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Research Article

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Development of a Circular Displacement Sensor Capable of Measuring Self-Deformation of Circular Structures

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Abstract

Generally, a straight displacement transducer is used to obtain displacement data to verify the safety of structural members and structures. A straight displacement transducer is also used to measure the absolute displacement in research laboratories or safety inspection sites such as bridges and buildings. In this study, for structures in which the displacement sensor could not be fixed at the location where the displacement was to be measured, a circular displacement transducer was manufactured to measure the displacement by installing a displacement gauge on the structure itself. In other words, when measuring the horizontal displacement of an upper part, such as a wind tower, a circular displacement transducer was installed inside the wind tower to integrate it with the structure, applying the principle that the structure itself can be used as a displacement transducer. This circular displacement transducer can be installed and used inside a circular structure. Whereas in the case of a telephone pole, it can be installed outside to measure displacement. It can be manufactured in various sizes and used.

Keywords: Circular Displacement Transducer, Internal Displacement, Wind Tower, Horizontal Displacement, Relative Displacement.

Introduction

Measuring the displacement of structures is very important in various industrial sites. This is because determining the displacement against the load applied to the structure is the easiest and most accurate way to determine the stability of the structure. In general, pin-type straight-line displacement transducers or slightly modified displacement transducers are mainly used in industrial sites. These displacement transducers are fixed between the ground or a fixed point that does not move and the target structure to measure the displacement.

Since pin-type displacement transducers must be fixed, they have limitations in measuring displacements of structures that cannot be fixed. However, in industrial sites, there are various types of structures where displacement transducers cannot be fixed. For example, wind power towers are constantly shaking horizontally, so it is very important to measure the horizontal displacement of the top part to evaluate the soundness of the tower, but there is currently no way to measure the horizontal displacement.

In order to solve these problems, this study developed a “Circular Displacement Transducer (CDT)” that can measure the relative displacement of a structure without a fixed point. The circular displacement transducer developed in this study is expected to be very useful when measuring displacement in a location with a circular cross-section such as a wind tower that does not have a support point to fix the displacement transducer.

Research Method

Concept and Principle of Sensor

The circular displacement transducer is installed along the inside of the target structure or member to measure displacement in a shape similar to the internal diameter of the target structure, as shown in Fig. 1. The circular displacement transducer itself is assembled into a circular shape by processing a steel plate with excellent elasticity and resilience. And a strain gauge is attached to each side of the steel plate in a direction perpendicular to the direction in which the load is applied, as shown in Fig. 2, for a total of four gauges.

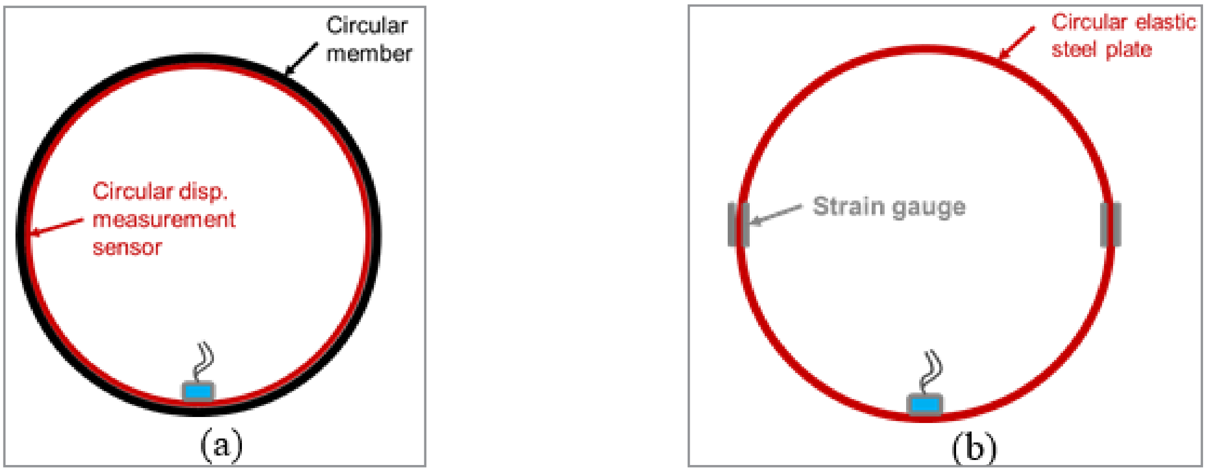


Figure 1: Schematics and Install Method of Circular Displacement meter : (a) Installation of Sensors Inside Pipes, (b) Schematics of Circular Displacement Meter

This allows the Full Bridge circuit to be configured to form a Wheatstone bridge. When a load is applied to the structure from the outside, deformation occurs in the circular member as shown in Fig. 2. And the signals measured from the four strain gauges attached to the circular steel plate can be combined and converted into displacement. The most important thing here is that the response range and response frequency of the measured signal vary depending on the elasticity and thickness of the steel plate that constitutes the circular displacement sensor. So the optimal product design is required depending on the size and purpose of the structure.

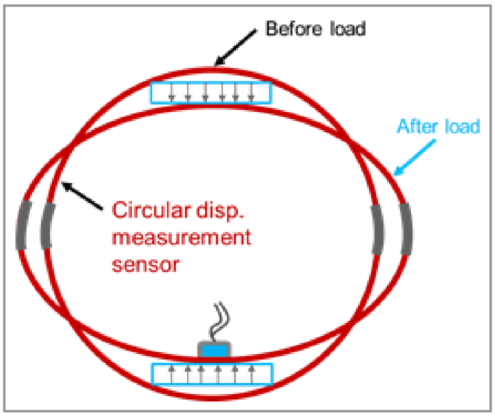


Figure 2: Working Principle of Circular Displacement Transducer

The operating principle of the Wheatstone bridge, which consists of four strain gauges attached to a circular displacement transducer, is as shown in Fig. 3.

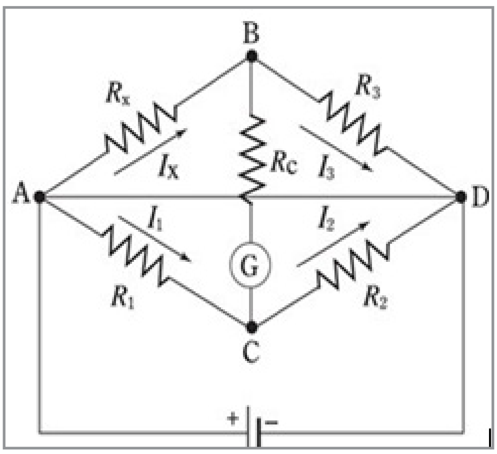


Figure 3: Wheatstone Bridge Circuit

In Fig. 3, the resistance values of R1 and R2 are already known, R3 is a variable resistor whose resistance value can be changed, and Rx is the unknown resistance to be measured. If the variable resistor R3 is adjusted appropriately so that no current flows through the galvanometer, the potentials at points B and C are the same. Therefore, the potential difference between A and B and the potential difference between A and C are the same.

$$V_{AB} = V_{AC}$$

Similarly, the potential difference between B and D is the same as the potential difference between C and D.

$$V_{BD} = V_{CD}$$

therefore

$$V_{AB} = V_{AC} \Rightarrow I_1 R_1 = I_X R_X$$

$$V_{BD} = V_{CD} \Rightarrow I_2 R_2 = I_3 R_3$$

Because here

$$R_1 R_3 = R_2 R_X$$

Since we already know the resistance value R1, R2, R3

$$R_X = \frac{R_1 R_3}{R_2}$$

Design and Prototype of the Sensor

Sensor Design

The circular displacement transducer is designed based on cutting and bending an elastic steel plate as a circular displacement transducer, as shown in Fig. 4.

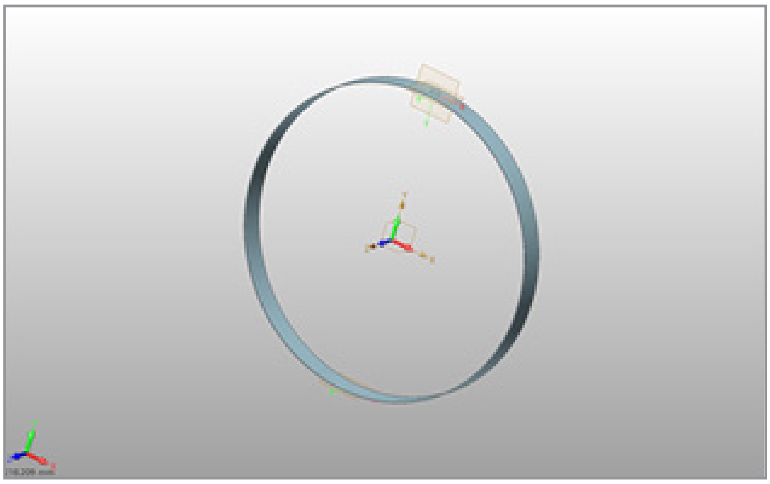


Figure 4: Design model of Circular Displacement Transducer

The design factors that constitute these circular sensors are composed of the length of the steel plate, which determines the diameter of the sensor as shown in Fig. 5. And the measurement range and precision of the sensor is determined by the thickness and width of the steel plate. The length can be easily determined because it is determined based on the size of the target structure to which it is to be applied. Whereas the thickness of the steel plate must be determined carefully because it is a factor that can be sensitive depending on the diameter of the circular sensor.

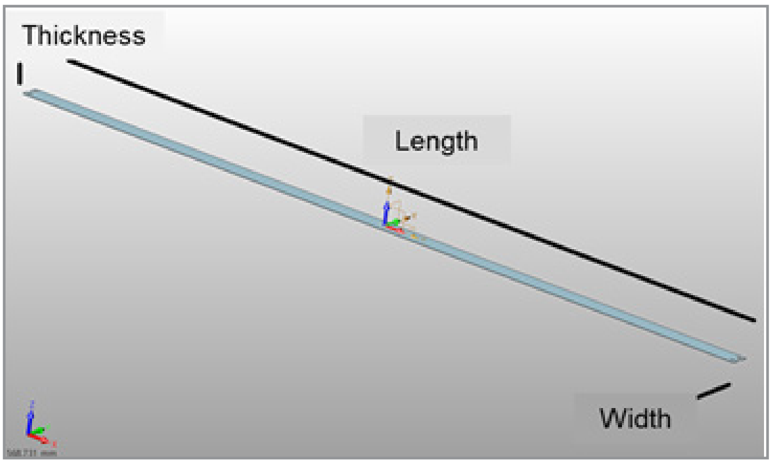


Figure 5: Design Factors for Circular Displacement Transducer

In this study, Ansys, a general-purpose structural analysis program, was used to design a circular displacement sensor that can be used for a 350 mm diameter steel pipe that is widely used in the market. A verification test was conducted using this steel pipe. The steel pipe used in the test has a diameter of 400 mm, a thickness of 7 mm, and a total length of 12 m. Since the diameter of the steel pipe is small compared to its length, it is expected that the deformation of the steel pipe will not be large, so the measurement range was designed to be 30 mm and the measurement frequency was designed to be 20 or higher.

Fig. 6 is a design model of a 350 mm diameter circular displacement sensor, and Fig. 7 shows the deformation when an arbitrary load is applied to the sensor. The most important thing here is that the response range and response frequency of the measurement signal vary depending on the elasticity and thickness of the steel plate that constitutes the circular displacement sensor. So the optimal product design is required depending on the size and purpose of the structure.

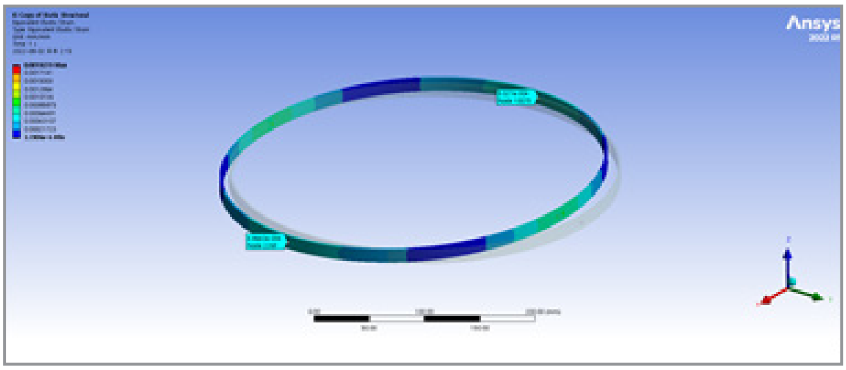


Figure 6: CDT model with a diameter of 350 mm

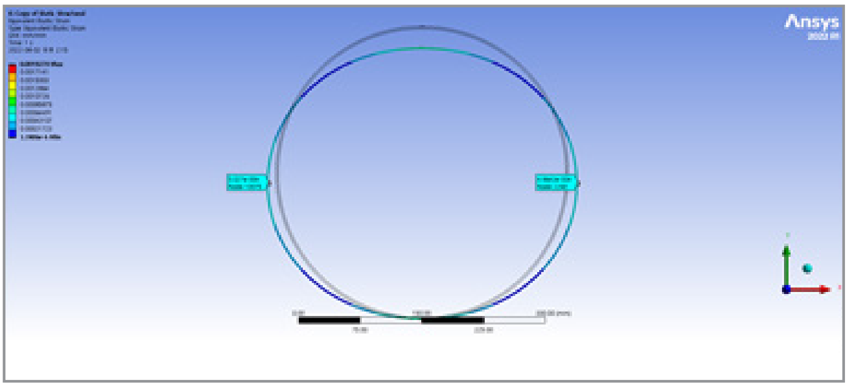
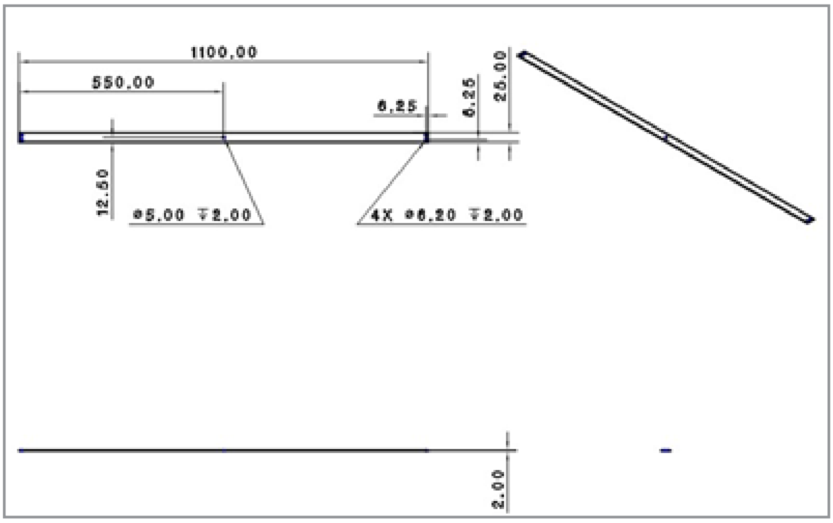
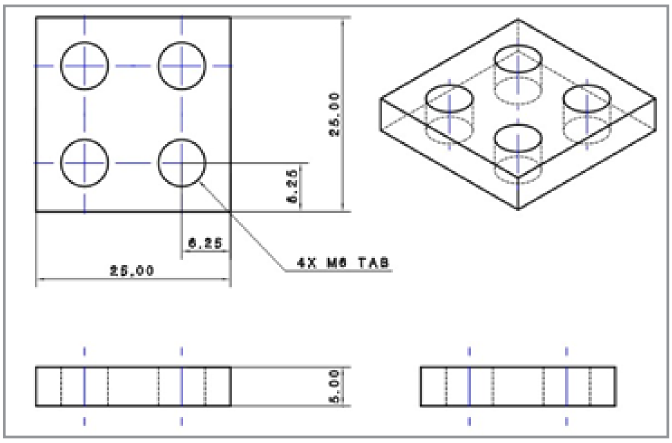


Figure 7: Strain diagram of a CDT with a diameter of 350 mm

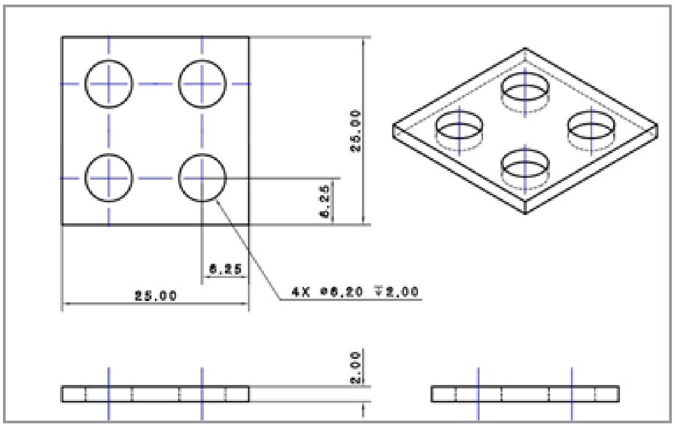
Through repeated structural analyses, the optimal sensor specifications suitable for verification testing were determined, and a prototype was manufactured using these. The prototype drawing is shown in Fig. 8.



(a)



(b)



(c)

Figure 8: Prototype drawing of circular displacement transducer : (a) Body drawing, (b) Connection block drawing, (c) Connection cover drawing

Prototype Production

Using the design drawings, two types of prototypes were manufactured as shown in Fig. 9. (a) The internal installation type is a circular displacement sensor that is installed inside a circular pipe to measure displacement, and (b) the external installation type is a sensor that is installed on a circular solid structure such as a concrete telephone pole to measure cracks and volume expansion. The two products have the same specifications except that the location of the sensor connection block is outside or inside the ring.

Even in the process of manufacturing these prototypes, we went through repeated trial and error due to errors in material selection and processing, and made various repetitive attempts until we were able to manufacture the sensor prototype.

(a)

(b)

Figure 9: Prototype of circular displacement transducer : (a) For interior installation, (b) For external installation

Member Performance Test

In order to verify the performance of the prototype of the circular displacement transducer, two commercially available steel pipes with a diameter of 400 mm and a length of 10 m were connected as shown in Fig. 10 and a performance test was performed as shown in Fig. 11.

As shown in Fig. 12, one end of the steel pipe specimen was firmly fixed to serve as a fixed-end boundary condition, and the other end was set as a free-end boundary condition and a load was applied in the transverse direction.

Figure 10: Steel pipe specimen for testing

Figure 11: Performance test using structure

Figure 12: Boundary conditions for performance testing (fixed end)

The circular displacement sensor was installed inside the steel pipe at the connection location of the steel pipe as shown in Fig. 13. And in order to compare with the data of the generally used straight displacement sensor, a straight displacement sensor was installed outside at the same location as the internal displacement sensor as shown in Fig. 14.

Figure 13: Installation of circular displacement transducer

Figure 14: Straight displacement transducer installed externally

Results and Discussion

Certified Performance Test Results of the Sensor

A prototype of the circular displacement transducer was commissioned to an authorized testing agency to perform a performance test on the sensor itself, and the test results are summarized in Table 1. The manufacturing error of the circular displacement sensor is 0.6%, and the measurement results according to the displacement amount in 10 mm units showed an error of less than 1.0% up to the design measurement range of 30 mm. On the other hand, the error tended to increase somewhat beyond the design range.

Therefore, it was confirmed that the circular displacement transducer designed in this study had excellent precision within the design range.

Table 1: Official test results of circular displacement transducer

Item	dia. (mm)	Measurement results according to the displacement change (mm)				
		10	20	30	40	50
#1	348.94	10.41	20.48	30.15	39.79	49.52
#2	346.82	10.01	19.90	29.79	39.62	49.32
#3	347.72	9.85	19.42	29.63	38.71	48.50
Ave.	347.83	10.09	19.94	29.86	39.38	49.12
error (%)	±0.6	±0.9	±0.3	±0.5	±1.6	±1.8

Material Performance Test Results

The results of the test are shown in Fig. 15. Here, a 350 mm diameter circular displacement transducer was installed inside a 400 mm diameter steel pipe, and a 20 kN load was applied in the transverse direction at a location 9.0 m from the fixed part of the steel pipe. The measurement results of the circular displacement transducer (CDT) were generally consistent with those of the external linear variable displacement transducer (LVDT) up to 30 mm, which is the design measurement range of the sensor. However, the measurement values of the two-displacement transducer showed some difference above 30 mm.

The reason for this difference was found to be that the circular displacement transducer was not firmly fixed when installed inside the pipe. That is, since there is a 50 mm gap between the circular displacement transducer and the steel pipe, it is judged that there was a slight difference between the displacement measured by the straight displacement transducer and the value measured by the circular displacement transducer [1-9].

Therefore, if a circular displacement sensor that can be installed inside a 400 mm steel pipe is installed, it is expected that the gap between the steel pipe. And the sensor will be minimized, thereby minimizing the error in measuring the deformation and displacement of the member. In other words, if a circular displacement sensor is installed inside an actual steel pipe, the error can be minimized by manufacturing and installing the sensor so that it can be installed inside the steel pipe while sufficiently considering the inner diameter of the steel pipe.

Likewise, in the case of external installation, it is judged that relatively accurate measurement values can be obtained by manufacturing a circular displacement sensor that can be installed in close contact with the outside of the pipe while considering the outer diameter of the pipe and installing it in close contact.

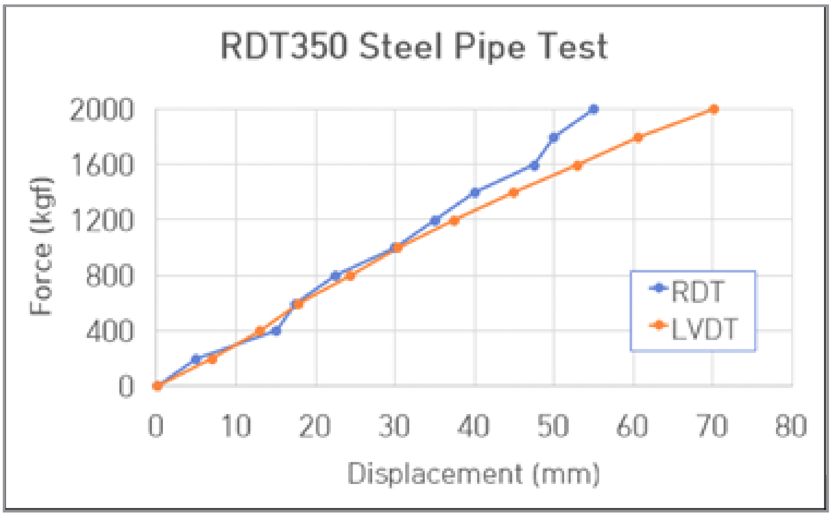


Figure 15: Load-displacement graph of test using 400 mm diameter steel pipe

Structural Analysis

Structural analysis was performed on the steel pipe member used in the performance test of the circular displacement transducer. As shown in Fig. 16, the general-purpose structural analysis program, Ansys 2022 R1, was used, and the maximum test load of 20 kN was applied to the location where the actual performance test was performed. At this time, the displacement by the analysis at the location where the circular displacement transducer was installed was approximately 72 mm, which showed similar results to the displacement measured by the external straight displacement transducer in Fig. 15.

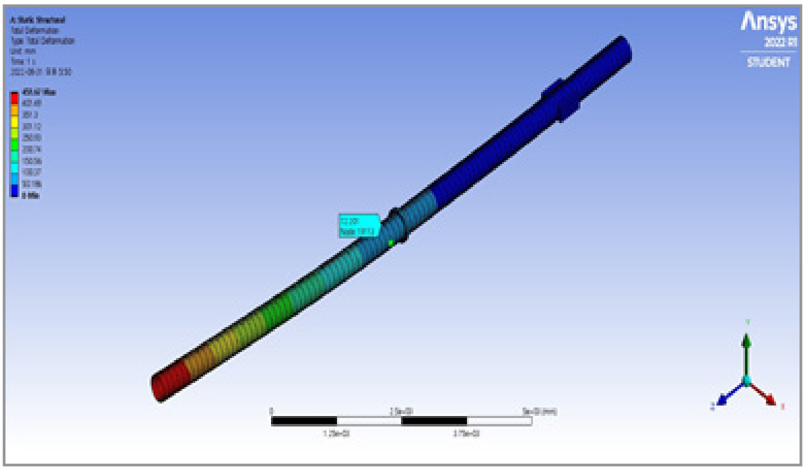


Figure 16: Structural analysis of round pipe test specimen

Conclusion

The purpose of this study is to develop a system that can measure displacement of a cantilever structure, such as a wind tower, which has a circular cross-section and no support point for fixing a displacement sensor, by installing a circular displacement transducer inside the structure and then utilizing the structure itself as a displacement meter system.

1. The circular displacement transducer consists of a connecting block that connects flat steel plates in a circular manner and four strain gauges that are attached perpendicularly to the direction in which the load is applied. The performance of the circular displacement transducer, such as the measurement range and frequency, is determined by the elasticity and thickness of the steel plate. In other words, in order to design a product with the target performance, the material of the steel plate and the optimal thickness suitable for the structure to which it is applied must be carefully determined.

2. The prototype of the circular displacement sensor was commissioned to an authorized testing agency to conduct a performance test on the sensor itself. As a result, the sensor manufacturing error was found to be 0.6%, which is relatively good. In addition, in the measurement results according to the displacement amount in 10 mm units, the error was less than 1.0% up to the design measurement range of 30 mm, but the error tended to increase somewhat beyond the design measurement range. Therefore, the prototype of the circular displacement sensor in this study is judged to be able to be used for the maintenance of structures in various laboratories or industrial sites due to its excellent precision and performance.

3. As a result of conducting a verification test by installing a 350 mm diameter circular displacement transducer on a 400 mm diameter steel pipe, the measurement results of the circular displacement transducer (CDT) were generally similar to those of the external linear displacement transducer (LVDT) up to 30 mm, which is the sensor design measurement range. However, the measurement values of the two transducers showed some difference above 30 mm. The main reason for this difference was found to be that the circular displacement transducer was not firmly fixed when installed inside the pipe.

4. sTherefore, if a circular displacement sensor that can be installed inside a 400 mm steel pipe is installed, it is expected that the gap between the steel pipe and the sensor will be minimized, thereby minimizing the error in measuring member deformation and displacement. In other words, if a circular displacement transducer is installed inside an actual steel pipe, the error can be minimized by manufacturing and installing the sensor so that it can be installed inside while sufficiently considering the inner diameter of the steel pipe.

And even when installed externally, it is judged that relatively accurate measurements can be obtained if the pipe is installed so that it can be installed in close contact with the outside of the pipe while considering the outer diameter of the pipe.

References

1. Jo, H., Park, J. W., Spencer Jr., B. F., & Jung, H. J. (2013). Development of high-sensitivity wireless strain sensor for structural health monitoring. Smart Structures and Systems, 11(5), 477-496.
2. Floyd, T. L., & Buchla, D. M. (2013). DC/AC fundamentals: A systems approach (pp. 236-242). Pearson.
3. Khan, A. S., & Wang, X. (2001). Strain measurements and stress analysis (pp. 56–68). Prentice Hall.
4. Park, S., Kwon, W., Joe, K., & Lee, S. (2022). Measurement of clamp load of hollow bolt using linear variable differential transducer sensor. Transactions of the Korean Society of Automotive Engineers, 30(9), 703-708.
5. Park, S., Kim, I.-G., Lee, H., & Kim, M.-S. (2015). Predic-

tion for large deformation of cantilever beam using strains. Journal of the Korean Society for Aeronautical and Space Sciences, 43(5), 396-404.
6. Kim, H. O., Lee, Y. H., Kim, Y. J., & Huh, H. D. (2018). Structural safety of 3 MW class wind turbine with various hole pattern arrangements. Transactions of the Korean Society of Mechanical Engineers B, 42(11), 697-704.
7. Shin, S. H., Kim, J. Y., Woo, J. Y., Kim, D. G., & Jin, T. S. (2023). Estimation of displacements using artificial intelligence considering spatial correlation of structural shape. Journal of Computational Structural Engineering Institute of Korea, 36(1), 1-7.
8. Jeong, H. S., Han, K. S., & Lee, Y. S. (2017). Measurement of retaining tensile load with the relative displacement detector of ground anchors. Journal of the Korean Geotechnical Society, 33(10), 59–69.
9. Bang, J. S., Kim, S. R., Han, J. W., & Lee, J. W. (2012). Damage estimation method for wind turbine tower using modal properties. Journal of the Korea Institute for Structural Maintenance and Inspection, 16(2), 87-94.