BOLETIN DE LA SOCIEDAD ESPAÑOLA DE
Cerámica y Vidrio
ARTICULO

Production and characterization of rainbow piezoelectric actuators. Advantages from other traditional devices.

P. DURAN-MARTIN, A. VAZQUEZ[1], D. DAMJANOVIC N. SETTER.
Ceramics Laboratory. Materials Dept. Swiss Federal Institute of Technology. 1015-Lausanne. Switzerland.
[1]Dto. de Ingeniería Eléctrica. E.T.S.I.I.B. Universidad Politécnica de Cataluña. Av. Diagonal, 647. Barcelona 08028. Spain.

A new actuator called RAINBOW is presently intensively studied because of the extremely large displacement that it is able to generate. The aim of the present work is to fully characterize the performances of this kind of actuator in terms of voltage, frequency and temperature dependence of both maximum displacement and force generated. These results will be compared with the performances shown in the literature for some other traditional piezoelectric actuators. The present work explores two types of compositions for RAINBOWS fabrication: electrostrictive based on PLZT and ferroelectric PZT-based. Results show that this actuator can be engineered upon their thickness to optimize the performances. Maximum displacement and generated force increase in a rate of 7446 10^{-12} m/V and 2.9 N/kV, respectively, per mm of increase of disk diameter. The change with frequency of these properties along 0.01Hz to 500Hz range keeps within 20% for maximum displacement and 10% for blocking force. Thermal stability of the performaces shows an unexpected 50% of variation through the studied range from –40°C up to 50°C.

Key Words: Piezoactuators, RAINBOWS, Production and Characterization.

Producción y caracterización de actuadores piezoeléctricos tipo RAINBOW. Ventajas respecto de otros dispositivos tradicionales

Un nuevo actuador piezoeléctrico denominado RAINBOW está siendo intensamente estudiado a causa de los extremadamente altos desplazamientos que es capaz de realizar. La motivacion del presente trabajo se centra en la caracterización exhaustiva de este tipo de actuadores, en términos de la dependencia del máximo desplazamiento y de la fuerza generados en función de la amplitud y la frecuencia del voltaje aplicado, asi como de la temperatura. Dicha caracterización será objeto en algunos casos de comparación con los resultados presentes en la literatura respecto de otros actuadores piezoeléctricos tradicionales. El trabajo explora dos tipos de composiciones utilizadas en la fabricación de RAINBOWS: una electrostrictiva basada en PLZT y otra ferroeléctrica basada en PZT. Los resultados obtenidos demuestran que este tipo de actuadores pueden ser diseñados en función de su espesor para optimizar sus propiedades. En término de máximo desplazamiento generado y máxima fuerza generada aumentan a razón de 7446 10^{-12} m/V y 2.9 N/kV, respectivamente, por cada mm de incremento del diametro del actuador. La variación con la frecuencia de dichas propiedades a lo largo del rango comprendido entre 0.01Hz y 500Hz se mantiene inferior al 20% en el caso de máximos desplazamientos, y del 10% para las fuerzas de bloqueo. La estabilidad de las propiedades en función de la temperatura presentan una inesperada variación del 50% en el rango térmico estudiado (desde -40ªC hasta 50ªC).

Palabras Clave: Piezoactuadores, RAINBOWS, Producción y Caracterización.

1.INTRODUCTION

It has been shown in the last several years that piezoelectric actuators may be successfully used in active vibration and noise control systems (1-3), due to their advantages over other type of actuators: fast response, high force generation, a small size and weight, and a relatively low cost. However, they show important disadvantages: the high driving voltage, non-linear and hysteretic response. These disadvantages can be minimized by choosing the right structure, composition and preparation conditions of the ceramics. For example, non-linearity can be controlled by tuning the composition of the material (i.e. "hard" and "soft" PZT ceramics). The high driving voltage can be reduced by using multilayer actuators.

There are several types of ceramic actuators (4): Linear-type multilayer actuators consist of a stack of thin piezoelectric layers, which generate large forces but moderate displacements (0.25µm under 250V/mm driving electric field). Bimorphs and other flextensional thin ceramic disks glued to elastic metallic endcaps or substrates (Moonies and Cymbals (5)) display large displacements (0.3-2µm under 250V/mm) but generate relatively low forces. Belonging to this group, a new actuator called RAINBOW (Reduced And INternally Biased Oxide Wafer) (6) is at present intensively studied because of the extremely large displacements (70-80µm for the same driving field) that it is able to generate (7).

RAINBOW devices are fabricated from high-lead-containing piezoelectric or electrostrictive ceramics by chemically reducing one side of the ceramic to form a domed, pre-stressed, monolithic metal/oxide structure. In general, the reduction of PZT bulk ceramic side in contact with a solid carbon block occurs as a result of oxidation at high temperature of the carbon. As a consequence of this heat treatment, an electrically conductive but electromechanically inert layer with black color is formed. Because of the thermal expansion coefficient mismatch between the reduced layer and the PZT layer, large internal stresses are generated in the ceramic part, resulting in bending deformation of the bulk ceramic after cooling to room temperature. These monolithic stress-biased structures exhibit amplified axial displacements. In addition, virgin RAINBOWs have been observed to be partially prepoled by internal stress (7). The fact of being a monolithic actuators make them promising systems because they would not present problems related to the ceramic-metal (like moonies and cymbals) or ceramic-electrode-ceramic (like multilayers) interfaces.

2. EXPERIMENTAL PROCEDURE

In present work, we will report results obtained on commercial RAINBOW actuators and home-made LC-RAINBOWS, as these are no longer commercially produced. In case of commercial one tested, the composition chosen was the electrostrictive PLZT that corresponds to the MPB 9/65/35 (Reference RBW3900), produced by Research Corporation Technologies. Different dimensions have been used: RWB3900B (ϕ=50mm and t=0.76mm) and RWB3900S (ϕ=31.6mm and t=0.76mm). LC actuators were prepared from ceramic disks of Pz29 composition of dimensions: ϕ=50mm and t=1.14mm.

2.1.- Sample Preparation

Classical procedure for preparing RAINBOW wafer from bulk ceramic samples was developed by Haertling at Clemson University (6,7). In that method the ceramic wafers are placed on a piece of high-density graphite block that had a polished surface. This assembly then is heated to 975°-1085° C with a heating rate of 300°C/h in a normal air atmosphere. The bulk ceramic is reduced at this temperature for a period of time (10-240min) and then cooled to room temperature rapidly. The different reduction temperatures and times are chosen in function of the different thickness ratios of the bulk ceramics used and the different material properties, such as grain size, density, and chemical reactivity of the different thickness ratios of the bulk ceramics used (8).

Commercial soft PZT ceramics from Ferroperm were used for fabricating the RAINBOW actuators. A circular commercial block of PZT-29 of 50 mm of diameter and 3.8mm of thickness was the base material, which was cut in thin plates of around 1mm thick. After thermal treatment at 975°C during one hour, the RAINBOW samples were sanded lightly on the reduced side to remove graphite rests. The RAINBOW actuators were then electroded by sputtering gold onto the mayor surfaces and poled under a dc field of 1.5 - 2.KV/mm in silicone oil at 150°C for 1 hour. After the poling process the RAINBOW actuators became flatter, indicating that internal thermal stresses were partially released.

2.2.- Experimental Settings

The characterization of the piezo-actuators was based on the inverse piezoelectric effect by means of measuring the free displacement and blocking force behaviour. Piezoelectric RAINBOWs wafers were driven by a Krohn-Hite 7602M amplifier ramping a maximum voltage up to +200V. The free displacement generated was collected by an MTI optical fiber probe, (MTI 2000 Fotonic Sensor, MTI Instruments, Latham, NY, USA). Force measurements under blocking force conditions (apparent zero displacement capability of the actuator by constraining it with an applied force) as well as static pre-load applied were measured with a very stiff force sensor developed in our laboratory using a piezoelectric material with a very low hysteresis ($SrBi_4Ti_4O_{15}$). The piezoelectrically induced charges from the force sensor were converted into voltage via a Kystler 5011 charge amplifier operating in virtual ground mode. The force displacement results were collected using standard ADC techniques and the experiments controlled and monitored using LabView software. For temperature dependent measurements, it was necessary to develop a new type of sample-holder that allows measurements in a wide temperature range (from –50°C up to 100°C). The temperature controller is a modified sophisticated cryogenic system Delta Chamber Temperature System that is able to heat up to 220°C and cool down to N_2-liquid temperature.

3. RESULTS AND DISCUSSION

3.1.- Displacement and Force Generation Performances:

In Figure 1, the maximum displacements achieved by three different RAINBOWs as a function of the applied voltage at 2Hz are compared. As shown, with these actuators it is possible to obtain large displacements for relatively low driving field, with the ratio of 0.34mm per V/mm. In multilayer actuators it would be necessary to apply an electric field of 370V/mm to obtain the same displacements (9). Assuming in the first approximation the linearity of the piezoelectric effect, we can fit the curves by a linear regression which slope corresponds to the effective piezoelectric coefficient, d_{33}^{eff}. The resulting values are 293000, 237000 and 156000 pC/N, respectively. Here, we must remark that the monolithic dome shape increase the effective d_{33} of the ceramic (100-500pC/N) by 3 orders of

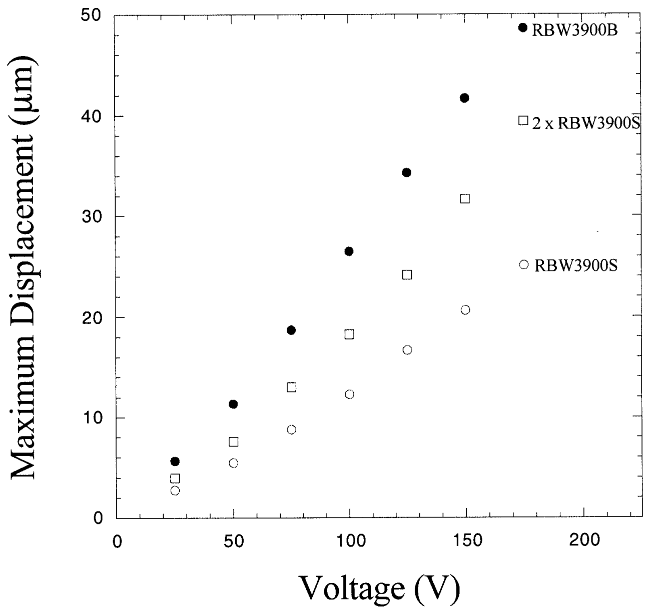

Figure 1.- Comparative behaviour for the two Commercial RAINBOWS under study, ● single RBW3900B(ϕ=50mm), □-two stacked RBW3900S and ○ single RBW3900S(ϕ=31.6mm), measured at 1Hz. The effective piezoelectric coefficients d33eff are 293000, 237000 and 156000 pC/N, respectively.

magnitude. This increment is achieved by combining both d_{33}(>0) and d_{31}(<0) in a final axial motion that is not available in a planar structure of the ceramic disk. All of them are commercial RAINBOWs of the same composition and have the same thickness, t=0.76mm, so differences can be explained due to their differences in diameters. Let us fit these d_{33}^{eff} as a function of their corresponding diameters by a linear expression. The sloop, 7446 10^{-12} m/V per mm of disk diameter, gives us an idea about the dimension that our RAINBOW should have to achieve the requested maximum displacement when making custom-designed devices. Furthermore, in most of potential applications, available space is a restrictive parameter that determines the device dimensions. Thus, it is important to test the possibility of reducing dimensions without decreasing the performances. So, two configurations of the same composition but different dimensions were tested: a big single disk (Reference RBW3900B) and two smaller disks (Reference RBW3900S), stacked and electrically connected in parallel. The results in Figure 1 show as well that it is possible to reach higher displacements with 3 stacked small element than with only a big one.

About force generation issue, in Figure 2, the blocking forces generated at different driving voltages levels are presented for two commercial RAINBOWs, RBW3900B and S. The corresponding generated force factors are 70 and 17 N/kV, respectively. The differences must be again related to the different diameters. As said above for actuator tailoring, in terms of force generation we should design our actuator, of this same composition, which could give about 2.9 N/kV more per each mm increase in diameter. Considering these results, RAINBOWS must be considered as promising candidates not only for large displacement applications but also as relatively large force providers.

3.2.- Frequency stability of the performance

For active control applications (1), the actuator must keep its properties over a wide frequency range, which is specific for each application. Figure 3 shows the maximum displacement dependence with frequency for all studied samples. All of them are driven with 175V/mm to make results comparable. Frequency stability of this parameter stays within 20% variation in the range between 1 and 500Hz. At higher frequencies the maximum displacement drops down very fast until almost reaching zero above 1kHz. As it can be seen, the frequency stability is significantly worse than in multilayer actuator (9). The comparative results show the same comparative trend already shown in Figure 1 for 2Hz, but now representing results on home made RBW3. Concerning RBW3 results it is clear that generated maximum displacement is lower than in other tested samples. This is expected due to a better performance in terms of displacement capabilities of PLZT in the MPB compositions via electrostrictive effect (1) than Pz29 (d_{33}=575pC/N, d_{31}=-240pC/N) (10) via piezoelectric effect.

The measured blocking forces on RAINBOW actuators as a function of the frequency for the tree different types of RAINBOWs, all driven with 50V/mm, is shown in Figure 4. In the studied frequency range, the force generated is more stable (difference less than 10%) than displacement, but again with the upper frequency limit of 500Hz. Comparing samples with same dimensions (RWB3900B and RBW3), the electrostrictive one produces higher forces than the piezoelectric. Nevertheless, the frequency stability is much better in piezoelectric one: relative variation within the studied frequency range is 10% for electrostrictive RAINBOW and only 1% for piezoelectric one.

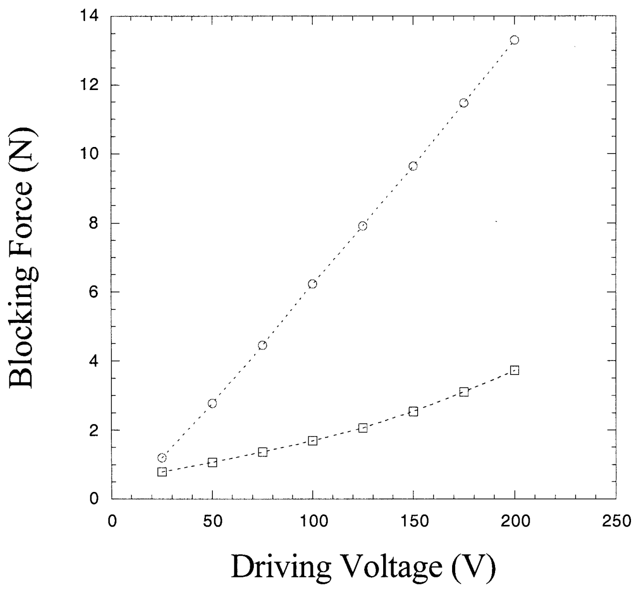

Figure 2: Comparative generated blocking force depending on the diameter of the actuator ○ - RBW3900B (ϕ=50mm), □- RBW3900S (ϕ=31.6mm). The corresponding Force Generation factors are 70 and 17 N/kV, respectively. Measurements were made at 1Hz for the same electric field applied to the samples.

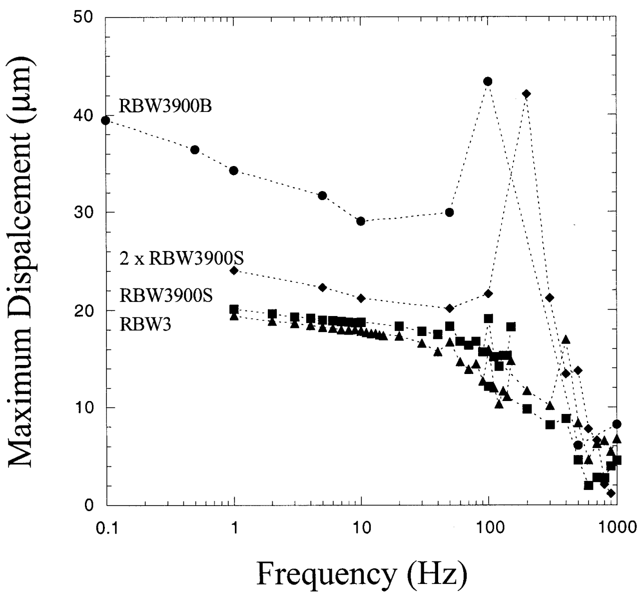

Figure 3.- Frequency stability, measured from 0.1Hz up 1kHz, of the maximum displacement exhibited by: ● - single RBW3900B actuator(ϕ=50mm), ◆ - double-stacked RBW3900S(ϕ=31.6mm), ■ - single RBW3900S(ϕ=31.6mm) and ▲ - single RBW3 (ϕ=50mm). All of them are driven with the same electric field level, 175V/mm.

3.3.- Temperature dependence of the properties

Another important topic in piezoelectric actuator applications is the temperature dependence of their properties. Several authors have studied this question on diverse systems (11,12), but never below –5°C. For certain applications, like noise reduction in aircraft nacelles by active damping, this is an important factor due to the real work conditions at which the actuators would be exposed. Thus, we have studied the variation of the performances with this parameter in a wide temperature range between –40°C and +50°C. Figures 5 present the variation of the maximum achieved displacement at different frequencies for RBW3900Sand Figure 6 for RBW3. In both cases, the variation is very important. For commercial RBW3900S, a reduction of 50% from higher to lower temperatures at frequencies lower than 500Hz is observed. At higher frequencies, in spite of the maximum displacement is much lower, there is almost no variation with the temperature. Figure 6 shows results of the same study-type for LC RAINBOW, RBW3. Bigger differences than in commercial RAINBOW has been found from higher to lower temperature. This is an unexpected result, as the temperature dependence of d_{33} and d_{31} do not change so much in the study temperature range (10). The highly temperature dependent internal stress could explain this behaviour. A more detailed study in this direction will be performed in the near future.

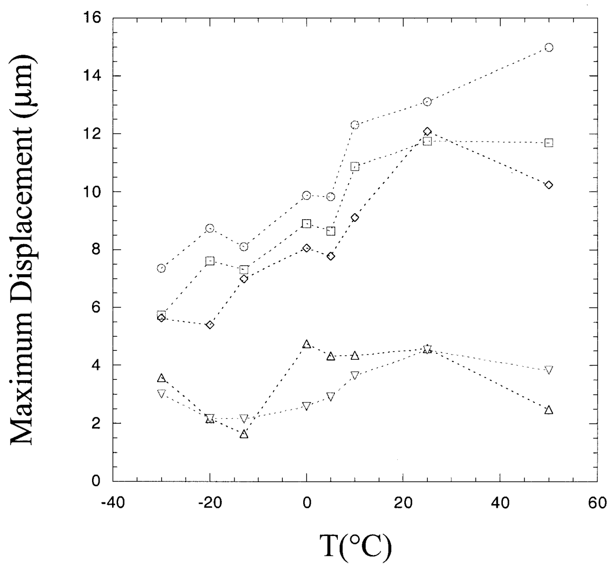

Figure 5: Commercial RAINBOW Actuator RBW3900S. Maximum displacement as function of temperature at different frequencies (○ - 1Hz, □- 10Hz, ◊ - 100Hz, Δ - 500Hz, ∇– 1kHz).

4.CONCLUSIONS

Authors have reported a fully characterization of a promising new type of piezoelectric actuators, called RAINBOW. Two composition have been tested and compared to come to the possibility for the performances engineering. The general features of commercial RBW3900 RAINBOWs are:

Large displacements with low driving voltage (effective piezoelectric coefficient, d_{33}^{eff}, varies between 156000 and 293000 pC/N depending of the diameter for samples of the same thickness (t=0.76mm). For custom designed applications, we have shown that we could reach 7446 10^{-12} m/V more per mm of increase of disk diameter. Maximum displacement has been found to be stable (variation less than 20%) within applied voltage frequencies from 0.01Hz to 500Hz.

In the same way, the generated blocking forces, depending of same diameter, varies from 70 to 17 N/kV. In terms of force generation we should design our actuator taking into account that we could obtain 2.9 N/kV more per each mm increase in diameter. About the force stability when changing the fre-

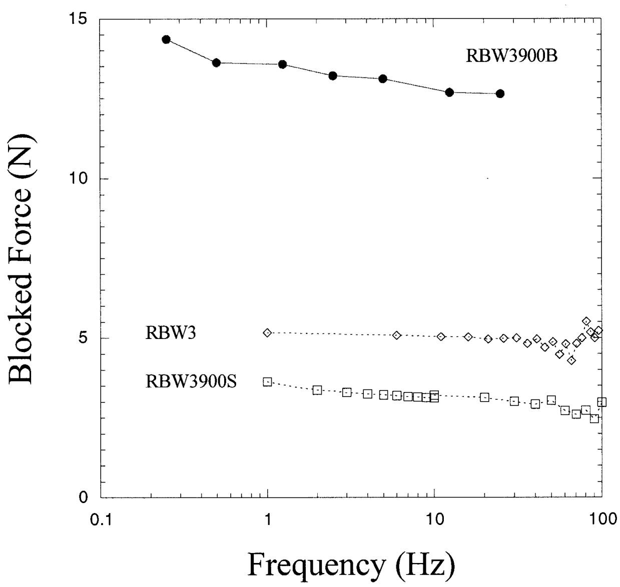

Figure 4: Blocking force measured as function of frequency with driving field of 50V/mm, for a commercial RAINBOW RBW3900B and S and LC-RAINBOW RBW3.

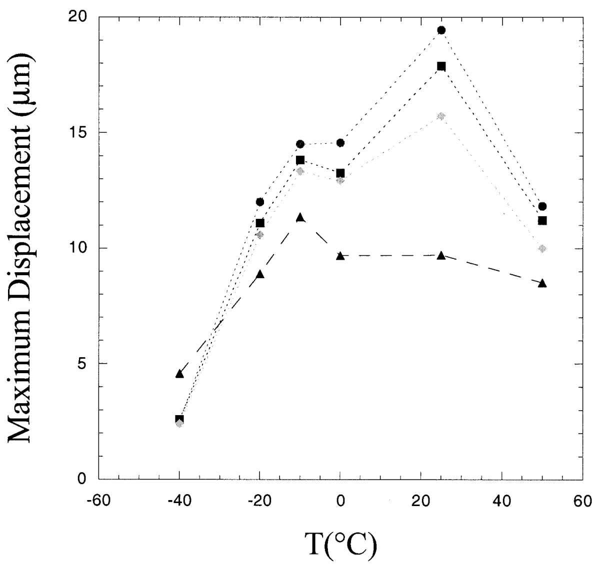

Figure 6: Maximum displacement as function of temperature at different frequencies (●- 1Hz, ■ - 10Hz, ◆ - 100Hz, ▲ - 1kHz) for LC-EPFL RAINBOW Actuator RBW3

quency of the driving field, we have shown again a limitation to 500Hz but with lower variation rate (10%).

Preliminary results on home-made ferroelectric Pz29 RAINBOWs showed that both generated maximum displacement and force are lower than in other tested samples. However, the frequency stability is better.

Concerning the study of the variation of the performances with the temperature, an unexpected large dependence has been found, that can be reduced if working at frequencies higher than 100Hz. This variation is less dramatic in the ferroelectric-based actuator. Nevertheless, this variation can not be explained just by change of the electrostrictive or piezoelectric coefficients with temperature, and it will be the subject for further study.

ACKNOLEDGEMENTS

The present work has been supported by OFES (Swiss Federal Office for Science and Education) on the framework of the European RANNTAC project (BE97-4121 / BRPR – CT97 – 0497). The authors also wish to thanks Ferroperm Ltd. for kindly providing the ceramic disks to make the LC-RAINBOWS.

REFERENCES

1. Proceedings of the 5th International conference on new actuators, Bremen, Germany, June 1996.
2. Proceedings of SPIE: ”Smart structures and materials 1994” February 1994, Orlando, FL, USA.
3. MRS Proceedings: “Materials for smart systems II”, vol. 459, 1996.
4. J.W. Waanders: “ Piezoelectric ceramics – properties and applications”, Philips, Eindhoven, 1991.
5. A. Dogan , “Flextensional moonie and cymbal actuator”, Ph. D. Thesis, The Pennsylvania State University, University Park, PA. (1994).
6. G.H. Haertling: “Chemically reduced PLZT ceramics for ultra-high displacement actuators”, *Ferroelectrics*, **154**, 101-106, (1994).
7. G.H.Haertling, “Rainbow ceramics – a new type of ultra-high-displacement actuator,” *Am. Cer. Soc. Bull.*, **73**, 93-96, (1994).
8. Q.M.Wang and L.E.Cross, “Analysis of High-Temperature Reduction Processing of RAINBOW Actuator”, *Mater. Chem. Phys*., (1999), in press.
9. P. Durán-Martín, D. Damjanovich y N. Setter, “Piezoelectric actuators for active noise control applications: a prospective study”. Proceedings of the Conferencia Hispano-Francesa de Aplicaciones Piezoeléctricas, Vol. **1** 107-110. (1999)
10. Ferroperm Piezoceramics Catalogue.
11. J.F. Fernandez, A. Dogan, J.T. Fielding, K. Uchino, R.E. Newnham, “Tailoring the performance of ceramic-metal piezocomposite actuators, “cymbals”.”, Sensors and actuators, A65, 228-237, (1998).
12. Y. Nakajima, T. Hayashi, I. Hayashi, I. Uchino, “Electrostrictive properties of a PMN stacked actuator”, Jap. J. Appl. Phys, 24 (2), 235-238, (1985).