Overview of Magnetostrictive Sensor Technology*

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ABSTRACT: As sensors become integrated in more applications, interest in magnetostrictive sensor technology has blossomed. Magnetostrictive sensors take advantage of the efficient coupling between the elastic and magnetic states of a material to facilitate sensing a quantity of interest. Magnetic and magnetostrictive theory pertinent to magnetostrictive sensor technology is provided. Sensing configurations are based on the utilization of a magnetostrictive element in a passive, active, or combined mode. Magnetostrictive sensor configurations that measure motion, stress or force, torque, magnetic fields, target characteristics, and miscellaneous effects are discussed. The configurations are compared and contrasted in terms of application, sensitivity, and implementation issues. Comparisons are made to other common sensor configurations as appropriate. Experimental and modeling results are described when available and schematics of the configurations are presented.

Key Words: magnetostriction, magnetostrictive sensors, Terfenol-D, noncontact torque sensor, thin film torque sensor, magnetostrictive transducers, noncontact strain sensor, magnetostrictive wave guide position sensor, magnetoelastic strain gages, magnetostrictive delay line displacement sensor and force sensor, magnetostrictive force sensor, amorphous ribbon force sensor, magnestostrictive fiber optic sensor, Terfenol-D magnetometer.

BACKGROUND

The last ten years have seen an explosion in sensor technology from the aerospace to industrial sectors. Indeed, the worldwide sensor market is a multi-billion dollar industry (Ristic, 1994). The recent increased interest in magnetostrictive sensor technology results from improvements in magnetostrictive material performance, experience with magnetostrictive applications, and increased use of sensors for a wide range of applications.

This article provides an overview of the current state of the art of magnetostrictive sensor technology. These devices rely on a material's magnetoelastic properties to convert a physical parameter of interest into an electrical dimension that can be processed and transmitted. Some sensor systems use the inherent magnetoelastic properties of the target to effect the detection of the property of interest. In other sensor configurations, it is the magnetostrictive properties of parts of the sensor, which allow the measurement of the property of interest. The sensor system will be defined as the sensor components themselves, the target, and supporting electronics.

Magnetism and Magnetostriction

In order to facilitate the description of magnetostrictive sensors in later sections, several equations describing magnetic and magnetostrictive effects are presented (Jiles, 1991).

Magnetostrictive materials convert magnetic energy to mechanical energy and vice versa. As a magnetostrictive material is magnetized, it strains. If an external force produces a strain in a magnetostrictive material, the material's magnetic state will change. This bi-directional coupling between the magnetic and mechanical states of the material provides a transduction capability that can be used in a variety of ways to measure a property of interest.

The magnetostrictive process relating the magnetic and mechanical states can be described with two coupled linear equations (Clark, 1980). These equations of state for a magnetostrictive element are expressed in terms of mechanical parameters (strain ε, stress σ,

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and Young's modulus at constant applied magnetic field E_y^H), magnetic parameters (applied magnetic field H, magnetic induction B, and permeability at constant stress μ^σ), and two magnetomechanical coefficients (the strain coefficient $d = \partial\varepsilon/\partial H|_\sigma$ and $d^* = \partial B/\partial\sigma|_H$).

$$\varepsilon = \frac{\sigma}{E_y^H} + dH \tag{1}$$

$$B = d^*\sigma + \mu^\sigma H. \tag{2}$$

In these equations ε and B are dependent on σ and H, which are externally applied. The application of a stress will cause a change in the magnetic induction as seen in Equation (2). This can also be expressed as a change in permeability by writing Equation (2) in a more general form,

$$B = \mu H. \tag{3}$$

In Equation (3), the effects of stress are included in the permeability, μ. Permeability can be monitored since both B and H can be related to measurable electrical quantities.

In the early nineteenth century, Oersted discovered that a moving charge generated a magnetic field in a plane perpendicular to the direction of charge motion. Thus, a current in a conductor could be used to produce a magnetic field around the conductor. Ampere's law describes this electromagnetic relationship. For a long, thin solenoid of number of turns, N_c, and length, L_c, a simple expression is derived,

$$H = \frac{N_c I}{L_c}. \tag{4}$$

Placing a magnetostrictive element inside such an excitation coil (solenoid) with an impressed current I provides an efficient means of magnetizing the element.

The law of electromagnetic induction (Faraday–Lenz law) describes how a magnetic flux, $\varphi = BA_c$ in area A_c, induces a potential in an electrical conductor to which it is flux-linked. In its simplest differential form, the Faraday–Lenz law is given by

$$V = -N_c\frac{\mathrm{d}\varphi}{\mathrm{d}t} = -N_c A_c\frac{\mathrm{d}B}{\mathrm{d}t}, \tag{5}$$

where V is the induced voltage in the solenoid of constant area A_c. The negative sign indicates that the voltage measured is 180° out of phase with flux φ. According to this law, a potential will be induced in any electrically conducting material that makes up the magnetic circuit.

The excitation coil described by Equation (4) can be used to generate a magnetic field in a sample spatially separated from the coil. According to Gauss's law of magnetism,

$$\nabla\cdot B = 0, \tag{6}$$

the divergence of B is zero. This means that the magnetic flux is always conserved. Thus magnetic flux lines close, defining a magnetic circuit, and elements of the magnetic circuit through which magnetic flux flows are said to be flux-linked. This makes it possible to magnetize one component of the magnetic circuit by generating a magnetic field in another component.

Based on the principle expressed by Equations (5) and (6), it is possible to measure the magnetic flux density in a magnetic circuit by the voltage induced in a flux-linked coil. These coils are often referred to as detection, receiving, or sensing coils.

Various aspects of a material's magnetic-mechanical coupling can be employed to sense parameters of interest. The Joule effect, the first of the magnetomechanical effects to be thoroughly documented (in 1842), is a longitudinal change in length due to an applied magnetic field. A transverse change in length and associated volumetric change are also observed. Although the Joule effect is usually associated with the actuation capability, numerous sensor configurations rely on the excitation of the magnetostrictor to facilitate sensing. The Joule effect has an important reciprocal effect known as the Villari effect; a stress induced in the material causes a change in the magnetization. This change in magnetization can be sensed, and once calibrated, used to measure the applied stress or force. The Villari effect has been the subject of much research (Lee, 1955; du Tremolet de Lacheisserie, 1993; Jiles, 1995) and has been employed in load cells, force cells, and accelerometers (du Tremolet de Lacheisserie, 1993). Another effect of interest is the Wiedemann effect, a twisting which results from a helical magnetic field, often generated by passing a current through the magnetostrictive sample. Twisting a magnetostrictive element or magnetized wire causes a change in the magnetization that can be measured and related to the external torque.

Sensing Configurations

Magnetostrictive sensors can be grouped together based on how the magnetomechanical properties of the system components are used to measure the parameters of interest, thus facilitating a comparison between sensor configurations. These groups are passive sensors, active sensors, and combined sensors.

Passive sensors rely on magnetomechanical coupling to link a measurable change in the magnetostrictive material to the external property or condition of interest. For example, according to the Villari effect, the change in the magnetization of the magnetostrictive sample is correlated to an externally imposed change in stress. A coil flux-linked to the magnetostrictive sample can be used to measure changes in magnetic flux as per Equation (5). Quantities such as external load, force, pressure, vibration, and flow rates can then be measured.

Active sensors use an internal excitation of the magnetostrictive element to facilitate some measurement of the magnetostrictive element that changes with the external property of interest. For example, an excitation coil could be used to excite the magnetostrictive sample with a known H as per Equation (4) and the detection coil used to measure B as per Equation (5). The permeability from Equation (3) can then be monitored for changes due to an external condition. Designs which employ two coils, one to excite the magnetostrictive element and one for measurement, are known as transformer type sensors. The most common active sensor design mentioned in literature is the noncontact torque sensor. Many configurations employ variations on a general theme of a magnetostrictive wire, thin film, or ribbon flux-linked to a target shaft subject to a torque. The change in magnetic induction or permeability can then be related to the torque on the specimen. In contrast with passive sensors, properties of active sensors, such as the bandwidth, resolution, or damping, can be tailored in the sensor design.

Finally, combined or hybrid sensors use a magnetostrictive element to actively excite or change another material which will allow measurement of the property of interest. For example, a fiber optic magnetic field sensor uses the change in length of a magnetostrictive element in the presence of a magnetic field (Joule effect) to change the optical path length of a fiber optic sensor. There are numerous examples of combined sensors, including those that measure current, shock (percussion), stress, frost, proximity, and touch. Stress can be measured using photoelastic material, and highly accurate displacement measurements can be made with the help of a magnetostrictive guide. Fiber optics and diode lasers have been used with magnetostrictive elements to measure magnetic flux density (magnetometers).

APPLICATIONS

Earlier works with magnetostrictives, such as nickel, iron, and permalloy identified many sensing applications. Some of the earliest uses of magnetostrictive materials from the eighteenth century and the first half of this century include the telephone receiver, hydrophone, and scanning sonar (Hunt, 1982), which were developed with nickel and other magnetostrictive materials that exhibit bulk saturation strains of up to 100×10^{-6}. In fact, one of the first telephonic receivers, tested by Philipp Reis in the 1860s, was based on magnetostriction (Hunt, 1982). In 1888, Ewing reported force measurements using a magnetostrictive device of iron and nickel, the first magnetostrictive force sensor (Ewing, 1900).

Currently work continues to develop giant magnetostrictive material such as Terfenol-D, which has applications as an actuator and as a sensor. This effort includes many scholarly papers and commercial patents. In addition, magnetostrictive amorphous wire and thin films find a variety of sensing applications. Examples of successful sensor designs include hearing aids, load cells, accelerometers, proximity sensors, torque sensors, magnetometers and many more (Ewing, 1900; du Tremolet de Lacheisserie, 1993; Calkins and Flatau, 1997). Numerous patents for sensors based on magnetoelastic properties have been issued in the United States, Japan, and other countries over the last decade (Fleming, 1990; du Tremolet de Lacheisserie, 1993).

The emphasis of this study is on applications, therefore the magnetostrictive sensors are grouped together based on the following measured property or quantity: torque, motion, force, magnetic field, material characterization, and miscellaneous properties. Owing to the large number of magnetostrictive sensor related patents and published papers, an effort was made to highlight commercially available sensors, followed by those with experimental verification. In several cases, the magnetostrictive configuration can be used to measure several quantities. For example, the magnetostrictive delay line (MDL) can be configured to measure force or displacement.

TORQUE SENSORS

Torque measurements have great benefit for many applications in a variety of industries, ranging from passenger cars, tractors, truck and off highway vehicle powertrains, manufacturing machinery, and stationary power plants. One example is the torque feedback closed loop control of automotive engines and transmissions. Three torque sensor configurations are described: a noncontact sensor, a thin film or a wire application, and a shaft sensor.

Noncontact Torque Sensor

The noncontact torque sensor is one of the most common torque sensor configurations. Some of the advantages of noncontact magnetostrictive torque sensors include minimal target requirement, rapid response, good stability, good accuracy in conjunction with high sensitivity, and capacity to withstand overloads. Noncontact torque sensors are advantageous because implementation is simple and fast. These torque sensors are traditionally based on the Villari effect, where a torque induced change in stress in the target causes a change in the magnetization of a magnetostrictive element in the sensor–target system. This change in magnetization can be measured directly (passive), or as a change in permeability measured under an active excitation. Fleming (1990) provides a thorough overview of torque sensor technology, focusing on magnetostrictive torque sensors.

The basic principle of the sensor configuration is shown in Figure 1. As a shaft is torqued, stress will develop at ±45° from the shaft axis. The C-shaped ferromagnetic core supports an excitation and detection coil and will be oriented to the 45° axis. The change in stress in the ferromagnetic shaft will cause a change in permeability of a ferromagnetic element flux linked to the shaft. Two variables in the sensor system are the air gap between the shaft target and the sensor core and current into the excitation coil. Various configurations based on these principles have been explored, including versions with multiple C sections (Fleming, 1990).

Fleming (1989) investigated several issues with these sensors, including nonlinearities due to sensor element properties, the effects of magnetic saturation, and excitation frequency. Current modeling efforts have extended prior linear models to include nonlinear magnetomechanical effects and magnetic saturation.

Thin Film and Wire Applied to Shaft

Other torque sensors apply the magnetostrictive material directly to the target. This idea was developed by Yamasaki et al. (1986) using a wire explosion spraying technique to adhere thin layers of Ni, Fe–Ni, and Fe–Co–Ni to shafts. In this method, the conductive wire is exploded into fine particles at high temperature which adhere strongly to the shaft. The wire explosion technique results in a strong adhesion, which provides increased sensor reliability. When the shaft is twisted the stress causes a change in the magnetization-applied magnetic field hysteresis loop. When two such regions of magnetostrictive material are surrounded by coils connected in a bridge circuit, a change in voltage due to a change in the torque can be detected (Mohri, 1984). A linear, nonhysteretic relationship between the bridge circuit output voltage and the torque was obtained. Ni and Fe_{42}-Ni_{58} provided the greatest sensitivity.

A second system using a 300 μm thick Ni layer applied by plasma jet spraying was investigated by Sasada et al. (1986). The instantaneous torque on a rotating shaft was related to the measured permeability using a pair of U-shaped magnetic heads positioned at ±45° from the shaft axis. The sensitivity of the air gap between the shaft and the magnetic heads was examined and a self-compensating method presented. A relatively linear sensitivity of 500 V/Nm with little hysteresis was measured. In addition, the output response of the sensor was found to be nearly independent of the rotational frequency.

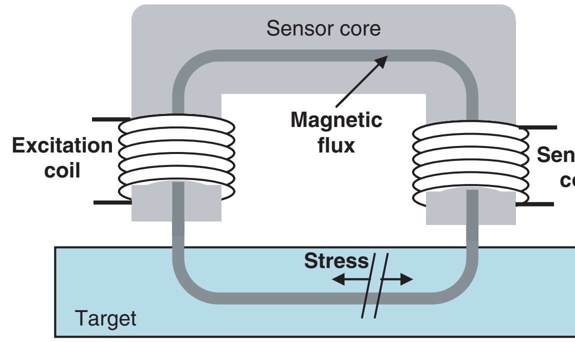

Figure 1. *Noncontact torque sensor with excitation and detection coils around the legs of a C-shaped ferromagnetic core (Fleming, 1989).*

Savage et al. (1993) obtained a US patent for a magnetostrictive torque sensor using a magnetostrictive wire helically wrapped around and connected to a shaft. Similar to the thin film configurations, the permeability, which changed with stress on the wire induced by the shaft, was monitored.

Sensor Shaft

Sensor shaft applications take advantage of the magnetostrictive effects of the target material itself. In the first example, the in-process detection of the working torque on a drill bit is related to its permeability (Sasada et al., 1994). An excitation coil surrounds part of the drill, including the shank and the flutes, as in Figure 2. Two sensing coils, one positioned over the flutes and one over the shank, are connected in series opposition allowing the measurement of the permeability. The permeability of the shank is less sensitive to changes in torque than the flutes and the difference in the output voltages of the two coils changes proportionally to the applied torque. In the second example, the sensor shaft is made of Cr–Mo steel, which is suitable for automobile transmission applications. Two grooved sections are surrounded by coils, which are configured in an ac bridge circuit. When torque is applied to the shaft, the Villari effect results in a change in impedance measured by the bridge. According to Shimada (1993) the sensor is robust with respect to temperature.

MOTION AND POSITION SENSORS

High volume applications in the automotive industry and elsewhere rely increasingly on motion and position sensors, such as those to measure acceleration, velocity, displacement, and strain. Velocity can be measured by a magnetostrictive transducer; position can be measured

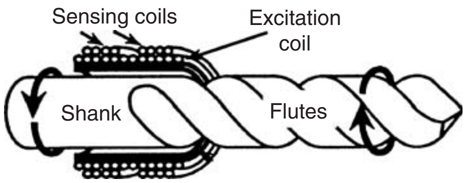

Figure 2. Noncontact measurement of torque on drill employing one excitation coil and two sensing coils, one over the shank and one over the flutes (Shimada, 1993).

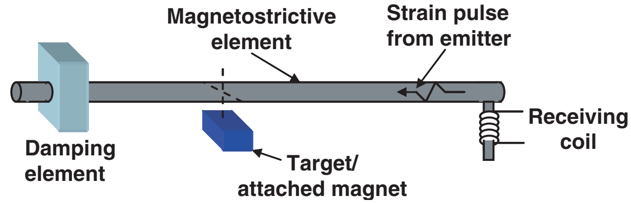

Figure 3. Magnetostrictive wave guide position sensor measures location of the moving permanent magnet attached to the target (Nyce, 1994).

by a magnetostrictive wave guide and a MDL; and strain can be measured by a magnetostrictive strain gage and a noncontact sensor.

Magnetostrictive Transducer

The existence of the Joule and Villari effects allows a magnetostrictive transducer to have two modes of operation, transferring magnetic energy to mechanical energy (actuation) and transferring mechanical energy to magnetic energy (sensing). In addition, a magnetostrictive transducer has the ability to both actuate and sense simultaneously. Applications, such as the telephone, scanning sonar, and others make use of this dual mode. For example, a Terfenol-D sonar transducer can be used as either a transmitter or receiver or both at the same time. Another potential use of dual mode operation is in active vibration and acoustic control. One transducer can be used to simultaneously sense deleterious structural vibrations and provide the actuation force to suppress them. Self-sensing control uses the sensed signal in a feedback loop to drive the transducer. This is accomplished by separating the voltage induced in the excitation winding via the Faraday–Lenz law from the excitation voltage. Numerous studies have described this effect and shown its utility (Pratt, 1993; Pratt and Flatau, 1993; Jones and Garcia, 1994).

Fenn and Gerver (1994) have developed, modeled, and tested a velocity sensor based on a permanent magnet biased Terfenol-D actuator. The transducer is connected to a moving target that strains the Terfenol-D core. The change in B is related to the change in strain of the Terfenol-D core by Equations (1) and (2). As explained by the Faraday–Lenz law (Equation (5)), a voltage proportional to the time rate of change of B in the Terfenol-D core is induced in the surrounding detection coil. Thus the output voltage from the transducer is a signal proportional to the velocity of the connected target. Peak sensitivities of 183 V/(m/s) were seen when the coil was left open. In addition, the coil could be shunted to provide passive damping capability and the voltage proportional to the target velocity monitored across the shunt resistor.

Noncontact Strain Sensor

Noncontact strain sensors use the magnetic field to couple the straining target to the sensing element. A noncontact system has several advantages (Kleinke and Uras, 1993). First, it is a noninvasive technique, which does not require mechanical bonding to the target. This can be a significant advantage, in particular for rotating targets. Second, the sensor can be moved to measure strain at different points easily and quickly, providing strain mapping capability. Finally, this sensor is rugged, with good sensitivity and overload capacity.

This sensor configuration is similar to the noncontact torque sensor shown in Figure 1. However rather than measuring strain due to torque only, it is designed to measure the target strain in any direction of interest. The C-shaped ferromagnetic sensor core is wound with an excitation and sensing coil. The excitation voltage causes a known magnetic field in the magnetic circuit consisting of the C-shaped sensor and target. Note that the flux path crosses the air gap between the sensor and the target. Owing to the Villari effect, as the target strains, the change in stress will cause a change in its magnetic state, altering the magnetic circuit permeability. This will be seen as a change in the voltage in the detection coil. In general, the sensor will detect changes in strain of targets made of ferromagnetic material; however, strains in nonferromagnetic material can be detected by applying a ferromagnetic material to their surface.

Magnetostrictive Wave Guide Position Sensor

An extremely versatile position sensor is based on a magnetostrictive wave guide. The system detects the position of a permanent magnet connected to the target, which is free to move along the length of a magnetostrictive wave guide. The emitter, shown in Figure 3, continuously pulses a current through the wave guide, producing a circumferential magnetic field. This combined with the longitudinal magnetic field produced by the permanent magnet results in a helical magnetic field. As described by the Wiedemann effect, a torsional strain pulse is induced in the wave guide; the triggered torsional acoustic wave travels at the speed of sound in both directions away from the permanent magnet along the wave guide. One end is fitted with a receiver, while the other end is connected to a damper. The damper attenuates the acoustic wave so that it will not reflect back corrupting the signal at the receiver. The receiver measures the time lapse between the current pulse and the acoustic wave, a quantity which is related to the distance between the receiver and the permanent magnetic/target. The acoustic wave can be measured by the change in permeability resulting from the strain pulse in the wave guide. In Figure 3, the receiver, or pick up element, is shown as a magnetostrictive ribbon welded to the wave guide which converts the torsional pulse to a longitudinal elastic pulse. The permeability of the ribbon, which changes due to the elastic pulse, is monitored (via the Faraday–Lenz Law) with a coil wrapped around the ribbon.

Several versions of this sensor are available commercially and discussed in literature. Nyce (1994) describes the operation of MTS model LP in detail. Current pulses with frequencies between 10 Hz and 10 kHz provide the excitation. The sensor performance is considered as a function of the magnetostrictive wave guide material and geometry. High magnetostriction, low attenuation, and good temperature stability are desired. Lucas Control System Products (UK and US) has developed the MagneRule Plus™ a compact position sensor for measurements up to 120″ with high linearity and repeatability. In addition, it can measure fluid level by connecting the permanent magnet to a float device placed in the fluid. Finally, Equipiel of France (Peyrucat, 1986) has developed the Captosonic position sensor which is capable of measuring distances up to 50 m with ±1 mm accuracy.

Magnetoelastic Strain Gage

Using the fact that the permeability of many magnetostrictive materials is stress sensitive, a strain gage made from strips of Metglass 2605SC has been developed by Wun-Fogle et al. (1989). The permeability of the ribbons decreased in tension and increased in compression. The ribbons were prepared by annealing in a transverse 2.6 kOe magnetic field at 390°C for 10 min and then rapidly cooled in saturation magnetic field. In order to maintain the high sensitivity, the ribbons were strongly bonded to the target in an initially stress-free condition. A highly viscous liquid bond was found to adequately attach the ribbons to the target, although it did result in a loss of DC response. For experimental verification, two ribbons were placed on the top and bottom of a beam and surrounded by two coils connected in opposition. The ribbons were excited by a 1 kHz external magnetic field. The net voltage in the coil system was related to the permeability change and hence strain of the ribbons. The strain measurement system compares favorably with conventional strain gages, with resolution down to 10^{-9} m at 0.05 Hz.

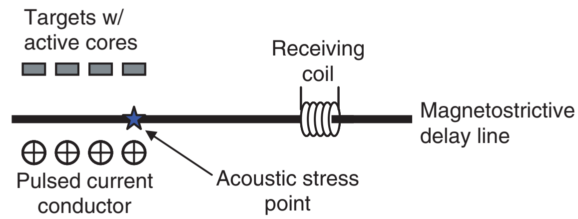

Figure 4. Magnetostrictive delay line, MDL, position sensor, with active core, AC, connected to target, pulsed current conductor, PCC, receiving coil, RC, and point of origin for acoustic stress, PO (Hristoforou and Reilly, 1994).

Magnetostrictive Delay Line Displacement Sensor

An innovative use of a MDL can be used to measure displacement. An acoustic pulse is propagated through the MDL and detected by a receiving unit. A current pulse through a conductor (PCC) orthogonal to the MDL generates a pulsed magnetic field in the MDL which generates an elastic wave, see Figure 4. An active core (AC) of soft magnetic material, placed near the PCC, is connected to the target and free to move relative to the MDL. The magnetic pulse and hence elastic wave generated in the MDL is sensitive to the magnetic coupling between the AC and MDL. As the target and AC move away from the MDL, the magnetic coupling between the PCC and MDL increases and the magnetic pulse and elastic wave in the MDL increase in strength. The output to the sensor is the pulse generated in the receiving unit coil (RC) as described by the Faraday–Lenz Law. The output voltage induced in the RC is sensitive to the gap distance between the MDL and AC, for MDL–AC displacement <2 mm. Most importantly the output is fairly linear and anhysteretic to the MDL–AC displacement. Sensitivities of 10 μV/μm have been reported using 24 μm thick Metglas 2605SC amorphous ribbon as the MDL (Hristoforou and Reilly, 1994). Permanent magnets were also used to maximize the generation of the acoustic pulse and the measured voltage in the RC. Multiple AC–PCC elements can be used with one MDL to form an integrated array. This novel aspect of the sensor system and several AC–PCC–MDL configurations are discussed by Hristoforou and Reilly (1994). Applications for this sensor include tactile, arrays digitizers, and structural deformations.

FORCE AND STRESS SENSORS

Force and stress sensors are found in a broad range of applications including vehicle active suspensions and engine mounts, active vibration control, manufacturing control, monitoring overloads on bridges, and active control of buildings against seismic events. The change in permeability (or magnetic flux) in a magnetic circuit due to strain in an element of the circuit can be used to measure both torque as described earlier and force. A combined torque–force sensor has also been developed (Zakrzewski, 1997). The magnetostrictive force sensor, MDL, and amorphous ribbon force sensor are described here.

Magnetostrictive Delay Line Force Sensor

The MDL displacement sensor configuration has been modified to produce a force distribution sensor (Reilly 1990; Hristoforou and Reilly, 1992). A force applied directly to the MDL will distort the acoustic signal generated by the emitter as described earlier. The change in the acoustic wave measured by a receiver coil is related to the force applied to the delay line. An experimental device tested by Hristoforou and Reilly used a Metglas 2605SC FeSiBC amorphous ribbon as the delay line embedded in a fiber glass channel. The channel bends under an applied force stressing the MDL, while ensuring that the PCC, oriented perpendicular to the MDL ribbon on the bottom of the channel, does not move relative to the MDL. For a given current, the voltage detected by the receiver coil due to a force F is proportional to the e^{-cF}, with calibration constant c. Integrated arrays for measuring force can be constructed with multiple MDL (each with a receiver) and PCC oriented perpendicularly. The values of multiple forces on the two-dimensional array can be backed out from the voltages measured by the receivers.

Magnetostrictive Force Sensor

Kleinke and Uras (1994) describe a force sensor which employs the change in electrical impedance of a magnetic circuit with stress to measure stress or force. It is similar in construction to the noncontact magnetostrictive strain sensor discussed in the motion sensor section. However, rather than a C shape, two magnetostrictive core spring elements are held in place by rigid end pieces as shown in Figure 5. A coil surrounds each core, one of which is used for excitation and the other for sensing. A constant amplitude ac current is impressed in the excitation coil generating an oscillating magnetic field. This results in a voltage in the detection coil with a magnitude proportional to the time rate of change of flux in the core elements (Faraday–Lenz law). An applied force on the sensor will cause a strain change in the magnetostrictive cores resulting in a change in the core magnetization. In this mode, where the applied magnetic field (H) is kept constant, a change in the output voltage from the detection coil is linearly related to the change in force. In a constant flux operation mode, the excitation current is allowed to vary in order to maintain the detection coil output voltage. In this case, the change in excitation current is related to the change in force. Compared with conventional force transducers, such as those which

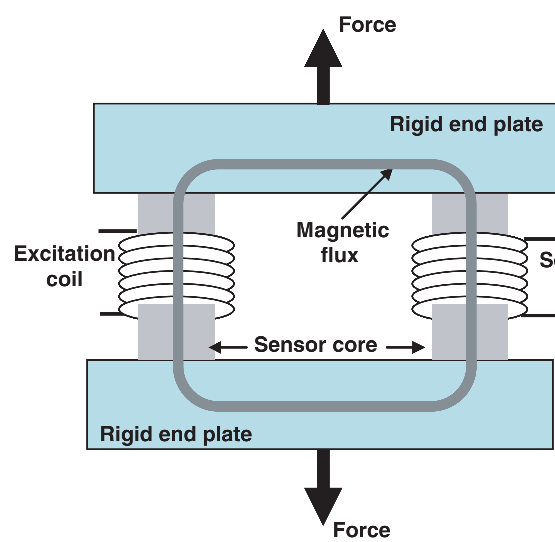

Figure 5. Magnetostrictive force sensor with two magnetostrictive cores surrounded by an excitation and a detection coil (Kleinke and Uras, 1994).

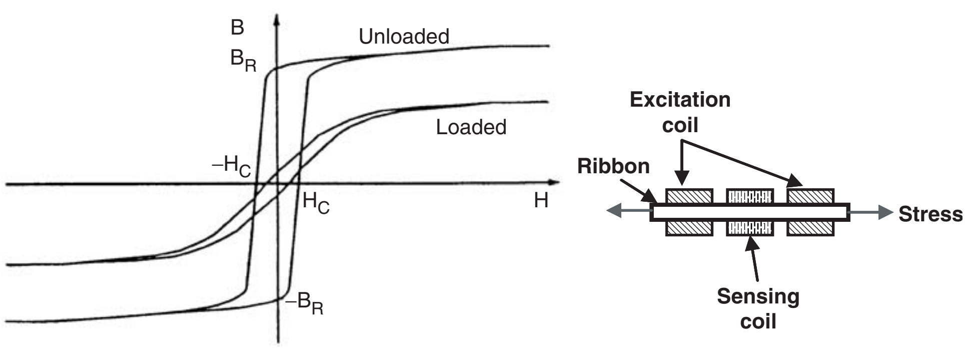

Figure 6. Magnetic induction versus applied magnetic field hysteresis loop loaded and unloaded for amorphous ribbon sensor (Seekircher and Hoffman, 1990).

employ strain gages, this force sensor is simpler, more rugged, and relatively inexpensive. In addition, the electronic requirements are simpler.

Amorphous Ribbon Sensor

A tensile force or stress sensor based on the strong Villari effect of amorphous ribbons, such as Ni, Fe, and Co based alloys, has been described by Seekircher and Hoffman (1990). A transmitting coil excites the ribbon while a pair of detection coils measures the maximum induction which is dependent on the stress. As shown in Figure 6, the maximum magnetic induction in the ribbon decreases as the load is applied. Loads below 4 N were measured with Co alloy ribbon of 25 μm thick by 3 mm wide with negligible hysteresis (Seekircher and Hoffman, 1990). The high Young's modulus of the ribbons results in very stiff, low displacement sensors, which can be load bearing elements. In some cases temperature compensation is required. A similar highly sensitive shock-stress sensor employing iron-rich amorphous ribbons is described in detail by Mohri and Takeuchi (1981).

MATERIAL CHARACTERIZATION SENSORS

The two magnetostrictive configurations discussed here use the active excitation of a magnetostrictive element to allow material characterization of the target.

Noncontact Magnetostrictive Sensor

This noncontact magnetostrictive sensor uses the magnetostrictive properties of the target material to excite elastic waves which can be measured and monitored to characterize the target (Kwun and Teller, 1995; Bartels et al., 1996; Brophy and Brett, 1996).

The system can be used directly on a target made of ferromagnetic material or by attaching a magnetostrictive material to a nonferromagnetic specimen. The magnetostrictive sensor has the advantage of being less intrusive and more simply implemented than traditional inspection methods.

The sensor, shown in Figure 7, consists of a transmitting element (pulse generator excitation coil, power amplifier, and bias magnet) surrounding the object, which generates the mechanical wave via magnetostrictive excitation. A receiving or sensing coil (signal preamp, data acquisition hardware, and permanent magnet), located at a distance from the excitation coil, measures a signal due to magnetostrictive waves. Changes in the material geometry will generate signals. These signals can be used to characterize the material and identify the onset of corrosion or measure internal stresses. Defects, such as

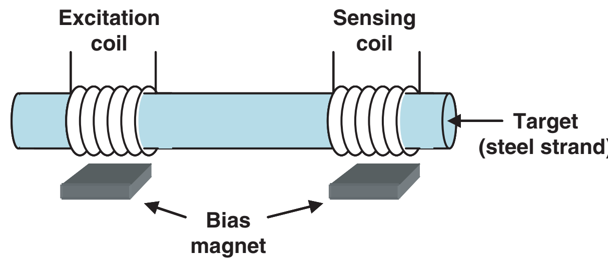

Figure 7. Magnetostrictive sensor for characterizing corrosion and monitoring ferromagnetic materials, such as pipes and strands (Brophy and Brett, 1996).

pitting, wall thinning, and cracks can be detected. Experimentation has shown that the wave attenuation increases with the degree of corrosion. This method has been used successfully to identify corrosion in strands, reinforced bars (including those imbedded in cement), water pipes, and other systems where noninvasive monitoring techniques are preferred.

Magnetostrictive Fiber Optic Sensor

An *in situ* fiber optic sensor coupled to a magnetostrictive element has been used for composite resin characterization (May and Claus, 1996). Thermoset polymer matrix composite cures can be monitored to allow adaptive control of the cure process, thus optimizing mechanical properties and reducing costs. The fiber optic sensor is coated with a magnetostrictive material, such as Metglas, and embedded in the composite resin. The magnetostrictive material is excited during the cure and the loss tangent, the ratio of the dissipated viscous energy to the stored mechanical energy, is measured. The loss tangent decreases to a minimum following solidification at which time the fiber optic sensor can be used for in-service health monitoring. This method of monitoring the cure process, known as dynamic mechanic analysis (DMA), is insensitive to the fiber optic sensor output.

MAGNETIC FIELD SENSORS

There are numerous designs for magnetic field sensors, including many which rely on magnetostrictive properties of component materials. These sensors vary considerably, in part because they are designed to detect magnetic fields of different strengths and frequencies (Foner, 1981). The most common configuration uses a magnetostrictive film coating an optic fiber. Other magnetic field sensors based on monolithic Terfenol-D samples are also described. Magnetostrictive amorphous metals, often in the form of ribbons, are extremely sensitive to external magnetic fields and have been used as the active element of a magnetometer (Weber and Jiles, 1992).

Finally, a magnetic field sensor has been developed based on MDL technology (Chung et al., 1991).

Magnetostrictive Fiber Optic Sensor

Numerous fiber optic magnetic field sensors have been developed. Yariv and Windsor (1980) proposed a now common configuration which uses a magnetostrictive film coating an optic fiber. The magnetic field causes the magnetostrictive film to deform, straining the optic fiber. This causes a change in the length of the optical path of laser. An interferometer is used to measure the phase changes. Mermelstein (1985) has shown that the resolution limit at DC to low frequency (< 1 Hz) of such a sensor is $\approx 3 \times 10^{-11}$ Oe.

Terfenol-D Magnetometer

A magnetometer design developed by Chung et al. (1991) employs a Terfenol-D sample to convert a magnetic field into a measurable quantity. A Terfenol-D rod strains in the presence of an ac magnetic field. This displacement can be measured accurately with a laser interferometer calibrated to output a signal related to the magnetic field. A dc magnetic bias on the Terfenol-D sample is used to optimize the output strain with magnetic field, resulting in values of up to $10\,\mu\varepsilon/G$. In addition, the sensitivity was found to be a function of the Terfenol-D mechanical prestress. Other magnetometer designs can be found in (Doherty et al., 1994; Yariv and Windsor, 1980; Mermelstein, 1985).

MISCELLANEOUS EFFECTS

Magnetostrictive sensors have been used to measure or monitor a number of other properties and characteristics. Some examples found in literature include hearing aid, MDL digitizer (Meydan and Elshebani, 1991), magnetoacoustic keyboard (Worthington et al., 1979), thermometer (Shirae and Honda, 1981), biomedical monitoring such as lung ventilation (Klinger et al., 1992a) and spine movement (Klinger et al., 1992b), and magnetic tagging for health monitoring of composites (White and Albers, 1996).

CONCLUSIONS

This article reviewed the state of the art of magnetostrictive based sensors. These devices rely on a material's magnetoelastic properties to convert a physical parameter of interest into an electrical dimension that can be processed and transmitted. The focus is placed on sensors that are commercially available and well established. These included the noncontact torque sensor, thin film torque sensor, noncontact strain sensor, magnetostrictive wave guide position sensor, magnetoelastic strain gages, magnetostrictive delay line displacement sensor and force sensor, magnetostrictive force sensor, amorphous ribbon force sensor, magnestostrictive fiber optic sensor, and Terfenol-D magnetometer. Magnetostrictive sensor technology continues to mature and will provide important capabilities to the growing commercial sensor marketplace in the years ahead.

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