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ACTUATORS BASED ON GIANT MAGNETOSTRICTIVE MATERIALS

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Abstract:
Magnetic field induced strain materials are classically represented by Giant Magnetostrictive Materials (GMM) such as Tb-Dy-Fe alloys offering magnetostrain of 0.1-0.2%. This family of smart materials has been extended for some years by cryogenic magnetostrictive materials such as Td-Dy and ($Tb_{1-x}Dy_x$)Zn offering magnetostrain of 0.2-1%. Even more recently, it has been completed by new Magnetic Shape Memory Materials (MSM) such as Ni-Mn-Ga offering magnetostrain of 2-6%. These materials have lead to quite various large stroke and large force actuators. Some of these actuators meet the requirements of applications in different fields such as space or machine tools. The object of this paper is to review the present situation and recent progresses in the field of magnetic field induced strain materials, actuators, modelling and applications, including commercial aspects.

Introduction

Magnetic field induced strain materials are classically represented by Giant Magnetostrictive Materials (GMM) such as Rare earth-iron discovered by A.E.Clark [1]. These materials feature magnetostrains which are two orders of magnitude larger than Nickel [2,3]. Among them, bulk $Tb_{0.3}Dy_{0.7}Fe_{1.9}$, called Terfenol-D, is commercially available since 1987 and presents the best compromise between a large magnetostrain and a low magnetic field, at room temperature. Positive magnetostrains of 1000 to 2000 ppm (0.1-0.2%) obtained with fields of 50 to 200 kA/m are reported for bulk materials [1,4], opening the possibility of building high power transducers and actuators. These results have renewed the interest for magnetostriction and have been followed for 20 years by many progresses in the fields of GMMs and their applications. For example, cryogenic magnetostrictive materials such as Td-Dy offering magnetostrain of almost 1% have appeared in 1989 [5] and open a field of development for magnetic field induced strain materials. More recently, this family of smart materials has been extended with Magnetic Shape Memory Materials (MSM) such as NiMnGa alloys [6] offering a magnetostrain of up to 6%.

The goal of this paper is to review the GMM last progresses, from the point of view of the actuator manufacturer. For this reason, MSM are also considered even if they are not strictly speaking magnetostrictive. This paper also reviews the present situation and the last three years of progress in terms of actuators based on magnetic field induced strain materials, modelling aspects, applications, and commercial considerations.
Contrarily to the previous Actuator Conf. review [7], magnetostrictive films and their application to microsystems are not included in this paper, and will be the object of a specific review planned for the Actuator 2004 conference.

Magnetostrictive Materials for actuators

From the commercial point of view, there are three available sources of Tb-Dy-Fe GMM: Etrema Products, Inc. (US) [8] founded in 1988 produces 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. Gansu Tianxing Rare Earth Functional Material Co, Ltd (China) [9] 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 new company (Figure 1) are rather similar to those of Etrema. MateriTek Co. Ltd (China) [10] is a third company producing Tb-Dy-Fe GMM. Both these companies exploit the wealthy resources of rare earth of China.

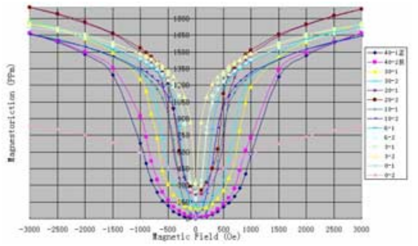


Figure 1 - Magnetostrain curves of Tb-Dy-Fe from [9]

Although more than 20 years old, Terfenol-D is still a subject of R&D works, interesting particularly for making high-power low-frequency transducers and low-voltage large-force actuators.
T.Nakamura [11] has undertaken the characterisation of a double-ended pre-stressed vibrator comprising a Terfenol-D rod. Such a test unit and its use are very similar to those already described in [12,13]. It allows finding out *in situ* piezo magnetic 'constants' of biased pre-stressed AC-excited Terfenol-D.

This device is shown hereafter because of the typical use of Terfenol-D rods it illustrates. The rod is magnetically biased by permanent magnet and pre-stressed by parallel bolts. It is surrounded by a solenoid coil for AC magnetic excitation (and added DC magnetic bias). Magnetic T-shaped end pieces are used for reducing reluctance of the magnetic return path, according to the open magnetic circuit concept [14,15].

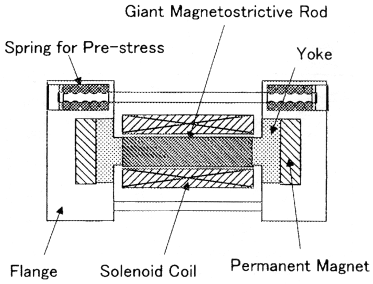


Figure 2 - Terfenol-D test unit [11]

Nakamura uses it to establish the trends of equivalent circuit constants such as stiffness, internal resistance, and force factor in response to the increase in pre-stress for enhancing the output. Furthermore, considering the linearity to the input level, the necessity of examining the optimum pre-stress region, in addition to the simple increase in pre-stress, was suggested.

R.Kellog [16] has opened a series of investigations about the blocked force of Terfenol-D transducers, that evaluate the maximum stress generated by the active material. It gives at no prestress a AC blocked stress of 44MPa at 2.2kOe excitation field and almost doubled values at 6.9MPa prestress (figure 3). Note however that such a field is difficult to produce in an actuator.

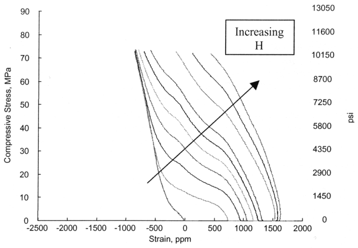


Figure 3 - Stress-strain load lines for applied field H from 0-2.4kOe at 200Oe steps (1400Oe missing) [16]

L.E.Faidley [17] presents a complementary work on the force capability of Terfenol-D. It shows that, with the same conditions, the blocked force is 12% higher at 100Hz than at 1Hz, and that a square wave instead of a sine also improves the blocked force. It demonstrates that it is of primary importance to characterise Terfenol-D in its conditions of use.

R.Kellog [18] has performed a detailed analysis of stress-strain relationship and Young's modulus variation (*ΔE* effect). According to conditions, *ΔE/E* varies about by 200-400%, thus rendering tuneable resonators feasible.

O.Thomas [19] has undertaken the analysis of the effect of sample thickness on the static magnetostrain and dynamic magnetoelastic properties of Terfenol-D. He shows that in reducing the sample thickness from 17.35 mm to 1.17 mm, the maximum dynamic strain coefficient d_{33} can be more than doubled. According to the author, the increase of operation frequency would be also beneficial, in correlation with L.E.Faidley.

Cryogenic magnetostrictive alloys are interesting for helium valves or positioning applications in space instruments such as the Next Generation Space Telescope (because reduced thermal noise is highly desired for improving the instrument resolution). These materials appear much superior to piezo ceramics at these temperatures and generate different works for characterisation and improved fabrication.

M.Wun-Fogle has characterised new rare-earth alloys $(Tb_{1-x}Dy_x)Zn$ [20]. The most interesting results are magnetostriction values of more than 5000ppm @77K, associated with high values of permeability and almost ideal coupling factor ($k_{33} > 90\%$).

J.Dooley of JPL [21] has pursued his work on Tb-Dy alloys by developing a textured polycrystal variant. This material exhibits a magnetostriction of 3500ppm, 56% of that of Tb-Dy single crystal, while being simpler to prepare.

Magnetostrictive composite materials have been initiated by L.Sandlung [22] for high frequency ultrasonic applications. These materials are made of Terfenol-D particles associated together with a polymer matrix. As this matrix provides an electric insulation between particles, the eddy currents that are responsible for losses cannot develop and the operation frequency can be as high as 100kHz. The drawback is a reduced magnetostriction of 900-1000ppm.

A recent work from G.P.McKnight [23] presents a way to remove this drawback. A composite material is prepared by using needle shaped [112] oriented particles and particles magnetic alignment. Its magnetostriction reaches almost 1600ppm, comparable to the bulk Terfenol-D alloy.

Other types of magnetostrictive composite materials are also investigated. They combine Terfenol-D layers with passive damping layers [24,25] for control of vibrations in structures.

Other magnetostrictive materials than Rare Earth Iron alloys may also receive some attention. For example $Fe_{1-x}Ga_x$ alloys from A.E.Clark [26] offer rather large magnetostriction coefficient d_{33} = 10-20nm/A and high relative permeability values of 40-100, while being able to support large stresses. Such materials might be useful in parts of active trusses.

The Magnetic Shape Memory (MSM) effect of Ni-Mn-Ga alloys was discovered by K.Ullakko in 1996 [6].

More recently, S.Murray [27], O.Heczko [28], or W.Wang [29] have shown that an off-stoichiometric composition such as an $Ni_{48}Mn_{31}Ga_{21}$ optimises the reversible magnetostrain which reaches more than 5% at room temperature. In MSM, that possess two phases, a martensite at low temperature and an austenite at high temperature, the magnetostrain is due to magnetically-driven twinned boundary motion inducing a martensitic variant redistribution. This is quite different from magnetostrictives, where the magnetostrain is due to a coupling between magnetic spin, electric orbital and lattice, implying a rotation of magnetization.

This material is commercially available since 1998 by Adaptamat Inc. (Finland) [30], and generates a lot of materials researches.

A paper from C.Henry [31] provides a comprehensive experimental analysis of $Ni_{49.7}Mn_{29}Ga_{21.3}$ single crystal. The experimental device (figure 4) comprises a sample placed in an initial prestress of 1MPa. Its twinned structure is dominated by the variants having magnetization parallel to stress. A magnetic field can be applied in the transverse direction, which grows the variants having magnetization parallel to field. This induces the material contraction along the field axis, and the extension in the other directions.

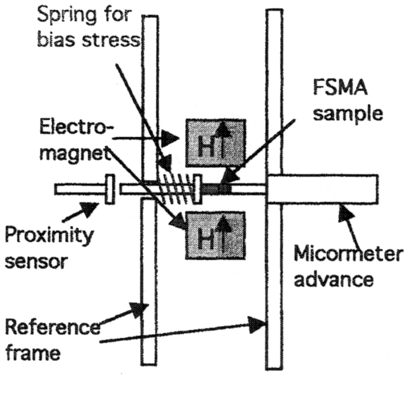


Figure 4 - Test system of $Ni_{49.7}Mn_{29}Ga_{21.3}$ MSM [31]

The magnetostrain curves at different pre-stresses (figure 5) shows that the optimal pre-stress for a maximum saturation strain of 3% at 6kOe is about 1.4MPa. Above 1MPa, the hysteresis is much more important than below. The curve slope d_{31} reaches 190nm/A, which is one order of magnitude larger than Terfenol-D. The authors correlate these results with a thermodynamic model.

Several other characterisation works associated with physical models can be found in [32] or [33]. Results about temperature effects can be found in [34,35].

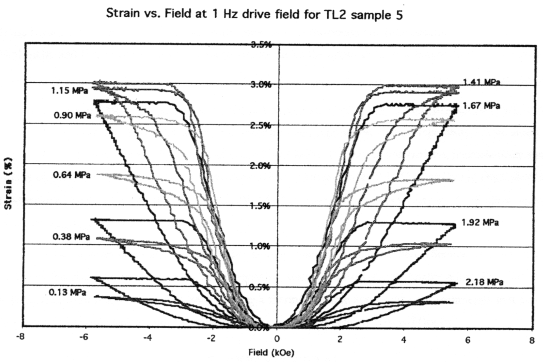


Figure 5 - Magnetostrain curves of MSM from [31]

Modelling Magnetostrictive Actuators

Modelling is a useful step for using efficiently the active material in applications. This is especially true in the case of Tb-Dy-Fe GMMs because they are rather expensive and require special care: they are subject to magnetic leakage flux and various kinds of losses. They own low tensile and transverse strengths. The structures where they are implemented may be complex (such as flextensional structures). As GMMs are dedicated to high force or high power applications, these issues need to be specially studied, particularly in dynamic cases.

According to a web search, the ATILA FEM software is the only commercially available CAD software dealing with magnetostrictive actuators [36]. It allows static, modal, harmonic or transient analysis of 3D active structures and their acoustic loading. The variational formulation forming the theoretical basis of the magnetostrictive problem in the software [13] is based on a magnetic scalar potential, which can only describe pre-defined spatial distribution of eddy currents. This basis is compatible with non-linear analysis [37]. However only the linear modelling has been implemented. In spite of these limitations, ATILA has been proven quite valuable in all devices (actuators, transducers and motors) using magnetostriction under bias and pre-stress conditions [38]. Several extensions of this software have been implemented for non-linear analysis of electrostrictive materials [39] and for hysteretic analysis of Shape Memory Materials [40], which could probably be transposed to GMMs and MSMs.

M. Kaltenbacher has undertaken a work [41] for removing the previous limitations. Its new formulation is based on the magnetic vector potential, which allows for dealing eddy currents in a general manner. Non-linear material relationships are accounted but not hysteresis. From the magneto-elastic point of view, it assumes a constant volume magnetostriction, which is not always true, for example when forced magnetostriction is produced at high fields [3].

Magnetostrictive Actuators & Applications

Quite different actuators based on Tb-Dy-Fe materials have been developed to cover various needs, as illustrated in the recent works or applications described hereafter. Three types of actuators are discussed:

- Direct actuators, without amplification;
- Amplified actuators including a displacement amplification mechanism
- Motors based on a friction drive mechanism, for achieving long strokes.

Etrema [8] is the main producer of off-the-shelves GMM actuators. Its range is limited to direct actuators but covers a wide range of strokes, forces and frequencies, including ultrasonic transducers.

Cedrat Technologies has developed a new Amplified Magnetostrictive Actuator, called AMA50, for aircraft applications, in the context of the MESA CSG 5th Framework Program [42]. A rod placed along the shell long axis produces flextensional deformations of the shell, generating magnified displacement in the direction of the shell short axis (Figure 6, Figure 7).

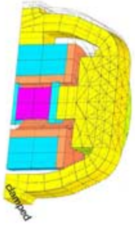


Figure 6 - ATILA FEM modelling of the AMA50

Figure 7 - View of an AMA50

The rod is pre-stressed by the shell and biased by 3 permanent magnets in series. The magnetic T-shaped parts placed at each ends of the rod are used according to the concept of open magnetic circuit. This actuator derives from the Amplified Piezo Actuator (APA), a concept from Cedrat Technologies [43] used in its piezo products [44] for air & space applications [45,46,47]. One targeted application of the AMA50 is proof-mass actuators for active vibration damping. In this application, the inertial mass function can be performed by the coil attached to one side of the actuator, the other one being fixed to the structure to damp. Figure 6 shows the strained structure in the first mode calculated with ATILA accounting for the magnetostrictive coupling. Compared to a proof-mass piezo actuator, which require the addition of an inertial mass, such GMM actuator would not be penalised by the coil mass, in terms of total weight. The measured free stroke of 1µm/A is in agreement with ATILA predictions. From this work Cedrat has concluded that GMMs from Txre and Etrema were rather equivalent. This displacement value appears more field-limited and power consuming than that of the APA60SM, for instance, which offers 0.3µm/V, but it is not clear if these parameters were stringent for the targeted damping application. F.Franco of the University of Naples gives first results about these applications in this conference [48].

J.H.Goldie has also developed proof-mass actuators based on GMM for anti vibration in noise-critical applications [49]. However, these are direct actuators. As a consequence, they are stiffer than the AMA50 and operate at higher frequencies.

P.Barlett has developed a high force low frequency amplified actuator for anti vibration in civil engineering structures in the context of the ACE E.C. program [50]. This large actuator is based on two 30mm diameter rods stacked to achieve a total length of 508mm and on a lever arm mechanism. According to the lever arm gain, the output displacements vary from 0.5 to 4mm and forces vary from 6 to 0.5kN.

A.Flatau has shown the feasibility of a high bandwidth tunable direct actuator for making a smart vibration absorber [51]. The actuator is based on a Terfenol-D rod and exploits the ΔE effect to achieve a relative frequency shift of about 50% of the first mechanical resonance frequency.

H.Eda has developed a high precision in-feed machine for non-defect grinding of 300mm diameter Si wafer for semiconductor industry [52]. It is based on a 2 dof mechanism using 3 GMM direct actuators. According to the authors, GMM actuators offer better performances, including positioning resolution. GMM actuators are controlled using hysteresis compensation. As a remarkable result, the machine achieves a positioning better than 0.625nm on a payload of 750kgf and produces flatness better than 0.2µm over the Si wafer surface.

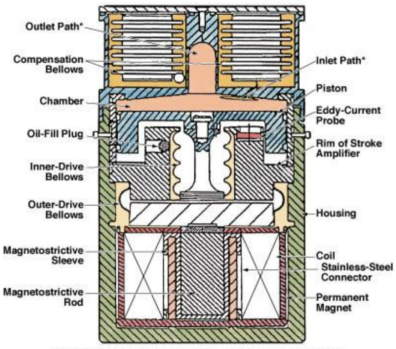
Etrema Products, Inc. has found applications of its direct GMM actuators in the field of machine tools (CNC lathe) for turning oval pistons and other non-round parts. This technology is exploited by Active

Technologies [53] under the name of Pulse-Turn™. According to this company, it can turn oval shapes at speeds as high as 6,000 rpm, while holding accuracy in the order of a few microns.

Q.Shuye has developed a broad band large moment exciter for direct excitation of rotational components as required in the study of structure-borne noise [54]. The device is based an inertial mass and on two 10mm diameter and 100mm length rods placed in parallel and excited out of phase. It fulfils the goal of the authors.

E. Monaco has proposed a new test procedure for damage analysis of structural elements based on low-frequency direct magnetostrictive actuators [55].

Michael Gerver has developed a magnetostrictive pump with few moving parts for space applications. [56]. It is based on an amplified actuator, which uses an hydraulic displacement amplifier (factor of 7.5). The pump is designed to have a flow rate of 30 milliliters per second and a pressure of 5 psi, and to consume about 25 W of electric power.



* Outlet and inlet paths include check valves not shown here.

Figure 8 - Magnetostrictive pump from [56]

P.Friedmann has designed magnetostrictive actuated control flaps for vibration reduction in helicopters [57]. His solution is based on a double amplification mechanism. A first one combines 2 GMM rods in a Lambda configuration (because of the Λ shape they form) as presented in Annex 1 of [13], at the exception of the hinges technology. A second one is a standard lever arm. According to the author, the required flap deflection of 10° should be achieved with rods of 1.6cm in diameter and 16.9cm in length.

About techniques required for fine control of magnetostrictive actuators, K Kuhnen has proposed in the context of MESA an inverse feedforward controller for hysteretic non-linearities [58].

Cryogenic GMM actuators were initiated in the context of US navy needs for low frequency projectors. They now receive a strong support from NASA for space applications, for valves [59] and for the NGST [60], through four development projects.

Among these, a linear motor developed by C.Joshi from Energen [61] uses a translating rod between two clamps to provide a long stroke actuator. The two clamps are operated by GMM actuators and release their hold on the rod when energized. The translating rod contains a GMM rod surrounded by a superconducting coil. The motor is mounted with the clamps attached to the backup structure and the end of the rod connected to the mirror surface through a flexure [62]. Typical strokes are 20mm by steps of 60µm, and resolution of 0.1µm. This actuator has also found an application in a tuning mechanism for Super conducting Radio Frequency cavities used in particle accelerators [63].

Thanks to their properties, MSM alloys are good candidates for making long stroke actuators without amplification mechanisms.

Adaptamat [30] has used its MSM for developing its own range of direct actuators. One example called the A5-2 is 20x30x140mm with shaft is shown hereafter. This actuator possesses a free stroke of 3mm and a blocked force of 3N. It can operate from DC to 300Hz.

Figure 9 - MSM actuator from [30]

Conclusion

R&D in the field of magnetic field induced strain materials is lively and fruitful, considering Tb-Dy-Fe alloys, cryogenic GMM and new MSM. These materials have lead to a wide range of large-stroke and large-force actuators. Some of these actuators meet the requirements of applications in different fields such as space or machine tools.

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References

[1] A.E. Clark, Ed.E.P. Wohlfarth, US ,Tome 1, 1980, pp.531-588.
[2] R.M., Bozorth, 2nd ed.,VanNostrand, NY, 1951, 980p.
[3] E. De Lacheisserie, Ed. CRC Press, USA, 1993, 410p.
[4] J.D Verhoeven., Appl. Phys. 66(2), 1989. pp.772-779.
[5] M.L.Spano, A.E.Clark, Wun Fogle, IEEE Trans Mag Vol.25, n.5, 1989, pp3796-3796.
[6] K.Ullako, J.K.Huang, C.Kantner, R.C.O'Handley, V.V.Kokorin, Applied Physic Letters V.69, n.13, 1996, pp.1966-1968.
[7] E.Quandt, F.Claeyssen, Proc. Actuator 2000, pp100-105.
[8] www.etrema-usa.com
[9] www.txre.net
[10] www.materitek.com
[11] T. Nakamura; I. Nakano; A.Kawamori; T.Yoshikawa Jpn. J. Appl. Phys.; pp 3658-3663.
[12] F. Claeyssen, D.Boucher, Proc. 2nd int. Workshop on power transducers for sonics & ultrasonics, Ed.Springer, 1989, pp 132-151.
[13] F. Claeyssen, Design and building of low-frequency sonar transducers based on Rare Earth Iron magnetostrictive alloys. Doct. Thesis, Ed. MoD, London (*in English*) or INSA Lyon (*in french*), Dist. Cedrat (F), 1989, 414p.
[14] F.Claeyssen, D.Boucher, A.Foggia, E.Sabonnadiere, Proc. Intermag 1989, IEEE Trans Mag, Vol.26, N.2, 1990, pp 975-978.
[15] M.E.H.Benbouzid, G.Reyne, G.Menier, S.A.Sportnic, Actuator 94, pub.Axon, Bremen, 1994, pp242-245.
[16] R. Kellog, A. Flatau, SPIE Smart structures and materials, Vol.3668, 1999, p#19, 12p.
[17] L.E.Faidley, M. Dapino, A. Flatau, Proc. SPIE Smart structures and materials, Vol 4327, 2001, pp 521-532.
[18] R. Kellog, A. Flatau, Proc. SPIE Smart structures and materials, Vol.4327, 2001, pp 541-549.
[19] O. Thomas; S.Mahon ; S. C.Busbridge; A. R. Piercy, IEEE trans. magn., 2001, Vol.37; n.4; pp 2687-2689.
[20] M.Wun-Fogle, J.B.Restorff, A.E.Clark, J.B.Cullen, T.A.Lograsso, Proc. SPIE Smart structures and materials, Vol.4333, 2001, pp163-165.
[21] J.Dooley, N.Good, J.Graetz, R.Chave, B.Fultz, Avances in Cryogenic Engineering (Materials), Vol.46, 2000, pp 383-389.
[22] Sandlung L., Proc. 3rd int. Workshop on power transducers for sonics&ultrasonics, Ed. Springer, 1992, pp 113-120.
[23] G.P.McKnight, G.P.Carman, Proc. SPIE Smart structures and materials, Vol.4333, 2001, pp178-183.
[24] B.Bhattacharya, B. R.Vidyashankar, S.Patsias, G. R.Tomlinson, P.F. Gobin; C.M. Friend, SPIE Smart structures and materials, 2000, Vol.4073, pp 204-214.
[25] V R.Buravalla, B.Bhattacharya; G. R. Tomlinson , D. J.Inman SPIE Damping and isolation, 2001; Vol.4331; pp.386-395.
[26] A.E.Clark, M.Wun-Foggle, J.B.Restorff, T.A. Lograsso, J.Cullen, IEEE Trans. Mag, Vol 37, No.4, 2001, pp 2678-2680.
[27] S.J.Marray, M.Marioni, S.M.Allen, R.C.O'Handley, T.A.Lograsso, Appl. Phys; Lett.vol 77 n.6, 2000, pp886-888.
[28] O.Heczko, A.Sozinov, K.Ullakko, Proc Intermag, IEEE Trans. Mag. 2000.
[29] W. H. Wang; G. H.Wu; J. L. Chen; S. X. Gao; W. S.Zhan; G. H.Wen, X. X. Zhang, Appl. phys. Lett, Vol.79; n8, 2001,pp1148-1150.
[30] www.adaptamat.com
[31] C.P.Henry, J.Feuchtwanger, D.Bono, M.Marioni, P.G.Tello, M.Richard, S.M.Allen, R.C.O'Handley, Proc. SPIE Smart structures and materials, Vol 4333, 2001, pp 151-161.
[32] V. D. Buchelnikov, V. S. Romanov, A. N. Vasilev, T. Takagi, Shavrov, J.of exp. and theor. Phys.; 2001;Vol 93;n 6;pp 1302-1306.
[33] A. A. Likhachev, K. Ullakko, G.Airoldi, S.Besseghini, J. phys., IV; 2001;Vol 88; pp8.293-8.298.
[34] O.Heccko, K.Ullakko, IEEE Trans. Mag. Vol.37, n.4, 2001, pp2672-2674.
[35] M. Pasquale, C.P. Sasso , S. Besseghini, V. Chernenko, IEEE Trans. Mag. Vol.37, n.4, 2001, pp2669-2671.
[36] ATILA, a 3D FEM CAD software for modelling piezoelectric and magnetostrictive structures, Ed. Isen, Dist. Cedrat (F), Magsoft (US), www.cedrat.com.
[37] F.Claeyssen, *in* A handbook of GMM, Ed. G.Engdhal, Academic Press, 1999, pp 352-386
[38] Claeyssen F., J. Alloys Compounds. 258, 1997, pp 61-73.
[39] J.C. Debus, B. Dubus, J. Coutte, J. Acoust. Soc. Am., Vol.103, n.6, 1997, pp3336-3343.
[40] A.C. Hladky-Hennion, S. Rafanomezantsoa, L. Buchaillot, P. Bouchilloux, Proc. SPIE Smart structures and materials, Vol 4326, 2001, pp143-150.
[41] M. Kaltenbacher, S.Schneider, R.Simkovics, H.Landes, R.Lerch, Proc. SPIE Modeling, Signal proc. and Control in Smart structures, Vol 4326, 2001, pp.
[42] www.eurice.de/mesa
[43] F.Claeyssen, R.Leletty, Proc. Piezoelectric Materials for the End Users, Ed.EPFL (CH), 8p.
[44] www.cedrat.com
[45] P.Guay, F.Claeyssen, R.Leletty, Proc Actuator 2002, Ed. Messe Bremen, B3.2, 4p.
[46] H.Mercier des Rochettes, P.Leconte, J.L.Petitniot, Proc Actuator 2002, Ed. Messe Bremen, B3.4, 4p.
[47] A.Abu-Hanieh, M.Horodinca, A.Preumont, N.Loix, J.P.Verschuren, Proc Actuator 2002, Ed. Messe Bremen, B2.1, 4p.
[48] F.Franco, E. Monaco, L.Lecce, Proc Actuator 2002, Ed.Messe Bremen, B2.3, 4p.
[49] www.satcon.com/sub/techcent/pub
[50] P.A. Barlett, S.J.Eaton, J.Gore, W.J.Metheringham, A.G.Jenner, Sensor and Actuators, A 91, 2001, pp 133-136.
[51] A.B.Flatau, M.J.Dapino, F.T.Calkins, J.Int. Mat. Syst. Struct., Vol11.,2000, pp 923-929.
[52] H.Eda, L. Zhou, H. Nakano , R. Kondo, J. Shimizu, JN CIRP Ann. Manufacturing Technology, 2001, Vol.50; n.1; pp225-228.
[53] www.activetechno.com
[54] Q.Shuye, Q.Guiming, Acoustic letters, vol.23, n.1,1999.
[55] E. Monaco, F.Franco, L.Lecce, J. intell. mater. syst. Struct, 2000, Vol 11; n.7, pp 567-578.
[56] www.nasatech.com/Briefs//Dec99/MSC22890.html
[57] P.P.Friedmann, G.P.Carman, T.A.Millot, Mathematical and computer Modelling 33, 2001, pp1203-1217.
[58] K. Kuhnen, H. Janocha, Proc. of the IASTED Int.Conf.on Modelling, Identification and Control, Innsbruck, Austria, 2001, pp.375 – 380.
[59] www.caltech.edu/ott/feature_show.tcl?feature_id=18
[60] www.ngst.nasa.gov/Hardware/text/actuator.html
[61] www.energeninc.com
[62] C.H.Joshi, Proc Actuator 2000, pp120- 125.
[63] C.Joshi, A.Pappo, D.Upham, J.Preble, Proc. Particle Accelerator Conf, Chicago, 2001,3p.