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GIANT DYNAMIC STRAINS IN MAGNETOSTRICTIVE ACTUATORS AND TRANSDUCERS

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1. 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]. High magnetostrains (in the range of 500 to 1000ppm) have also been obtained in rare earth-iron thin films [6]. More recently, magnetic-field controlled materials have been extended with Magnetic Shape Memory Materials (MSM) such as NiMnGa alloys [7] offering a magnetostrain of more than 5%. 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.

In this paper, the way to get giant dynamic strains is presented in relation with the role of the prestress and the magnetic bias. It is known that at mechanical resonance, a high prestress is highly beneficial because it allows the production of giant dynamic strains, which peak-to-peak amplitudes are higher than the static ones [8]. However it is shown in this paper that it has also some advantages for producing high dynamic strains below resonance.
The production of giant dynamic strains is presented by means of the analysis of the field and stress limits in a simple linear magnetostrictive actuator. Then illustrations of these possibilities are shown through different actuation devices based on GMM.

2. The theory of magnetostriction in GMM devices

Although magnetostrictive materials are non linear [1,2], the behaviour of most of magnetostrictive devices may be rather well described using a linear theory, because the active materials are biased. The bias conditions are defined by the magnetic bias $\mathbf{H_o}$ and the mechanical pre-stress $\mathbf{T_o}$, applied along the magnetostrictive rod axis, referred to as the third axis. Experimental results obtained on high power transducers (see §5) show that linearity can be rather good even with large excitation fields and large dynamic strains.

Then, considering only the variations around this initial bias state, the material behaves in a quasi-linear manner and follows piezomagnetic laws:

$$\begin{cases} \mathbf{S_i} = \mathbf{s^H_{ij}}\,\mathbf{T_j} + \mathbf{d_{ni}}\,\mathbf{H_n} \\ \mathbf{B_m} = \mathbf{d_{mj}}\,\mathbf{T_j} + \boldsymbol{\mu}^{\mathbf{T}}_{\mathbf{mn}}\,\mathbf{H_n} \end{cases} \quad \begin{matrix} \mathbf{i,j=1,..,6} \\ \mathbf{m,n=1,..,3} \end{matrix} \tag{1}$$

where :

$\mathbf{s^H}$, $\mathbf{d}$ and $\boldsymbol{\mu}^\mathbf{T}$ are the tensors of constant-H compliance, piezomagnetic constants and constant-T permeabilities, respectively. They are called the magneto elastic coefficients.

S and **T** are the tensors of varying strain and stress, **B** and **H** are the vectors of varying induction and magnetic field. In the actuators, **H** is called the excitation field.

The real situation in the material can be reconstructed by adding the bias static situation to the variations. For instance the real field in the material is the vectored sum of static magnetic bias $\mathbf{H_o}$ and the varying magnetic field **H**.

The Grain Oriented Terfenol-D, which is isotropic in the plane perpendicular to the average grain axis, can be classified into the 6mm crystal class, which leads to a particular distribution of zero magneto elastic coefficients [9]. Note that the values of the non-zero coefficients depend strongly on the bias and the prestress [9, 10]. Complete sets of values for the tensors $\mathbf{s^H}$, $\mathbf{d}$ and $\boldsymbol{\mu}^\mathbf{T}$ and for the tensors $\mathbf{c^H}$, $\mathbf{e}$ and $\boldsymbol{\mu}^\mathbf{S}$ of Terfenol-D have already been established [9, 11] and are updated in table 1. Longitudinal coefficients ('33') and shear coefficients ('15') may be determined using length expansion and shear magnetostrictive resonators [12, 13]. Other coefficients may be found using some special assumptions [9].

$k_{33} = 0.80$	$k_{31} = 0.31$	$k_{15} = 0.33$
$\mu_{33}{}^T = 3.0\mu_0$	$\mu_{11}{}^T = 8.1\ \mu_0$	
$d_{33} = 8.5\text{x}10^{-9}$	$d_{31} = -4.3\text{x}10^{-9}$	$d_{15} = 16.5\text{x}10^{-9}$
$s_{33}{}^H = 3.8\text{x}10^{-11}$	$s_{11}{}^H = 4.4\text{x}10^{-11}$	$s_{13}{}^H = -1.65\text{x}10^{-11}$
$s_{12}{}^H = -1.1\text{x}10^{-11}$	$s_{44}{}^H = 24\text{x}10^{-11}$	$s_{66}{}^H = 11\text{x}10^{-11}$

Table 1 - Terfenol-D magnetoelastic coefficients at 30MPa prestress and 100kA/m bias.

This complete set of 3 dimensional equations and coefficients can be used in a Finite Element Model such as the ATILA software. A variational principle for magnetostrictive devices [9, 14], has been implemented within the ATILA computation code for piezoelectric transducers [15, 16]. This software has been therefore extended to the computation of 2D and 3D magnetostrictive transducers. Different types of resolutions have been developed: Constant-current quasi-static, harmonic or modal analysis (Antiresonances and resonances). It has been used at first for the analysis of magnetostrictive transducers and actuators [17]. Then, it has been demonstrated that it permits the analysis of piezoelectric and magnetostrictive friction motors [18, 19].

However, Terfenol-D is often used in long rod, subjected to an excitation field parallel to the rod axis. In this case, the simple theory of the longitudinal mode can be applied. Such a theory can be used to get a preliminary design, before to use numerical models such as ATILA FEM.

In such a situation, it is supposed that the transverse excitation fields are negligible ($\mathbf{H_1} = \mathbf{H_2} = 0$). In theory a pure longitudinal mode ('33' mode) is obtained starting from the assumption that radial stresses are equal to zero ($\mathbf{T_1} = \mathbf{T_2} = 0$) and there is no shear effect ($\mathbf{T_4} = \mathbf{T_5} = \mathbf{T_6} = 0$), leading to the following equations:

$$\begin{cases} S_1 = S_2 = s_{13}^H\ T_3 + d_{31}\ H_3 \\ S_3 = s_{33}^H\ T_3 + d_{33}\ H_3 \\ B_3 = d_{33}\ T_3 + \mu_{33}^T\ H_3 \end{cases} \quad (2)$$

The '33'-mode coupling coefficient associated with this mode is given by the following expression :

$$\mathbf{k_{33}^2} = \frac{\mathbf{d_{33}^2}}{\mathbf{s_{33}^H}\ \mu_{33}^T} \quad (3)$$

This coefficient represents the capability of the material to convert electric energy into elastic energy. According to experimental results (table 1) obtained using a dual mass resonator [13] and in agreement with other methods, its value is high in Terfenol-D even with high prestress and bias. As will be shown further, the combination of a high coupling, a high prestress and a high bias is required to obtain giant dynamic strains [8].

3. GMM linear actuators : static, dynamic & resonant strains

It is interesting to analyse the behaviour of linear actuators because most applications are based on such actuators. It is also important to note that the applications often request to minimise the volume of magnetostrictive materials used in the actuator. The only way to meet this requirement is to get the maximum stroke from the actuator. The parameters which govern the stroke limits are analysed in this section.

The maximal displacements are determined by the field limits and the stress limits (and in practice also by the available electric power and the heating), which are fixed by the magnetic bias $\mathbf{H_o}$ and the mechanical pre-stress $\mathbf{T_o}$.

The magnetic bias $\mathbf{H_o}$ is a static magnetic field required in the GMM to avoid the doubling frequency phenomena. Maximum applicable AC field $\mathbf{H_3}$ is limited by $\mathbf{H_o}$: With some margins to account for non linearity it gives:

$$\mathbf{H_3} < \alpha_H\ \mathbf{H_o} \quad (4)$$

with typically a margin $\alpha_H = 80\%$.

The mechanical pre-stress $\mathbf{T_o}$ is a compressive static stress applied in the GMM to avoid tensile forces. As GMM and other active materials are brittle, it is considered not possible to operate them in tension. Thus it is considered that the maximum applicable stress $\mathbf{T_3}$ is limited by $\mathbf{T_o}$: With some margins it gives :

$$\mathbf{T_3} < \alpha_T\ \mathbf{T_o} \quad (5)$$

with typically a margin $\alpha_T = 80\%$.

In order to analyse the role of these limits versus frequency, a typical Direct Magnetostrictive Actuator from Cedrat Technologies, called DMA100L is considered. This actuator was designed and for a high temperature pump application. This actuator is based on a Terfenol-D rod (Part 1) of 100mm long and 10mm in diameter, surrounded by a coil winding. It comprises an excitation coil with 1000 turns and a bias field coil. This coil is fixed via its support (Part 3) on the actuator bottom (Part 5). The magnetic T-part (part 2) is based on the open magnetic circuit concept [20]. Washers are used to prestress the Terfenol-D rod and to maintain a firm contact between the rod, the magnetic T-parts and the output axis on the top of the actuator (part 4). The magnetic bias field can be adjusted for 0 to 100kA/m. The mechanical prestress can also be adjusted from 0 to 40MPa. The Terfenol-D properties considered for the analysis are given in the following table taken from [21]. The magnetic bias field is chosen to get the best coupling factor for the selected prestress. Values of case 2 are rather consistent with Table 1 values. Two different couples of bias and prestress are considered to allow for a comparison of the actuator performances.

Figure 1 – View of the DMA100L

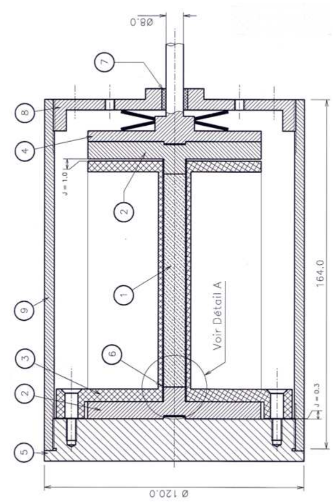


Figure 2 – DMA100L drawing

Case	To	Ho	μ^T_{33}/μ_o	d_{33}	s^H_{33}	k_{33}
	Mpa	kA/m		nm/A	10^{-12}/Pa	%
1	15	31	8.4	15.5	47.5	69
2	40	100	4.3	9.1	34.5	67

Table 2 – Sets of longitudinal mode coefficient versus bias and prestress

The analysis of limits is performed using usual equivalent circuits methods, based on equations (3) and (4). With this method, the actuator can be analysed as a system including a compliance $\mathbf{k^H}$ (at constant field), an effective mass **M** and a mechanical quality factor $\mathbf{Q_m}$ due to mechanical losses.

For the analysis, the mass **M** is taken as M=0.25kg, corresponding in practice to the actuator front mass. The compliance is $\mathbf{k^H} = L / (\mathbf{A}.\, \mathbf{s^H}_{33})$, where L is the rod length and **A** is the rod section.
The device resonance frequency is given by :

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k^H}{M}} \tag{6}$$

Because $\mathbf{s^H_{33}}$ varies with prestress and bias, the resonance frequencies varies around 1.3kHz with these parameters.
The magnetostrictive part is activated by a longitudinal field $\mathbf{H_3}$ produced by a coil driven by an excitation current **I**. In such a system, all the strain is converted to displacement of the free mass.
Under quasi static conditions, according to (2) and neglecting prestress spring stiffnesses for a first approximation (which gives $\mathbf{T_3}$=0), the strain $\mathbf{S_3}$ of Terfenol-D in the actuator is :

$$\mathbf{S_3 = d_{33}\, H_3} \tag{7}$$

With case n°2, it gives a maximum peak strain in static conditions $\mathbf{S_{max}}(f{=}0) = \mathbf{d_{33}} \cdot \alpha_H \cdot \mathbf{H_o}$= 728ppm, corresponding to a peak-peak strain of 1450ppm.
The displacement **u** is simply : $\mathbf{u} = \mathbf{L}.\ \mathbf{S_3}$. It gives a maximum static displacement of 145µm peak-to-peak. The corresponding current **I** is in a first approximation given by **I = H.L/N** , leading to **I** = 8A peak. The displacement per Ampere is then equal to : $\mathbf{u}(f{=}0)/\mathbf{I}$ = 9µm/A

At resonance $\mathbf{f_r}$, it can be shown using equivalent circuit models that the strain amplitude is amplified by the Q factor and is related to the stress as following :

$$\mathbf{S_3 = Q_m\, d_{33}\, H_3} \quad (8)$$

$$\mathbf{S_3 = s_{33}^H\, T_3} \quad (9)$$

With case n°2, this leads to a maximum displacement par ampere : $\mathbf{u}(f{=}f_r)/\mathbf{I}$ = 90 µm/A

A further analysis based on equivalent circuit has been performed using COMPACT tool from Cedrat Technologies, which is based on conventional equivalent circuit analysis and has been experimentally validated. It is presented on figure 3.

The displacement par Ampere **(u/I)**(f) allows to find the resonant frequency and all the above results. It also shows that a low prestress (case 1) is better than a high prestress (case 2) in terms of displacement per volt, both in static and at resonance. This is why low prestress may be a good choice for positioning applications.

The actuation force par Ampere **(F/I)**(f) is the force produced by the rod against the moving mass. It is zero in static because the inertial force is zero. It goes to a maximum at resonance and tends to a constant values above the resonance. This asymptotic value is the blocked force per Ampere.

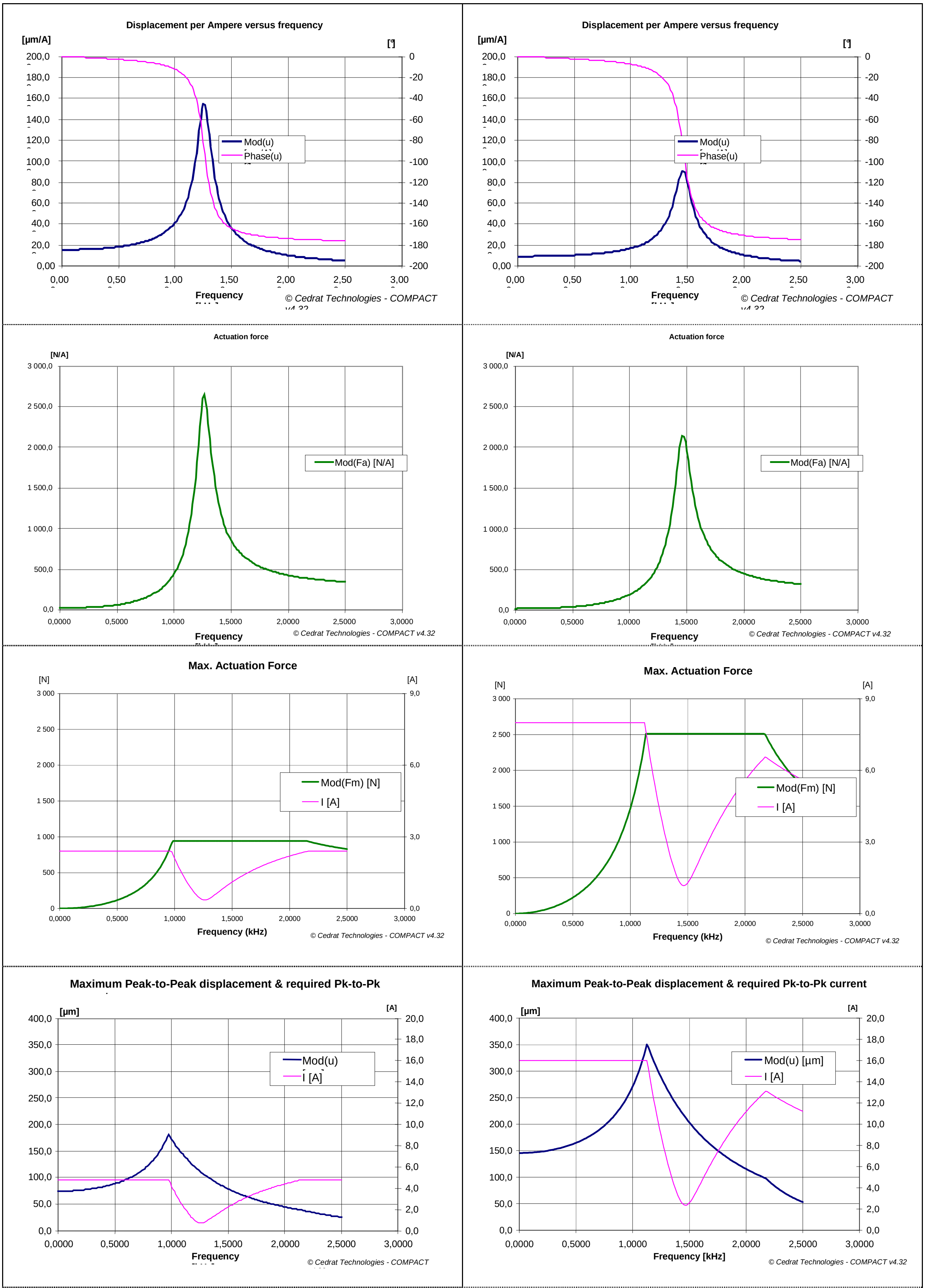
The maximum actuation force $\mathbf{F_{max}}$(f) is the result of actuation force par Ampere **F/I**, the maximum current due to the field limit $\mathbf{I_{field\ limit}}$ and the force limit $\mathbf{F_{stress\ limit}}$:

$$\mathbf{I_{field\ limit} = H_{max}.L/N = \alpha_H \cdot Ho \cdot L/N} \quad (10)$$

$$\mathbf{F_{stress\ limit} = T_{max}.A = \alpha_T \cdot To \cdot A} \quad (11)$$

In case 1, $\mathbf{I_{field\ limit}}$ = 2,4A and $\mathbf{F_{stress\ limit}}$ = 940N while in case 2, $\mathbf{I_{field\ limit}}$ = 8A and $\mathbf{F_{stress\ limit}}$ = 2500N. One can check the field limit is meet below resonance while the force limit is meet around resonance. In this frequency region, it is used to determine the maximum current due to the force limit versus frequency : $\mathbf{I_{stress\ limit}}(f) = \mathbf{F/I}(f) / \mathbf{F_{stress\ limit}}$.

Because of higher prestress and higher bias, case 2 allows to apply higher currents than case 1. As a consequence, the maximum displacement $\mathbf{u_{max}}$ (f) is higher in case 2 than in case 1. In addition, for case 2, the maximum displacement at resonance (1.47kHz) reaches 210µm peak-peak (corresponding to a strain of 2100ppm). It is higher than the maximum static displacement of 145µm peak-peak, but it requires a much lower current. One can show this is the frequency where the vibration is produced with the best electromechanical efficiency. This property is used for making low voltage sound or vibration generators working at resonance. This effect has been predicted [8] and experimentally checked at first on Cedrat Technologies MAP and MAS resonators (§4). In the case of the DMA100L, experiments show results relatively closed to this simplified theory. With a prestress of 40Mpa, the measured displacement in quasi static condition reaches 110µm peak-to-peak at 8A peak, while at resonance 160µm peak-to-peak was achieved at 1.5A peak. The difference is due to the stiffness of the prestress washers and can be easily predicted by more complex models.



Case 1 – Low bias & prestress | *Case 2 – High bias & prestress*

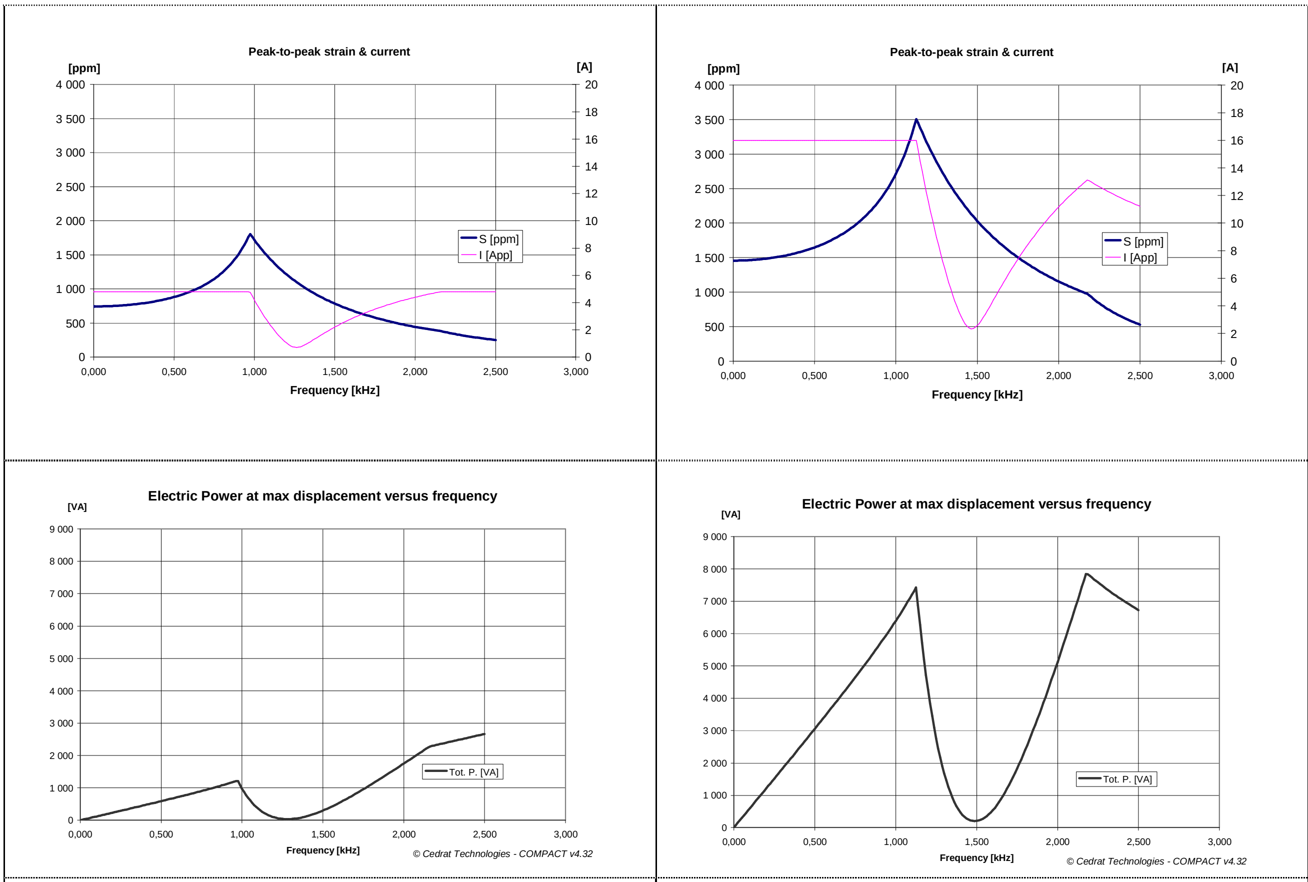
Figure 3 – Displacement per Ampere ; Actuation force par Ampere ; Max force ; Max displacement

An other interesting point is the possibility to produce a dynamic stroke as high as in static in a wide frequency range, from DC up to above the resonant frequency. This is a very useful feature for wide band vibration generators and active control of vibrations for active damping applications.

It is even possible to get higher displacements than in static and at resonance, when working below resonance. In the case 2, the absolute maximum displacement (accounting for the margins α_H and α_T) reaches 350µm. With the rod length L=100mm, it corresponds to a peak-to-peak dynamic strain of 3500ppm, which far above the maximum static strains of Terfenol-D (figure 4).

However as shown in figure 4, the requested electric power (including reactive power) becomes very high. This is the main disadvantage of using giant dynamic strain below resonance. Another one is the heating. This can be solved by cooling but it is feasible only on large actuators such as sonar transducers [9, 17].

Above resonance, the displacement decreases, but the forces increases. The use of high prestress is also beneficial for getting high dynamic forces. Proof mass dampers are typical applications concerned by this results because these are dynamic forces generators working above resonance.



Case 1 – Low bias & prestress | *Case 2 – High bias & prestress*

Figure 4 – Max displacement & Requested electric total power

This comparison between case 2 and case 1 shows the importance of a high prestress and bias for dynamic applications. This is true both for vibrations produced by the actuator but also for the external vibrations exerted on the actuator. The ability to manage dynamic forces is also important in transient (on-off) applications because of displacement overshot and associated high stresses.

4. Materials for applications

Today there are several available sources of GMM: Etrema Products, Inc. (US) [22] founded in 1988 produces Tb-Dy-Fe rods with dimensions varying from 2 to 68mm in diameter and from 6 to 250mm in length, as well as plates and powder. The US Navy has supported its development for low frequency sonar transducers. For example, Etrema is the GMM provider for hybrid transducers of the Surface Tactical Array Replacement (STAR) Ship Sonar [23, 24] for the US Navy. US Navy continuously supports Etrema and maintains a serious effort to improve Terfenol-D (as regard corrosion for example) as well as to develop Galfenol material [25].

Gansu Tianxing Rare Earth Functional Material Co, Ltd (China) [26] founded in 1998 produces rods with dimensions varying from 5 to 50mm in diameter and up to 200mm in length. Magnetostriction curves of GMM from this company are rather similar to those of Etrema. China Rongtech [27] and MateriTek Co. Ltd [28] are other chinese companies producing Tb-Dy-Fe GMM. All these chinese companies exploit the wealthy resources of rare earth of China. One trend in China is to develop a capability to manufacture large rods (70mm in diameter and 250mm in length) [29], which is far above the size of largest MLA components.

Table 3 presents the static and dynamic strain performances of Terfenol-D compared with other active materials. The static strain is the peak to peak stroke obtained vary the magnetic field in quasi static conditions. As shown by equations (6,7), the dynamic strain at resonance is determined by the stress limit accounting for the material prestress. Because Terfenol-D can bear high prestress while being still active, the dynamic strain can be very high, and can be much larger than static strains.
Not included in table 3, 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. Efforts are performed to improve lamination techniques.
Another approach initiated by FEREDYN [5] to limit eddy current and still pursued [30, 31, 32] consists in composite GMM, made of grains of magnetostrictive alloys combined with an electrically insulated binder such as a polymer. It allows operation up to 100kHz, but the electromechanical performances are smaller than competing materials.
Galfenol is a more recent magnetostrictive alloy made of Iron and Gallium (Fe-Ga) [32, 33]. It is robust and is still active even in case of large prestress. It offers a strong potential for high dynamic strains. Because of it is robust, prestress could maybe avoided while keeping such dynamic strains, which could lead to new types of vibrators [34].

For actuation purposes, bulk and composite GMM are in direct competition with other active materials.

Standard 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. Magnetic-field controlled Shape Memory Material (MSM) is a new type of Shape memory alloys based on Ni Mn Ga alloy [35, 36]. They are not strictly speaking magnetostrictive, but from the engineering point of view they behave as a magnetostrictive material. They offer very large strains but low stresses. Their giant static strain (up to 5%) may be of very high interest for making new large stroke actuators. However this material is very brittle and cannot bear high prestress: A paper from C.Henry [37] provides a comprehensive experimental analysis of $Ni_{49.7}Mn_{29}Ga_{21.3}$ single crystal including the variation of static performance versus prestress. The experiments shows that above a prestress of 1Mpa, the material activity decreases rapidly. It is why their expected dynamic strain calculated with (5) and (9) is quite limited (table 3).

To compare with GMM, 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 [38], 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.

Compared with piezoelectrics, Terfenol-D offers a larger 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 is higher than piezo ceramics. This is a big advantage for high power devices operated at resonance [17]. Further comparison between magnetostrictive and piezoelectric actuators can be found in [39].

In spite of its limited application range, new cryogenic GMMs made of TbDyZn are being developed for the NGST project of NASA [40, 41]. They may find interest in some future space missions for positioning of optics in telescopes. They offer large strain (5000ppm) at low temperature (77K).

		Terfenol-D GMM	Composite GMM	Galfenol	PZT-4	Soft PZT MLA	MSM
Max static strain	ppm	1800	1000	320	600	1250	50000
Coupling coeff.	%	70	35	40	67	65	75
Young's modulus	GPa	25	20	45	60	40	7
Max prestress	MPa	50	30	80	50	40	1
Max dyn. Strain at resonance	ppm	4000	3000	3500 *	1600	2000	140 *

Table 3 - Properties of GMM, MSM and PZT piezo ceramics. For comparison, all strains are given peak-to-peak. Given values have been experimented at Cedrat Technologies [42, 43], excepted MSM and Galfenol dynamic strains (*)which have been calculated with the stress limit

5. The principles and the properties of various applications

The design problem of magnetostrictive linear driver offering large dynamic strains has been addressed at Cedrat through several actuators (figure 5) [44, 45]. Their goal was to check the large dynamic strains of Terfenol-D drivers for sonar applications and to compare different means for generating high prestress and bias.

These actuators are identical except in their bias system. They are all based on one driver and two symmetrical head-masses. The heavy masses have been chosen to produce a free-free resonance around 1kHz. Their driver contains a total length of Terfenol-D of 100 mm. The rod diameter is 20 mm. The first actuator, called MB, is biased with a DC current in a coil giving a bias field from 0 to 160 kA/m. The second one, MAP, is biased with permanent magnets placed outside the dynamic flux circuit and producing field about 90kA/m bias field. A 10mm-thick coil permits using it against high loads. Due to the magnets and the coil, the diameter, excluding the masses, is about 70mm. The third actuator, MAS, is biased with cylindrical permanent magnets placed in series between slices of Terfenol-D. The magnets shape have been optimised with FLUX2D [46] and their effect on the deformation has been calculated with ATILA [16]. They produce a 90kA/m bias field. It has also a 10mm-thick coil. It is slightly longer than the others, but its diameter is only 50mm. Some experimental properties of the MB, MAP, MAS drivers are compared in table 4.

			M.B.	M.A.P.	M.A.S.
Bias	H_o	(kA/m)	100	90	90
Prestress	T_o	(MPa)	30	40	35
Coupling coefficient	k_{eff}	(%)	52	55	35
Max. dynamic strains at resonance	S_{pp}	(ppm)	2020	3000	3500

Table 4 - Experimental properties of the MB, MAP, MAS drivers

Figure 5 – Shear resonators, MAS and MB linear actuators

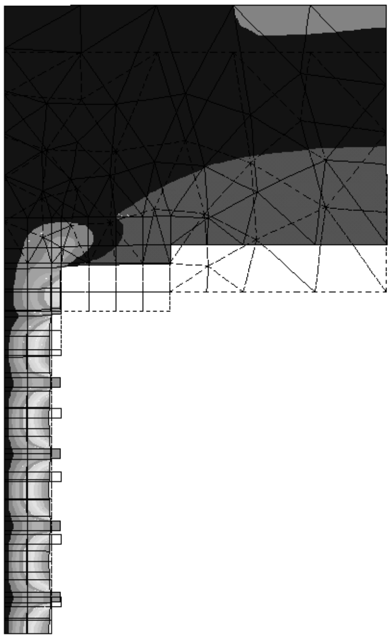


Figure 6 - Deformed shape (continuous lines), structure at rest (dotted lines) and radial displacements (shading) of the MAS, accounting for axial and plane symmetries, computed with ATILA FEM software.

The MAS owns the smallest coupling factor. It is due to the series magnets which introduce magnetic reluctances, uncoupled longitudinal compliances and radial stiffnesses. These last mechanical effects cannot be correctly explained by simplified theory (§4) but they are clearly predicted by ATILA software, as shown in figure 6. In spite of these effects, the MAS presents high dynamic strains. The research of the absolute strains limits of linear drivers shows that the highest strains are obtained below resonance. The curve of the absolute maximum strain versus frequency of the unloaded MAS (figure 6) has been calculated taking into account both the field limit and the stress limit at each frequency, following a similar method as presented in §4 but using FEM results. It defines an optimised law of current which depends on frequency. The measured maximum strains is 4000ppm. It is obtained well below resonance as described in the §4.

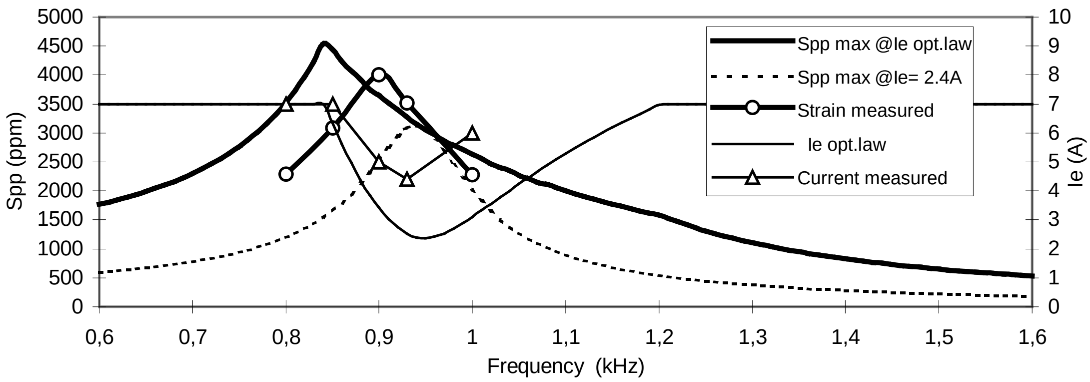


Figure 7 - Calculated curves of MAS : peak-to-peak strain S_{pp} at constant current I=2.4A, strain with optimised current I_e law, and corresponding current I_e law - Measured values of strains of MAS and corresponding currents

The Tripode Tonpilz-type sonar transducer [17, 47] is a good example for showing the high power capability of Terfenol-D. It is 31cm long and 30cm in diameter. It is based on three drivers, each of them including a 100 mm-long, 20mm in diameter Terfenol-D rod. Their prestress is 50Mpa. The maximum theoretical expectations was a headmass displacement of 110µm, a Terfenol-D strain of 3250ppm, an output power of 4kW and a source level of 208.6dB ref.1µPa @ 1m. Experimentation was performed to achieve about 90% of the theoretical performance. The headmass displacement was measured with an accelerometer giving 98µm at 1.2kHz (figure 9) corresponding to a 2900 ppm peak-to-peak strain in Terfenol-D. An output power of 3.8kW and a sound level of 208,1dB are obtained (figure 8). This performance is achieved with an acceptable linearity (figure 9).

Figure 8 - Sonar transducer Tripode

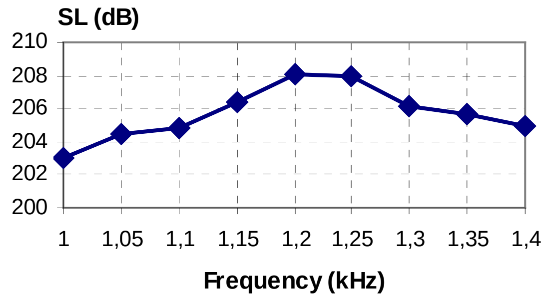


Figure 9 - Tripode measured Sound Level versus frequency

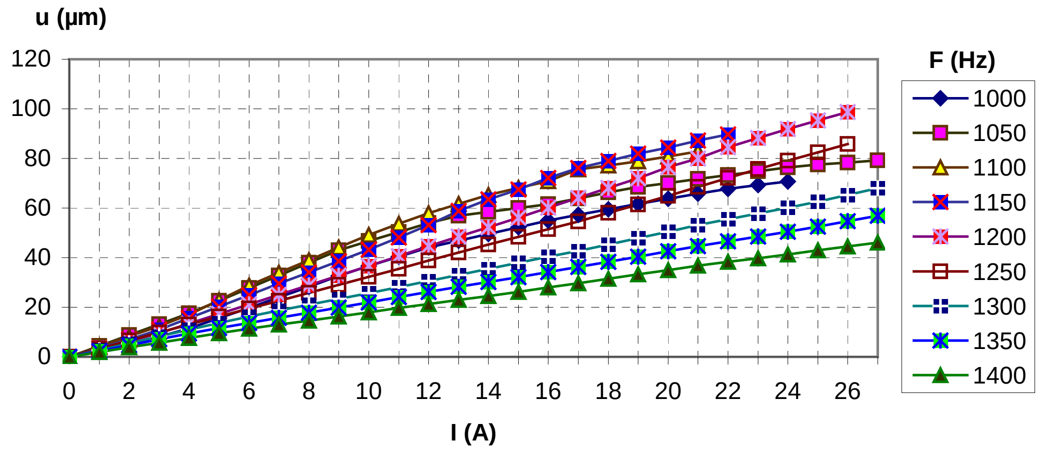


Figure 9 - Displacement of the head mass versus excitation current I at different frequencies

This methodology has been applied to develop ultrasonic magnetostrictive transducers (figure 10) for ultrasonic cleaning (figure 11). Its resonant frequency is 20kHz. It is based on composite GMM for avoiding eddy currents and for limiting losses. The peak to peak strain at resonance is higher than 2000ppm, allowing to produce 20µm stroke in a compact transducer.

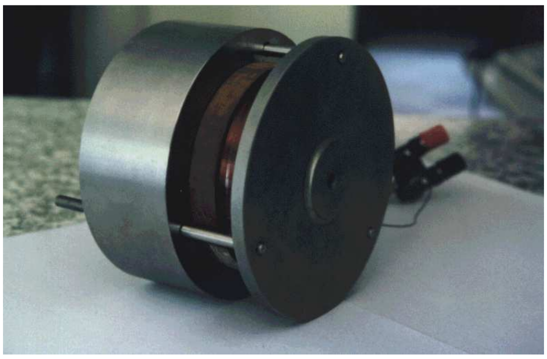


Figure 10 - Ultrasonic magnetostrictive transducer

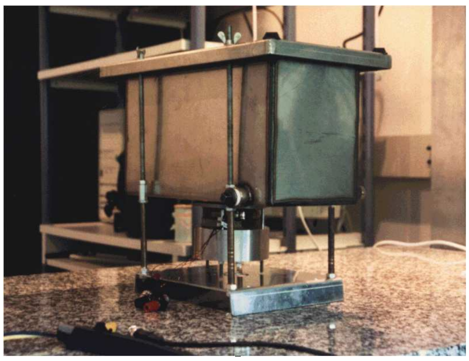


Figure 11 - Ultrasonic cleaning unit

Another type of actuation devices developed by Cedrat Technologies are amplified magnetostrictive actuators, so called AMA. Such actuators are based on a shell which performs both the prestress of the magnetostrictive rod and the amplification of displacement. It is a concept patented by Cedrat Technologies and mostly used for manufacturing Amplified Piezoelectric Actuators [48].
A typical AMA structure is presented on figure 12 and 13. The long active axis is a stack of permanent magnets in series with 7 short rods of Terfenol-D 8mm in length, 8mm in diameter. It is prestressed at about 30Mpa and biased at about 100kA/m. When the active stack expands along to the long axis, the shell contracts producing an amplified displacement on the short axis, of a factor 2.2 in static and 3.3 at resonance. Because of this effect and the stack structure, this structure cannot easily be analysed without a 3D model. The figure 14 presents the low frequency deformation of the actuator computed with the ATILA FEM accounting for the 3D piezomagnetic coupling, the 3D structure and the current excitation into the coil.
According to ATILA, 1 Ampere in the coil produces a 16kA/m H field and in quasi static condition, this field generates a 11.0 µm peak displacement.
The response curve of displacement par ampere, measured at excitation low level, gives a displacement per ampere of 10.5 µm/A, which confirms the computation result, and shows a resonance at 3.1kHz with a Q factor of 20.
With these values, ATILA shows that at resonance, the maximum current is 1.45Apeak and the maximum H field is 23 kA/m, because with these values the dynamic stresses amplitude in the rod meet the prestress value. This leads to a theoretical peak-to-peak displacement equal to 640 µm.
Measurements at resonance with this current gave a large peak-to-peak displacement equal to 505µm. The difference is explained by the non linearities occurring at high level. Indeed the Q factor at high level was found about 16, which is lower than the one measured at low level. From this displacement and the amplification factor calculated with ATILA, the Terfenol-D deformation is found equal to about 2730ppm peak-to-peak.
The figure 15 presents a smaller AMA, called the AMA50, based on the same structure. Figure 16 shows the AMA modelling in a proof mass configuration. In this case, the coil acts as the mass generating the inertial forces. The actuator is used at resonance and above resonance and works as a large bandwidth generators of dynamic forces [49].

Figure 12 – Dismounted AMA 400

Figure 13 – AMA400

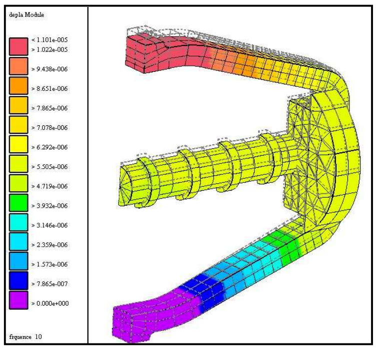


Figure 14 – ATILA modelling of the AMA400

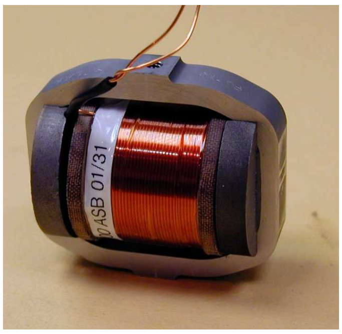


Figure 15 – AMA50

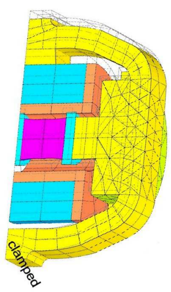


Figure 16 – ATILA modelling of the AMA50

6. Conclusion

The large static magnetostrain capability of Giant magnetostrictive materials is well known.
This paper has presented their capacities in terms of giant dynamic strains. It shows that it is possible to get such strains at resonance and also in a frequency range below resonance. This implies to use a high prestress and magnetic bias, and to define the appropriate excitation current law. In this case, considering standard Terfenol-D materials, the dynamic strains can reach values up to 4000ppm peak-to-peak, to compare with the static magnetostrain values of about 1600ppm peak-to-peak.
The method used to determine the excitation current versus frequency for producing such high dynamic strains has been explained by considering a conventional Direct Magnetostrictive Actuator from Cedrat Technologies and by outlining the role of the bias and prestress.
Different applications, including sonic and ultrasonic transducers as well as direct and amplified magnetostrictive actuators have been presented in detail to show that such giant dynamic strains can be produced in applications. Other applications like resonant motors [50, 51, 52, 53] and actuators for pumps [54, 55] have also been designed by Cedrat Technologies considering the GMM capacities in terms of giant dynamic strains.

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