EFFECT OF AN ALTERNATING EXCITATION AND THE APPLICABILITY OF A MAGNETOSTRICTIVE TRANSDUCER FOR A LONG-RANGE GUIDED WAVE INSPECTION

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Abstract

There are several incidents regarding a leakage of pipes which are in the category of a safety class as well as a non-safety class in nuclear power plants. However, in many cases, because of their geometrical complexity and inaccessibility, it is difficult to inspect them by the conventional ultrasonic methods. The magnetostrictive transducer technique has several advantages for practical applications, such as a 100-percent volumetric coverage of a long segment of a structure, a reduced inspection time and its cost effectiveness, as well as relatively simple structure. Recently it has been found that the magnetostrictive properties of Fe-Co-V alloy showed superior to the conventional Ni strip. The guided wave signal amplitudes by the Fe-Co-V alloy strip are much higher than those of the Ni strip. However, the alternating excitation should be kept as low as possible to avoid unwanted vibration modes. In this paper, the effect of an alternating excitation on the DC bias magnetization of the Fe-Co-V alloy strip was investigated. In order to apply a DC magnetization along the circumference of a small bore tube, an automotive battery is used to bring the Ni strip to a saturated magnetization. In addition, an in-bore torsional guided wave probe was applied to an inspection of a heat exchanger tube. The signal quality was not good enough to compare the case of DC magnetization along the circumference by using a high power DC supply. However, it has a good advantage in that the in-bore guided wave probe can be accessed from the inside of the tube and it can be used for screening purposes such as a heat exchanger inspection.

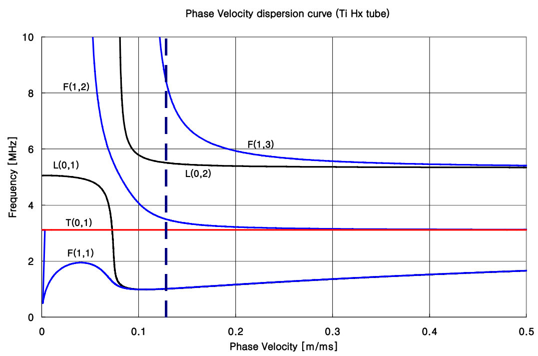
1. Introduction

Long-range guided wave inspection technique is a much more effective method for rapidly surveying a piping for defects such as cracks and corrosion pits [1]. These techniques are currently being applied to develop long-range inspection systems for applications in areas such as a non-destructive evaluation and health monitoring of large metallic structures. Guided waves refer to mechanical waves that propagate in a bounded medium (pipe, rod, tube, plate) parallel to the plane of its boundary. Since the wave is guided by the geometric boundary of a medium, it's geometry has a strong influence on the wave characteristics.

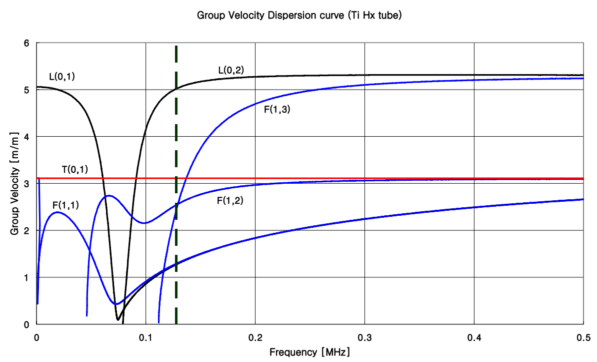
A guided wave method could be a solution, therefore an axial guided wave technique for a pipe or a tubular structure for a long-range nondestructive testing and an evaluation method has been actively developed over the last two decades [2-5]. Because an infinite number of vibration modes are theoretically possible and the dispersion characteristics of the guided wave, where the propagation velocity of the modes are changed with the frequency and the thickness, the dispersion relationship should be determined and the inspection parameters should be optimized. A computer program for a calculation of the dispersion curve has been developed and the dispersion curves of the phase velocity and the group velocity were calculated for a known dimension and bulk wave velocity of a pipe, as shown in Fig. 1 [6]. The modes and frequencies can be optimized from the dispersion curves.

Among the numerous vibration modes and frequencies, a torsional vibration mode can be selected for a field implementation. Because the torsional vibration mode, T(0,1) has no dispersion characteristics, such as no velocity change with the frequencies, a sharp signal pattern can be obtained in the time domain. In addition, the acoustic energy is less affected by the outer medium during a propagation along a pipe because the wave structure of the T(0,1) mode has no radial displacement component, like that of a shear horizontal (SH) mode in a plate. This fact has an advantage in a field inspection especially when the pipe is filled with water or the pipe has insulation on the outer surface. Therefore, the T(0,1) vibration mode can travel a longer distance with a lesser attenuation.

However, it is not easy to fabricate a transducer with conventional piezoelectric elements. They are generally very expensive because they require a special array transducer with many piezoelectric elements with an accurate electronic control. The electromagnetic acoustic phenomena can be used for a generation and reception of the T(0,1) mode in a pipe. The magnetostrictive transducer technique uses a probe that generates and detects guided waves electromagnetically in the test pieces. In this paper, an applications of a magnetostrictive transducer technique with the T(0,1) mode and the L(0,1) mode for a long-range guided wave inspection of a small-bore tubes in a nuclear power plant are presented.



(a) Phase velocity dispersion curve



(b) Group velocity dispersion curve

Fig. 1 Dispersion curves of a heat exchanger tube with an outer-diameter of 20.1mm and a wall thickness of 0.71mm (Material: Titanium).

2. Magnetostrictive Transducer Technique

The magnetostrictive transducer technique is a practical tool for a generation and reception of a guided wave in a material under testing. For a wave generation, it relies on the magnetostrictive (or Joule) effect: the manifestation of a small change in the physical dimensions of the ferromagnetic materials, in the order of several parts per million in carbon steel, caused by an externally applied magnetic field. For receiving elastic waves, it relies on the inverse magnetostrictive (or Villari) effect: a change in the magnetic induction of a ferromagnetic material caused by a mechanical stress or strain [1].

The magnetostrictive transducer requires that the ferromagnetic material being tested is in a magnetized state. This is achieved by applying a direct current bias magnetic field to a material by using either a permanent magnet (an electromagnet) or a residual magnetization induced in a material. A direct current bias magnetization is necessary to enhance the transduction efficiency of a transducer. The operating wave mode of the magnetostrictive transducer is controlled by a relative alignment between the direct current bias magnetic field and the time varying magnetic field produced by a transducer.

The principle of the magnetostrictive transducer for a generation of the torsional vibration mode is illustrated in Fig. 2. The transducer is configured to apply a time varying magnetic field to the material under investigation. Also it picks-up the magnetic induction changes in a material caused by the guided wave. For the torsional vibration T(0,1) mode in a pipe, the magnetostrictive transducer is ring-shaped (a nickel foil magnetized along the circumferential direction) and it utilizes a coil that encircles the pipe, as shown in Fig. 2.

Generation and reception of the guided wave signals are controlled to operate it in one direction so that the area of the structure on either side of the transducer can be tested separately. The wave direction control is achieved by employing two coils with a gap of one quarter of the wavelength (1/4λ) for a specific frequency, as illustrated in Fig. 2, and the phase array principle in the magnetostrictive transducer instrument. From the viewpoint of a practical application to the pipe, if the gap between the two coils is too short to apply it to an actual pipe due to a finite width of the ferromagnetic strip, it can be three-quarters of the wavelength (3/4λ), but applying the two coils with an alternating current of an opposite direction.

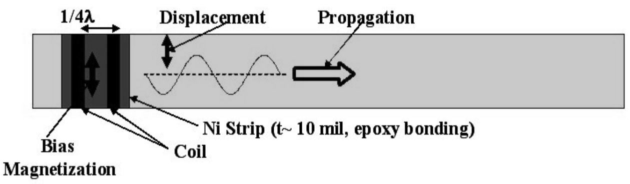


Fig. 2 A schematic design for the torsional vibration mode with a magnetostrictive transducer.

For the longitudinal wave modes in a cylindrical test piece and the Lamb wave modes in plates, a parallel alignment is used. Fig. 3 shows the setup for the longitudinal vibration mode with a magnetostrictive transducer. A set of yoke-type permanent magnets made of Nd-Fe-B alloy is used for a DC bias magnetization along the longitudinal direction in the tube. The guided waves propagate in a direction parallel to the direction of the time varying magnetic field produced by the magnetostrictive transducer.

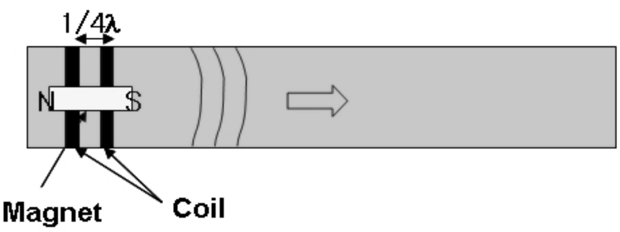


Fig. 3 A schematic design for a longitudinal vibration mode with a magnetostrictive transducer.

3. Experimental Setup

3.1.1. Effect of alternating excitation

Because the alternating excitation power should not exceed the DC magnetic bias in the strip there is a limitation for a high power electrical excitation. For the investigation to obtain an optimum parameter, an alternating excitation was varied by a serial connection of a variable potentiometer.

In order to investigate the effect of an alternating current when compared to a DC bias magnetization, a Fe-Co-V alloy strip was bonded to a straight carbon steel pipe with an outer-diameter of 63.5 mm, a wall thickness of 6.5 mm and length of 6 m. The strip was located at 1/3 of the pipe, so reflections from the pipe end appear every 2 m position.

3.1.2. DC bias magnetization along the circumference for a small bore tube

A DC bias magnetization along the circumference of a tube is required for a generation of a torsional vibration mode, T(0,1). Generally, a circumferential magnetization of a magnetostictive strip can be achieved by moving a permanent magnet along the circumference. Practically, however, it is not easy for a tube with a small diameter.

Alternatively a high current along the axial direction can generate a circumferential magnetization. A DC electric current source, such as an automotive battery or a DC power supply that can supply at least 50 Amperes of DC current can be used for this purpose. One should be careful so as to prevent the wires from overheating, thus one should not apply the DC current more than 4 second.

A 304 stainless steel tube for a heat exchanger with dimensions of an outer-diameter of 20.1 mm, wall thickness of 0.7 mm and length of 6 m was used for the experiment. An automotive battery of 200 Amperes was used for the circumferential DC bias magnetization.

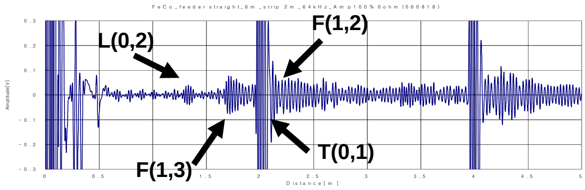
3.1.3. In-bore torsional guided wave probe

In order to apply the torsional guided wave from the inside of a heat exchanger tube, a probe consists of a hollow cylinder waveguide, magnetostrictive strip, and drawbar mechanism [7]. The magnetostrictive probe installed on the hollow cylindrical waveguide generates and detects torsional waves in the waveguide. This waveguide is expanded by the drawbar to create an intimate mechanical contact between the waveguide and the inside surface of the tube being tested. To allow for an expansion of the waveguide at the tip, the tip area is longitudinally slit at several orientations around the waveguide circumference. The torsional wave pulse generated by the magnetostrictive strip propagates towards the end of the waveguide inserted into the tube and is coupled to the tube through the mechanical contacts formed at the tip area and then it propagates along the length of the tube. The reflected signals are detected by the magnetostrictive transducer via a inverse process. A damping material is placed on the end of the waveguide opposite the inserted end to minimize the wave reverberations in the waveguide.

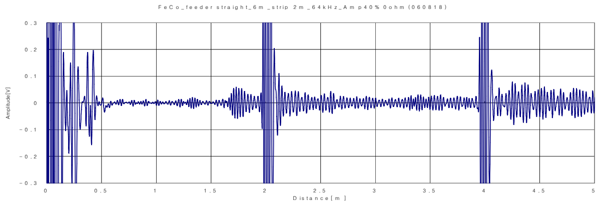
4. Results and Discussion

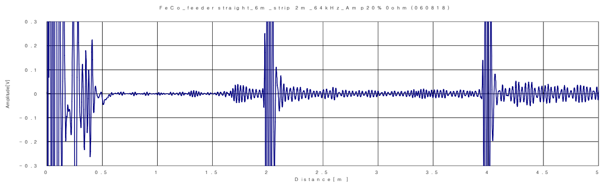
4.1.1. Effect of an alternating excitation

Because the magnetostrictive properties of Fe-Co-V alloy strip are much superior to the Ni strip, we can expect a higher intensity of the reflections. However, one should be careful when applying an alternating magnetization because the coercive force of Fe-Co-V alloy is much less than that of the Ni strip in the magnetic hysteresis curve.
If the alternating magnetization exceeds the coercive force, an unwanted signal or different vibration mode might appear in the time domain.
The effect of an alternating magnetization is shown in Fig. 4. If the alternating voltage is 300 Vpp with a frequency of 64 kHz, an unwanted vibration mode, L(0,2), F(1,3), and F(1,2) modes are generated in addition to the T(0,1) mode. This can be seen from the group velocity dispersion curve, shown in Fig. 5.
Except for the torsional vibration mode, T(0,1), longitudinal or flexural vibration modes are possible at the frequency of 64 kHz. They can be correlated to the signals with a different time, based on their dispersion curves.



(a) 300 Vpp


(b) 120 Vpp


(c) 60 Vpp

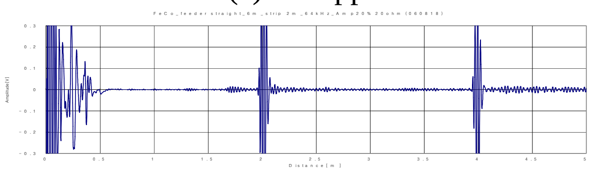

(d) 60 Vpp and 20 Ω attenuator

Fig. 4 Effect of alternating voltage.

The shape of a signal can be analyzed by the dispersion characteristics of each mode. The L(0,2) mode has a little dispersion characteristics at a frequency of 64 kHz, which results in a relatively sharp signal shape. In contrast, the flexural vibration modes, F(1,3) and F(1,2) mode at the operating frequency show drastic dispersion characteristics, which results in a broad signal shape.
When we apply 300 Vpp, which is the highest alternating voltage, L(0,2) and F(1,3) modes appear earlier and F(1,2) mode appears later on the basis of the T(0,1) mode signal. As the voltage decreases, these flexural vibration modes and the longitudinal vibration mode decrease and eventually disappear.
It should be noted that the alternating excitation should be kept as low as possible to avoid unwanted vibration modes.

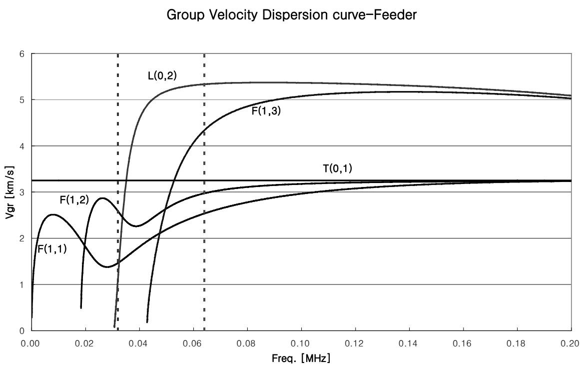


Fig. 5 Group velocity dispersion curve for a carbon steep pipe with an outer-diameter of 63.5 mm, a wall thickness of 6.5 mm.

4.1.2. Circumferential magnetization for a small bore tube

A Ni strip was bonded to a stainless steel tube with an epoxy glue and DC magnetized circumferentially by using an automotive battery. The capacity of 200 Ampere of the battery is believed to be enough to create a saturated magnetization of Ni strip.

The guided wave signals obtained from the wear notches in a 6-m long stainless steel heat exchanger tube by using a magnetostrictive transducer technique are shown in Fig. 6. Since the Ni strip was located 150 mm from the end of the tube, several peaks were observed. They can be correlated to the different beam paths, shown in Fig. 7.

The number of cycles for an excitation was set as one. From the enlarged signal shape shown in Fig. 8, it can be concluded that the signal shape was not changed regardless of the wave reflected from the end of tube several times

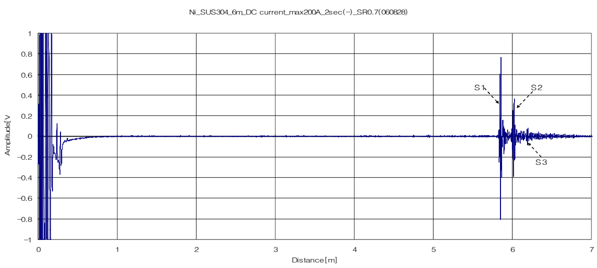


Fig. 6 Signals from the stainless steel tube by a circumferentially bias magnetized Ni strip.

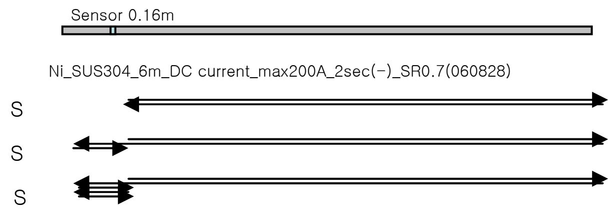


Fig. 7 Explanation of different signals with different beam path

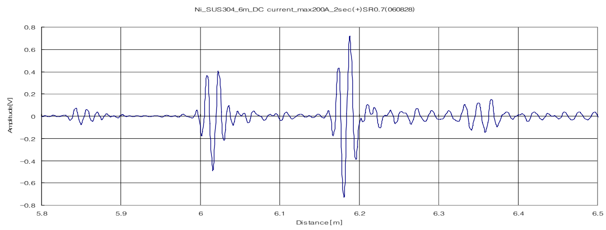


Fig. 8 Enlarged signal shape from different reflection of the tube end.

4.1.3. In-bore torsional guided wave probe

Fig. 9 shows the ultrasonic signals obtained from a stainless steel tube using an in-bore torsional guided wave probe. The dimensions of the tube are an outer diameter of 22.23 mm, wall thickness of 1.2 mm, and length of 6 m. The signals at and near the zero distance are those reflected from the probe tip and reverberating in the waveguide of the probe. The signal reflected from the far end of the tube is indicated as the 'tube end'. The dead zone caused by the tip reflected and reverberating signals in the probe was approximately 500 mm.

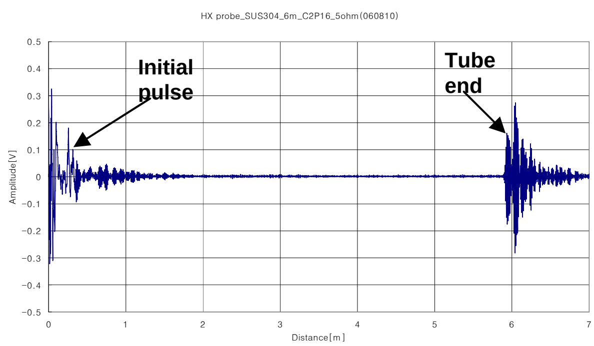


Fig. 9 Signal from stainless steel 304 heat exchanger tube using in-bore torsional guided wave probe.

5. Summary

a) The effect of an alternating excitation when compared to DC bias magnetization was investigated. Even though the Fe-Co-V alloy strip shows much higher signals then the Ni strip, one should be more careful when applying an alternating excitation. It is noted that the alternating excitation should be kept as low as possible to avoid unwanted vibration modes.

b) In order to apply a DC magnetization along the circumference of a small bore tube, an automotive battery is believed to be enough to create saturated magnetization in a Ni strip.

c) In-bore torsional guided wave probe was applied to a heat exchanger tube. The signal quality was not good when compared to the case of a DC magnetization along the circumference by using a high power DC supply. However, the in-bore guided wave probe can access the inside of a tube, so it can be used for a screening purpose for a heat exchanger inspection.

Acknowledgements

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6. References

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