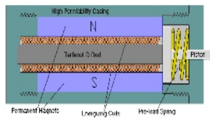


"One of the key attributes of a smart structure is considered to be distributed sensing and actuation. Current drives in magnetostrictive sensing and actuation are both in terms of developing new materials as well as nano-composites of existing materials to enhance the efficiency in sensing and actuation."

Terfenol and Galfenols: Smart Magnetostrictive Metals for Intelligent Transduction

By B. Bhattacharya

Magical power of magnets awed people of early civilizations as a strange force from the rocks that attracts shoes and swords without revealing itself! Wealthy Egyptians believed magnets could prevent aging. Cleopatra used to put magnetic beads on her forehead which were supposed to retain her beauty for ever! Since then a galaxy of applications of magnetism have been recorded in the history ranging from navigation tools, war-arms, motors, generators, levitators, spectroscopic instruments, computer-memory chips and even items for magnetic therapy.

In 1842, James Joule noted that a ferromagnetic sample changed its length with the application of magnetism. This effect of change in size by magnetic force ('striction' = compressed, pressured or tensed') was noted as 'magnetostriction' and named after him as 'Joule effect'. Later, in 1865, the reciprocal phenomenon, that is the change in magnetisation due to the change in stress in a material is found by Villari and has been subsequently acknowledged as 'Villari effect'.

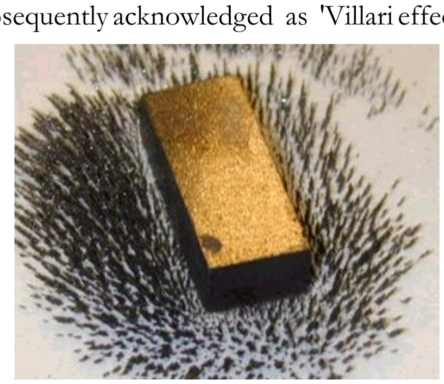


Figure 1: A small block of Terfenol -D magnetostrictive material, source: Etrema Products Inc., USA

In due course of time, two other related effects are discovered. It is observed that magnetostrictive rods are subjected to twisting in the presence of Helical Magnetic field. This effect is known as Wiedemann effect. In this effect, magnetic field is generated by passing current through a magnetostrictive sample. The inverse of Wiedemann effect is known as Matteuci effect and is used in magnetostrictive torque sensors.

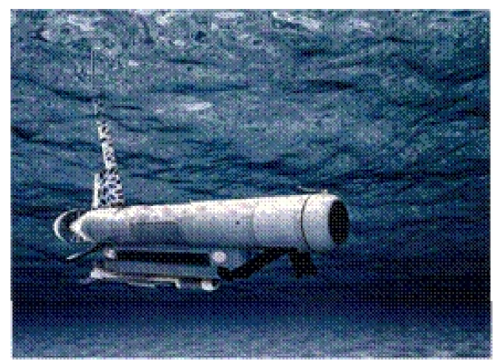


Figure 2 : TALON (Tactical Acoustic Littoral Ocean Network) sonar system uses Magneto strictive Terfenol -D for under -water submarine detection, source : Etrema Products

The discovery of Joule effect in ferromagnetic materials triggered the development of new sonic sensors, substituting piezoelectric oscillators. Initially during the first world-war, piezoelectric transducers were extensively used for the generation of precise sonic signals and sensing thereafter. Paul Langévin invented the first sonar type device for detecting the 'echo-location' of submarines using the piezoelectric properties of quartz. However, with the discovery of magnetostrictive effects, new transducers are developed that can take almost unlimited power and can be overloaded without damage.

Magnetostrictive transducers are found to be very much cost-effective in the low-frequency band and could be effectively used for deep-sea measurements. Since then, magnetostrictive materials are being used for special purpose under-water transducers, for example, in the latest TALON system shown in Figure 2.

A closer look on Magnetostriction

Although Magnetostriction is broadly defined by a change of size in certain ferromagnetic materials in presence of a magnetic field, a more rigorous description is necessary to discuss the evolution of such materials.
Magnetostriction involves two processes in a macroscopic scale (as shown in Figure 3). First, the domain walls of ferromagnetic material start to migrate in presence of a magnetic field and then the domains rotate or re-orient themselves with respect to the magnetic field. Magnetostriction is a combined effect of these two processes.

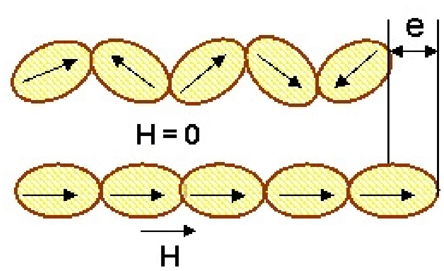


Figure 3: Magnetostriction (e) in materials due to the domain migration and reorientation under applied magnetic field H

If a crystal of ferromagnetic material is initially at a compressed state, the effect of Magnetostriction becomes more pronounced. All ferromagnetic elements show certain degree of Magnetostriction. It is observed that Cobalt which saturates around 50 μstrain can achieve maximum saturation. In Table 1, the Magnetostriction noted in different materials is provided. The last three materials in the bottom of the table can produce very high magnetostriction due to high magnetic anisotropy of rare earth metals like Terbium (Te) and Dysprosium (Dy). In fact, it was known for quite some time that the rare-earth metals of the Lanthanide group (Gd, Te, Dy and Ho) had high magnetic anisotropy due to their open 4f shell; however, in pure form, this useful property is retained up to very low temperature. Clark [1] and his co-workers at Naval Ordinance Laboratory, USA,had successfully prepared stoichiometric alloys containing Fe, Dy, and Tb of the form $Tb_xDy_{1-x}Fe_y$ (x = 0.3, y = 1.9-1.95) and named it as Terfenol-D ('Ter' - Terbium, Fe - Iron, NOL - Naval Ordinance Lab, D - Dysprosium).

Material	Magnetostriction (ppm)	Curie Temp (K)
Fe	14	633
Ni	33	1043
Co	50	350
Permalloy	27	713
$DyFe_2$	650	635
$TbFe_2$	2630	703
$Tb_{.6}Dy_{.7}Fe_{1.9}$	2400	653

Table 1: Magnetostriction in some Ferromagnetic Materials

Year	Event
1842	Magnetostriction discovered in Nickel by Joule
1865	Villari discovers inverse Joule Effect
1926	Anisotropy in single crystal iron
1965	Rare-earth metal magnetostriction in Terbium and Dysprosium by Clark
1972	$TbFe_2$ and $DyFe_2$ at 300 °K by Clark
1975	Terfenol-D by Clark
1994	Polymer Matrix and Terfenol-D particulate composite (Sandlund et al)
1998	Discovery of Galfenol – a more rugged MS material at NSWC (Clark)
2002	Oriented particulate Composite (Carman)

Table 2: Important timelines in the evolution of magnetostrictive materials

Terfenol-D, operated under a mechanical bias can strain up to 2000 microstrain in a field of 2 kOe at room temperature. This high temperature large magnetostriction is also referred as Giant Magnetostriction in the literature. For typical transducer and actuator applications, Terfenol-D is one of the most commonly used magnetostrictive materials today.
A time-line for all the major events in the history of evolution of magnetostrictive materials is shown in Table 2.

Magnetostrictive Actuators based on Giant Magnetostriction

The discovery of giant magnetostriction in 1975 by Clark at naval ordinance laboratory, USA inspired the investigation of such materials as actuators. The important behaviour of these materials in a coupled electro-mechanical environment is presented below:

Direct Effects	Indirect Effects
Joule Effect : Magnetostriction: Change in sample Dimension in the magnetic field	Villari Effect: Change in magnetisation due to applied stress
Wiedemann Effect : Torque induced by helical magnetic field	Matteuci Effect: Helical anisotropy and EMF induced by a torque
Magnetovolume Effect: Volume change due to magnetostriction	Nagoka-Honda Effect: Change in the magnetic state due to change in the volume

The top two effects are mostly used in developing actuators and sensors for vibration control. The constitutive relationships are shown in Figure 4.

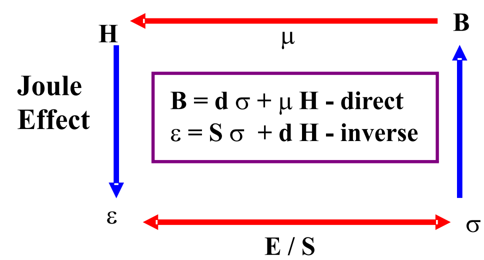


Figure 4: Coupled field effects for actuators and sensors

The high strain output of magnetostrictive materials, especially in Terfenol-D has inspired the development of linear actuators. Reed, Hiller and Wise developed independent models of large sized magnetostrictive actuators using Terfenol-D driven plungers. These models are proposed for the control of high frequency vibration and acoustic noise control. Anjanappa *et al* have successfully developed magnetostrictive mini-actuators for the control of mechanical vibration. A typical MMA is shown in Figure 5. Pre-load springs and permanent magnets are used to put the piston in zero-position and also to reduce hysteresis. The energizing coil around the rod is used to activate the Terfenol-D rod for dynamic application.
This type of actuators can be easily embedded inside a laminated composite structure and used for vibration control. Anjanappa has proposed a simple magneto-thermo-elastic model for stress-strain relationship in such actuator and is expressed as shown in the first equation on page 37.

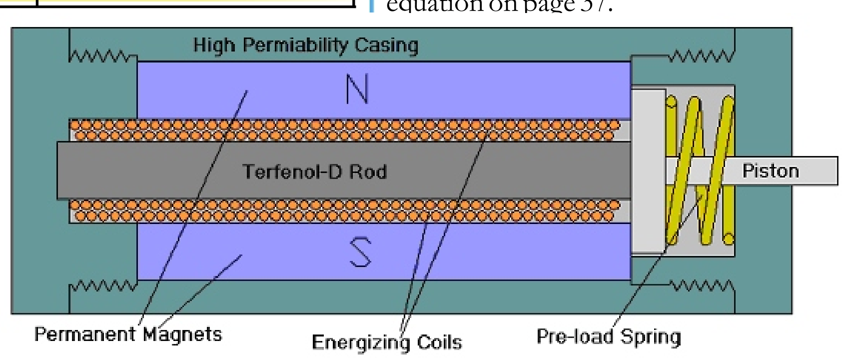


Figure 5: Detailed View of a Magnetostrictive Actuator; Source : Cameron MacWilliam, University of Western Sydney

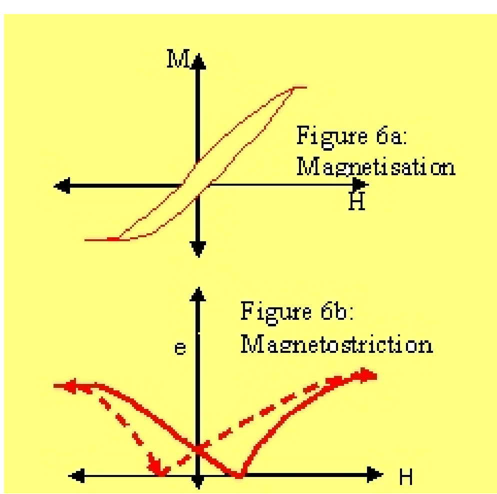
The first term in the right hand side expression corresponds to the elastic strain, the second

$$\varepsilon_c(t) = S(\sigma + \sigma_o) + d\,G\,i(t) + \alpha\,K \int e^{-t/C}\,{}_i^2\,(t)\,dt$$

ε - strain, S- compliance modulus, σ - stress, σ_o – pre-stress, d – magneto-mechanical constant, G – control parameter, i(t) – control current, α - equivalent thermal coefficient of the housing, and C – a parametric constant

due to the magneto-elastic coupling (note that magnetisation is expressed in terms of applied current in the energizing coil) and the last term corresponds to thermal effect in the coil.

It has been observed that the maximum hindrance to the performance of such actuators occur due to thermal disturbances. If the control current is not stopped a little *a priori* to the almost attenuated vibration, the thermal strain causes rebuilding of vibration and it may even lead to instability. Two other related issues to the magnetostrictive actuator are: (a) presence of inherent non-linearity and (B) hysteresis in the system. Figures 6a and 6b, depict a pair of typical magnetisation and magnetic strain generation curves which implies the non-linearity of the MMAs.



Magnetostrictive Sensors based on Villari effect

The use of magnetostrictive materials in vibration sensing is relatively less explored. Developing thin film sensors out of Terfenol-D blocks is difficult and quite expensive. Two approaches are made to encounter this problem: (a) development of particulate composite in which Terfenol-D particles of micron to sub-micron size is dispersed in a suitable resin and cured to form sensors and (b) development of thin-film metallic glasses as magnetostrictive (MS) sensors. We will discuss about the particulate composites in the next section. Considering the second group of sensors, Histoforou is one of the pioneers in the use of thin-film based Magnetostrictive sensors. It is found in 1978 that the rapid cooling of iron, nickel and cobalt alloys together with one of the elements like boron, silicon or phosphorous can produce metallic glasses of magnetostrictive nature. Hristoforou has used such amorphous materials in the form of wires to develop sensors based on magnetic delay-line (MDL) technique (see Figure 7). The basic idea of MDL is to sense the change of signals passed from an excited source to the receiving end whenever the amorphous wire is excited by a pulsed current. The transmitting MS coil generates an elastic wave using the magneto-elastic coupling which travels through the attached test member and is received by the receiving MS coil as a current signal due to the same coupling. Since elastic waves travel slower than electromagnetic waves, a millisecond phase difference between the transmission and receiving coil signals can be used to differentiate between healthy and cracked specimens.

The magnetostriction in the MDL is defined by the following simple phenemenological relation:

$$H(x,t) = f(x)\,I(t) = 1/(\sqrt{(a^2 + x^2)}\ \ I(t)$$

$$\lambda(H) = \lambda_s\,(1-e^{-\alpha H}\ ),\ \ \alpha>0$$

H – applied pulsed magnetic field, I(t) - applied current, a - distance between the pulsed conductor and MDL, λ_s - saturation magnetostriction, α - a material parameter

Recent advances in this field are taking place in developing miniaturised MDLs. Using a few mm long Iron-based MDL, and a three-layered receiving coil, the sensors could be developed for deformation and vibration sensing in a very small region. Hristoforou has developed a $Ni_{81}Fe_{19}/SiO_2/Ni_{81}Fe_{19}$ three-layered MR structure below a magnetostrictive $Fe_{70}Si_{15}B_{15}$ thin film, separated by a silicon dioxide layer. The insulating layers and $Fe_{70}Si_{15}B_{15}$ amorphous thin films have been deposited by r.f. sputtering method. The $Ni_{81}Fe_{19}$ thin films (about 0.05 µm in thickness) are deposited by electron beam vacuum evaporation.

Such devices would enormously help crack detection in large steel pipes and cables. Thin 'Metglas' ribbons are also in high demand for the bio-medical instruments.

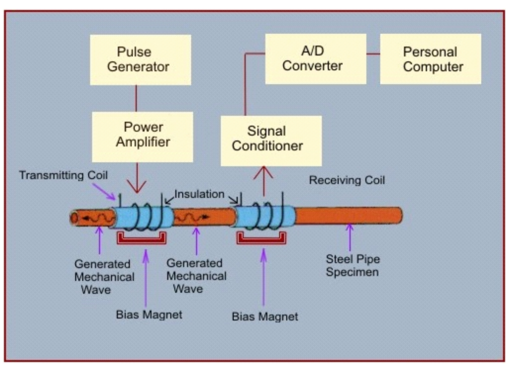


Figure 7: Magnetostrictive Delay Line Sensor – Source SwRI, Sweden

Magnetostrictive Particulate Composites for Vibration Sensing and Actuation

One of the key attributes of a smart structure is considered to be distributed sensing and actuation. MMAs and MDLs discussed in earlier sections refer mostly to pointed actuation and sensing of static and dynamic deformation. With the advent of advanced composites, researchers became interested to find the feasibility of embedding magneto-strictive sensors and actuators inside laminated composites. In 1994, Sandlund *et al* proposed a method of mixing and degassing Terfenol-D particles in epoxy resin. The resulting mixture after curing was found to possess substantial magnetostriction (up to 1000 strain). The advantage of the new actuators was the embeddability into composite laminate. However, it has been shown by Anjanappa *et al* that the constitutive relationship as defined in Figure 4, no longer remains linear and at most a piece-wise linear relationship should be used based on different ranges of magnetostriction. Bhattacharya had developed an energy-based vibration analysis procedure based on the magnetostrictive particulate composites. By using extended Hamilton's principle it was shown that the governing equations of motion for an asymmetric laminated composite beam could be expressed as below:

$$A_{11}u_{,xx} - B_{11}\, w_{,xxx} - F_1 C w'_{,xx} - m\, u'' = 0$$

$$-B_{11}u_{,xxx} + D_{11}\, w_{,xxxx} + F_2\, C\, w'_{,xx} + m\, w'' = G(x,t)$$

Stiffnesses for n-layered laminate are defined as:

$$A_{11}, B_{11}, D_{11} = \Sigma_{i=1,n} \int Q^{(i)}_{11}\,(1,z,z^2)\, dz$$

Active Control as:

$$F_1, F_2 = \int C\,(1,z)\,\delta m\, dz, \quad C = \text{Control Gain}$$

Mass as:

$$M = \Sigma_{i=1,n} \int \rho^{(i)}\, dz$$; Operators '/' denotes temporal and ',' spatial differentiation

Closure

Current drives in magnetostrictive sensing and actuation are both in terms of developing new materials as well as nano-composites of existing materials to enhance the efficiency in sensing and actuation.

Magnetic materials group at Naval Surface War Centre, USA has recently developed a new magnetostrictive actuator called Galfenol. Galfenol, though possess a lower active free-strain (about 1500 strain) it can be used under robust mechanical and chemical environment. Another new class of such material is Ferromagnetic Shape Memory Alloy (FSMA). FSMA consists of a composite of ferromagnetic material and a Shape Memory Alloy (SMA). The function of ferromagnetic material is to induce magnetic force which is then used to induce the stress in the SMA, resulting in the stress-induced martensite transformation. This procedure guarantees a fast response system as well as large active strain combining the advantages of magnetostrictive material and shape memory actuators.

Work is also going on to develop nano-structured magnetostrictive composites. It has been shown by Mcknight and Carman that if the magnetostrictive particles are oriented towards the 111 axis during composite development, the availability of free-strain is enhanced up to 2400 strain. Nano-structuring of such particles using spark-eroded nickel and Terfenol-D particles farther reduces the hysteresis and the eddy-current loss drastically.

The greatest advantage of magnetostrictive transducers is the capability of non-contact sensing and actuation. New patents are being taken towards non-contact energy dissipation from a mechanically active medium such as a rotating hard-disk or a high speed compressor blade. The mystic force that has been awed for thousands of years has become one of the best friends of mechatronic engineers today.

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About the author: Bishakh Bhattacharya obtained his Ph D from the Indian Institute of Science, Bangalore in 1997. Subsequently, he did his post doctoral studies in the University of Sheffield, UK. Later he was involved in an EPSRC project with DERA, Farnborough, UK. He is currently a joint faculty of the Department of Mechanical Engineering and Design Programme at IIT-Kanpur. His research interest includes Dynamics and Control of Flexible Structures, Advanced Composite Materials, Intelligent Systems and Product Design.