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Non-destructive Method of Stress Evaluation in Linepipes Using Magnetic Anisotropy Sensor†

SAKAI Yoshiaki*1 UNISHI Hiroyuki*2 YAHATA Teruo*3

Abstract:

JFE Engineering has developed a unique non-destructive stress measuring method using a magnetic anisotropy sensor and various evaluation systems applying this technology. This paper describes the principle of the stress measuring method and the experimental results which demonstrate the usefulness of the method in evaluating the stress levels in linepipes under working conditions for maintenance purposes.

1. Introduction

From the viewpoint of maintenance, the measurement of the stress levels in linepipes is an effective tool for evaluating the safety of a pipeline system. In a structure, stress is generally measured by the strain gauge method, but it is difficult to measure the stress level in an existing pipeline system using strain gauges without destructive inspection, with accompanying stress relieving work. Moreover, the range of application of this technique is naturally limited because destructive inspection is impossible in operating pipeline systems.

Against this background, the authors studied a stress measuring method using magnetic anisotropy (hereinafter referred to as the magnetostrictive method) as a simple non-destructive method of measuring and evaluating the stress in a pipeline system under working conditions and developed various application techniques using this method.[1,2]

This paper presents an outline of this technology and an overview of applications.

2. Principle of Stress Measurement Using Magnetostrictive Method

In the magnetostrictive method, as shown in **Fig. 1**, stress measurement is performed by placing a magnetic anisotropy sensor on the object of measurement. The following explains the principle of operation when the sensor is placed under a stress condition, as shown in Fig. 1. When tensile stress is applied to the object being measured, the magnetic property called permeability increases slightly in the direction of stress, causing magnetic anisotropy. If electric current passes through the coil wound around core E under this condition, a larger part of magnetic flux from the sensor leg E_1 flows directly to E_2 in the shortest route. However, a part of the magnetic flux also flows though core D, as shown by the arrows, because the permeabilities between E_1 and D_1 and between D_2 and E_2 are larger than those between E_1 and D_2 and between D_1 and E_2 by $\mu_X - \mu_Y$.

When the magnetic circuit described above is formed in an alternating current magnetic field, an induced current flows through the coil wound around core D, producing voltage V, which is given by Eq. (1).

$$V = K_0 \cdot (\mu_X - \mu_Y) \quad \cdots\cdots (1)$$

where, K_0 : A constant determined by excitation conditions, coil conditions, magnetic properties of the material, etc.

Since the anisotropy of permeability, $\mu_X - \mu_Y$, is proportional to the difference in stress, $\sigma_X - \sigma_Y$, in two perpendicular directions, Eq. (1) can be rewritten as Eq. (2)

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*1 Production Engineering Res. Dept.,
Tsu Res. Lab.,
JFE Engineering


*2 Pipeline Technology Sec.,
Gas Pipeline Engineering Dept.,
JFE Engineering


*3 Gas Pipeline Technology Dept.,
JFE Koken

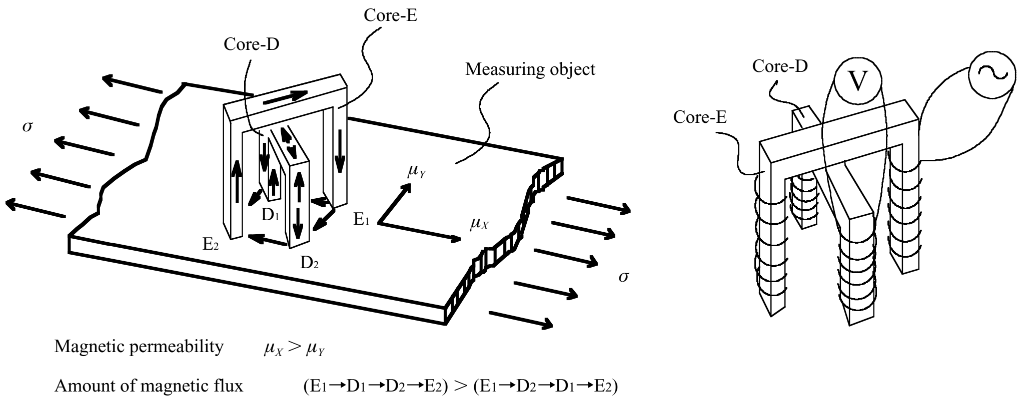


Fig. 1 Principle of magnetic anisotropy sensor

$$V = K \cdot (\sigma_X - \sigma_Y) \quad (2)$$

where, K: A constant determined by excitation conditions, coil conditions, magnetic properties of the material, etc.

Thus, if the proportional constant K (hereinafter referred to as magnetostrictive sensitivity) is known, the difference in stress can be obtained as the output voltage of the magnetic anisotropy sensor.

According to the principle, the output voltage takes the form of a sine wave with a cycle of 180° when the sensor is rotated around the measuring object, and the direction where the output voltage displays its maximum value corresponds to the principal stress direction. Under this condition, if the stress in the measuring object exists in a uniaxial or nearly uniaxial stress field, an approximate principal stress can be measured.

According to the principle, the stress obtained by a magnetic anisotropy sensor is measured as the absolute stress, i.e., the sum of residual stress component and external stress component.

3. Method of Measuring Bending Stress in Pipe Using Magnetostrictive Method

The magnetostrictive stress measuring method which is based on the principle and features described above was used to develop a system for measuring bending stress in a linepipe.

3.1 Principle of Bending Stress Measurement

The output voltage from the magnetic anisotropy sensor varies in a certain degree owing to the variance in residual stress in the measurement object. Consequently, it is difficult to estimate the external stress acting on the whole object using a local measurement. The authors therefore devised a stress estimation method called as the cosine curve fitting method, as discussed below.

Generally, the distribution of the axial stress component generated over the full circumference of a pipe subjected to a bending moment takes the form of a cosine curve, as illustrated in **Fig. 2**. This means that it is possible to obtain an output voltage in the same cosine curve shape when measured over the full circumference of the pipe with a magnetic anisotropy sensor. This output voltage, V, can be expressed as shown in Eq. (3).

$$V = A + B \cdot \cos(\theta - C) \quad (3)$$

where, θ is the angular position on the pipe and A, B, and C are parameters.

Therefore, the magnitude of bending stress can be extracted and also evaluated as parameter B (amplitude) by statistically processing the output voltage from

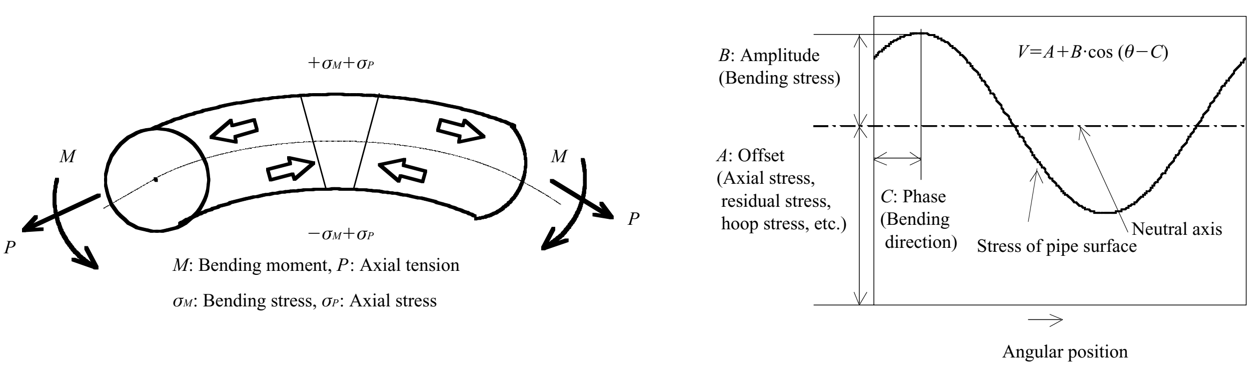


Fig. 2 Conceptual illustration of stress distribution of pipe surface under bending load

the magnetic anisotropy sensor in the regression curve described by Eq. (3). Parameter A uniformly distributes on the pipe surface. It is a kind of offset component which is the sum of axial stress, stress caused by internal pressure, residual stress, the electrical offset of the magnetic anisotropy sensor, etc., and is extremely difficult to separate into individual factors. Parameter C corresponds to the phase angle of the sensor from the measurement starting position and indicates the bending direction of the pipe.

3.2 Experimental Results

The principle described above was confirmed experimentally. The test pipe was an SGP150A pipe. In the experiment, the same section of the pipe was measured with a magnetic anisotropy sensor at a circumferential pitch of 5° in a no-load condition, that is, with no bending stress, and under a 150 MPa equivalent bending stress load. Parameters A, B, and C were obtained by regression in Eq. (3) by the least square method. The results are shown in **Fig. 3**.

According to them, even in a no-load condition, the magnetic anisotropy sensor output gives a certain amount of deviation due to residual stress. However, parameter B, which is the amplitude of the cosine curve obtained by the least square method, in other words, the bending stress component, is sufficiently small and is basically unaffected by this deviation. The measured results under bending load also contain some remaining deviation associated with residual stress, as in the no-load condition. However, a distribution with a clear cosine curve shape was obtained as a whole, as predicted from the theory discussed above. Thus, the bending stress component was successfully extracted and is unaffected by residual stress.

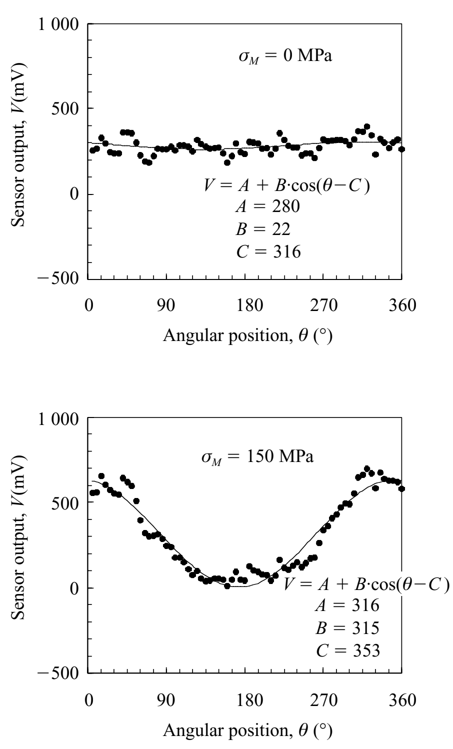


Fig. 3 Sensor output distribution on pipe surface

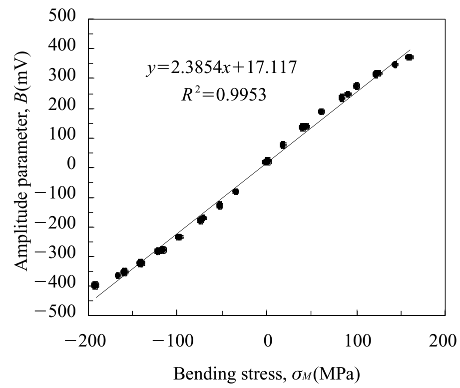


Fig. 4 Relationship between bending stress and amplitude parameter, B

It may be noted that the bending moment in this experiment was applied in such a way that the 90°–270° position formed the neutral axis; that is, bending was applied in the 0°–180° direction. However, parameter C, which indicates the direction of bending, was 353°, which roughly coincides with the loading direction of the bending moment. Parameter A, which is the offset component, showed a slight change when loading was applied, but this was attributed to a moderate axial stress component caused by the loading method. The relationship between the applied bending stress and parameter B obtained by this method is shown in **Fig. 4**. Parameter B shows a substantially linear relationship with bending stress, indicating that parameter B accurately expresses the magnitude of bending stress.

Because the slope of the line in Fig. 4 corresponds to magnetostrictive sensitivity, which was mentioned previously, the magnitude of bending stress can be obtained by dividing parameter B by magnetostrictive sensitivity. In Fig. 4, magnetostrictive sensitivity was obtained by applying a bending moment to an actual pipe. However, a simple method of obtaining magnetostrictive sensitivity using a small test piece cut from part of the pipe has also been established.

3.3 Development of Bending Stress Measuring System

As discussed above, the authors confirmed the possibility of extracting the magnitude and direction of bending stress with high accuracy, unaffected by residual stress, by regression of the magnetic anisotropy sensor output voltage in a cosine curve. A simple magnetostrictive technology for measuring bending stress in pipes in the field, called the “bending stress measuring system for linepipes,” was developed based on this principle.

The system hardware consists of a tracking rail corresponding to the pipe diameter, a scanning head which enables the magnetic anisotropy sensor to scan the pipe while traveling on the rail, and a laptop personal computer for equipment control and analysis of the measured results. The magnetic anisotropy sensor is moved automatically around the circumference of the pipe by the scanning head and measures the stress distribution on the pipe surface. The measured results are analyzed in real time by the personal computer, which displays the magnitude and direction of bending stress.

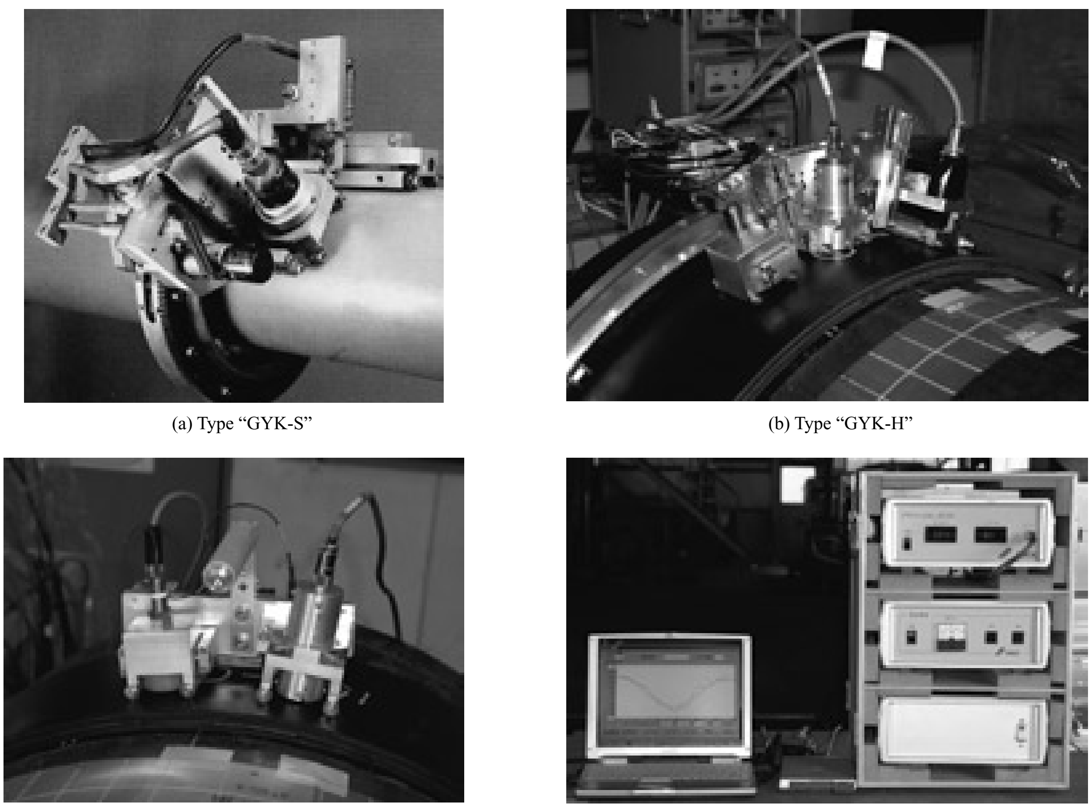
The magnetostrictive sensitivity changes depending on the distance between the sensor and pipe surface or lift-off. However, the developed system is equipped with an automatic compensation function which detects the actual amount of lift-off and corrects the magnetostrictive sensitivity correspondingly.

Three versions of the system have been developed, GYK-S, -H, and -M types. The GYK-S type is used with small- and medium-diameter coated pipes, PLP pipes, and others with the maximum coating thickness of approximately 6 mm. The GYK-H type is applicable to large-diameter pipes and is used with heavy-coating pipes with coating thickness up to 15 mm, enabling direct measurement on the coating without coating removal.

The measuring time depends on the pipe diameter, but the entire process from measurement through anal-

Table 1 Specifications of the bending stress measuring system for linepipes

Controller	Weight	20 kg
	Dimensions	*W*335×*D*345×*H*485 mm
	Operating system	Windows 98, Windows Me, Windows 2000
	Power source	AC100 V, 50/60 Hz, 0.5 kVA
Scanning head	Weight	1.6 kg (GYK-S), 4.4 kg (GYK-H), 1.1 kg (GYK-M)
	Dimensions	*W*180×*D*210×*H*150 mm (GYK-S) *W*300×*D*300×*H*150 mm (GYK-H) *W*200×*D*160×*H*140 mm (GYK-M)
Tracking rail	Applicable pipe size	100 A, 150 A, 200 A, 300 A, 400 A, 600 A, 750 A (GYK-S) 600 A , 750 A (GYK-H) 80 A≧, Using hand-held jig (GYK-M)



(a) Type "GYK-S" (b) Type "GYK-H"

(c) Type "GYK-M" (d) System contoroller and lap-top PC

Photo 1 Types of bending stress measuring system for linepipes ysis can be completed in approximately 2 min with the minimum rail size of 100 A and 4 min with the maximum rail size of 750 A. In cases where it is difficult to attach the rail, the manual-type GYK-M with a handheld jig can be used.

The specifications of the bending stress measuring system for linepipes are shown in **Table 1**, and the appearances of the devices are shown in **Photo 1**.

4. Stress Evaluation Technique for Curved Pipes under Cross-sectional Hooping Using Magnetostrictive Method

The cosine curve fitting method described in Chapter 3 is effective for evaluating bending stress in a straight pipe. However, actual piping systems do not consist only of straight pipes, but frequently include curved pipes called elbows, bends, and others. When moments act on a piping system which includes these curved pipes, in some cases, excess stress is generated in the curved pipes by hooping of the pipe cross-section. The following describes an approach to the measurement of cross-sectional hoop stress in curved pipes.

4.1 Kármán's Theory of Hoop Stress

Kármán's theory of cross-sectional hoop stress (hereinafter called Kármán's Equation) is known as a theoretical explanation of the cross-sectional hoop stress generated in a bent pipe under bending moment.[3–5)]

According to Kármán's Equation, stress in the pipe's longitudinal (axial) direction, σ_L, and that in its circumferential direction, σ_C, can be expressed as follows:

$$\left.\begin{aligned}
\sigma_L &= \frac{kMr}{I}\left\{\sin\phi - \frac{6}{5+6\lambda^2}\sin^3\phi + \frac{9\nu\lambda}{5+6\lambda^2}\cos2\phi\right\}\\
\sigma_C &= \frac{kMr}{I}\left\{\nu(\sin\phi - \frac{6}{5+6\lambda^2}\sin^3\phi) + \frac{9\lambda}{5+6\lambda^2}\cos2\phi\right\}\\
\lambda &= \frac{tR}{r^2}\\
k &= \frac{10+12\lambda^2}{1+12\lambda^2}
\end{aligned}\right\} \quad \cdots\cdots (4)$$

λ : Pipe factor
k : Flexibility factor
ν : Poisson's ratio
R : Curvature radius of curved pipe
r : Pipe radius
t : Pipe wall thickness
I : Moment of inertia of pipe cross section
M : Moment applied to curved pipe
ϕ : Angular position on pipe (Curved pipe side = 0°)

A modified version of the equation presented above, considering the effect of internal pressure and high-order approximation analysis, has also been proposed.[6)]

It is therefore considered possible to evaluate the distribution of hoop stress by measuring the whole circumference of a curved pipe subjected to bending moment with a magnostrictive sensor and statistically processed the measured results to regress in Eq. (4).

4.2 Experimental Results

The possibility of evaluating cross-sectional hoop stress in a curved pipe by Kármán's Equation using the magnetostrictive method was confirmed experimentally.[7)] The test pipe was a 90° long elbow of 300 A pipe. An in-plane deformation load was applied in a testing machine. The stress at the central section of the curved pipe subjected to load was measured by the strain gauge method and the magnetostrictive method, and the results were compared.

As an example, **Fig. 5** shows the measured results for a curved pipe subjected to inward bending (direction of closing the curved pipe), named with the back side (outer side) of the pipe as 0° and the belly (inner side) as 180°. When regression was performed on the measured results obtained by the magnetostrictive method, the result showed an approximate agreement with the stress obtained by the strain gauge method and no effect by the

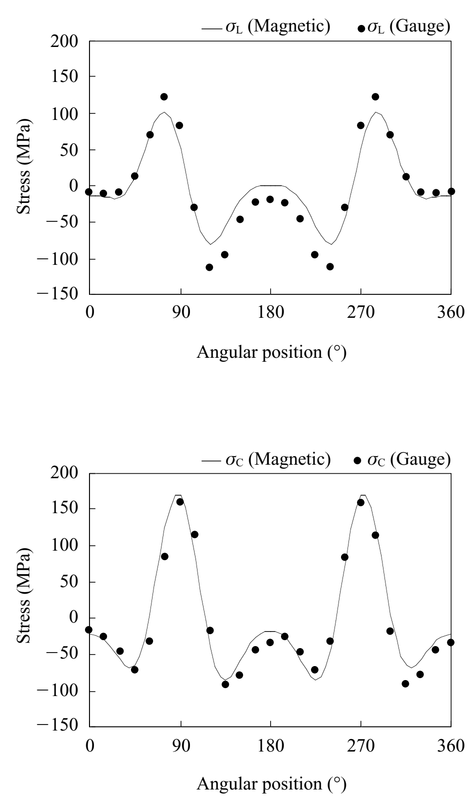


Fig. 5 Stress distribution on curved pipe surface under bending load

residual stress in the pipe.

5. Linepipe Safety Evaluation Method

Under practical conditions, various factors limit the locations where stress measurements can be performed on linepipes. For such cases, a combination of direct stress measurement/evaluation by the magnetostrictive method and the finite element method (FEM) calculation is effective. The following presents examples of techniques in which the magnetostrictive method is applied under the actual working conditions:

5.1 Bridge Crossing with Pipe

Linepipes are generally laid underground. However, at a river crossing, the pipe may be constructed as part of a roadway bridge or an exclusive-use linepipe bridge as shown in **Fig. 6**. Although bridge abutments and pier foundations are strong and secure, there are cases in which non-uniform subsidence occurs at the back side of the abutments due to compaction (consolidation) of the ground. In such cases, the linepipe is affected by a bending moment, with the passage through the abutment acting as a fulcrum, generating bending stress in the pipe.

The linepipes constructed on bridges are normally accessible for measurement, as the pipes are left exposed with painting or coating for protection. Therefore, the following method is used in stress evaluations:

(1) At bridge parts ①, ②, and ..., where the pipe is accessible, stress is measured and evaluated directly by the magnetostrictive method.
(2) The amount of subsidence at the back side of the bridge abutment is given by an FEM calculation, and the amount of subsidence at which the stress in the bridge section of the pipe agrees with the measured values in (1) is obtained.
(3) The stress distribution in the linepipe system as a whole is verified, assuming that the calculated subsidence in (2) corresponds to actual subsidence.

As a simpler method, measurement is made at the same locations on the bridge are evaluated by the magnetostrictive method periodically, for example, once/year, and the progress of bending stress is monitored. This information is also effective as a reference for determining maintenance control policy.

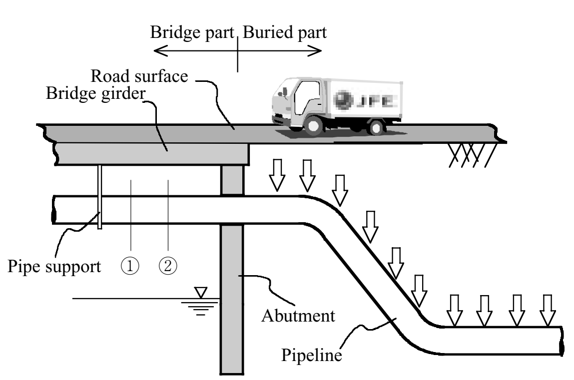


Fig. 6 Conceptual illustration of application to pipeline across the river

5.2 Support Adjustment

In factory piping systems, plant piping, pipelines laid in culvert, etc., pipes are fixed to the foundation by supports. However, in some cases, non-uniform subsidence causes bending stress and cross-sectional hoop stress in piping systems of these types.

In the conventional method, these pipeline systems are controlled by measuring the amount of pipe subsidence, estimating stress from the measured subsidence by FEM analysis, and adjusting the level of the supports (stress relieving) when the estimated stress exceeds the control value.

With systems of this type, direct evaluation/control is possible by evaluating bending stress and hoop stress at an arbitrarily selected position by the magnetostrictive method, which can be applied without removing the pipe coating. The magnetostrictive method can also be used to monitor stress changes in real time during stress relieving work, making it possible to optimize stress relieving and confirm the effectiveness of work.

6. Conclusion

This paper describes the principle of stress measurement in linepipes by the magnetostrictive method and a stress measurement system for linepipes applying this technology. Experimental results confirming the effectiveness of the magnetostrictive method and examples of practical application under working conditions were also presented.

The key features of the magnetostrictive method may be summarized as follows:

(1) Bending stress in a straight pipe can be measured and evaluated without removing the pipe coating.
(2) Stress due to cross-sectional hooping deformation in a curved pipe can be measured and evaluated without removing the coating.
(3) Measurement work is simple, and evaluation can be performed in an extremely short time.
(4) The entire system is lightweight and compact and has excellent portability in the field.

Taking advantage of the features of the magnetostrictive method described above, this technology has already been applied at a wide variety of sites, including gas pipelines, plant piping, waterworks pipelines, water conduit pipes, steel pipe piles, and others, and had a record of actual use at approximately 450 sites as of the end of Mar. 2003.

When applied in linepipe stress control, the magnetostrictive method enables more accurate and appropriate maintenance control by providing direct information on stress, in addition to conventional indirect information such as age, ground conditions, environmental conditions, and subsidence. In the future, the authors intend to expand the range of application of this technology through continuing improvement.

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