ON MAGNETOSTRICTIVE TRANSDUCER APPLICATIONS

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ABSTRACT

This paper provides an overview of magnetostrictive transducer technology. The bi-directional coupling between the magnetic and mechanical states of a magnetostrictive material provides a transduction mechanism that can be used both for actuation and sensing. The current interest in design of adaptive smart structures, coupled with the advent of materials that exhibit high sensor figures of merit, such as Metglas and giant magnetostrictive materials such as Terfenol-D has lead to a renewed interest in the engineering of optimized magnetostrictive transducer designs. A survey of recent applications for giant magnetostrictive materials as both sensors and actuators and their use in smart structure applications will be presented along with a brief discussion of some pertinent device design issues. Examples of magnetostrictive actuation used to produce displacements, force and acoustic waves are summarized. Magnetostrictive sensor configurations that measure motion, stress or force, torque, magnetic fields and target characteristics are discussed. A very brief look at transducer modeling and experimental results is included and schematics of a number of actuator and sensor configurations are presented.

BACKGROUND

Since the mid-seventies, there has been a steady growth in research on smart structures and a particular emphasis has been the need for the development of actuators with increased bandwidth, force and displacement capabilities. Additionally, the last ten years has seen an explosion in sensor technology. Indeed, by the year 2000 the worldwide sensor market is expected to top \$13 billion[1]. The recent increased interest in magnetostrictive device technology results from improvements in magnetostrictive material performance, experience with magnetostrictive applications, and in this age of "information technology", the increased use of sensors, actuators, and their combined use in conjunction with control systems for an ever increasing range of applications.

Magnetism and Magnetostriction

In order to facilitate the description of magnetostrictive devices in later sections, several equations describing magnetic and magnetostrictive effects are presented. Magnetostrictive materials convert magnetic energy to mechanical energy and vice versa. As a magnetostrictive material is magnetized, it strains. If a 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 provides a transduction mechanism that can be used to simultaneously produce and measure a property of interest. The magnetostrictive process relating the magnetic and mechanical states can be described with the two coupled linear equations, Eqns. (1,2)[2-5]. These equations of state, written below in terms of axial parameters only, are expressed in terms of mechanical parameters (strain ε, stress σ, Young's modulus at constant applied magnetic field E_y^H), magnetic parameters (applied magnetic field H, magnetic induction B, permeability at constant stress μ^σ), and two magnetomechanical coefficients (the strain coefficient $d = (d\varepsilon / dH)|_\sigma$ and $d^* = (dB / d\sigma)|_H$.) Thus, neglecting temperature and three dimensional effects,

$$\varepsilon = \sigma / E_y^H + d H \tag{1}$$

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

where ε and B are dependent on the externally applied quantities σ and H. The application of a stress will cause a change in the strain and also produces a change in the magnetic induction. This later effect can also be expressed as a change in permeability by writing Eqn. 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 as described in equations 4 and 5.

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In the early 19th 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. Amperes law describes this electromagnetic relationship. For a long, thin solenoid having a number of turns N_C and a 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 and producing controlled strain and force output[7].

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

$$V = -N_c \frac{d\varphi}{dt} = -N_c A_c \frac{dB}{dt}, \tag{5}$$

where V is the induced voltage in the solenoid of constant area A_C. 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,

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

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 detection coil.

Transduction

Magnetostrictive materials are magneto-elastic in the sense that they do work in the process of converting between magnetic and elastic (or mechanical) energy states. However, magnetostrictive transducers are generally classified as electro-mechanical devices or electro-magneto-mechanical because their input and output are generally electrical and mechanical in nature. The conversion of magnetic energy to and from electrical and/or mechanical is transparent to the device user. A common two-port schematic appropriate for both magnetostrictive sensing and actuation devices is given in Figure 1. The magnetostrictive driver is represented by the center block, with the transduction coefficients T_{me} (mechanical due to electrical) and T_{em} (electrical due to mechanical) indicative of both the magneto-elastic attributes characterized by Eqns. 1 and 2 and the electro-magnetic attributes associated with conversion between electrical and magnetic fields characterized by Eqns. 4 and 5. The transduction process relating the electrical and mechanical states can be described with two coupled linear equations[8]. These canonical equations are expressed in terms of mechanical parameters (force F, velocity v, mechanical impedance Z_m), electrical parameters (applied voltage V, current I, electrical impedance Z_e), and the two transduction coefficients:

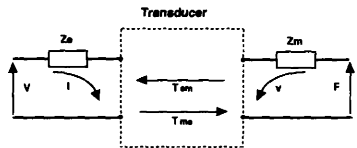

Figure 1. Two port transducer schematic.

$$V = Z_e I + T_{em} v \tag{7}$$
$$F = T_{me} I + z_m v. \tag{8}$$

Examples of device specific performance in response to different DC magnetic bias levels, stress and frequency are shown in Figures 2-4 respectively. Figure 2a depicts the effect of DC bias on five minor hysteresis loops collected by driving the device at 0.7 Hz with an applied of ±5 kA/m as the DC magnetic bias was increase from 5 to 45 kA/m in increments of 10 kA/m. Figure 2b shows frequency response functions of acceleration per input current, where the change in the transducer's axial resonant frequency varies from 1350 Hz to over 2000 Hz reflecting the effect of DC bias on the elastic modulus (the delta E effect)[3]. (Note that the device housing resonance at 3300 Hz is not effected by the changing DC magnetic field.) Figure 3 illustrates the sensitivity of major strain-applied field hysteresis loops to variations in mechanical load or prestress. The upper traces in Figures 4a-c are Bode plots of strain per applied field, strain per magnetization and magnetization per applied field, respectively. The lower traces are minor

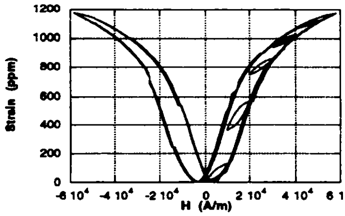

Figure 2a. Strain versus applied field major hysteresis loop and minor loops for AC fields of ±5 kA/m at 0.7 Hz at DC bias levels of 5, 15, 25, 35, and 45 kA/m. Device mechanical load is a prestress of 6.9 MPa.

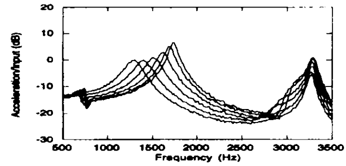

Figure 2b. Acceleration per input current frequency response functions at DC bias levels of (from left to right): 20, 30, 36, 42, 50, and 60 kA/m.

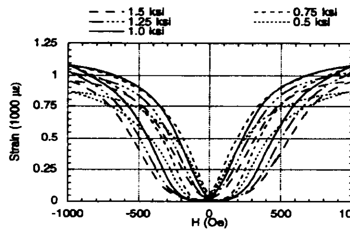

Figure 3. Strain versus applied field major hysteresis loop corresponding to device mechanical loads of prestress: 3.5, 5.2, 6.9, 8.6 and 10.4 MPa (0.5, 0.75, 1.0, 1.25 and 1.5 ksi).

hysteresis loops of these quantities recorded at (from left to right) frequencies of 10, 100, 500, 800, 1000, 1250, 1500 and 2000 Hz.

Such information can be used to implement calibration and control schemes to facilitate the use of magnetostrictive devices in a variety of applications and can be used for optimization of device performance. For example, information from Figures 2a and 3 might be coupled to optimize DC magnetic bias in real time to produce specified strains under varying mechanical loads. Figure 2b demonstrates the ability to tune a system's resonant frequency in real time. This can be coupled with information on frequencies that minimize losses. Hysteresis loop data from Figure 4a can be used to tailor swept frequency operation for the most efficient electro-mechanical performance. Additionally, this suggests the ability to target operating conditions for minimization of internal heating under continuous operation, which is of particular concern for ultrasonic operation.

Another significant loss factor that is associated with the transduction of electric to magnetic energy under dynamic operation is eddy currents. Eddy current power losses increase with approximately the square of frequency and thus have a significant impact on the operational bandwidth of devices. Laminations in the magnetostrictive core help to mitigate the effects of eddy currents, however, materials such as Terfenol-D are brittle and costly to laminate. Materials such as insulated magnetic particles or the silicon steels in common use in motors and power systems are suitable for the magnetic circuit components that make up the transducer housing, as they simultaneously support flux conduction and offer high resistivities. Magnetostrictive composites that use non-electrically conducting matrix material yield reductions in eddy current losses. They have been proposed for extending device output bandwidth by an order of magnitude, from roughly 10kHz to close to 100kHz[9]. Such composites offer great promise as high frequency magnetostrictive drivers.

ACTUATION CONFIGURATIONS

Nickel was used in many of the early magnetostrictive sonar devices and is still being used in commercially available ultrasonic cleaners available from, for example, Blue Wave Ultrasonics. Other examples of magnetostrictive material use in commercial applications include Terfenol-D based devices such as the underwater communication systems produced by Trigger Scuba, Inc., the acoustic pressure wave source (P-Wave) produced by ETREMA Products, Inc. for enhancing oil well production rates, and precision micropositioners produced by Energenic, Inc.

In order to illustrate the needs and issues of different transducer applications, we classify magnetostrictive transducers in three broad categories as follows: (1) High power, low frequency applications. These applications are typically associated with under-water acoustic generation and

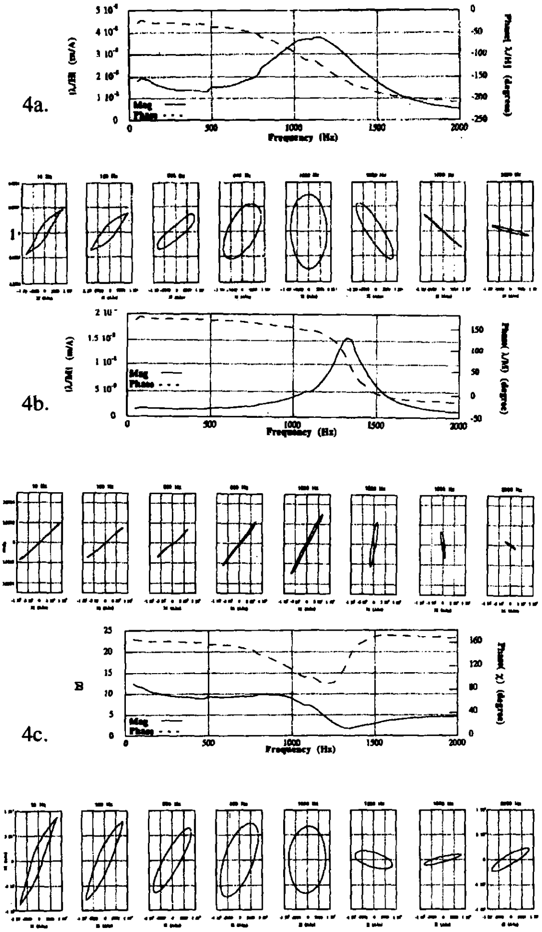

Figure 4. a) Strain per magnetization bode plot and strain versus magnetization minor loops (±400 microstrain vs. ±10 kA/m). b) Strain per magnetization bode plot and strain versus magnetization minor loops (±100 kA/m vs. ±10kA/m). c) Magnetization per applied field Bode plot and magnetization versus applied field minor loops (±400 microstrain vs. ±100 kA/m). From left to right, hysteresis minor loop data collected at: 10, 100, 500, 800, 1000, 1250, 1500 and 2000 Hz.[11]

communications. The designs discussed here are the flextensional transducer, the piston-type, and the square-ring. (2) Motion/force generation applications. In this category, we include transducers designed to do work against external mechanical loads. The motion may be linear, such as in the inchworm or Kiesewetter motors or rotational. (3) Ultrasonic applications. This category involves a fairly broad range of actuators, whose final use may actually vary from surgical applications to cleaning devices and use in high speed machining.

Despite the differences between the three categories, there is intrinsic commonality to all magnetostrictive actuators based upon the magneto-mechanical nature of the device. It is common practice to subject the material to magnetic bias and mechanical prestress. A magnetic bias is generally supplied with permanent magnets located in series or parallel with the drive motor, and/or with DC currents. The mechanical bias is typically applied by structural compression of the driver with springs or via the transducer structure itself, such as in flextensional transducers.

High power, low frequency applications

Dynamic strains are of primary importance in low-frequency, high-power transducers, namely those for sonar and underwater communications. At and near mechanical resonance, strains greater than the static saturation strain can be obtained. Three of the more common devices for sonar applications are the flextensional, the piston, and the "ring" types of actuators.

Flextensional transducers radiate acoustic energy through flexing of a shell, usually oval-shaped, caused by the longitudinal extension and contraction of a cylindrical drive motor mounted in compression inside the shell. These transducers are capable of producing high power at fairly low frequencies. Their history dates back to 1929-1936, when the first flextensional device for use as a foghorn was first built and patented by Hayes at the NRL. It is characteristic of flextensional transducers to have two types of radiating modes: a low frequency flexing mode associated with bending of the shell and a higher frequency breathing mode, in which the whole shell expands and contracts in unison. As the name implies, the desired mode of vibration is a flexural one. However, the breathing mode is acoustically more like a monopole, thus it is usually of higher efficiency and improves the effective system magnetomechanical coupling factor. This higher mode has a strong effect on the parameters used to describe the flexural modes and hence, it cannot be overlooked. Moffett *et al.*[10] report on a flextensional Terfenol-D powered acoustic projector operated at a depth of 122 m (400ft) driven to a source level of 212 dB. Design considerations include performance needs and often competing technical issues related to magnetic circuit design, variations in mechanical load and prestress with changing submersion depths, the effects of cavitation at shallow depths, and stress-induced fatigue in the shell.

The Tonpilz (*Tonpilz* is German for 'sound mushroom') transducer is a common piston-type design. It lacks parts likely to suffer fatigue-induced failure due to bending, which is one of the advantages of piston-type designs over conventional flextensional transducers. The transducer has a magnetostrictive rod surrounded by a drive coil that provides ac and dc magnetic field excitation, a mechanism for pre-stressing of the rod, a front radiating surface (piston), and a countermass. Permanent magnets (Alnico V, SmCo, Neodemium Boron, etc.) may be located in parallel or in series with the magnetostrictive driver.

The ring transducer concept was first developed during the late 1920's[12]. The interest on ring transducers during those early days was based on their ruggedness and lower cost compared to other available transducer technologies. A typical ring transducer might consist of four magnetostrictive rods are arranged to form a square with four curved pistons that are the radiating surfaces enclosing the square and attached to the corners of the square. Square ring transducers are capable of providing either omni- or directional sound propagation at low frequencies[13]. Monopole operation is achieved with the rods acting in unison. Dipole operation is accomplished by switching the magnetic bias on two of the rods and maintaining a constant direction on the AC magnetic field on all four rods. This feature translates into a transducer having two effective resonant frequencies and Q values, one for each mode of operation.

Motion/force generation applications

There is a growing interest in use of magnetostrictive devices as a source for motion and/or force, and in particular for use in conjunction with smart structures for active vibration control. These linear motor systems fall into the two general categories of piston devices and inchworm devices.

The basic components found in piston devices are shown in Figure 5. The primary distinction between these devices and the sonar piston-type actuators discussed above is that instead of acoustic radiation into water, the output design objective is mechanical forces over a bandwidth of DC to ≈5 kHz. An example of the performance that can realized using magnetostrictive actuators for active vibration control is presented in Figure 6 in which a simple analog proportion control scheme was applied to achieve significant vibration control (>33 dB at both mode 1 and 2). A recent commercial device that exhibits high acoustic output capabilities and the ability to operate under down-hole conditions is P-Wave (Etrema Products Inc.), a 27 Watt acoustic, 250-400 Hz acoustic source used to enhance oil production.

There are several variations on the inchworm motor concepts that move a shaft relative to the motor housing, and they all generally rely on two separate capabilities, a clamping force and a pushing force. Motors with linear shaft output rates of 20 mm / sec have been designed that can develop 1000 N of force with a 200 mm stroke[14].

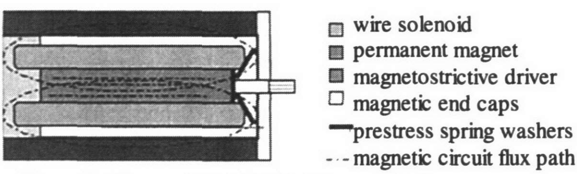

Figure 5. Components of basic magnetostrictive actuators.

Ultrasonic applications

Although generic ultrasonic devices are similar to their low frequency counterparts, e.g. they require the same components described in Figure 5, there are several problems associated with operation at

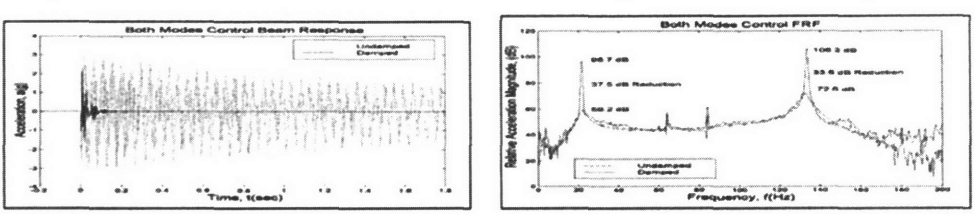

Figure 6. Magnetostrictive actuator performance for active vibration control of the transient responses of a 40" x 2" x 1" 0.125"-thick aluminum 'C' channel beam to impact excitation[15].

frequencies of greater that 20kHz. Hysteresis losses within a magnetostrictive driver will introduce high internal heat dissipation. Eddy currents will introduce both heat and a skin effect that effectively shields the core of the driver from an applied magnetic field. Impedance mismatches at ultrasonic frequencies make transfer of energy from the driver to the surrounding medium difficult[16]. The use of laminated and/or composite magnetostrictive materials reduces losses associated with eddy currents. The use of amplifying horns having application specific profiles, in conjunction with quarter wave and half wave resonant device operation, enhance energy output.

SENSING CONFIGURATIONS

Magnetostrictive sensors can be classified as passive sensors, active sensors, and combined or hybrid sensors, based on how the magnetomechanical properties of the system components are used to measure the parameters of interest.

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 the magnetic induction or permeability can then be related to the torque on the specimen.

Finally, combined or hybrid sensors use a magnetostrictive element to actively excite or change another material to 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).

Early work with magnetostrictives such as nickel, iron, and permalloy identified many sensing applications. Some of the earliest uses of magnetostrictive materials from the 19th century and first half of the 20th century include telephone receiver[8], hydrophones, and scanning sonar[17], 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[8]. In 1888, Ewing reported force measurements using a magnetostrictive device of iron and nickel, the first magnetostrictive force sensor[18]. In addition to giant magnetostrictive materials such as Terfenol-D, 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[6,18,19]. Numerous patents for sensors based on magnetoelastic properties have been issued over the last decade[6,20].

The emphasis of this overview is on applications, therefore the magnetostrictive sensors are grouped together based on the following measured property or quantity: torque, motion, force, magnetic field, and material characterization. Due 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. Note that some sensor designs can be used to measure several quantities, such as the magnetostrictive delay line, which 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 non-contact sensor, a thin film or a wire application, and a shaft sensor.

Non-contact torque sensor. The non-contact torque sensor is one of the most common torque sensor configurations. Some of the advantages of non-contact magnetostrictive torque sensors include minimal target, rapid response, good stability and accuracy in conjunction with high sensitivity, and capacity to withstand overloads. Non-contact 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 gives a thorough overview of torque sensor technology, focusing on non-contact magnetostrictive torque sensors[20].

The basic principle of the sensor configuration relies on that as a shaft is torqued, stress develops at ± 45° from the shaft axis. For the example shown in Figure 7, a 'C' shaped ferromagnetic core with both an excitation and a detection coil is oriented to the 45° axis. The change in stress in the ferromagnetic shaft causes 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 include versions with multiple C sections surrounding the shaft to maximize sensitivity and minimize errors introduced through out-of-round shaft rotation[20]. An alternative design relies on direct transfer of the torque to a magnetostrictive sleeve and detection of the magnetostrictive response induced by the torque[21].

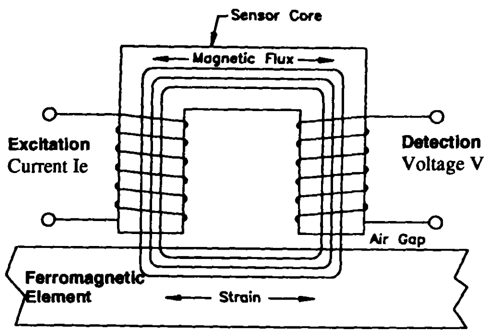

Figure 7: Non-contact torque sensor with excitation and detection coils around the legs of a C shaped ferromagnetic core[21].

Fleming[22] and Garshelis[23] have both investigated several issues with these sensors, including non-linearities due to sensor element properties, the effects of magnetic saturation, temperature, excitation frequency and design of passive sensors in which a Hall probe can be used to monitor torque induced changes in the magnetoelastic sensor material.

Thin film and wire applied to shaft. Other torque sensors apply the magnetostrictive material directly to the target. This idea was developed by Yamasaki, Mohri and collaborators using wire explosion spraying technique to adhere thin layers of Ni, Fe-Ni, and Fe-Co-Ni to shafts[24]. 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 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[25]. 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.*[26]. 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. Savage *et al.* obtained a U.S. patent for a magnetostrictive torque sensor using a magnetostrictive wire helically wrapped around and connected to a shaft[27]. 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[28]. An excitation coil surrounds part of the drill including the shank and the flutes, as in Figure 8. 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 *et al.* the sensor is robust with respect to temperature[29].

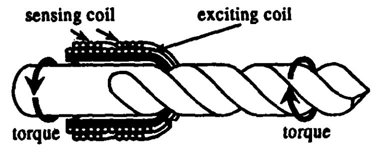

Figure 8. Non-contact measurement of torque on drill employing an excitation coil and two sensing coils; one over the shank and one over the flutes[26]. ©IEEE 1994.

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 by a magnetostrictive wave guide and a magnetostrictive delay line; and strain can be measured by a magnetostrictive strain gage and a non-contact 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 papers have described this effect and shown its utility[30-32].

Fenn and Gerver have developed, modeled, and tested a velocity sensor based on a permanent magnet biased Terfenol-D actuator[33]. 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 (Eqn. 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.

Non-contact strain sensor. Non-contact strain sensors use the magnetic field to couple the straining target to the sensing element. A non-contact system has several advantages[34]. 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 non-contact torque sensor shown in Figure 7, however it measures the target strain in any direction of interest. The C shaped ferromagnetic sensor core is wound with an excitation and detection 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 target. Due 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 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 9, 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 direction away from the permanent magnet along the wave guide. One end is fitted with a receiver, while the other end is connects to a damper. The damper attenuates the acoustic wave so 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 9, 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 describes the operation of MTS model LP in detail[35]. 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 (U.K. and U.S.) 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 (France) has developed the Captosonic position sensor which is capable of measuring distances up to 50 meters with ±1mm accuracy[36].

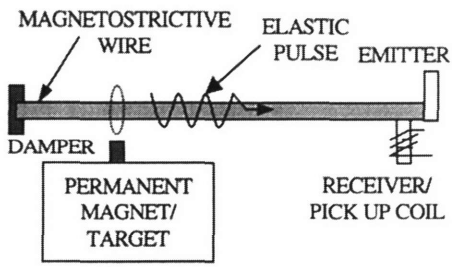

Figure 9. Magnetostrictive wave guide position sensor[33].

Magnetoelastic strain gage. Using the fact that the permeability of many magnetostrictive materials is stress sensitive, a strain gage made from strips of Metglas 2605SC has been developed by Wun-Fogle and associates[37]. 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 minutes, 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 1kHz 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} at 0.05 Hz.

Magnetostrictive delay line. An innovative use of a magnetostrictive delay line can be used to measure displacement. An acoustic pulse is propagated through the magnetostrictive delay line and detected by a receiving unit. A current pulse through a conductor (PCC) orthogonal to the magnetostrictive delay line (MDL) generates a pulsed magnetic field in the MDL which generates an elastic wave, see Figure 10. 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 so the magnetic pulse and elastic wave in the MDL increases in strength. The output to the sensor is the pulse generated in the receiving unit coil (RC) as described by 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 less than 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[38]. 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[38]. Applications for this sensor include tactile arrays, digitizers, and structural deformations.

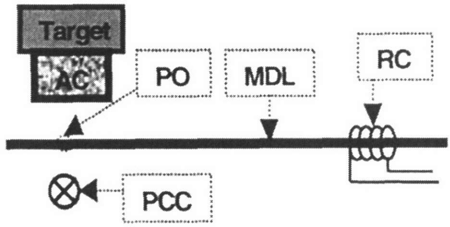

Figure 10. Magnetostrictive delay line, MDL, position sensor, with active core (AC) connected to target, pulsed current conductor, (PCC) receiving coil (RC) and acoustic stress point of origin (PO)[36].

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 previously and force. A combined Torque-Force sensor has also been developed[39]. The magnetostrictive force sensor, magnetostrictive delay line, and amorphous ribbon force sensor are described below.

Magnetostrictive delay line. The magnetostrictive delay line (MDL) displacement sensor configuration has been modified to produce a force distribution sensor[40,41]. A force applied directly to the MDL will distort the acoustic signal generated by the emitter as described previously. 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 pulsed current conductor (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 describe a force sensor which employs the change in electrical impedance of a magnetic circuit with stress to measure stress or force[42]. It is similar in construction to the noncontact magnetostrictive strain sensor shown in Figure 7. However, rather than the C shape, two magnetostrictive core spring elements are held in place by rigid end pieces. 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 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[43]. A transmitting coil excites the ribbon while a pair of detection coils measures the maximum induction which is dependent on the stress. 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[43]. 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[44].

Material characterization sensors

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

Magnetostrictive sensor. This non-contact magnetostrictive sensor uses the magnetostrictive properties of the target material to excite elastic waves which can be measured and monitored to characterize the target[45-47]. 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 11, consists of a transmitting coil (pulse generator, power amplifier, and bias magnet) surrounding the object, which generates the mechanical wave via magnetostrictive excitation. A receiving coil (signal preamplifier, 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 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 system where noninvasive monitoring techniques are preferred.

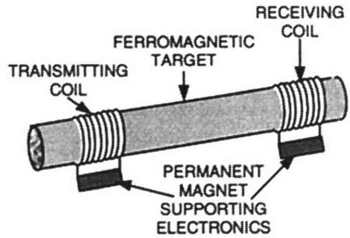

Figure 11. Magnetostrictive sensor for characterizing corrosion and monitoring ferromagnetic materials such as pipes and strands[45].

Magnetostrictive fiber optic sensor. An in situ fiber optic sensor coupled to a magnetostrictive element has been used for composite resin characterization[48]. 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[49]. 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[55]. Finally, a magnetic field sensor has been developed based on magnetostrictive delay line technology[56].

Terfenol-D magnetometer. The first magnetometer design, developed by Chung et al., employs a Terfenol-D sample to convert a magnetic field into a measurable quantity[50-52]. 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 $\mu\varepsilon$/Gauss. In addition, the sensitivity was found to be a function of the mechanical prestress.

Magnetostrictive fiber optic sensor. Numerous fiber optic magnetic field sensors have been developed. In 1979 Yariv and Winsor proposed a now common configuration which uses a magnetostrictive film coating an optic fiber[53]. 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 has shown that the resolution limit at DC to low frequency (less than 1 Hz) of such a sensor is approximately 3×10^{-11} Oe[54].

Miscellaneous other devices

Magnetostrictive sensors have been used to measure or monitor a number of other properties and characteristics. Some examples found in literature include hearing aid, magnetoelastic delay line digitizer[57], magnetoacoustic keyboard[58], thermometer[59], biomedical monitoring such as lung ventilation[60] and spine movement[61], and magnetic tagging for health monitoring of composites[62].

CONCLUDING REMARKS

Advances in magnetostrictive material technologies continue to create new opportunities for transducer design and application engineers. The strains and forces achievable with the newer giant magnetostrictive materials and transducers, their high coupling coefficients and high energy densities have justified their use in an ever-increasing number of sensor and actuator applications. As evidenced by the resurgence on patented magnetostrictive devices, particularly related to sensor applications, designers continue to find new opportunities for advancing transduction capabilities by incorporating magnetostrictive elements in their sensor and actuator systems. For related overview articles, the reader is referred to references 6, 15, 20, and 63.

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