Module 6: Smart Materials & Smart Structural Control

Lecture 32: Magnetostrictive Material

The Lecture Contains:

Magnetostrictive Material

Magnetostriction is mostly found in the magnetic transition materials like iron, cobalt and nickel and also in the rare earth materials like lanthanum and terbium. The grains of these materials consist of numerous small randomly oriented magnetic domains, which can rotate and align under the influence of an external magnetic field. The magnetic orientation or alignment brings forth internal strain in the material, which is known as **magnetostriction**.

Similar effect is also found in the dielectrics under high electric field, which is known as **electrostriction**. These electro-mechanical phenomena are quite different from the piezoelectricity as these are essentially non-linear in nature and under unbiased field, the response is always unidirectional. In other words, the materials can only expand irrespective of the direction of the magnetic field applied to it.

The phenomenon of magnetostriction was discovered in nickel by James Joule in 1840. It was also observed later in other Ferromagnets and their alloys, although the maximum achievable strain was limited to 150 μ -strain only. Soon after, the discovery of low-temperature magneto-elasticity in rare earth elements, likes Tb (terbium), Dy (dysprosium) and Sm (samarium), has given a fresh impetus for continuing the search of magnetostrictive materials suitable for developing transducers.

Clark has obtained room-temperature magnetostriction in the alloy of Tb and Fe, which also has higher Curie temperature (around 700^0K). Subsequently, it is found that by adding another rare earth material called dysprosium with Tb-Fe alloy, the magnetic anisotropy in the alloy can be reduced, thus generating even larger strains. The commercially available and well-known magnetostrictive material Terfenol-D is an example of the aforementioned alloy of terbium, iron and dysprosium. However, the proportion of Tb, Fe and Dy varies depending on specific requirement of magneto-elasticity and temperature characteristics.

It is shown experimentally that the 'Terfenol' compound made using the composition $Dy_{0.73}Tb_{0.27}Fe_{1.95}$ produces less free strain than the same compound made of $Dy_{0.7}Tb_{0.3}\ Fe_{1.95}$ composition. However, in the former, the strain varies more linearly with the magnetic field as compared to the latter. This makes the first alloy more suitable for actuation purpose. Also, substituting dysprosium from Tb-Fe alloy by other rare earth materials like holmium or samarium, elastic characteristics can be significantly changed.

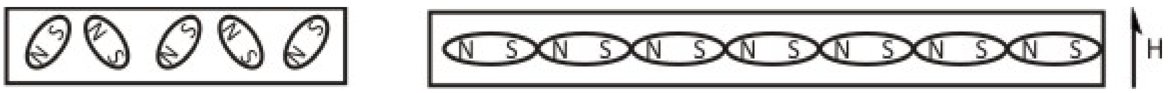

Fig 32.1: Magnetostrictive material with magnetic dipoles. Note the strip expands due to the application of magnetic field

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In the linear region of actuation and sensing (assuming the vector quantities along the direction of maximum response) the constitutive equations of magnetostriction are given by

$$S = s^H s + d H \qquad (32.1)$$

$$B = d s + \mu^s H \qquad (32.2)$$

where *S* is the strain, *s* the mechanical stress, *H* the magnetic field intensity and *B* the flux density. The compliance value at a constant magnetic intensity is denoted by s^H,*d* is the magneto–mechanical constant and μ^s is the permeability of the medium under constant stress condition. The equations are of the same form as that of piezoelectricity. However, the study of any typical *S–H* and *B–H* curve [10-20] brings out the following observations.

The relationship between magnetostriction and applied magnetic field is highly dependent on the intensity of the magnetic field. The relationship is approximately linear when the intensity of the applied magnetic field *H* is much lower than the intensity of the polarizing field H_{pol} (field at which the magnetic domains are initially aligned). The non-linearity begins as *H* approaches H_{pol} and the curve gradually flattens out signifying saturation or completion of all the domain alignments. Typically, for Terfenol-D rods under stress-free condition, such a relationship is approximately linear in the range of magnetic field from 0 to 100 Orsted.

The maximum free strain generated by magnetostriction is quite large, almost twice as much as that of PZT. Yet, unlike piezoelectric material, the reversal of magnetic field does not result in the reversal of strain here. Particularly, for dynamic applications like vibration suppressions, reversal of actuation strain is very much necessary. Hence, for such applications these actuators are operated with a biased magnetic field such that with respect to the biasing centre, reversal of strain occurs. The technique, however, reduces the availability of actuation strain by approximately 50%; thus lowering its edge over the piezoelectric materials.

It is observed that hysteresis is present in the *B–H* curve and is usually absent in the *B–S* curve. As a result, the combination of the two curves shows hysteresis in the *S-H* curve. The extent of hysteresis depends on the stoichiometry of the material and pre-stressing on the actuator.

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Comparison of the material properties between magnetostrictive materials

A comparison of the material properties of various available magnetostrictive materials is shown in Table 32.1.

Table 32.1: Material properties of magnetostrictive materials and aluminium

Material Properties	Terfenol-D	Metglas	Isotropic Composite	Anisotropic Composite	Aluminium
E_m (GPa)	25-35	55-60	19.7	17.0	73.0
ρ (Kg/m^3)	9250	7470	7500	6800	2630
d (nM/A)	15.0	-	3.7	5.9	0
Λ (μ -strain)	1500	52	400	630	0

Apart from Terfenol-D, the other smart materials included in the list are some of the more recent varieties in this field. Metglas or Vitrovac is a commercially available compound of iron (Fe), silicon (Si) and boron (B).

The other two materials consist of composites of Terfenol powders mixed with non-metallic binders. The binders work as insulating layers and effectively reduce the eddy current loss at higher frequencies of the applied magnetic field. The isotropic and anisotropic properties are attributed to random or biased magnetic dipole orientation of Terfenol powders during manufacturing. Table 32.1 shows that Terfenol-D rod produces the highest free-strain Λ . It is considered to be the most effective material from the point of view of actuation strain generation. However, it has poor tensile strength and it is the heaviest among the magnetostrictive materials.

On the other hand, Metglas possesses better mechanical properties, although it generates the lowest actuation strain. It is used mostly as a sensing material. In the two composite magnetostrictive materials, the energy conversion efficiency is quite low (*k=0.28* and *0.40*, respectively) rendering these unsuitable for low-frequency applications. Magnetostrictive materials with the capacity of high strain generation and wide bandwidth of operation promise wider applications in smart structures in near future.

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