MAGNETOSTRICTIVE ACTUATORS COMPARED TO PIEZOELECTRIC ACTUATORS

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INTRODUCTION

Magnetostriction occurs in the most ferromagnetic materials and leads to many effects [1,2]. The most useful one to refer to is the Joule effect. It is responsible for the expansion (positive magnetostriction) or the contraction (negative) of a rod subjected to a longitudinal static magnetic field. In a given material, this magnetostrain is quadratic and occurs always in the same direction whatever is the field direction. Giant Magnetostrictive Materials (GMM), especially Rare earth-iron discovered by A.E.Clark [3], feature magnetostrains which are two orders of magnitude larger than Nickel. Among them, bulk $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, called Terfenol-D, presents the best compromise between a large magnetostrain and a low magnetic field, at room temperature. Positive magnetostrains of 1000 to 2000 ppm obtained with fields of 50 to 200 kA/m are reported for bulk materials [3,4]. In the 90s, bulk magnetostrictive composite materials have been developed for high frequency ultrasonic applications [5]. More recently, high magnetostrains (in the range of 500 to 1000ppm) have also been obtained in rare earth-iron thin films [6].

In the applications of bulk materials these expansion strains are rarely used directly because a linear behaviour is preferred. The linearity is obtained by applying a mechanical pre-stress and a magnetic bias in the active material. Quasistatic actuators are using GMA in these conditions for positioning, vibration control, stepping motors and fluid control applications.

In case of using a mechanical resonance, these conditions are highly beneficial because it allows the production of giant dynamic strains, which peak-to-peak amplitudes are higher than the static ones [7]. Main applications using resonance are high power transducers.

The following sub-chapters will review both the recent developments concerning bulk GMM and their applications as actuators [8], outlining their interest compared with competing technologies, especially piezoelectric materials and actuators. This review has been performed in the context of the ASSET thematic network, as a continuation of Cedrat Technologies permanent survey activity [9, 10] in the fields of active materials and applications.

BULK MAGNETOSTRICTIVE MATERIALS

For actuation purposes, bulk GMM and composite GMM are in direct competition with piezoelectrics ceramics (Table 1). Shape memory alloys (SMA) offer much higher force and strains than these materials, but because of a much lower time constant due to thermal control they cannot be compared with them. Present commercially available electrostrictives don't show significant advantages over piezoelectrics. Piezoelectric ceramics are the most popular active materials because of good strain performances, shape versatility and easy electric control.
Among these materials, the soft piezo ceramics in multi layer technique for actuators [11], called the MLAs, performed a major breakthrough because of large strains at relatively low electric voltage values (100-200V depending on the internal electrode distance). Therefore GMM, which appeared in the 80s, have been in competition with the MLAs since their development in the 90s.
Terfenol-D from ETREMA [12] is the best-established commercially available material offering the largest field-induced strain in static condition. Its coupling factor in adequate pre-stress and bias condition is equivalent to that of piezo ceramics. Its Youngs modulus is still the lowest, which is an advantage for producing low-frequency resonators of compact size. Due to the low stiffness value and its

ability to operate under large pre-stress, the dynamic strain at resonance [7,8] is higher than piezo ceramics. This is a big advantage for high power devices operated at resonance.

Not mentioned in Table 1, the maximum sizes of Terfenol-D rods are 65mm in diameter and 175mm in length, which is far above the size of largest MLA components.
Again not included in Table 1, eddy currents induce a frequency limitation of bulk Terfenol-D to some kilohertz. The use of thin lamination can overcome this limit, but it increases the price because of lost material and machining. ETREMA is currently improving its lamination techniques [12].
Another approach initiated by FEREDYN [5] and still pursued [13,14] consists in composite GMM, made of Terfenol-D grains in an electrically insulated binder. It allows operation up to 100kHz, but the electromechanical performances are smaller than competing materials.
In spite of its limited application range, new cryogenic GMMs made of TbDyZn are being developed for the NGST project of NASA [15,16]. They offer large strain (5000ppm) at low temperature (77K).
At last, Magnetic Shape Memory materials (MSM) such as NiMnGa alloys [17] were not considered in this analysis because not strictly speaking magnetostrictive (although magnetic field controlled), magneto-mechanical coupling coefficients not yet well established and few applications. However their giant strain (up to 5%) may be of very high interest for making new large stroke actuators.

		Terfenol-D GMM	**Composite GMM**	**PZT-4**	**Soft PZT MLA**	**MSM**
Max static strain	ppm	1800	1000	600	1250	50000
Coupling coeff.	%	70	35	67	65	?
Young's modulus	GPa	25	20	60	40	7
Max prestress	MPa	50	30	50	40	?
Max dyn. strain	ppm	4000	3000	1600	2000	?

Table 1 - Properties of GMM and PZT piezo ceramics.
For comparison, all strains are given peak-to-peak.
Given values have been experimented at Cedrat Technologies [8,18,19]

QUASI-STATIC APPLICATIONS OF GMM

Actuators for quasi-static operations are used at a frequency below the first coupled device resonant frequency.
The simplest quasi-static actuators just use the deformation of the active material. In case of a GMM, a coil surrounding the GMM rod is required to create the magnetic fields. It explains why the diameter of direct magnetostrictive actuators (Figure 1) is generally larger than that of direct piezo actuators (Figure 2).

Figure 1 – Direct magnetostrictive actuator (largest one) based on a 1cm diameter 10cm long rod, offering 100µm stroke (Cedrat Technologies realisation)

Figure 2 – Direct piezoelectric actuators DPA90 (longest one) based on a 1cmx1cm section 9cm long MLA, offering more than 100µm stroke (Cedrat Technologies products [21])

Such actuators are characterised by their ability to produce displacements and forces. Their maximum displacement is the free displacement u_f (i.e. the non-loaded displacement), and their max force is the blocked force F_b (i.e. the force when no displacement is generated). The energy defined as $E_e = u_f \,.\, F_b /2$ represents the max actuator elastic energy that can be electrically coupled. The max output energy that is equal to $E_e/4$ according to [20] represents the energy that can be transferred to a load. This criterion is often also put in relation with a second one depending on the application. In miniature systems, it is generally wished to have this output energy in a small size. In embedded applications, the required mass and required electric power is important. In some other applications like inflammable environment, the required voltage is essential. Table 2 compares some commercial actuators based on GMM [12] and on MLA [21]. Both offer the same range of displacement, force and elastic energy. GMM actuators require much lower voltage. Additionally they offer a mechanical centring by magnetic bias without electrical supply, while MLA actuators need a DC voltage for centring. Because of their capacitive nature, the power consumption of piezo actuators is very low at low frequency, while magnetostrictive actuators are inductive components with Joule losses. Such losses can be reduced with a coil based on a large section of copper (Figure 1) but then the mass is increased.

Such GMM actuators have been found valuable for various applications [22] in the fields of vibration damping or control [20,23,24,25,26,27,28,29], broad band shakers [30,31], engraving [32], audiodontic vibrator [33] and space [16].

GMM stepping motors are more complex actuators than previous types. To get a long stroke, they use an accumulation of small steps produced by quasi static deformation of the active materials. The Kiesewetter linear motor is a famous example [34], which is still studied under NASA funding. This concept allows positioning actuators with holding force at rest and long stroke (20-50mm). Initial versions [34,35] were based on a rod moving in a tube, while last versions are considering a slab moving between two plates [36]. These configurations provide an improvement as regard recovery of play due to wear. Some other GMM stepping motors have also been studied by NASA [37,38], TOYOTA [39] and labs [40]. However, contrary to piezo motors, no industrial exploitation of GMM motors have been reported.

M = Magnetostrictive P = Piezoelectric		M	M	P	P	P
Actuator Reference		AA-090H	AA-140J	PPA90L	DPA90	APA120ML
Centring		Yes	Yes	No	No	No
Voltage @1Hz	V	8	11	170	170	170
Electric power @1Hz	W	18,5	25,0	<0,1	<0,1	<0,1
Free displacement	µm	90	140	90	90	120
Blocked force	kN	1,7	1,7	3,5	3,5	1,4
Output elastic energy	mJ	19	30	39	37	21
Height	mm	148	199	107	112	45
Volume	cm^3	327	440	43	55	36
Mass	kg	1,70	2,30	0,15	0,31	0,17
Outout energy/mass unit	mJ/kg	11	13	270	120	140

Table 2 – Properties of GMM and MLA actuators [12,21]

In the context of the US More Electric Aircraft initiative, an electro-hydraulic jack based on a GMM pump and two GMM flow control valves is being developed [12]. This device operates as an inchworm. However, there is no released experimental data.

The limited development of these actuators may indeed be explained by the fact that it is impossible to get a good electromechanical efficiency in GMM devices in quasi-static conditions [9].

RESONANT APPLICATIONS OF GMM

At the opposite, when operated at resonance against a high mechanical load, the electromechanical efficiency of a GMM can reach about 50% [9,41]. Furthermore, at resonance, dynamic strains can be larger than static magnetostrains (tab 1) [7].

Using Terfenol-D at device resonance has been shown possible in acoustic transducers since 1979 [42] for sonar application. The interest of applying giant dynamic strain to sonar transducers, in order to get GMM transducers with higher power than PZT transducers was theoretically shown in 1991 [43,44]. In 1993, through a R&D project for the French Navy, Cedrat designed and built, with the collaboration of Eramer, a 1 kHz tripode magnetostrictive transducer emitting 4 kW of acoustic power. At this time, the prototype (see Figure 3) displayed higher power density transducer than PZT Tonpilz sonar transducer. This superiority was clearly established in 1995 [41] with low frequency Terfenol-D flextensional transducers from NUWC producing more than 10kW acoustic power, leading to a higher power density than piezo transducers. This result is in line with an announcement of ETREMA [12]: funding of Terfenol-D development from US DoD for Navy needs has reached $7,000,000 over these last 3 years. In a civil field, such low frequency acoustic transducers find application in petroleum production [12].

GMM composite transducers have been developed showing potential interest in plastic welding, sonar and ultrasonic cleaning (see Figure 4) [5,18,14], but the present material's low coupling factor is limiting their power performance.

Figure 3 – Low Frequency High Power Magnetostrictive Tripode Transducers - R&D project Cedrat-Eramer for French Navy

Figure 4 – High Frequency Magnetostrictive Transducer for Ultrasonic Cleaning Source - R&D project Cedrat-Feredyn (ECAMMA coord. by Syncom)

The possibility of using bulk GMM at resonance for making motors with large actuation and holding torque (Figure 5, Figure 6, Figure 7) was shown for the first time in 1996 [8]. In a first analysis, the good results achieved in high power transducers could be transposed to motors using resonance. However, serious problems (tribology, noise…) have to be solved to prove this potential. Comparable piezo motors (Figure 8) operating at ultrasonic frequencies are both technically and commercially much more advanced [21].

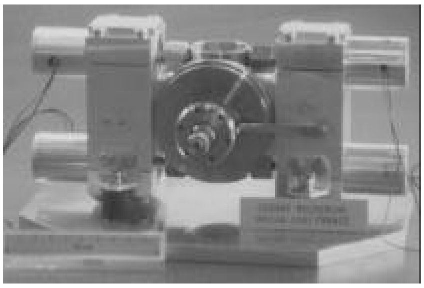

Figure 5 – Multi-Mode Magnetostrictive FLEX-M1. Motor built by Cedrat

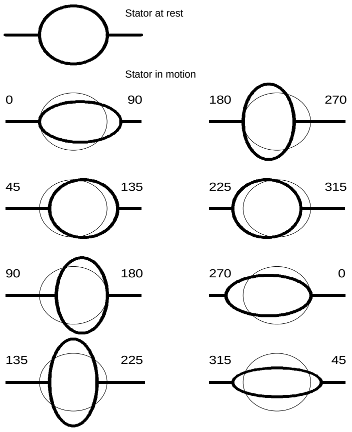

Figure 6 – Principle of FLEX-M1 stator. Stator at rest and in motion versus the actuators phases

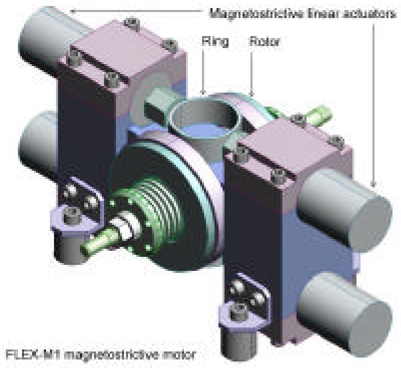

Figure 7 – Multi-Mode Magnetostrictive FLEX-M1 Motor

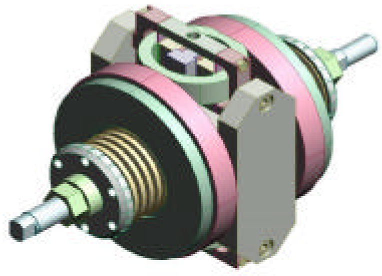

Figure 8 – Piezoelectric Motor based on the UPD20 Ultrasonic Piezo drive, a piezo product from Cedrat

CONCLUSION

Giant Magnetostrictive Materials (GMMs) are in competition with piezo ceramics, especially MLAs but found their place in specific applications such as low voltage actuators, large force actuators, high power low frequency transducers and space cryogenic positioning. In other cases, MLA piezoceramic actuators are often more interesting because of their low power consumption and high output energy per mass unit.

GMMs are also expending toward thin films [45]. Due to their 'giant' magnetostrains, these new active materials are candidates for a broad range of micro-components including micro pumps [45], micro actuators [46], micro motors using resonance [8, 47], micro valves [48].

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