Principles of Active Vibration Control: Magneto- and Electrostrictive Materials in Vibration Control

Introduction: Magneto- and Electrostrictive Materials

Both magnetostrictive and electrostrictive materials demonstrate a shape change upon the application of magnetic or electric fields. This small shape change is believed to be caused by the alignment of magnetic/electric domains within the material upon the application of the fields. The advent of specialized engineering materials enables the use of these materials in active vibration control applications thanks to the increased deformation strains.

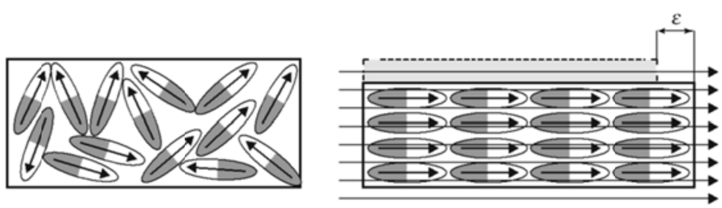


Fig. 8.36 Randomly oriented magnetic field

Magnetostrictive Materials

Magnetostrictive (MS) materials change their shape when subjected to a magnetic field. A common example of the magnetostrictive effect in everyday life is the humming noise emitted by electric transformers. This is due to the expansion and contraction of metallic parts in response to magnetostriction, induced by the changing electromagnetic field. Nearly all ferromagnetic materials demonstrate this property, but the shape and volume change is very small. Ferromagnetic materials have a structure divided into magnetic domains exhibiting uniform magnetic polarization. The applied magnetic field causes the rotation of these domains and in return a slight shape change on a macroscopic level. Figure 8.36 illustrates the randomly oriented magnetic domains within the material and the reorientation after the magnetic field is applied. The reciprocal phenomenon to magnetostriction is called the *Villari effect*. This describes the change of magnetic properties under applied load.

The deformation in magnetostrictive materials is characterized with the magnetostrictive coefficient ι_{ms} , which expresses the fractional length change upon applying a magnetic field. The shape change of the material is zero at zero magnetic field, however upon the application of the field it grows linearly according to the magnetostrictive coefficient until the material reaches magnetostrictive saturation.

The application of certain rare earth materials into an alloy allowed using the effect of magnetostriction in real-life engineering applications. Early types of magnetostrictive alloys demonstrated large magnetostriction, but only by applying high magnetic fields or at cryogenic temperatures [4]. These difficulties were eliminated by the introduction of *Terfenol-D*,which continues to be the most common magnetostric-tive material [4]. Terfenol-D exhibits about 2000 με at room temperature, while Cobalt, which demonstrates the largest magnetostrictive effect of the pure elements, exhibits only 60 με strain. Another common material goes by the trade name *Metglas 2605SC*, yet another by *Galfenol*.

The typical recoverable strain of magnetostrictive materials like Terfenol-D is in the order of 0.15%. Maximal response is presented under compressive loads. Magnetostrictive actuators have a long life span and may be used in high precision applications. Actuators may be used in compression alone as load carrying elements. Pre-stressing the actuators may increase both efficiency and the coupling effects [4].

Electrostrictive Materials

Electrostriction is closely related to magnetostriction. Due to electrostriction, all dielectrics change their shape upon the application of an electric field. The physical effect is similar to magnetostriction as well: non-conducting materials have randomly aligned polarized electrical domains. If the material is subjected to a strong electric field, the opposing sides of these domains become charged with a different polarity. The domains will be attracted to each other, thus reducing material thickness in the direction of the applied field and elongating it in a perpendicular direction.

All dielectrics exhibit some level of electrostriction; however, a class of engineering ceramics does produce higher strains than other materials. Such mate-rials are known as relaxor ferroelectrics, for example: lead magnesium niobate (PMN), lead magnesium niobate-lead titanate (PMN-PT) and lead lanthanum zirconate titanate (PLZT).

The elongation of electrostrictive materials is related quadratically to the applied electric field:

$$\varepsilon = const \cdot E^2 \qquad (8.14)$$

where ε is strain and E is electric field strength. The relative percentual elongation for PMN-PT is 0.1% or 1000 $\mu\varepsilon$, but this is achieved under a field strength of 2 MV/m. Typical strains for special electrostrictors is in the range of 0.02−0.08%.

MAGNETOSTRICTIVE MATERIAL

Magnetostriction is a property of ferromagnetic materials that causes them to change their shape or dimensions during the process of magnetization. The variation of material's magnetization due to the applied magnetic field changes the magnetostrictive strain until reaching its saturation value, λ.

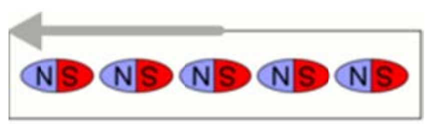


Fig. 8.37 Ferromagnetic materials

EXPLANATION:

Internally, ferromagnetic materials have a structure that is divided into domains, each of which is a region of uniform magnetic polarization. When a magnetic field is applied, the boundaries between the domains shift and the domains rotate, both of these effects cause a change in the material's dimensions. The reciprocal effect, the change of the susceptibility of a material when subjected to a mechanical stress, is called the Villari effect. Two other effects are thus related to magnetostriction: the Matteucci effect is the creation of a helical anisotropy of the susceptibility of a magnetostrictive material when subjected to a torque and the Wiedemann effect is the twisting of these materials when a helical magnetic field is applied to them. The **Villari Reversal** is the change in sign of the magnetostriction of iron from positive to negative when exposed to magnetic fields of approximately 40000 A/m (500 oersteds). On magnetization a magnetic material undergoes changes in volume which are small - of the order 10^{-6}.

Magnetostrictive materials can convert magnetic energy into kinetic energy, or the reverse, and are used to build actuators and sensors. The property can be quantified by the magnetostrictive coefficient, L, which is the fractional change in length as the magnetization of the material increases from zero to the saturation value.

MAGNETOSTRICTION AND MAGNETOSTRICTIVE MATERIALS:

Magnetostriction is the changing of a material's physical dimensions in response to changing its magnetization. In other words, a magnetostrictive material will change shape when it is subjected to a magnetic field. Most ferromagnetic materials exhibit some measurable magnetostriction. The highest room temperature magnetostriction of a pure element is that of Co which saturates at 60 microstrain. Fortunately, by alloying elements one can achieve "giant" magnetostriction under relatively small fields. The highest known magnetostriction are those of cubic laves phase iron alloys containing the rare earth elements Dysprosium, Dy, or Terbium, Tb; $DyFe_2$, and $TbFe_2$.

However, these materials have tremendous magnetic anisotropy which necessitates a very large magnetic field to drive the magnetostriction. Noting that these materials have anisotropies in opposite directions, Clark[(1)] and his co-workers at NSWC-Carderock, prepared alloys containing Fe, Dy, and Tb. These alloys are generally stochiometric, of the form $Tb_xDy_{1-x}Fe_2$ and have been coined Terfenol-D. Terfenol-D, operated under a mechanical-bias, strains to about 2000 microstrain in a field of 2 kOe at room temperatures. For typical transducer and actuator applications, Terfenol-D is the most commonly used engineering magnetostrictive material.

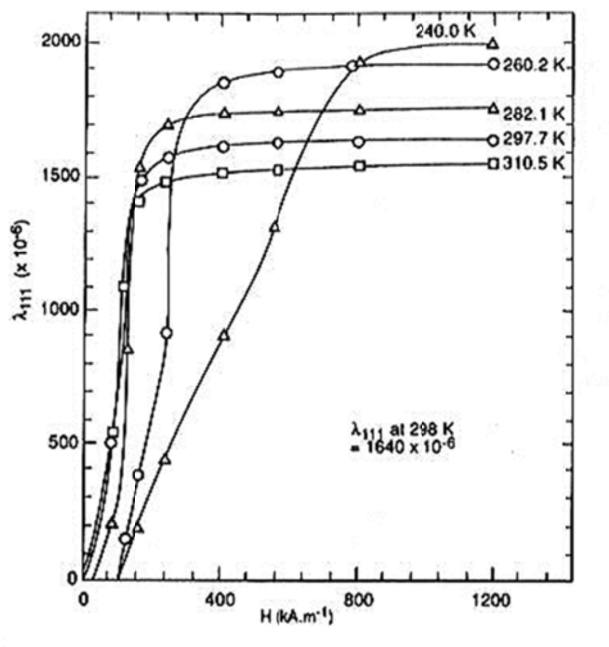


Fig. 8.38 Terfenol-D response around room temperature, [Clark]

The mechanism of magnetostriction at an atomic level is relatively complex subject matter but on a macroscopic level may be segregated into two distinct processes. The first process is dominated by the migration of domain walls within the material in response to external magnetic fields. Second, is the rotation of the domains. These two mechanisms allow the material to change the domain orientation which in turn causes a dimensional change. Since the deformation is isochoric there is an opposite dimensional change in the orthogonal direction. Although there may be many mechanism to the reorientation of the domains, the basic idea, represented in the figure, remains that the rotation and movement of magnetic domains causes a physical length change in the material.

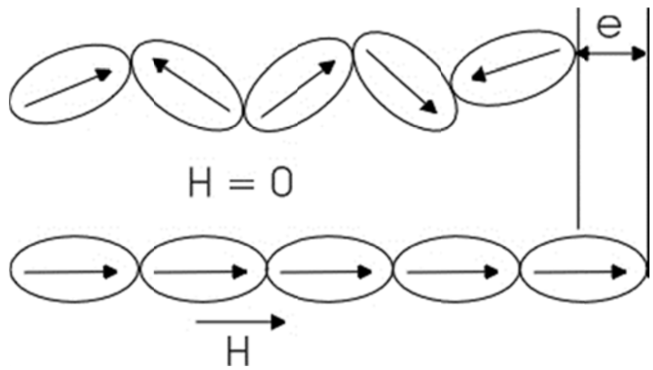


Fig. 8.39 Magnetostrictive mechanism

Magnetostrictive materials are typically mechanically biased in normal operation. A compressive load is applied to the material, which, due to the magneto-elastic coupling, forces the domain structure to orient perpendicular to the applied force. Then, as a magnetic field is introduced, the domain structure rotates producing the maximum possible strain in the material. A tensile preload should orient the domain structure parallel to the applied force though this has not yet been observed due to the brittleness of the material in tension.

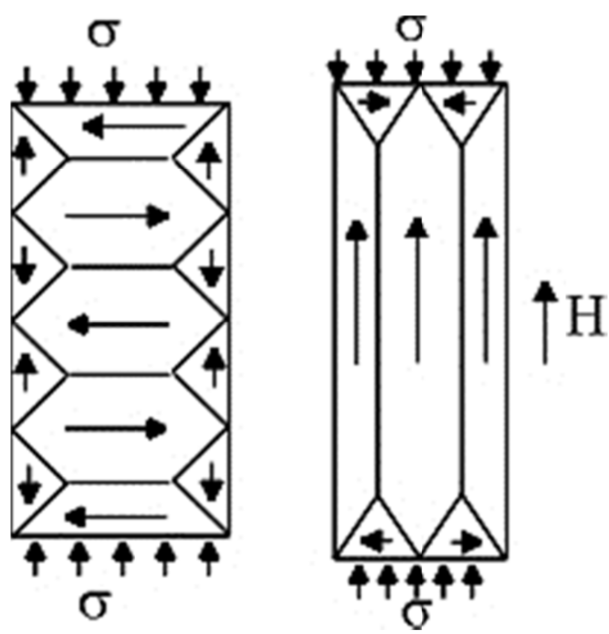


Fig. 8.40 Magnetostrictive materials

Magneto- and Electrostrictive Materials in Vibration Control

A mechanically amplified MS actuator for low frequency (1-10 Hz) vibration damping applications is suggested in, where the achievable displacement is rated between 0.5–4 mm and the force between 0.5–6 kN. Commercial actuator prototypes are also available; examples of such actuators are featured in Fig. 3.10[7].

From the point of vibration control, MS actuators may deliver a high force output with high frequency [5]. The underlying dynamics is a complex combination of electrical, mechanical and magnetic phenomena, which is further complicated by the nonlinear hysteretic behavior of Terfenol-D. The linear properties of MS actuators hold only under the following assumptions:

- low driving frequency
- reversible magnetostriction without power loss
- uniform stress and strain distribution

Under these assumptions the magnetomechanical equations are as:

$$\mathbf{S} = \mathbf{s}_H \sigma + \mathbf{g}\mathbf{H_m} \qquad (8.15)$$

$$\mathbf{B_m} = \mathbf{g}\sigma + \mu_\sigma \mathbf{H_m} \qquad (8.16)$$

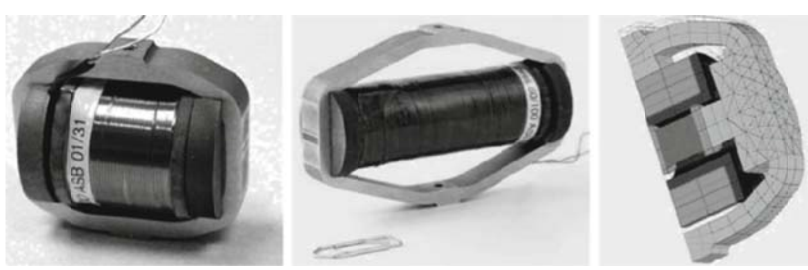
where $\mathbf{S}$ is strain, σ is stress, $\mathbf{s}_H$ is mechanical compliance at constant applied magnetic field strength $\mathbf{H}$, $\mathbf{g}$ is the magnetic cross-coupling coefficient, μ_σ is magnetic permeability at constant stress and $\mathbf{B_m}$ is magnetic flux within the material.

Piezoelectricity is in fact a subclass of electrostrictive materials. However, while electrostrictive materials are nonlinear, piezoelectric materials behave linearly, which is an important feature for control applications. Moreover, electrostriction is not a reversible effect; unlike magnetostriction or piezoelectricity, the material does not generate an electric field upon the application of a mechanical deformation. Another important feature of electrostrictive materials is that they do not reverse the direction of the elongation with a reversed electric field — note the quadratic dependence. Therefore, electrostrictive transducers must operate under a biased DC elec-tric field. In comparison with piezoelectric materials, electrostrictive materials demonstrate a smaller hysteresis.

Braghin et al. introduces a model of magnetostrictive actuators for active vibration control in [5]. The authors propose a linear model for MS actuators, which is suitable for control design below the 2 kHz frequency range. This simple linearized numerical model has provided a good match with the experimental result for an inertial type of MS actuator. Such a linearization is not only important for the design of traditional feedback control systems, but is also essential for real-time model predictive control using MS actuators. Despite the complicated coupling, hysteresis and nonlinearity the static actuation displacement of MS actuators remains linear. A linear SDOF system is the basis for the further analysis of the behavior of an MS actuator in a work by Li et al.

The vibration suppression of composite shells using magnetostrictive layers is discussed in a work by Pradhan et al. The author formulated a theoretical model for composite shells and found that magnetostrictive layers should be placed further away from the neutral plane. In addition, thinner MS layers produced better damping. The MS actuator-based vibration damping of a simply supported beam is discussed by Moon et al., where the experimental setup shows a significant reduction of vibrations in comparison with the scenario without control.

The use of electrostrictive actuation in vibration control is relatively uncommon. Sonar projectors are the typical field of use for electrostrictive actuators; however, this does not concern vibration attenuation rather generating acoustic waves. An electrostrictive actuator has been utilized by Tzou et al., for the control of cantilever vibrations. They achieved only minimal damping under control when compared to the free response without actuation.



a) Miniature MS actuator **(b)** MS actuator **(c)** FEM analysis

Fig. 8.41 Prototypes of different magnetostrictive actuators are shown in (**a**) and (**b**), while (**c**) features a FEM simulation of a deformed magnetostrictive actuator [5]

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