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A Novel Magnetic Flux Leakage Sensor System for Inspecting Large Diameter Pipeline

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The magnetic flux leakage (MFL) type non-destructive inspection can be performed only when the metal object is sufficiently magnetically saturated. Therefore, since the general MFL sensor system used for pipeline inspection must sufficiently saturate the pipe, the weight and size of MFL sensor system are inevitably increased according to the diameter or thickness of the pipe. However, if the weight of the MFL sensor system is excessively increased, it is difficult to drive, and thus it is difficult to inspect a pipe having a large diameter. In this paper, the novel MFL sensor system which can be inspected large-diameter pipes without increasing the weight of the MFL sensor system is proposed and compared to the conventional MFL sensor system used for the pipe inspection. Since the proposed MFL sensor system is a system that saturates the pipe locally, it has the advantage of being able to inspect the pipe regardless of the pipe diameter.

Keywords : magnetic flux leakage (MFL), nondestructive testing, pipe inspection

1. Introduction

The magnetic flux leakage (MFL) type nondestructive testing (NDT) is a method of applying a large magnetic field to a pipe and detecting the magnetic flux leaking due to a defect to inspect the condition of the pipe. The MFL type NDT is widely used for pipe inspection because it can detect all defects, even relatively small and defects occurring on the inner and outer walls [1-6].

The structure of the conventional MFL sensor system used for pipe inspection is a structure in which a single MFL sensor module including magnets is placed entirely in the circumferential direction of the pipe [4-8]. Therefore, the size and weight of the conventional MFL sensor system is determined by the diameter of the pipe. The MFL sensor system used in small diameter pipe inspections is small and light enough to be driven by driving device or fluid pressures such as gas or water. On the other hand, in the case of a large-diameter pipe inspections, a large number of MFL sensor modules are required to place a single MFL sensor module in the entire circumferential direction of the pipe [4-8], and the MFL sensor system becomes heavy. When the MFL sensor system becomes heavy, a high-torque driving device or high fluid pressure are required for moving the MFL sensor system. Few pipes have high enough fluid pressure to move a heavy MFL sensor system, even with a large diameter pipe. In particular, since the flow rate as well as the fluid pressure is relatively low in the water pipe, it is very difficult to inspect the pipe using the conventional MFL sensor system. Therefore, it is necessary to study the MFL sensor system for inspecting large-diameter pipes.

In this paper, the novel MFL sensor system is proposed that can inspect pipes using only one or two MFL sensor modules, regardless of the pipe diameter. Since the MFL modules inspect the pipe while rotating, the proposed MFL sensor system requires only one or two MFL sensor modules. Since the proposed MFL sensor system it uses one or two MFL sensor modules, it is structurally simple and has a light weight. In this paper, the proposed MFL sensor system is analyzed using finite element analysis (FEA) and verified through experiments.

2. System Structure and Inspection Method

The MFL sensor module used in most MFL systems, including the proposed MFL system, consists of a pair of magnets, a yoke, and sensors as shown in Fig. 1. Because of the simple structure, most MFL sensor modules for MFL sensor systems can be designed through simple

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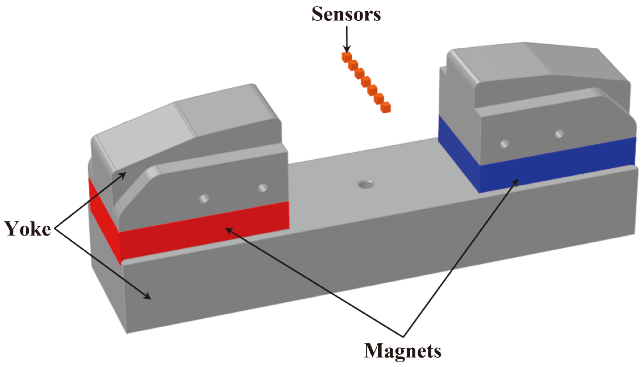


Fig. 1. (Color online) Basic structure of MFL sensor module.

formulas, when the pipe thickness and target magnetic flux density are determined [6].

In most MFL sensor modules for conventional MFL sensor systems used for pipe inspection, a pair of magnets for applying a magnetic field to the pipe are arranged in the axial direction of the pipe, and sensors for sensing the leaked magnetic flux are arranged in the circumferential direction of the pipe. Also, the conventional MFL sensor system, using MFL sensor modules, has a structure in which the MFL sensor modules including a pair of magnets are arranged in the circumferential direction of the pipe so that the entire pipe can be inspected at a time. Due to the structure of the conventional MFL sensor system for inspecting pipe, the number of MFL sensor modules depends on the diameter of the pipe. For this reason, the MFL sensor system for inspecting large-diameter pipes has a disadvantage in that a large number of MFL sensor modules are used and heavy, and sometimes the pipe cannot be inspected due to its weight.

However, the structure of the proposed MFL sensor system differs from that of the conventional MFL sensor system as shown in Fig. 2. First, in the conventional MFL sensor system, a large number of MFL sensor modules are arranged in the circumferential direction of the pipe, whereas in the proposed MFL sensor system, only one or two MFL sensor modules are arranged at regular intervals. In addition, to connect MFL modules, a connection structure of arm and a shaft to connect a separate motor to the arm are added. Unlike the proposed MFL sensor system, the MFL sensor module, used in proposed MFL sensor system, is similar in structure to the conventional sensor module. However, since the proposed MFL sensor system does not have an adjacent MFL sensor module, the magnetic flux due to the MFL sensor module for the proposed MFL sensor system spreads widely and the magnetic flux density of the pipe is low, compared to the MFL sensor module for the conventional MFL sensor system. Therefore, the MFL sensor module for the proposed MFL sensor system has the difference that it requires a slightly larger magnet, compared to the conventional MFL sensor system.

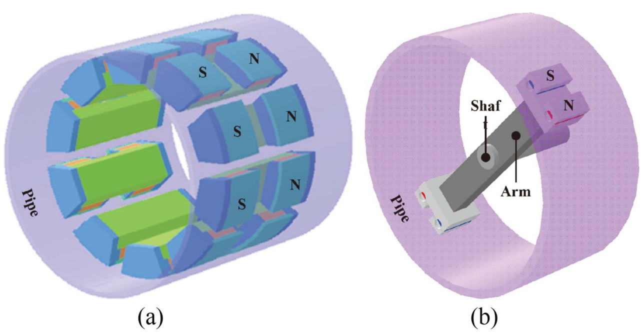


Fig. 2. (Color online) The structure of (a) Conventional MFL sensor system (Ref. [6]). (b) Proposed MFL sensor system.

The proposed MFL sensor system differs not only in structure but also in pipe inspection method. The conventional pipe inspection method of inspecting the pipe using the MFL sensor system moves the MFL sensor modules attached to the pipe along the pipe using a fluid pressure such as gas or a driving device. While the MFL sensor module is moving, the sensor senses leaked flux and stores or transmits data to inspect the pipe. That is, conventional MFL sensor module inspects the pipe while moving along the pipe together with the system. On the other hand, the proposed MFL sensor system inspects the pipe while rotating the sensor module along the inner circumference of the pipe using a separate rotating device separated from the driving device.

The proposed MFL sensor system moves by using a separate driving device. Of course, the conventional MFL sensor system can be moved using a separate driving device, but the movement method of conventional and the proposed MFL sensor system is slightly different. The conventional MFL sensor system moves continuously, while the proposed MFL sensor system stops at one point, inspects the pipe, moves a certain distance, and stops again to inspect the pipe. Through this movement method of system and the rotation-type inspection method, the proposed MFL sensor system can inspect the entire pipe as in the conventional sensor system. In other words, unlike the conventional method which requires inspection of the large-diameter pipe with a large number of MFL sensor modules, the proposed MFL sensor system can be inspected by only one sensor module in large-diameter. However, it takes a long time to inspect the pipe because the MFL sensor module must rotate every time the sensor system moves and stops repeatedly at each point. The inspection speed can be increased by increasing the rotational speed of MFL sensor module, but there is a limit to increasing the rotational speed of the MFL sensor module due to the motion-induced eddy current [10-12]. The inspection time can be shortened by increasing the number of MFL sensor modules, but as the number of MFL sensor modules increases, the weight increases, so it is necessary to determine the appropriate number of sensor modules. In this paper, the proposed MFL sensor system using two sensor modules is analyzed.

3. Analysis Using FEA

Since the conventional MFL sensor system has a large number of MFL sensor modules in the circumferential direction, there is no need to consider reduction of the magnetic flux density due to the magnetic flux dispersion. However, in the proposed MFL sensor system, the magnetic flux is dispersed in the pipe because the magnetic field is applied by only one module. Therefore, even if the same sensor module is used, the flux density of a pipe due to applied field of the proposed MFL sensor system is lower than the flux density of the conventional MFL sensor system.

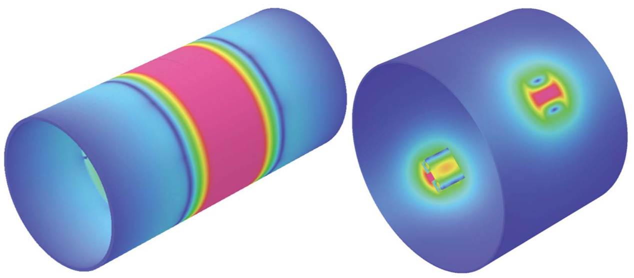
In the MFL typed NDT, if the magnetic flux density is low, the magnitude of the defect signal is generally small [4-10]. Furthermore, if the pipe is not saturated, the magnitude of the defect signal is similar to the noise signal, and it is difficult to determine whether or not the defect is defective.

In this paper, the magnetic flux density analysis results of the conventional MFL sensor system and the proposed MFL sensor system are compared in order to determine whether the proposed MFL sensor system can detect defects.

Figure 3 shows the distribution of magnetic flux density in the pipe using the conventional and the proposed MFL sensor systems. As described above, the conventional MFL sensor system has a uniform magnetic flux density distribution in the circumferential direction of the pipe because the MFL sensor modules are arranged in the circumferential direction of the pipe. In addition, it can be seen that there is no magnetic flux fringing in the pipe and the pipe is sufficiently saturated magnetically. However, since the proposed MFL sensor system applies a magnetic field with only one MFL sensor module, it does not sufficiently saturate the whole of the pipe, but partially saturates it unlike the conventional MFL sensor system.

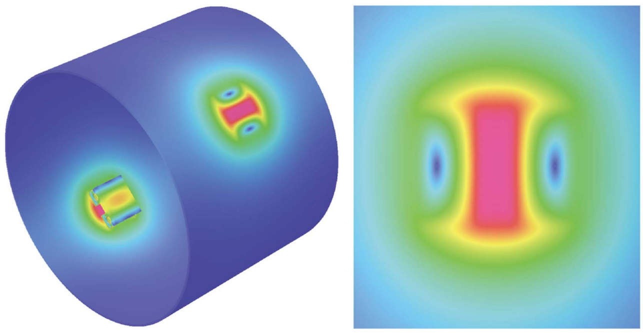
Figure 4 shows the flux density of the pipe due to the proposed MFL sensor system. As shown in Fig. 4, the pipe is partly magnetically saturated by the proposed MFL sensor system. In the conventional MFL sensor system, a large number of sensor modules inspect pipes while moving in the pipe axis direction. However, sensor modules, used in the proposed MFL sensor system, inspect pipes while rotating in the pipe circumferential direction. Therefore, there is no need to saturate the entire pipe, so partial magnetic saturation has no effect on the pipe inspection.

In order to compare the defect signals of the conventional and the proposed MFL sensor systems, the defect signals



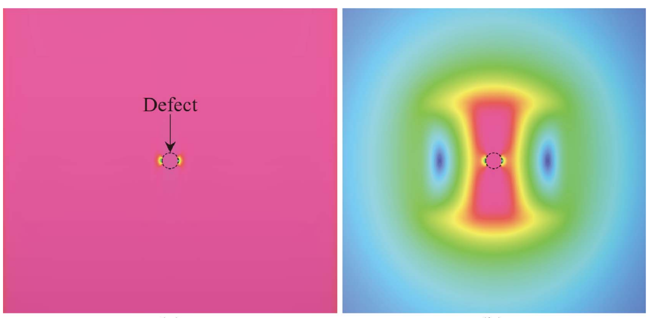
(a) (b)

Fig. 3. (Color online) The distribution of magnetic flux density of (a) Conventional MFL sensor system. (b) Proposed MFL sensor system.



(a) (b)

Fig. 4. (Color online) The distribution of magnetic flux density of proposed MFL sensor system. (a) Total view. (b) Partial enlargement.



(a) (b)

Fig. 5. (Color online) The change of magnetic flux density in the pipe caused by a defect (a) in the conventional MFL sensor system. (b) in the proposed MFL sensor system.

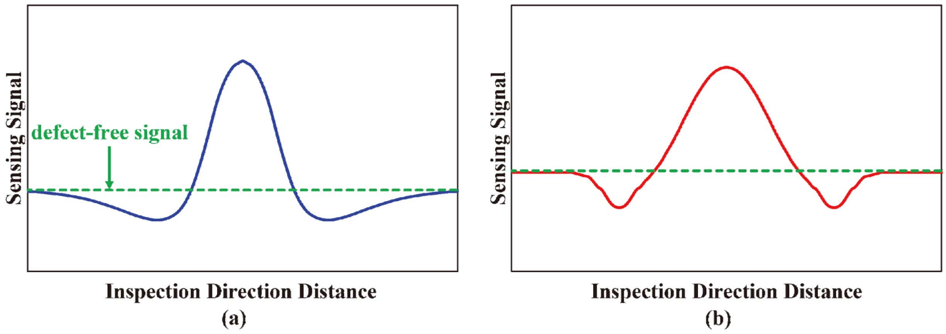


Fig. 6. (Color online) The defect signal according to the movement distance of the MFL sensor module of (a) Conventional MFL sensor system. (b) Proposed MFL sensor system.

are analyzed using FEA.

Figure 5 shows the change of magnetic flux density in the pipe caused by a defect in the conventional and proposed MFL sensor systems. As shown in Fig. 5, it can be seen that when a defect occurs, both MFL sensor systems have the same tendency to change flux. In other words, it can be expected the signal detected by a defect to be the same in both MFL sensor systems.

Figure 6(a) and (b) show the defect signal according to the movement distance of the sensor module of the conventional and the proposed MFL sensor system, respectively. Since both the conventional and the proposed MFL sensor system are inspected using the MFL sensor module, the signals due to defects are similar. In the inspection using the MFL sensor module, even if there is no defect, the leaked magnetic flux is detected, which is called 'base level' and is indicated by a green dotted line. As shown in Fig. 6, both MFL sensor systems have a constant base level in the movement direction of the sensor module. That is, the signal according to the movement direction of the sensor module of the proposed MFL sensor system is the same as that of the conventional MFL sensor system.

Figure 7(a) and (b) show the defect signal in the sensor arrangement direction perpendicular to the sensor module movement direction at a point of the conventional and the proposed MFL sensor system, respectively. As shown in Fig. 2(a), in the conventional MFL sensor system, MFL sensor modules are arranged in the circumferential direction, which is the sensor arrangement direction, and can magnetically saturate the pipe almost constant in the circumferential direction. Therefore, as shown in Fig. 7(a), the base level, which is the magnetic flux detected by leaking out of the pipe, is constant in the sensor arrangement direction in the conventional MFL sensor system. On the other hand, as shown in Fig. 2(b), the proposed MFL sensor system only partially magnetically saturates the pipe because it uses only one or two MFL sensor modules. Therefore, the base level of the proposed MFL sensor system is not constant in the sensor arrangement direction perpendicular to the moving direction of the MFL sensor module, and is shown in Fig. 7(b). However, the defect signal has the same characteristic that the signal changes the most at the center of the defect and the change decreases as the distance from the defect increases in both MFL sensor systems. In other words, as shown in Fig. 6 and Fig. 7, the signal characteristics of the proposed MFL sensor system are the same as those of the

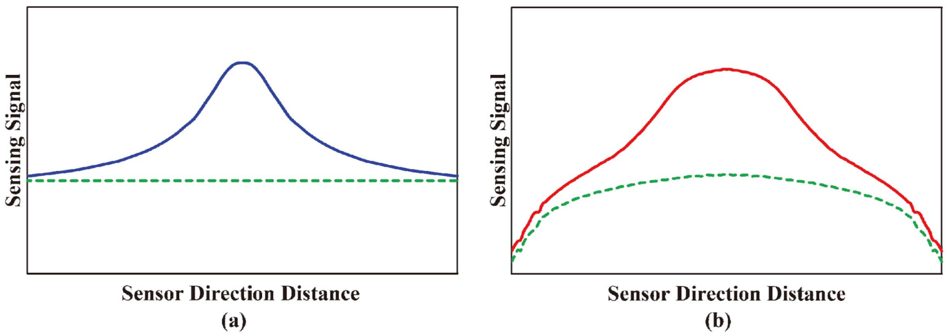
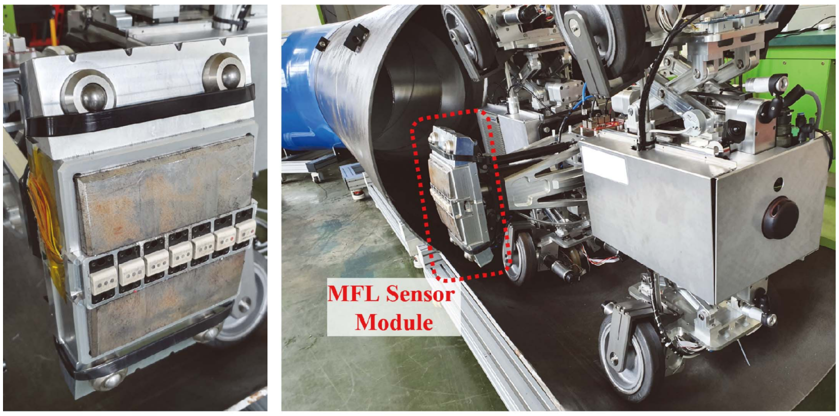


Fig. 7. (Color online) The signal for each sensor at the defect position in (a) Conventional MFL sensor system. (b) Proposed MFL sensor system.



(a) (b)

Fig. 8. (Color online) (a) MFL sensor module used in the experiment. (b) Proposed MFL sensor system.

conventional MFL sensor system except for the base level of the sensor arrangement direction. Since the characteristics of the signals are the same, the signal analysis or defect shape estimation method applied to the conventional MFL sensor system can be applied as it is to the proposed MFL sensor system without a new signal analysis method for the proposed MFL sensor system.

4. Experiment

In order to verify that the defect signal of the proposed MFL sensor system is the same as the finite element analysis result, the experimental setup is constructed as shown in Fig. 8.

The MFL module, as shown in Fig. 8(a), is inspected while rotating inside the pipe using the proposed MFL sensor system as in Fig. 8(b). The experiment is carried out by manufacturing defects in a pipe with a diameter of 1000 mm and a thickness of 9 mm.

Figure 9 shows the test bed, the test specimen, and the defect layout of the pipe, used in the experiment [13]. Figure 10 shows the experimental results using the proposed MFL system.

As shown in Fig. 10(b), the signal detected by the sensor of the MFL module is sensed in the similar form as Fig. 6(b). As shown in Fig. 10(a), most of the defects are detected, and abnormal signals are also detected due to due to the weld, which is made in manufacturing of a large-diameter pipe.

Since the proposed MFL sensor system uses only a single MFL module, it is difficult to sufficiently saturate the pipe unlike the conventional MFL sensor systems. Therefore, the amount of leaked magnetic flux due to defects in the proposed MFL sensor system is smaller than that of the conventional MFL sensor system. Therefore, small defects such as 9 mm × 9 mm × 0.9 mm may be

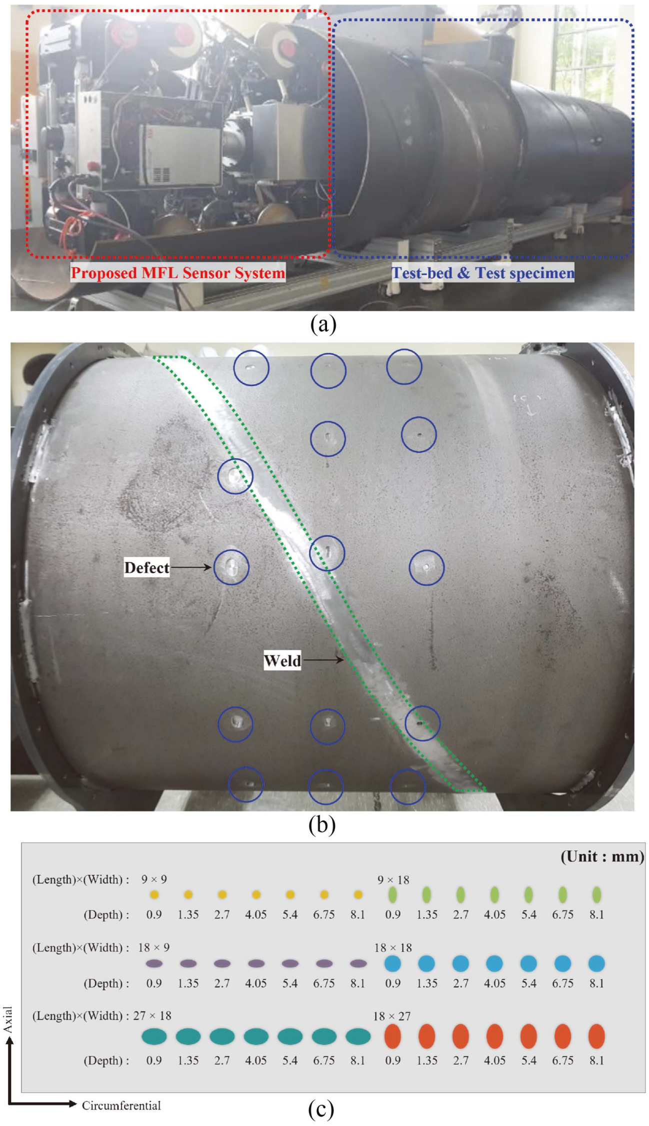


Fig. 9. (Color online) Photograph of (a) the test bed. (b) the test specimen used in the experiment (Ref. [13]). (c) The defect layout of the pipe.

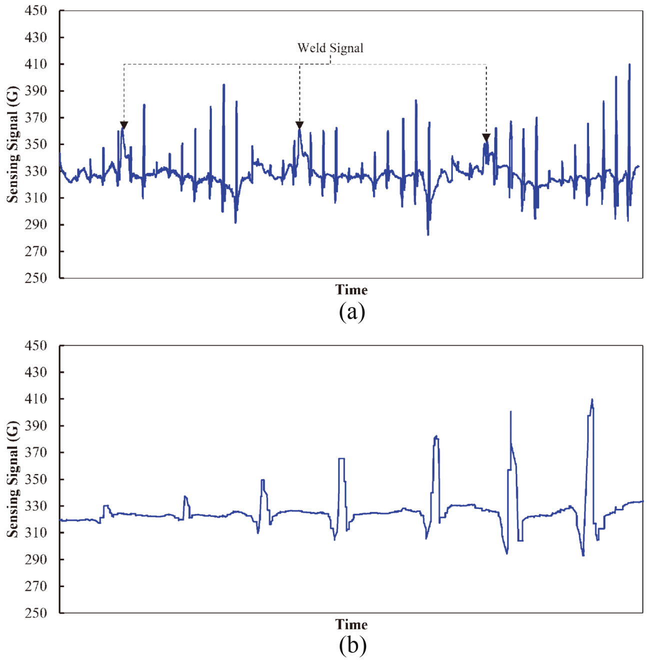


Fig. 10. (Color online) (a) Overall experimental results. (b) The experiment result of 18 mm × 27 mm defects.

difficult to detect. In addition, since the applied magnetic field greatly changes according to the posture of the MFL module, such as the distance from the pipe or the inclination of the MFL module, there is a disadvantage that the amount of leaked magnetic flux varies greatly depending on the posture of the MFL module. Therefore, additional research is needed to compensate for the disadvantages caused by saturating the pipe with only one single module.

5. Conclusion

In this paper, the novel MFL sensor system that can inspect large-diameter pipes is proposed. In the conventional MFL sensor system, single MFL modules are arranged in the circumferential direction of the pipe and inspect while driving inside the pipe. Therefore, as the diameter of the pipe increases, the number of single MFL modules required and the weight of the MFL sensor system increase. As the weight of the MFL sensor system increases, a large force is required to drive the MFL sensor system, so the conventional MFL sensor system is not suitable for large-diameter pipe inspection.

However, the proposed MFL sensor system is relatively light in weight, because only one single MFL module, regardless of the pipe diameter, inspects the pipe while rotating. Therefore, the proposed MFL sensor system can inspect pipes of all diameters regardless of the diameter of the pipe. However, the proposed MFL sensor system cannot be used for small diameter pipes due to ancillary parts such as arms and motors. If the proposed system is to be used for small-diameter pipe inspection, it is necessary to study the miniaturization of the proposed system. In addition, additional research is needed to compensate for the disadvantages caused by saturating the pipe with only one single module, such as a small amount of leaked magnetic flux and sensitivity according to posture.

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