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Review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguides

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ABSTRACT

A magnetostrictive patch transducer (MPT) is a transducer that exploits the magnetostrictive phenomena representing interactions between mechanical and magnetic fields in ferromagnetic materials. Since MPT technology was mainly developed and applied for nondestructive ultrasonic testing in waveguides such as pipes and plates, this paper will accordingly review advances of this technology in such a context. An MPT consists of a magnetic circuit composed of permanent magnets and coils, and a thin magnetostrictive patch that works as a sensing and actuating element which is bonded onto or coupled with a test waveguide. The configurations of the circuit and magnetostrictive patch therefore critically affect the performance of an MPT as well as the excited and measured wave modes in a waveguide. In this paper, a variety of state-of-the-art MPT configurations and their applications will be reviewed along with the working principle of this transducer type. The use of MPTs in wave experiments involving phononic crystals and elastic metamaterials is also briefly introduced.

Contents

1. Introduction

Magnetostrictive transducers operate in accordance with the magnetostrictive principle. They have been used to generate and measure ultrasonic waves at frequencies ranging between roughly 20 kHz and 1–2 MHz for nondestructive testing (NDT) of waveguides such as pipes and plates. This paper reviews the underlying physics of the magnetostrictive phenomena and the state-of-the-art magnetostrictive patch transducers (MPTs) with various applications for nondestructive testing of waveguides.

Magnetostriction is a coupling phenomenon involving a magnetization process and dimension/shape change in ferromagnetic materials such as iron, nickel, and cobalt [1,2]. As illustrated in Fig. 1(a), a ferromagnetic material exhibits a change in its length (size) if it is subject to an external magnetic field. The size-changing effect is called the “Joule effect” [3]. On the other hand, the “Villari effect” [4] that is illustrated in Fig. 1(b) refers

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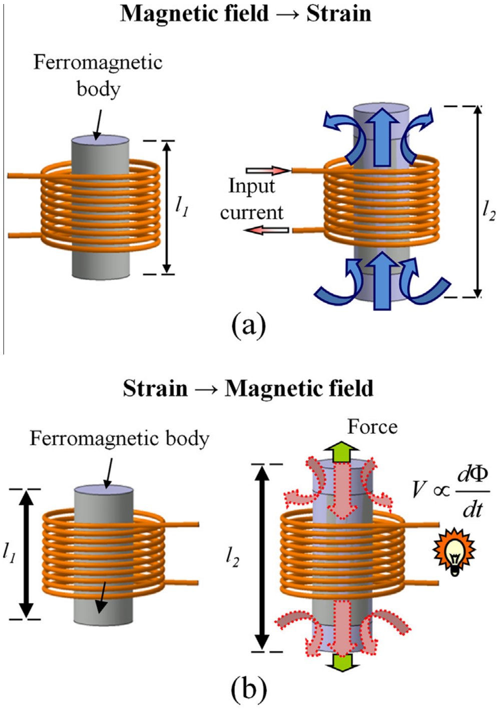

Fig. 1. Schematic descriptions of (a) Joule effect and (b) Villari effect.

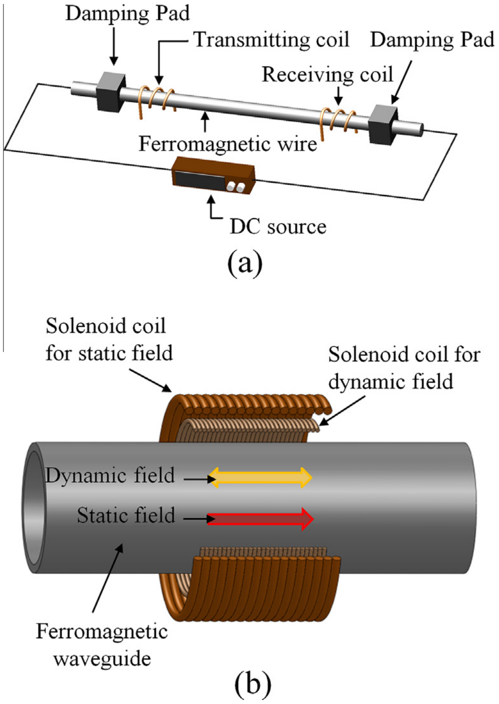

Fig. 2. (a) A setup to generate and measure a torsional wave in a ferromagnetic rod according to the Wiedemann and its reversed effects. (b) The generation and sensing of a longitudinal wave in a ferromagnetic pipe using magnetostrictive phenomena.

to the reverse phenomenon such that if there is any change in the length (size) of a ferromagnetic material, the material induces a magnetic field. When a ferromagnetic material is subject to a static magnetic field in one direction and a dynamic field from a direction orthogonal to the direction of the static field, a shearing deformation is developed in the material; this phenomenon is called the "Wiedemann effect" [5]. It was originally observed in a direct-current-flowing rod subjected to a time-varying longitudinal magnetic field as illustrated in Fig. 2(a); Fig. 2(a) is a sketch of the experimental setup that is used to measure a torsional wave in a rod, as depicted in [6]. The developed shearing deformation created by the Wiedemann effect results in a torsional wave in the rod. In this paper, all of these phenomena, whereby a magnetization process and mechanical deformation are coupled in a ferromagnetic material—either in sequence or *vice versa*—will be referred to as "magnetostrictive phenomena," unless there is a need to explicitly distinguish.

The first application of the magnetostrictive phenomena was possibly made in a magnetostrictive delay line [7,8] and the phenomena have been widely applied in the design of sensors that measure position, mass, field and others. (Refer to [9,10] for more comprehensive reviews on this subject.) The development of materials that exhibit strong magnetostrictive effects, such as Terfenol-D that is a giant magnetostrictive iron–terbium–dysprosium alloy [11], led to the popularity of actuators, transducers, and motors which were reliant upon magnetostrictive phenomena for their operation [12–15]. Studies on magnetostrictive-material characterization [16] and constitutive modeling [17–21] were also published.

Since magnetostrictive phenomena were used for the generation and measurement of guided waves [6,22,23], significant progress has been made in the development of magnetostrictive transducers which excite and measure guided waves for nondestructive testing (NDT) applications. Compared with other popular transducers used for NDT, such as piezoelectric transducers, magnetostrictive transducers have the following advantages: good sensitivity, durability, the absence of direct wiring to a transducer or test specimen, long-range inspection, easy implementation, and cost-effectiveness [24]. Since the operation of a magnetostrictive transducer involves a magnetic field for the generation and sensing of mechanical waves in a test specimen, it is often perceived as a kind of electromagnetic acoustic transducer (EMAT). In a non-ferromagnetic conductive material which is subject to a static bias magnetic field, an applied dynamic magnetic field induces the Lorentz force within it, thereby generating mechanical waves; the reversed mechanism of EMATs is used to sense elastic wave motions. In the case of a ferromagnetic material, an applied magnetic field induces magnetostriction as well as the Lorentz force, but magnetostriction is usually the dominant mechanism of ultrasonic wave transduction. In this paper, the term "EMAT" will be used to designate transducers that mainly use the operational Lorentz-force mechanism, while the transducers that mainly or solely use the operational magnetostrictive phenomena will be called "magnetostrictive transducers," unless stated otherwise.

In Figs. 2–4, a number of transducers and experimental settings that use magnetostrictive phenomena to generate and measure elastic waves in waveguides are schematically shown; in Fig. 2, elastic waves are generated and measured by the magnetostrictive phenomena of ferromagnetic waveguides. In Figs. 3 and 4, however, transducers that use thin magnetostrictive patches which are bonded onto or coupled with waveguides are shown; in these cases, the magnetostrictive effect and its reverse effect mainly occur in the patch. Elastic waves can therefore be excited and measured in both ferromagnetic and non-ferromagnetic waveguides if magnetostrictive "patch" transducers, as shown in Figs. 3 and 4, are employed. For convenience, magnetostrictive transducers with (Figs. 3 and 4) and without (Fig. 2) magnetostrictive patches will be denoted by "MPT" and "MsT," respectively.

While this paper is focused on MPTs, it is worth examining the development of MsTs because the operating principle is basically the same. Kwun and his colleagues pioneered MsT technology by demonstrating the generation and measurement of various wave