Applications of Giant Magnetostrictive Materials (Terfenol-D)
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ABSTRACT
The particular focus of this paper represents the applications of the giant magnetostrictive materials, these are Terfenol-D standard actuator, hybrid Linear Motor, Terfenol-D in sonar transducers, Terfenol-D electro-hydraulic actuator, giant magnetostrictive thin film applications, Passive damping, energy harvesting, velocity sensing and others applications. In addition also compare with other smart materials.

Keywords: GMM, Terfenol-D, Magnetostrictive materials, Giant Magnetostrictive materials, SMA

1 Introduction
Magnetostriction materials are smart materials which can change their shape under the influence of an external magnetic field. The change in length of magnetization materials can be caused by the influence of magnetic field. Giant magnetostrictive materials are branch of a magnetostrictive material namely the rare-earth–metalloid compounds was started was started in the 1960s.

Magnetostrictive materials can convert magnetic energy into kinetic energy, or the vice versa. Magnetostriction, $\lambda$, is a phenomenon where a magnetic body shrinks or expands in the direction of the magnetization as a function of an applied magnetic field. It is measured as:

$$\lambda = \frac{\delta l}{l_0}$$

Where $\delta l$ is the resulting strain after magnetic field applied and $l_0$ is the length of the material on unmagnetized state. The increase in length is proportional to the applied magnetic field. Magnetostriction $\lambda$ can be positive or negative depending on materials properties. The magnetostriction dependence on $H$ which can form the magnetostriction function $\lambda(H)$ of the material and can be hysteretic or anhysteretic (Ref 1). For this purpose, it could be useful to bring in one more material parameter, namely the $\lambda(H)$ slope and another constant. Under given uniaxial mechanical stresses, value of flux density $B$, according to Le Chatelier's principle magnetoelastic effect is:

$$\frac{d\lambda}{dH} = \frac{dB}{d\sigma}$$

It means, that when result of the product $\sigma\lambda$ is positive, value of flux density $B$ increases under stresses. Another most important effect namely Villari effect is the name given to the change of magnetic flux density when material is subjected to a mechanical stress. The Villari effect is reversible and is used in sensor applications.

2 Giant Magnetostrictive materials
All magnetic materials are essentially magnetostrictive. Classical magnetostrictive materials have $\lambda$ values from as low as a few ppb up to a few decades ppm and include Fe–Co–Ni-rich alloys. Through the
addition of Al, Cu and Nb (Ref 3), have controllable magnetostriction values that usually can decrease down to a few ppb. They are generally designed with low coercivity and magnetostriction, in order to be used in electromagnets, electric machines and transformers.

Another category of materials, giant magnetostrictive materials (GMM) have been observed for its magnetostriction as high as 1000–2000 ppm (Ref 4). Td$_{0.3}$Dy$_{0.7}$Fe$_{1.9}$ commercially called as Terfenol-D, has been known for its magnetostrictive properties and representative of giant magnetostrictive materials. Properties of Terfenol-D is given below. However, properties depend on preparation method of the materials and it can vary according to different conditions.

<table>
<thead>
<tr>
<th>Terfenol-D property</th>
<th>Value Range</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal composition</td>
<td>Tb$<em>2$D$</em>{x}$Fe$_{y}$</td>
<td>0.27&lt;x&lt;0.3 and 1.9&lt;y&lt;2.0</td>
</tr>
<tr>
<td>Density</td>
<td>9250 kg/m$^3$</td>
<td></td>
</tr>
<tr>
<td>Compressive strength</td>
<td>305-880 MPa</td>
<td>Preferred in applications</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>28-40 MPa</td>
<td>To be avoided in application</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>9.0-12.0</td>
<td>Permeability at constant stress</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>3.0-5.0</td>
<td>Permeability at constant strain</td>
</tr>
<tr>
<td>Maximum achieved strain</td>
<td>2000-4000 ppm</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Properties of Terfenol-D (Ref 5, 6, 9)

Shape memory alloy and piezoelectric are most popular smart material for research and commercial applications. Comparison of physical properties between Terfenol-D and other SMAs is listed below by table 2.

<table>
<thead>
<tr>
<th>Typical features</th>
<th>PZT</th>
<th>Terfenol-D</th>
<th>SMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongation</td>
<td>0.1%</td>
<td>02%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Energy density</td>
<td>2.5 KJ/m$^3$</td>
<td>20 J/m$^3$</td>
<td>1 J/m$^3$</td>
</tr>
<tr>
<td>Bandwith</td>
<td>100 KHz</td>
<td>10 KHz</td>
<td>0.5 KHz</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>10%</td>
<td>2%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 2 Comparison between Terfenol-D and other SMAs (Ref 6, 7, 8, 9)

3 Applications

3.1 Standard Terfenol-D Actuator

A standard Terfanol-D actuator is produced by ETREMA Products, Inc. produces. It is producing high displacements up to 250 microns and operating at frequency up to 2500 Hz. Very low magnetic flux leakage is important feature of this kind of actuator. Frequency can be increased up to 25000 Hz by using ultrasonic actuator (Ref 77). Fig 1 shows the standard Terfanol-D actuator.
3.2 Linear and Hybrid Linear Motor based on Terfenol-D
Linear motor brings out the excellent advantages such as high forces, unlimited stroke and short response time. Hybrid linear motor is an upgrade version model of linear motor with few changing. Terfenol-D is used as push device and using piezoelectric actuators to control the end clamps. A prototype of inchworm was developed which achieved a stall load of 26 lb and free speed of 1 in/s (Ref 78). There has relationship between normal electrical phase and the magnetic coils due to natural drive timing is provided by Terfenol-D rods and piezoelectric actuator. By adding switching device, it can be operated at variable operating frequency. Moreover, precise resolution is produced by a hybrid linear motor with long travelling distance under inchworm motion principle is developed. (Ref 11).

3.3 Terfenol-D Electro Hydraulic Actuator
Terfenol-D can be used in linear motion actuators in combination with hydraulic technology. The performance of an experimental Terfenol-D electro hydraulic actuator driven by a 12.7 mm diameter, 114 mm length Terfenol-D rod is evaluated over a range of applied input frequencies, loads, and currents. The peak performance achieved is 37 W (Ref 12), moving a 220 N load at a rate of 17 cm/s and producing a blocked pressure of 12.5 Mpa. By using this actuator, high power density and fast accurate actuation can be achieved.

3.4 Terfenol-D in sonar transducers
For having excellent feature of the giant dynamic strains of Terfenol-D has been more accepted by transducer designer (Ref 13). Such strain levels, as well as high field limit, high coupling and high compliance, are well suited for high-power transducers both for acoustics (loudspeakers, sonars).
Several types of transducer were invented based on different features and mechanism such as Tonpliz transducer, double ended vibrators, Flextensional transducers (Ref 14).

An experiment was done where the maximum theoretical expectation was a head mass displacement of 110 µm, a Terfenol-D strain of 3250 ppm, an output power of 4 kW and a source level of 208.6 dB. Experimentation was performed to achieve about 90% of the theoretical performance. The head mass displacement was measured with an accelerometer giving 98 µm at 1.2 kHz corresponding to a 2900 ppm peak-to-peak strain in Terfenol-D. An output power of 3.8 kW and a sound level of 208.1 dB are obtained (Ref 5). High power densities achieved now in Terfenol-D are 10 times higher than those of PZT transducers.

3.5 Magnetostrictive thin film applications
As the major application of a magnetostrictive thin film micropump prototype is made. The micropump is operated using an oscillating rectangle pulse for the membrane actuation. Another application of thin film, a magnetostrictive thin film linear ultrasonic motor was fabricated (Ref 15) using a micromachined Si (100) substrate and TbFe films (Fig. 4).

3.6 Passive damping and energy harvesting
Magnetostrictive Terfenol-D transducers are an excellent alternative for viscoelastic dampers. In addition, it can easily replace the piezoelectric actuators for damping and self-sensing. High stiffness, primary load carrying capability and high power density can be achieved by using this transducers (Ref 16-17).

Vibration-based energy harvesting has received great attention over the last decade (Ref 18). Magnetostrictive Terfenol-D based device construct to convert ambient mechanical vibration into electricity has been designed. A greater frequency range as compared to state-of-the art devices for harvesting energy. Terfenol-D based energy harvesting device has just drawn attention (Ref 19) to it’s due to very good quality for energy density after piezoelectric material.
Except above applications giant magnetostrictive materials are very popular for application to magnetic surface acoustic wave devices (Ref 20). Moreover, it has excellent application for magnetic actuation of bending and torsional vibrations for 2D optical-scanner application (Ref 21).

4.0 Conclusion
In recent days the application of shape memory alloys (SMA) as actuators, sensors, transducers and damper in smart structures is a quickly developing field. Selecting SMA is one of the difficult jobs among the project. Terfenol-D has some unique properties such as magnetic property, electro chemical property, durability, thermal stability and many more. We can use Terfenol-D in those applications where it can be well suited based on its physical properties.

REFERENCES
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