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An overview of magnetostriction, its use and methods to measure these properties

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Abstract

The paper provides a description of the magnetostriction effects, and an explanation why it occurs. It lists a number of devices where the properties have been put to use, and describes a range of methods which have been used to measure these properties.

Keywords: Magnetostriction; Magnetic field strength; Magnetic sensors and actuators

1. Introduction

A magnetostrictive material will change shape when it is placed in a magnetic field. Most ferromagnetic materials exhibit some measurable magnetostriction. Since the phenomenon involves a bidirectional energy exchange between magnetic and elastic states, these materials provide a mechanism both for actuation and sensing applications. They are also successfully employed in a wide variety of devices for vibration control of mechanical equipment.

The nature of this effect is illustrated in Fig. 1. A rod of a magnetic material of length L, is shown surrounded by a coil of wire carrying an electrical current so that a magnetic field, H, is produced along the rod [1]. With the current flowing, the length of the rod increases by a small amount ΔL. The strain $\Delta L/L$ is called the magnetostriction (for which the symbol λ is used).

Fig. 1(a) also shows that in addition to an increase in length in the direction of the field, there is also, usually a decrease in length in the perpendicular directions, and as a result of this, the volume of the rod remains nearly, but not quite, constant. Fig. 1(b) also reveals two important features of magnetostriction: firstly for high values of H, λ eventually reaches a constant value λ_{sat}, indicating saturation, and secondly the sign of λ does not change when the field H becomes negative. The rod increases in length for both positive and negative values of the magnetic field strength. (Magnetostriction is therefore a second order effect [2].)

The principal magnetostrictive effects observed experimentally are: (1) The Joule effect. This can be an extension or a contraction in the same direction as the magnetic field or in some other direction. (2) The volume effect (volumetric expansion), a very weak effect. (3) The Wiedemann effect (a shear strain response to the magnetic field, analogous to the tensile or compressive strain produced in the Joule effect). In addition, inverse effects are also observed, such as the Villari effect. In this case there is a change in magnetic permeability in response to an applied stress. This is also referred to as a magnetostrictive effect or a magnetomechanical effect. For most transducer applications the maximum force or movement are desired as outputs, and so the Joule effect or its inverse, the Villari effect are the most useful in technology. Therefore the discussion that follows will concentrate primarily on these effects. Information on other effects can be found in reference [3].

2. An explanation why magnetostriction occurs

The two largest contributions to magnetic effects arise because of the movements of unpaired electrons. Because electrons spin, a magnetic field is produced, and because electrons also move in orbitals around the atomic nucleus, another magnetic field is also produced. There is an interaction between these magnetic fields, which causes the spins of different unpaired electrons close to each other to align along the same direction, and there is also an interaction causing the orbitals to align also in the same direction, if there is freedom to do so [4].

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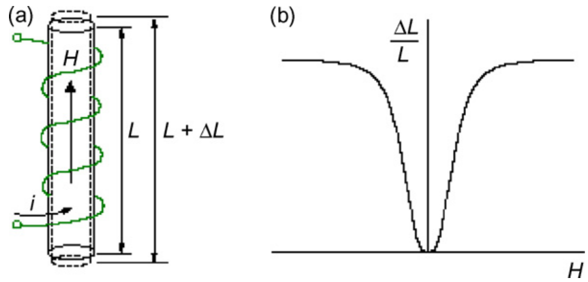

Fig. 1. Joule magnetostriction. (a) The changes in shape in response to the magnetic field H. H is proportional to the current that passes through the solenoid. (b) The relationship between $\Delta L/L$ and H.

However in crystalline solids the atoms are arranged in regular patterns and the distance between one atom or ion and its neighbours is fixed within certain limits. General attractive forces cause the atoms to approach each other and to be as close to each other as possible. However the limiting factor opposing this movement is the orbitals of the outer electrons of each atom or ion. The orbitals cannot cross over each other. Now, with the exception of the electrons involved in electrical conductivity in metals, it is among the outer electrons where unpaired electrons are likely to occur, and it is these same electrons that give rise to the magnetic properties of the material.

Electron orbitals are normally depicted as circular, but this is only true for the smallest and simplest of atoms or for the innermost electrons in more complex atoms. In the magnetic materials of greatest interest the outer electron orbitals are highly unsymmetrical, being elongated in one direction and flattened in another.

Also in crystal lattices the distance between an individual atom or ion and its nearest neighbour depends on where that neighbour is. For atoms arranged in a rectangular pattern, the nearest neighbour is the next atom in the row, but the nearest in a direction at 90° to that row may be further away, and the nearest in a direction at 45° to the row is likely to be even further away, and so on. There is therefore in most crystal lattices scope for accommodating electron orbitals, which are elongated in one direction.

It follows that there are directions which are specific to certain crystals where it is easy to magnetise the material, and, as a result small groups of atoms or ions tend to organise themselves spontaneously into magnetic domains where the spins and orbitals of unpaired electrons are all aligned. However the domains cannot be very large because of energy considerations. Unless an external magnetic field is imposed on the material, energy is minimised where there are a large number of domains present in a sample of material, with the magnetic field in each domain orientated in a different direction.

When an external magnetic field is created, the domains, which are aligned most closely with the external field will grow while all other domains will be reduced in size [5]. Depending on the orientation of the crystal, there will be some cases where electron orbitals cannot become aligned to the direction of the external magnetic field without a change taking place in the distances between the atoms or ions. These distances must increase to allow the orbitals to become aligned. These changes in length may cause the crystal structure to become elongated in the same direction as the magnetic field, or to become elongated in one of more directions at right angles to this direction. In this last case, there may also be a contraction of the crystal in the same direction as the magnetic field.

3. Applications of magnetostriction

One advantage of magnetostriction actuators over other types is that their driving voltages can be very low which is useful in medical applications, and in general simplifies the amplifier design. When a magnetostrictive material is subjected to an alternating magnetic field, the material vibrates at twice the frequency of that field, and this magnetostrictive vibration is the major source of the humming sound emitted by transformers. Conversely, if a magnetostrictive material is subjected to a mechanical stress, its magnetic permeability will change because of the inverse magnetostrictive effect. If, at the same time the material is subjected to an alternating magnetic field produced by a coil with an alternating current, the magnetic flux density pattern will also change as a result of the change in magnetic permeability. This effect can be detected in a separate “pick up” coil where the alternating magnetic flux will induce an alternating emf whose magnitude varies with the magnetic permeability of the material. This effect is exploited in magnetostrictive transducers, which are capable of converting electrical energy into mechanical energy.

Modern magnetostrictive materials such as Terfenol-D are often manufactured as rods with residual magnetic fields nearly perpendicular to the rod axis. This is because domains in the material with magnetic fields already aligned with the rod axis do not change in direction when an external magnetic field is applied along the rod axis. They do not therefore contribute to the magnetostriction. Consequently a rod which has domains aligned randomly will only produce about two fifths of the maximum possible magnetostriction. Therefore it is desirable to arrange all the domains to be aligned in any direction, which is perpendicular to the rod axis. This can be approximated in the manufacturing process. Nevertheless a mechanical pre-load is required in order to achieve the initial condition of no alignment along the direction of the rod axis. Effect of pre-stress on the dynamic performance of a Terfenol-D transducer has been studied in [6].

3.1. Actuator applications

The commercial magnetostrictive material, which is most commonly used in actuation applications, is Terfenol-D. This is because in its performance a high conversion energy density, a large force and a fast response can be achieved over a broad frequency bandwidth. The main applications in actuation are sonar transducer [7–10], linear motors [11–15], rotational motors [16–18], and hybrid magnetostrictive/piezoelectric devices [19–21].

3.2. Sensor applications

The most common sensors are torque sensor [22,23], position sensors [24,25], and force sensors [1].

4. Measurements of magnetostriction

Magnetostriction measurement techniques can be broadly classified as either direct or indirect, depending on whether the strain is measured directly or the magnetostriction is deduced from a measurement of some other property dependent upon strain. Direct methods enable the magnetostrictive strain to be measured as a function of the applied field, whereas indirect methods are suitable only for measuring the saturation magnetostriction λ_{sat}.

4.1. Direct measurements

For crystalline materials, the use of strain gauges is the most common method; they are easy to handle, but limited in sensitivity. The most sensitive method is the capacitance method [26]. Direct methods require a special sample preparation. The most common techniques are as follows.

4.1.1. Strain gauge methods

These methods are widely used for measuring magnetostriction in both crystalline and amorphous materials [27]. The advantages of these methods are that it can be used over a wide temperature range, and that the cost is low. Some of them can only be used on materials in the form of a ribbon, in which case, they are not suitable for wires or thin films. [28].

A suitable strain gauge is illustrated in Fig. 2. It consists of a thin film with a wire attached to it, which meanders over an area of the film. The electrical resistance of the wire varies in proportion to the amount of strain it experiences. As the strain gauge is flexed, its resistance increases. However the change is very small and therefore a Wheatstone bridge is necessary to carry out an accurate measurement. Dummy loads can be used

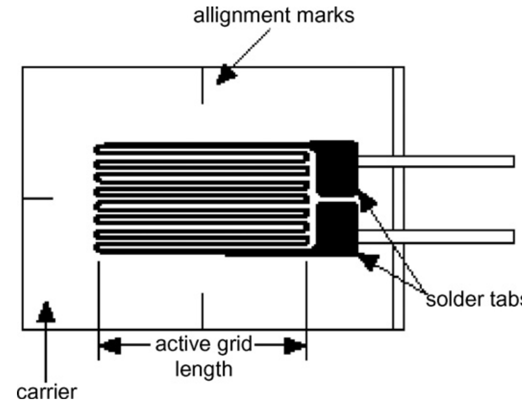

Fig. 2. General set up of a strain gauge.

for calibration and to compensate for temperature and magnetic field changes. It is convenient for studying large or moderate magnetostrictions above 10^{-6}, which is the case in industrial laboratories [29]. This strain gauge was developed by Goldman in 1947. A similar system is described by Chaudhri et al. [30]. This was capable of measuring strain down to a level of 10^{-6}.

4.1.2. Dilatometry methods

4.1.2.1. The tunnelling tip dilatometer. A system based on this approach was described by Brizzola et al. [31]. The construction of this system is shown in Fig. 3. This system consists of four main parts: the solenoid, a magnetostrictive sample, which conducts electricity, the tunneling tip which is a position-sensitive detector, and the feedback control circuit. A quartz tube is mounted inside the solenoid, along its axis, to hold the magnetostrictive sample, which is a ribbon, a wire or a rod.

A piezoelectric activator is used to control the position of the tunneling tip. By feeding back information on the tunneling current as a control signal to the piezoelectric activator, a constant gap width between the tip and the sample is maintained. Thus, the length change of the ribbon can be determined by monitoring

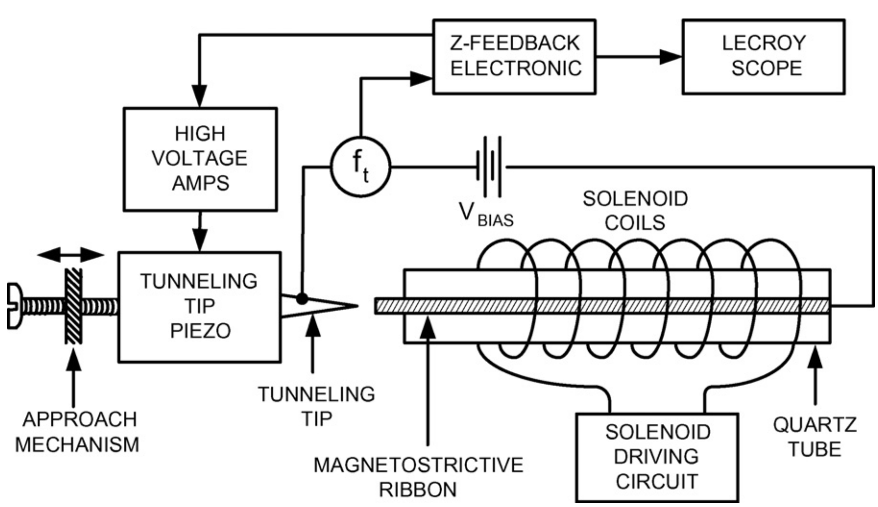

Fig. 3. Tunneling tip dilatometer for measuring magnetostriction.

the feedback control signal. Displacements ranging from 10^{-9} to 10^{-5} have been measured.

4.1.2.2. Capacitance dilatometrys. Capacitance displacement sensors are widely used for application where high sensitivity is required. The capacitance method is one of the most sensitive methods for measuring small length changes of solids. In practice the accuracy is limited frequently by the mechanical sample quality. However, to reach the highest possible sensitivity and reproducibility, special effort is required in the design of the capacity cell. Any change in the dimension of the sample caused by the magnetostriction is observed as a variation in capacitance across the two electrodes, one of which moves with the change in dimension of the sample [32]. One of the first capacitance cells was described by White in 1961, where he employed a variable-gap capacitance with a guard electrode [33]. Later on, Tsuya et al. adapted this three terminal capacitance dilatometer for measuring the magnetostriction of spherical samples 0.5–10 mm in diameter. As most of this capacitance cell assembly was made of copper, both thermal drifts and mechanical vibrations were markedly reduced leading to high sensitivity and reliability in measuring the magnetostrictions of small spherical crystals.

A similar experimental method was developed by Boley et al. [34], with the aim of being sufficiently accurate to rank different ferromagnetic materials according to their magnetostriction properties. This is a significant consideration in producing effective magnetoelastic torque sensors. In this method, the magnetostriction effects were generated by a large oscillating magnetic field, capable of reaching saturation levels for the material, and then detected by a change in capacitance.

Briss et al. designed another three terminal capacitance cell, capable of measuring a large range of magnetostriction values between room temperature and 4 K using a superconductive split-coil magnet [35]. The specimen used is normally disc-shaped, and the magnetic field is applied in the plane of the disc and can be rotated in this plane. They found that at lower temperatures the giant anisotropy torque of terbium fractured the glue bond, and recommended an alternative method of mounting to overcome this problem. One possibility under consideration is the use of a thin-walled cylindrical support, slit at intervals around the circumference to accommodate any volume change or distortion of the perimeter of the specimen.

Apart from the use of the capacitance method in a steady or slowly varying magnetic field, this method can also be used in pulsed fields. Heremans et al. described a special capacitive instrument for these fields [36]. They have stated that these techniques are in principle less sensitive than steady state capacitance dilatometry. However, in spite of the numerous technical difficulties with capacitance measurements in highly transient fields, the pulsed magnets approach presents practical advantages such as the time required for measurement is very short, it can be operated at any temperature, and temperature drifts are avoided.

4.1.3. Optical interferometry

The traditional optical method is the simplest method; the deformation of magnetic substances is measured using an optical lever [37]. The change in length can be measured as a change in the reflection angle of an optical beam that is reflected by a mirror, which is attached to the optical lever. When the sample deforms with an increase in the magnetic field, the deformation in the rod causes the rotation of the optical lever. This method, however, requires a relatively large sample, and therefore cannot be applied for the measurements of tiny samples of a size of less than 1 mm [37].

Laser light is used in a number of methods and provides high measurement precision. A recent publication by Rafferty et al. [38], describes a method using laser light. A copper solenoid consisting of 5555 turns was used to generate a static magnetic field in a suitable non-metallic test frame for the laser displacement sensor. With this system, magnetic field strengths of 750 G could be achieved. The magnetostriction measurements are estimated using the principle of triangulation. The magnetostrictive properties of Terfenol-D based materials obtained from two different suppliers were used to test the system. Both exhibited positive magnetostriction, with values in good agreement with those in the literature. A major advantage of this method is that no contact is required between the probe and the sample. Problems include drift of the laser beam due to thermal effects.

Optical methods have made remarkable progress for the measurement of very small displacements [39,40], and their application permits the measurement of magnetostriction in tiny samples with high accuracy, and without any contact between the probe and the sample.

A new optical technique was applied to the magnetostriction measurement in bulk samples [39]. This technique utilizes an optical fibre bundle, ac-modulated light and lock in detection. Deformation of the sample is determined from the ratio of incident and reflected light intensities. Magnetostrictions as small as 5×10^{-7} in 1 mm thick samples can be measured by this method.

Squire et al. have described a fibre optic dilatometer for measuring magnetostriction in ribbon samples [41]. This dilatometer uses the sample as a shutter between two optical fibres as depicted in Fig. 4. One end of the sample is attached to a rigid base; the sample is otherwise free to strain along its axis.

Magnetostriction strain in the sample changes the amount of light transmitted between the optical fibres. This system is capable of measuring the magnetostriction of ribbon samples with a sensitivity of 10^{-7} as a function of the applied field. One useful improvement that would make calibration simpler

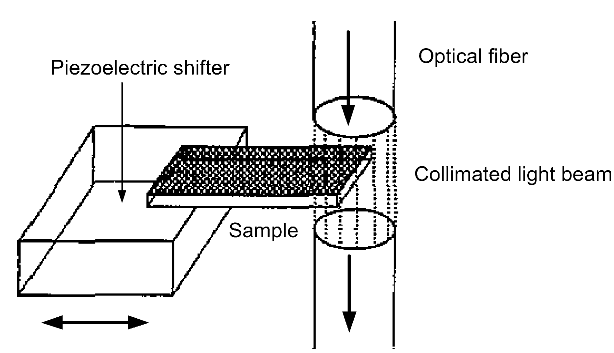

Fig. 4. Principle of the fibre optic dilatometer.

and more repeatable would be to operate the system in a closed loop mode. A piezoelectric actuator would move the end of the sample furthest from the optical fibre, so that the same amount of light would be transmitted between the optical fibres at the other end of the sample. The displacement is thus known to the precision of the actuator without further calibration.

Bellesis et al. described a version of a cantilever method in which the deflection is sensed by a laser Doppler interferometer [42]. Using films about 1 μm thick deposited on 250 μm silicon substrates, they obtained a resolution of about 10^{-8} for saturation magnetostriction.

4.2. Indirect measurements

Indirect measurements are techniques based on the Villari effect, which is the inverse of Joule magnetostriction. A stress applied to a sample will produce a change in the magnetic permeability of that sample. These techniques are designated as indirect measurements of magnetostriction because they do not produce a direct measure of the sample length change. Several techniques based on this effect have been used in the measurement of magnetostriction.

4.2.1. Ferromagnetic resonance (FMR)

This type of technique involves the application of a known stress to the sample and determination of the permeability by the observation of the shift in the ferromagnetic resonance.

Smith et al. have developed the technique [43]. The resonance arises because a capacitance and an inductor are present in the same circuit. Knowing the frequency and the capacitance an estimation of the inductance can be made, which leads to an estimate of the permeability. The main advantage of this technique is the possibility of measuring the properties of very small samples.

4.2.2. Small-angle-magnetization rotation (SAMR)

In this method, a static magnetic field, high enough to saturate the sample is applied in the longitudinal direction, and a small ac field is applied by another solenoid in the transverse direction. This produces a magnetic field rotation, which may be detected as an induced voltage in the sensing coil, a third coil, around the sample [44]. Additionally, a variable tensile stress is applied to the sample. As the stress is varied, the dc field is also varied in order to keep the voltage in the sensing coil constant. This change in the dc field gives the magnetoelastic contribution to the anisotropic stress field, from which the saturation magnetostriction constant can be determined, for various values of applied stress. Using this technique, Hernando et al. have been successful in measuring magnetostriction constants as small as 10^{-9} [45].

4.2.3. Strain modulated ferromagnetic resonance (SMFMR)

This makes use of the application of a known dynamic stress produced by a piezoelectric transducer, and the measurement of the line shift using look-in techniques. This type of technique has been used by Henning et al. to measure saturation magnetostriction constants as small as 10^{-9} [46].

5. Conclusion

Magnetostriction can be measured by direct and indirect methods. For crystalline materials, the use of strain gauges is most common. Strain gauges are easy to handle but limited in sensitivity. The most sensitive method is the capacitance method, but requires a special sample preparation. Optical measurement methods are amongst the oldest, but there are also many very accurate methods developed more recently.

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