MEASUREMENT AND GENERATION OF TORSIONAL WAVES FOR PIPE DAMAGE DETECTION BY MEANS OF A NEW OBLIQUELY-ORIENTED MAGNETOSTRICTIVE STRIP CONFIGURATION

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Abstract: The objective of this investigation is to develop an efficient method to generate and measure torsional waves in non-ferromagnetic pipes by using magnetostrictive transducers. In the conventional method to generate torsional waves in pipes, a nickel strip is bonded circumferentially to the test specimen and pre-magnetized along the circumferential direction by permanent magnets. Then, the application of the alternating current onto the solenoid coil encompassing generates tensile waves at some angle relative to the pipe axis. If the applied current is appropriate, the generated tensile wave is converted into the desired torsional waves. Though this method is very useful, it has some disadvantages. Among others, it requires the pre-magnetization of the strip, which is not desirable for long-term on-line inspection. To overcome this problem, we propose a new strip configuration; several pieces of nickel strips are bonded at oblique angles with respect to the pipe axis. Because the strip is so oriented that the applied current onto the surrounding solenoid coil can generate torsional waves without the pre-magnetization of the nickel strips. The validity of the proposed transducer configuration as well as its good performance is verified through a series of experiments.

Introduction: The guided-wave technology becomes a powerful tool for the non-destructive inspection of cylindrical waveguides such as pipes and tubes.[1-4] Since guided waves can travel over several meters without significant attenuation, a large portion of a waveguide can be efficiently inspected. For waveguide inspection, various wave modes such as longitudinal, torsional, and flexural modes can be employed, but the non-dispersive first branch of the torsional wave mode is the most attractive. However, the torsional wave itself is difficult to generate compared to longitudinal waves, so it has been used only in limited applications. Motivated by this, we are concerned with the efficient generation and measurement of torsional waves in a waveguide. The specific objective in this investigation is to develop a new method to generate and measure the torsional waves using the magnestostrictive nickel patches, so a new magnetostrictive transducer configuration will be proposed.

The magnetostriction effect or the Joule effect[5] is the phenomenon in which a piece of ferromagnetic material elongates or shrinks when it is placed under a magnetic field. The inverse magnetostriction effect or the Villari effect[6] is the reverse phenomenon of the Joule effect. Although the magnetostrictive transducers (including sensors) have been applied and studied in many cases,[7-11] the transducer has been investigated only recently by Kwun[12] for the generation of torsional waves and its application for damage detection. Kwun's transducer consists of a nickel strip and a solenoid coil surrounding the strip as shown in Fig. 1. The strip is bonded circumferentially to a test specimen such as a pipe, and a permanent magnet is rubbed on the nickel strip for pre-magnetization. Though his transducer has been successful, there exists the problem of adjusting the alternating current which is sent through the solenoid coil to generate torsional waves. In addition, the nickel strip always needs be pre-magnetized before the transducer is used. Therefore, the transducer is not suitable for long-term on-line monitoring of underground pipes.

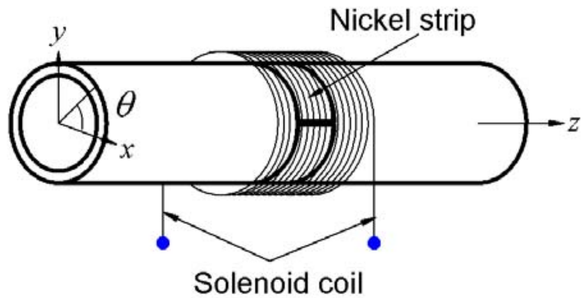

Figure 1 Kwun's magnetostrictive transducer for generating and measuring torsional waves.

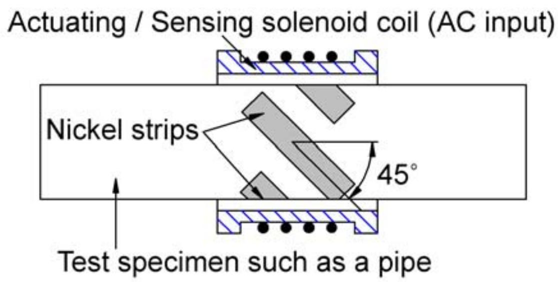

Figure 2 The proposed magnetostrictive transducer for generating and measuring torsional waves

To overcome the above-mentioned drawbacks, a new transducer configuration shown in Fig. 2 is proposed. Several pieces of nickel strips are attached to the test specimen at the orientation of 45 degrees from the axis of the test specimen. Different orientation angles may be considered, but we will mainly work with the orientation of 45 degrees in this work. By bonding the strips at an oblique angle, pre-magnetization is not needed and the generated wave mode can be insensitive to the magnitude of the current input to the solenoid coil. The sensitivity of the proposed transducer improves when a bias magnetic field is applied. In this work, the damage location estimation in aluminum pipes was considered as a practical application. To verify the performance of the proposed transducer, several experiments were performed.

Theoretical background: Among several wave modes generated in a waveguide, the first branch of the torsional wave mode is completely non-dispersive as shown in Fig. 3. Therefore, the group velocity of the wave belonging to the first branch is independent of frequency. Since no other wave mode or branch has the non-dispersive characteristics, it is best to use the pulse that can be decomposed within the first branch of the torsional wave mode for long-range damage detection. The proposed transducer uses the magnetostrictive effects in actuating and measuring torsional waves, so the physics of the magnetostrictive effects such as the Joule effect and the Villari effect should be explained. The Joule effect[5] refers to the phenomenon of the dimension change of a piece of ferromagnetic material when it is placed under a magnetic field. The Villari effect[6] represents the inverse phenomenon of the Joule effect.

The Joule effect and the Villari effect may be expressed by the following two equations for one-dimensional situations:

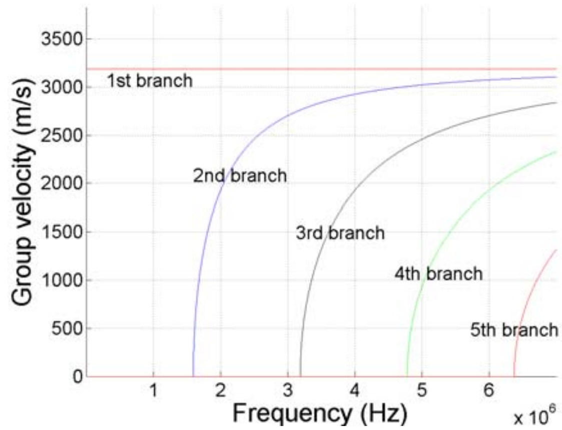

Figure 3 The group velocity of the torsional wave in an cylindrical aluminum shell with the inner and outer radii $a = 11.5$ mm and $b = 12.5$ mm.

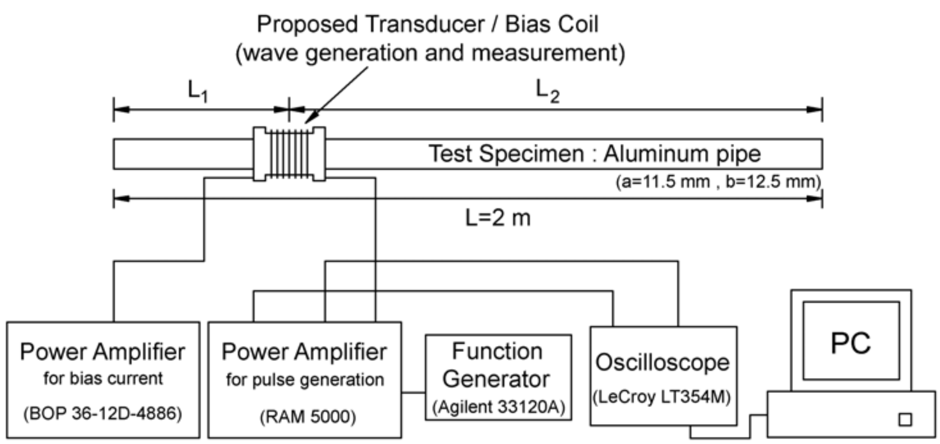

Figure 4 The schematic diagram of the experimental setup

$$\varepsilon = \frac{\sigma}{E^H} + q^* H \tag{1}$$

$$B = \mu^\sigma H + q\sigma \tag{2}$$

where ε, σ, B, and H represent the strain, stress, magnetic flux density and magnetic strength, respectively. The material constants E^H, q^*, μ^σ, and q denote Young's modulus under a constant magnetic strength, the coupling coefficient of the Joule effect, the permeability under a constant stress and the coupling coefficient of the Villari effect, respectively. A general theory on the magnetostrictive effect including the analysis of hysteresis and irreversibility can be found in Jiles.[13]

The elastic deformation or wave in a ferromagnetic material can be converted to voltage change by means of solenoid coil surrounding the material. The stress developed in the ferromagnetic material will change its magnetic state and the resulting magnetic flux Φ enclosed by the solenoid coil can be measured by the Faraday-Lentz law to give the voltage change V between the two ends of the sensing solenoid coil:

$$V = -\frac{d\Phi}{dt} = -\frac{d}{dt}(N\phi) \tag{3}$$

where t is the time, N is the number of solenoid coil turns, and ϕ is the magnetic flux encircled by a single turn of the coil. The magnetic flux ϕ is an integral of the magnetic flux density B over the cross-sectional area enclosed by the solenoid coil.

Experimental setup: Figure 4 shows the schematic diagram of the experimental setup. Experimental measurements of the torsional wave were made on an aluminum pipe (length L=2 m, outer radius b=12.5 mm, thickness t=1 mm). The transducer installed in Fig. 4 is the proposed magnetostrictive transducer consisting of the nickel strips and the solenoid coil in Fig. 2. The length and outer diameter of the coil of 64 turns are 19.2 mm and 28 mm, respectively, and the coil serves both as the actuating coil and the sensing coil. The dimensions of nickel strip are: length of 25 mm, width of 3 mm, and thickness of 0.15mm. Four pieces of nickel strips are bonded to the aluminum pipe at the orientation of 45 degrees by epoxy (Model: 3M DP460). The bias coil was installed to supply the static bias magnetic field and the bias current was at 0.5 A.