of the magnet *lm* is as in (8),

$$l_m = \frac{B_t}{p \cdot B_s} \cdot \frac{t}{1 - \alpha/t} \tag{8}$$

where *t* is the thickness of the pipe, α the depth of defect or corrosion, *Bt* the target magnetizing flux density at the pipe.

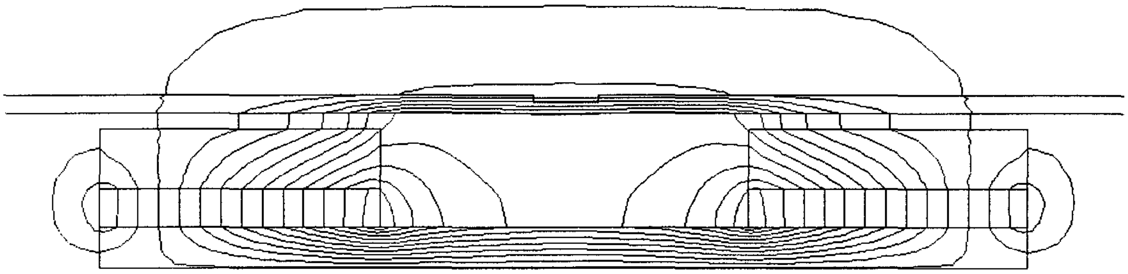


Fig. 4. Magnetic flux Leakage computed by finite element analysis.

4. Sensing Signals

For the measurement, we made 8 inches diameter gas pipe with several types of artificial defects and MFL PIG with 6 legs. In each leg, magnetizing yoke and magnet were equipped with 3 sets of Hall sensors. Fig. 5 shows the radial component of magnetic field. The thickness t of the pipe is 5.8 mm, the depth of the defect is 0.3t and the length is t. The magnitude and width of the calculated signals are bigger than measured as expected. As the depth of the defect increasing, the magnitude of the sensing signal is also increasing as in Fig. 6. In this figure, the axial component Bz and the radial component Br of the magnetic flux density are displayed in case of the defect depth 0.1t, 0.3t and 0.9t, respectively. The computed magnitude of the MFL signals with respect to defect depths is compared with measurements in Fig. 7.

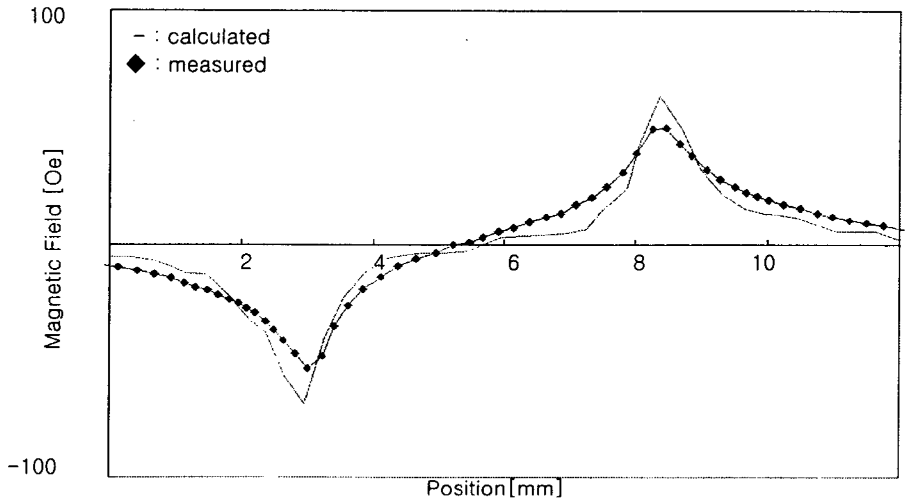


Fig. 5. Measured and calculated MFL signals. The depth of the defect is 0.3t and the length is 1.0t, respectively. (pipe thickness t=5.8mm)

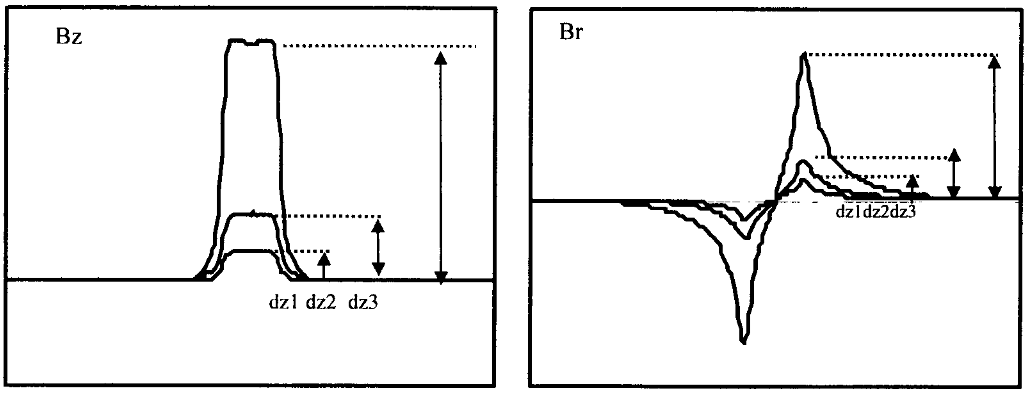


Fig. 6. Sensing signals with respect to the defect depth. (dz1 : 0.1t, dz2 : 0.3t, dz3 : 0.9t) The width of the defect remains constant.

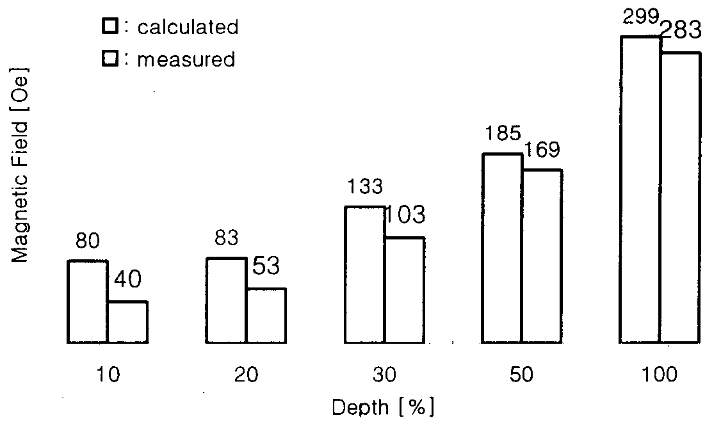
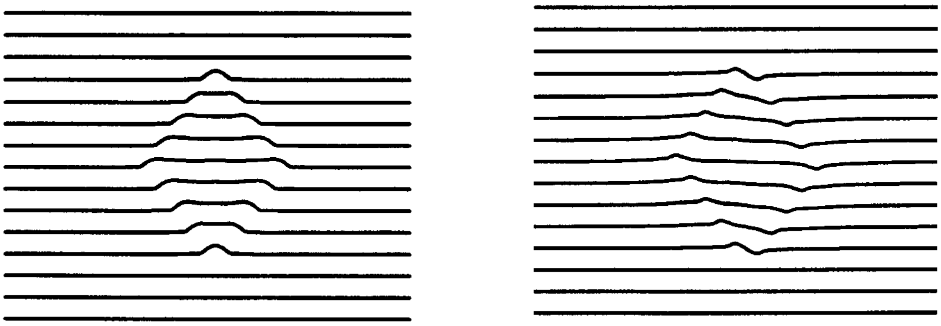


Fig. 7. The magnitude of the MFL signals with respect to defect depths

5. Composed Images of the defects

If we measure the defect signals with several sets of the sensor, the defect image can be composed. Fig. 8(a) shows the sensing signals with axial and radial components in the artificial hollowed rhombic defect. Based on the signals of Fig. 8(a), the image of the hollowed rhombic defect could be composed as in Fig. 8(b). Image compositions from the signals were performed with Matlab software. In case of the grooved rhombic defects, the signals and the composed images are in the Fig. 9. In the figures, the radial component of the magnetic field gives better image than axial components.



(a) Leakage flux of the axial (Bz) and radial (Br) components in hollowed rhombic defect

6. Conclusions

Because the MFL type NDT system is highly nonlinear magnetic system, the detecting signal depends on the operating point of the magnet. In this paper, the optimum design method of the magnetic system to maximize the MFL signals in NDT is described. Because the sensitivity of the MFL sensor mainly depends on the change of the leakage flux, the design method is optimized to define the operating point in B-H curves for the maximum leakage. The computed MFL signal by nonlinear finite element method is verified by measurement using Hall sensors mounted on the 6 legs PIG in the 8 inches test tube with defects. The rhombic defects could be successfully composed from the defect signals. It is shown that the radial component of the leakage flux gives more definite images than axial component.

References

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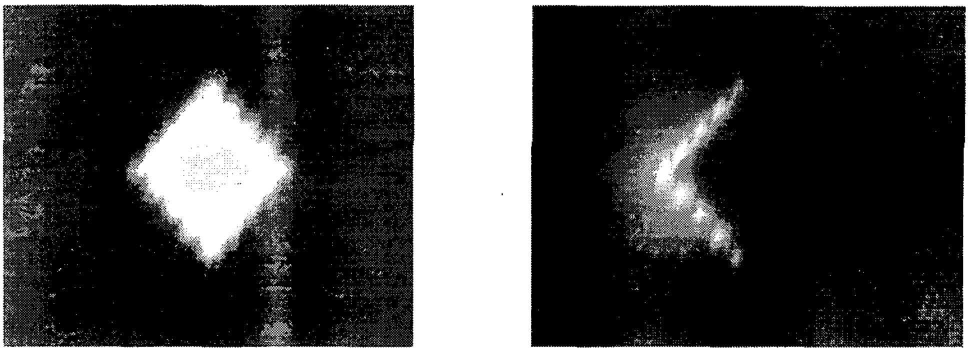
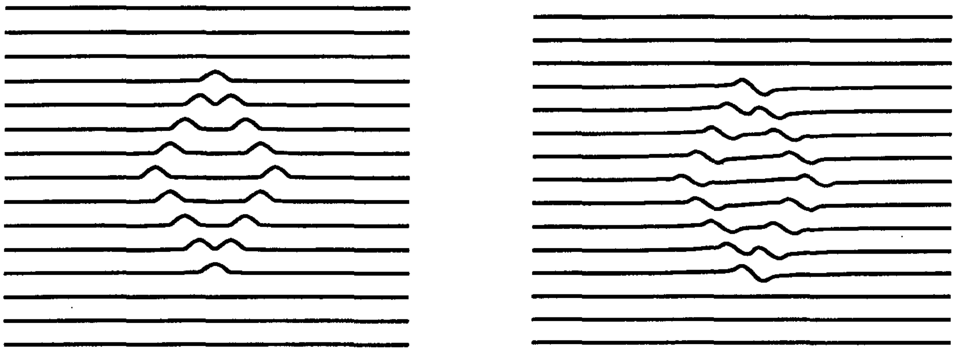
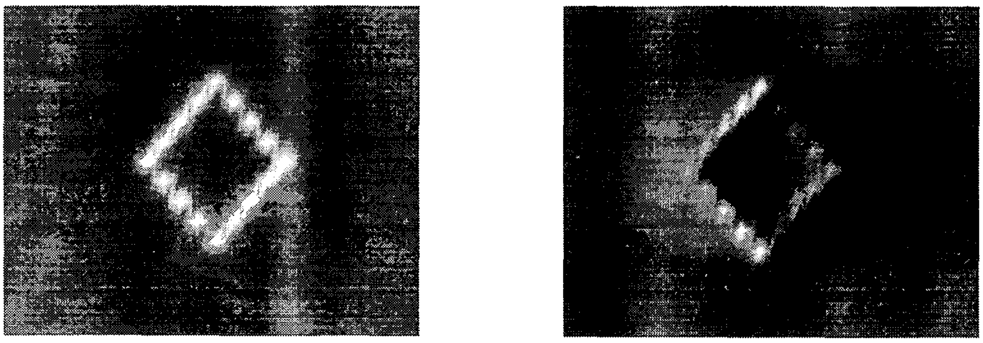


(b) Composed images of the signals in hollowed rhombic defect

Fig. 8. Detected MFL signals and composed images of the artificial hollowed rhombic defect.



(a) Leakage flux of the axial (Bz) and radial (Br) components in grooved rhombic defect



(b) Composed images of the signals in grooved rhombic defect

Fig. 9. Detected MFL signals and composed images of the artificial grooved rhombic defect.