Defect Estimation of a Crack in Underground Pipelines by CMFL Type NDT System

Hui Min Kim *, Hui Ryong Yoo **, Sung Ho Cho **
Dong Kyu Kim **, Sung Ja Koo **, Gwan Soo Park *

Abstract – A defect which is axially oriented with small size is hard to detect in conventional system. CMFL(Circumferential Magnetic Flux Leakage) type PIG(Pipelines Inspection Gauge) in the NDT(Nondestructive Testing), is operated to detect this defect called axially oriented cracks in the pipe. It is necessary to decompose the size and shapes of cracks for the maintenance of underground pipelines. This article is focused on the decomposing method of the size and shape of the axially oriented cracks by using inspection signal data for defect.
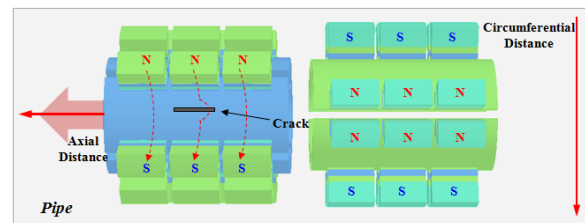
Keywords: Pipelines, Nondestructive testing, Circumferential magnetic flux leakage, Crack

1. Introduction

The MFL(Magnetic Flux Leakage) testing method is one of the most commonly used effective NDT(Nondestructive Testing) methods and has been applied for the highly efficient inspection of metal losses in various kinds of ferromagnetic materials such as underground pipelines [1]-[3].

The CMFL type nondestructive testing method is applied to detect axially oriented cracks of gas pipelines [4]. In CMFL type NDT system, the object is magnetically saturated by the magnetic system with permanent magnet and yokes. CMFL PIG generates circumferentially oriented magnetic fields that can maximize the leakage field in the vicinity of cracks on the pipe [5].

In this paper, the MFL type nondestructive testing system for detecting axially oriented cracks with small size called the CMFL PIG is performed which can be applicable in pipelines. The CMFL PIG is designed and the distribution of the magnetic flux leakage is calculated by using numerical analysis [6]-[7]. Also, a simple module of the CMFL PIG and metal test specimens of the pipe included axially oriented cracks are made for an experiment. Therefore, by simulating and measuring the sensing signals such as flux leakage density, it is not only possible to determine the location of the crack but also estimate the shape of axially oriented cracks.

---

*   Dept. of Electrical Engineering, Pusan National University, Korea.
     (hmkim@pusan.ac.kr, gspark@pusan.ac.kr)
** R&D Division, Korea Gas Corporation, Incheon, 1124-1, Korea.
     (yoohr@kogas.or.kr,   shcho@kogas.or.kr,   giberdong@kogas.or.kr,
     sjkoo@kogas.or.kr)

Fig. 1. The diagram and operating principle of CMFL PIG

2. Design and Analysis

2.1 Optimum design of simple module of the CMFL System

The size of magnets is designed by using a magnetic circuit theory that can be optimized. The length of magnet is 180 mm, width is 64 mm and height is 25 mm. The residual magnetic flux density of magnet is 1.24 T and the coercive force is 880,000 A/m. In order to detect the leakage signal in the vicinity of the crack, hall sensors are used for measuring the magnetic leakage field as a magnetometer. In Fig. 2, Sensor heads which consist of 15 hall sensors are loaded in simple module of the CMFL PIG. The number of sensor heads is 11. Hall sensors are arranged about 1.9 mm interval with each other and they are placed to 3 mm from surface of the pipe. The performance test of CMFL System is performed with a pipe specimen as shown in Fig. 3.

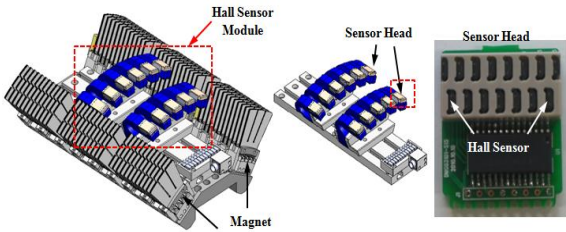### 2.2 Magnetic field analysis using finite element method

The calculation of magnetic flux density on the surface of the pipe or leakage flux density in the vicinity of the
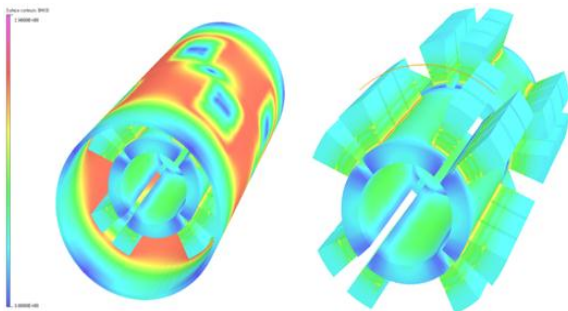
crack is performed by finite element method as shown in Fig. 4. As a result, the magnetic flux density is saturated at 1.7~1.8 T so that is enough to magnetize of pipe.

Fig. 2. The distribution of magnetic flux density on the CMFL PIG and pipe
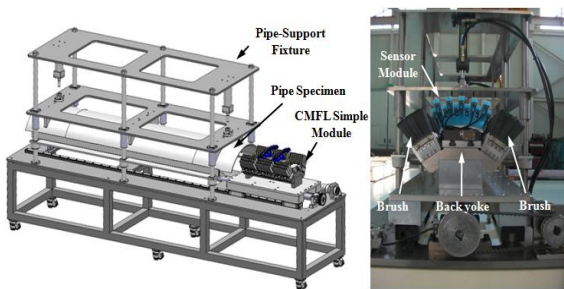
Fig. 3. The structure for performance test of CMFL System

**Fig. 4.** The distribution of magnetic flux density on the CMFL PIG and pipe

3. Analysis of Defect Signal

The leakage magnetic flux densities in the vicinity of axial cracks are performed by finite element method as shown in Fig. 5. When the pipe has been damaged by axial cracks, sensing signal is distorted partially as in Fig. 5. Wherever axial cracks are detected on the pipe, both distribution and amplitude of sensing signal for magnetic leakage field are depended on the size and shape of cracks.

3.1 Signal distribution with respect to the length of cracks

Fig. 6 shows the distribution of defect signals on the axial distance detected by Hall sensors are proportional to the length of cracks when the width and depth of crack are the same. The amplitude of sensing signals is also increasing with respect to the crack length.
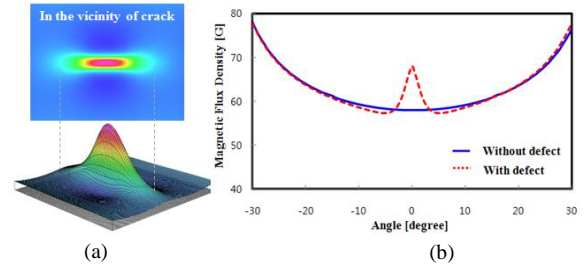

Fig. 5. Numerical analysis of defect signal: (a) Magnetic leakage field in the vicinity of crack, (b) Analysis of leakage field signal at sensor position

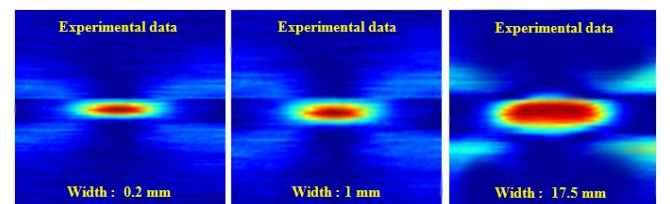### 3.2 Signal distribution with respect to the width of cracks

In Fig. 7, it shows that the distribution of defect signals on the circumferential distance is proportional to the width of cracks when the length and depth of crack are the same. The amplitude of sensing signals is also increasing with respect to the crack width.

3.3 Signal distribution with respect to the depth of cracks

Fig. 8 shows the variation of sensing signals with respect to 20 %, 40 %, 60 % of the crack depth when the length and width of crack are the same. The peak amplitude of the leakage field is mainly dependent on the crack depth. The leakage signal with respect to depth size is more complicated because it implies the effect of length and width simultaneously. So, it is necessary to build an algorithm to derive the accurate size of the defect from the measured sensing signals.
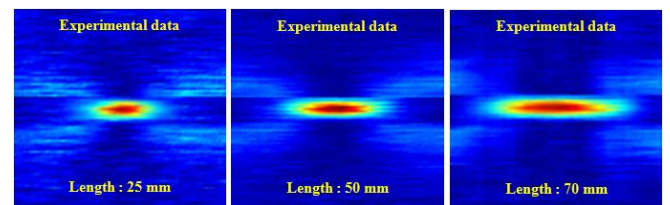
Fig. 6. Leakage field signal with respect to the defect length

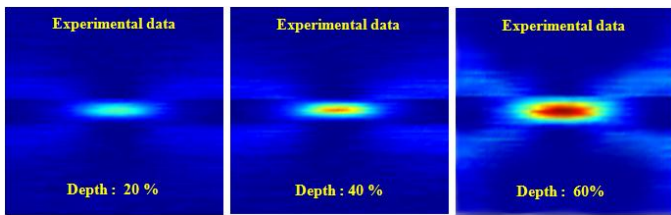**Fig. 7.** Leakage field signal with respect to the defect width

Fig. 8. Leakage field signal with respect to the defect depth

4. Defect Estimation

The shape of cracks on the surface of the pipe can be estimated from the distribution and the amplitude of leakage signals. Patterns of leakage field signal with respect to sensing path distance are shown in Fig. 9. In Fig. 9, the size of length and width of a crack would be derived simply from the width of leakage signal along the length and width directions respectively. But, it is hard to determine the depth of a crack simply by using the width of sensing signal because the width of sensing signal is hardly changed according to depth size of a crack as depicted in Fig. 9. Therefore, it is necessary to find the functional relationship with algorithm between sensing signals and crack depth with length and width.
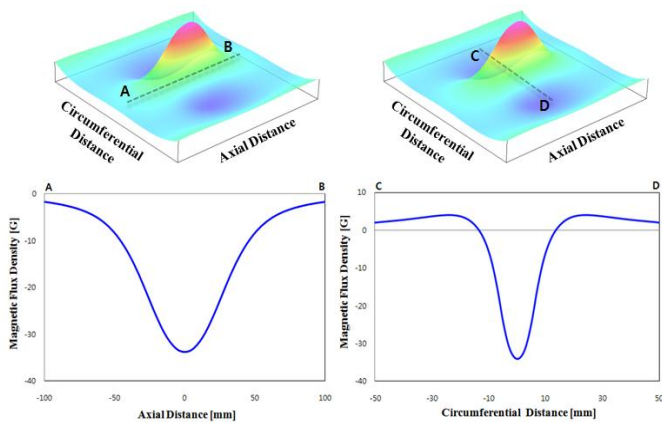

Fig. 9. Magnetic leakage field distribution according to sensing path

4.1 Estimation of the length of a crack

The relation between the length of crack and the width of leakage signal on the axial direction is linearly dependent. As shown in Fig. 10, the length of a crack is determined from the pulse width of 65 percent of the peak amplitude of signal in this system. It is possible to verify the ratio of the numbers of estimation by using both FE simulation and experimental measurement. We had already known the reference crack when we did experimental work. Because the reference crack has the information for defect size and shape, so it is already known factor. Therefore, from the

distribution of leakage signal on the axial direction, the ratio of estimation such as 65% is determined as the length of reference crack even if PIG's magnetic system is changed. If the system size is changed, the amplitude of leakage signal will be changed but the estimating rate will not be changed.

4.2 Estimation of the width of a crack

To estimate the crack width, it is necessary to consider the relation between defect width and signal width on the circumferential direction. In Fig. 11, the width of a crack is determined from the pulse width of 45 percent of the peak amplitude of signal in this system.
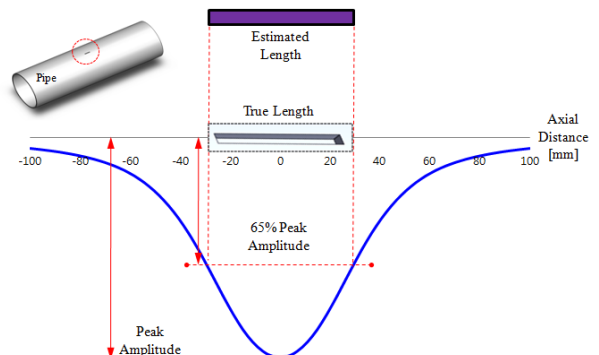

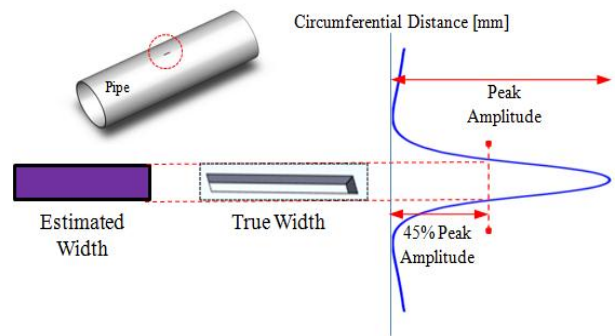**Fig. 10.** Estimation of crack length on axial direction

Fig. 11. Estimation of crack width on circumferential direction

4.3 Estimation of the depth of a crack

The amplitude of leakage field is dependent on the crack shape such as length, width and depth. But the peak amplitude of the leakage field is mainly dependent on the crack depth. Fig. 12(a) shows a quadratic functional relationship between depth size and peak amplitude of signal when the length and width of crack is 70 mm, 10 mm respectively. So the depth of a crack can be expressed as a quadratic function of the peak amplitude of leakage signal along with length and width. So, the equation of depth could be expressed as following;

$$D_{depth} = C_2(l,w)B_{peak}{}^2 + C_1(l,w)B_{peak} + C_0(l,w) \qquad (1)$$

Where $B_{peak}, C(l,w), l, w$ denote the peak amplitude of leakage signal, shape factor, defect length and defect width, respectively.

The algorithm to determine the variables in (1) is shown in Fig. 13. Beforehand, the defect signal is depicted by Hall sensors in CMFL System. The length and width of a crack are determined by using estimation method as previously presented. Then the shape factors of depth equation (1) could be obtained by polynomial surface fitting with respect to defect's length and width. Fig. 13 describes the algorithmic process of determining the shape factors and Fig. 12(b) shows the results of shape factors for several cracks oriented on the axial direction on the underground pipeline. The shape factors depend definitely on the magnetic system of MFL PIG. However, once the factors are obtained as in Fig. 12(b), the depth of the axial crack could be easily computed by (1).
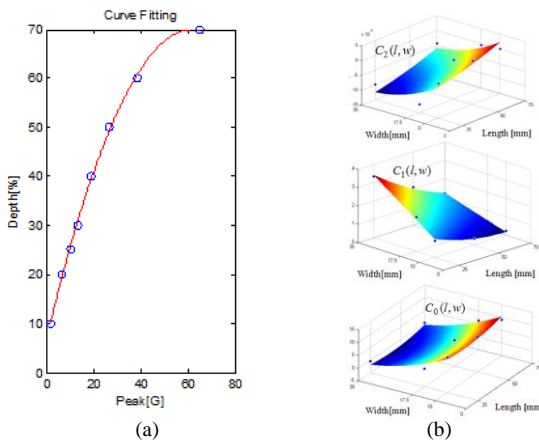

Fig. 12. (a) The peak amplitude of leakage signal with respect to crack depth, (b) Result of shape factors to find coefficients of depth equation
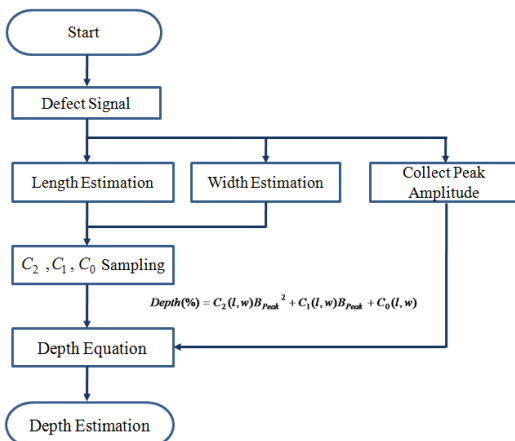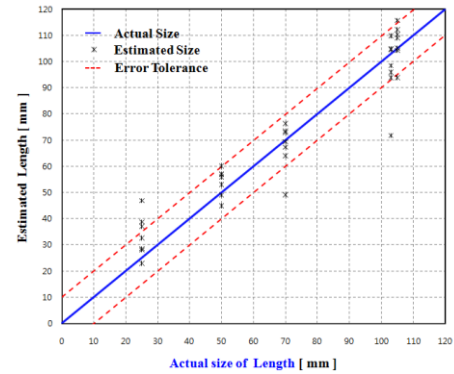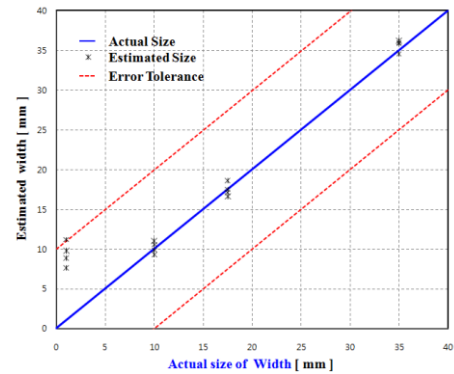

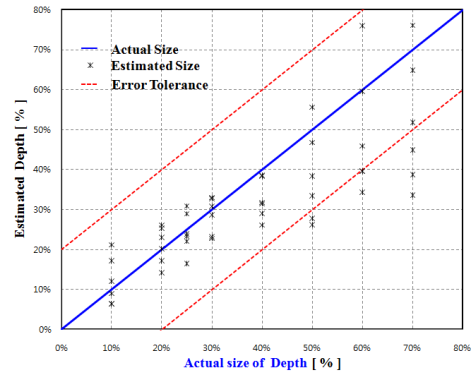**Fig. 13.** Algorithm for determining shape factors of crack depth

5. Results and Discussion

(a) Results of length estimation of a crack

(b) Results of width estimation of a crack
(c)

(c) Results of depth estimation of a crack
Fig. 14. Results on the estimation of shape of axial cracks

By measuring the defect signals such as magnetic flux leakage density and using the mechanism of estimation, it is possible to determine the shape of cracks. The estimation results are presented comparing to real size of cracks in Fig. 14. The error tolerance for length and width is generally 10 mm, and admitted depth tolerance is 20 %. Fig. 14 shows that the length and width of axially oriented crack is well fitted within tolerance to the real size. The most depth of axial crack is also within tolerance in the figure. In Fig. 14(c), there are some errors in case of more than 50% depth of crack. They are general phenomenon in MFL type

nondestructive test when we try to detect a deep crack on the surface of the pipe. This is the reason why there are such nonlinear effects of magnetic saturation in the pipe. When a deep crack occurs in the pipe, the area of pipe is rapidly decreased and magnetic fields are strongly influenced by nonlinear characteristic of material. However, that is not really problem because the small size crack is detected very well before it could be grown gradually and it could be managed by using our estimation approach in advance. In this paper, the algorithm for estimating crack depth is proposed in Fig.12~Fig. 13. Results in Fig. 14 show that the estimated results are within error tolerance. Estimated results, especially for small cracks damaged less than 30%, are well estimated, which is important for commercial maintenance. Before the cracks are damaged over 50%, pipeline should be replaced new one in the maintenance scheme.

6. Conclusion

In this research, we propose the new type of MFL PIG as a nondestructive testing method to detect axially oriented cracks with small size. To evaluate the performance of the system, magnetic field analysis using the finite element method is performed. Also, sensing signal data is compared to the result of simulation through preliminary experiments. As a result, by measuring the defect signal from magnetic flux leakage, it is able to determine where the crack is and estimate the shape of axial cracks.

Acknowledgements

References

[1] G. S. Park, "Analysis of the velocity-induced eddy current in MFL type NDT", IEEE Trans. Magnetics, vol. 40, no. 2, pp.663-666, March 2004.
[2] Z. Zhang, L. Udpa, S. S. Udpa, Y. Sun, J. Si, "An Equivalent Linear Model For Magnetostatic Nondestructive Evaluation", IEEE Trans. Magnetics, vol. 32, no. 3, May 1996.
[3] S. Lukyanets, A. Snarskii, M. Shamonin and V. Bakaev, "Calculation of magnetic leakage field from a surface defect in a linear ferromagnetic material : an analytical approach", NDT & E International, vol. 36, issue 1, pp.51-55, Jan. 2003.
[4] H. M. Kim, Y. W. Rho, H. R. Yoo, S. H. Cho, D. K. Kim, S. J. Koo, G. S. Park, "A study on the measurement of axial cracks in the Magnetic Flux Leakage NDT system", Automation Science and Engineering (CASE), 2012 IEEE International Conference on, pp. 624-629.
[5] H. Haines et. Al., "Advanced MFL Signal Analysis Aids Pipe Corrosion Detection", Pipeline & Gas Industry, pp. 49-63, Mar. 1999.
[6] R. C. Ireland and C. R. Torres, "Finite element modeling of a circumferential magnetizer", Sensors and Actuators, vol. 129, issue 1-2, May 2006.

Hui Min Kim received B.S. and M.S. degrees in electrical and electronic engineering from Pusan National University. His research interests are design and analysis of electrical machine.

Hui Ryong Yoo received Ph.D. degree in mechanical engineering from Pukyong National University. His research interests are nondestructive testing and application for pipeline.

Sung Ho Cho received Ph.D. degree in mechanical engineering from Sungkyunkwan University. His research interests are nondestructive testing and application for pipeline.

Dong Kyu Kim received Ph.D. degree in mechanical engineering from Pukyong National University. His research interests are nondestructive testing and application for pipeline.

Sung Ja Koo received M.S. degree in computer engineering from Dongguk University. Her research interests are nondestructive testing and application for pipeline.

Gwan-Soo Park received his B.S. degree from Seoul National University, Seoul, Korea in 1985, and his M.S. degree from Seoul National University of Electrical Engineering, Seoul, Korea in 1987, and his Ph.D. degree in Electrical Engineering from Seoul National University, Seoul, Korea in 1992. He is now working with Pusan National University and his research interests are Application of Electric Machines and Electromagnetic Devices.