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A comparative analysis of Piezoelectric and Magnetostrictive actuators in Smart Structures

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This paper introduces a comparative analysis of Piezoelectric (PZ) and Magnetostrictive (MS) actuators as components in smart structures. There is an increasing interest in functional structures which are able to adapt to external or internal perturbations, i.e. changes in loading conditions or ageing. Actuator technologies must perform concomitantly as sensors and actuators to be applicable in smart structures. In this paper we will comparatively analyze the possibility of using PZ and MS actuators in smart structures and in so doing their capability to act concomitantly as sensors and of modifying their material characteristics. We will also focus on the analysis of how them can be integrated in structures and on the analysis of the most appropriate structures for each actuator. The operational performance of PZ (Stacks) and MS actuators will be compared and eventually some conclusions will be drawn.

Keywords: Piezoelectric actuators, Magnetostrictive actuators, smart structures.

Un estudio comparativo de actuadores Piezoeléctricos y Magnetoestrictivos para estructuras inteligentes

Este artículo presenta un estudio comparativo de actuadores Piezoeléctricos (PZ) y Magnetoestrictivos (MS) como elementos integrantes de estructuras inteligentes. Existe un interés creciente en estructuras activas que puedan adaptarse a perturbaciones tanto internas como externas, por ejemplo, ante cambios en carga estructural o ante su envejecimiento. Para que un actuador forme parte de una estructura inteligente, debe poder actuar también como sensor. Este artículo presenta un estudio comparativo del uso de actuadores PZ y MS en estructuras inteligentes y, como consecuencia, de su habilidad para actuar y medir simultáneamente así cómo para modificar sus características mecánicas. Nos centraremos también en el análisis de como pueden integrase en estructuras y cuales son las más indicadas para cada actuador. Se compararán las características operacionales de los actuadors PZ multicapa y los MS.

Palabras clave: Actuadores Piezoeléctricos, Actuadores Magnetoestrictivos, estructuras inteligentes

1. INTRODUCTION

There is a vast set of transducing materials on which emerging actuator technologies (EATs) are being based. Emerging actuators are characterized by exploiting new (or at least newly developed) transducing phenomena. This is the case of piezoelectricity, electrostriction, magnetostriction, electro- and magneto-rheology as well as thermal or magnetically triggered Shape Memory transformations, see (1) for a comprehensive discussion.

Most of these transducing phenomena are reversible in that they allow the conversion both from mechanical to electrical energy and from electrical to mechanical energy. As such, materials exhibiting such transducing phenomena can be exploited both as sensors and as actuators. In other instances, they can perform concomitantly in both directions.

Amongst the different EATs, the best established technologies are Piezoelectric (PZ) actuators and Magnetostrictive (MS) actuators. Both technologies allow two directional transduction, and various studies have addressed the concomitant implementation of MS and PZ technologies as sensors and actuators, (2).

Electroceramics have been proposed as the basis for developing acceleration sensors, (3), in the development of solid state gyroscopes or for pressure sensors in the field of biomechanics, (4). In all these instances, the direct piezoelectric effect is exploited and the deformation of the electroceramic is somehow related to the target physical variable to be sensed.

In a similar fashion, the Villari effect in magnetostrictive actuators, that is the reverse magnetostrictive effect, has been used to develop force sensors, see (5) for more details. In addition, a particular instance of the reverse magnetostrictive effect, the so-called Matteuci effect has been exploited in the development of torque sensors.

However, during the last decades, the application of both PZ and MS materials to emerging actuators is gaining momentum. On the one hand, PZ materials have been proposed as the basis of both resonant and non-resonant actuators. Most likely, the Travelling Wave Ultrasonic Motor, (6), can be regarded as the paradigmatic resonant PZ actuator. Amongst the various different non-resonant drives, inchworm actuators, multimorph benders and PZ stack actuators are the most relevant implementations, (1). On the other hand, MS materials have led to non-resonant actuators, and have been chiefly applied in active control of vibrations, (7).

Both MS and PZ actuators have been successfully proposed as constitutive components of smart structures. The fundamental feature in this approach is the concomitant sensing and actuation. In this context, simultaneous sensing and actuation using piezoelectric materials has been extensively studied, (8). In this instance, the intrinsic requirements for setting up the magnetic and the electrical field in MS and PZ actuators respectively lead to significant differences in the type of smart structures they can be integrated in.

The present paper has the main objective of establishing a comparison between MS and PZ materials as the basis for emerging actuators in smart structures. In so doing, a first section will briefly set the basis of both piezoelectricity and magnetostriction. Section 3 will be devoted to study the active modulation of the stiffness both in MS and PZ materials as a property commonly exploited in the integration of active materials in smart structures. Section 4 will analyze the properties of MS and PZ materials with regard to concomitant sensing and actuation. This will lead to a discussion of various different approaches in integrating MS and PZ actuators in active structures in section 5. Eventually, their operational characteristics will be discussed in section 6 and the paper will end with a section devoted to highlighting some conclusions.

2. PIEZOELECTRICITY AND MAGNETOSTRICTION

2.1. Piezoelectricity and electrostriction

The piezoelectric effect can be described as modification of the polarization of a dielectric arising from the mechanical energy of the stress. Materials exhibiting such an effect are said to be piezoelectric materials. The piezoelectric effect is reversible in the sense that when an electric field is applied, a mechanical strain will arise. This is the converse piezoelectric effect.

The quasi-linear, low hysteresis piezoelectric effect can be mathematically described by what are known as constitutive equations. The reader is referred to (1) for a detailed derivation of these equations. Here we will only introduce them as they are relevant to the next sections:

$$\begin{aligned} S_{ij} &= c^{E}_{ijkl} T_{kl} + d_{mij} E_m \\ D_k &= d_{kij} T_{ij} + \varepsilon^{T}_{km} E_m \end{aligned} \qquad [1]$$

The piezoelectric effect as described by equation [1] is present in poled piezoelectric ceramics. However, some materials exhibit a quadratic dependence of the strain on the polarization known as an Electrostrictive effect. The constitutive equation describing the quadratic relationship between strain and polarization is:

$$S_{ij} = Q_{ijkl} P_k P_l \qquad [2]$$

Equation [2] can now be expanded in Taylor series around a DC bias electric field, E_0. For small variations of the electric field around the DC bias, it follows:

$$\Delta S_3 = 2M_3 E_3 \Delta E \quad \text{and} \quad \Delta S_1 = 2M_{11} E_3 \Delta E \qquad [3]$$

The functional relationship between strain and applied electric field is quadratic. Equation [3] indicates that the electrostrictive behavior of small AC electric fields around a DC bias electric field may be regarded as the same as the piezoelectric behavior with a remanent polarization equivalent to the bias electric field, i.e. $P_0=E_0/(\varepsilon-\varepsilon_0)$.

2.2 Piezomagnetism and Magnetostriction

Magnetostriction is the phenomenon whereby magnetic domains in a ferromagnetic material are reoriented and aligned in response to an applied external magnetic field. As a consequence of the magneto-elastic coupling in these materials, there is a macroscopic change in length in the direction of imanation.

Magnetostriction can be described as being the analog of piezoelectricity in the magnetic domain. In fact, magnetostriction is a process of transduction between elastic mechanical energy (strain) and magnetic energy. However, there are evident significant differences between the two phenomena. The equations governing the magnetostrictive effect, magnetostriction constitutive equations, contain both linear and quadratic terms in the magnetic field strength. In tensor notation this is:

$$\begin{aligned} S_{ij} &= c^{H}_{ijkl} T_{kl} + d_{mij} H_m + m_{ijkl} H_k H_l \\ B_k &= d_{kij} T_{ij} + \mu^{T}_{km} H_m \end{aligned} \qquad [4]$$

where S_{ij} is the mechanical strain, T_{kl} is the mechanical stress, c^{H}_{ijkl} is the mechanical compliance under zero magnetic field ($H=0$), H_m is the magnetic field strength, μ^{T}_{km} is the magnetic permeability under constant mechanical stress, d_{mij} are the piezomagnetic displacement coefficients coupling linearly magnetic and mechanical variables, m_{ijkl} is the magnetostrictive coefficient coupling quadratically magnetic and mechanical variables, and B_k is the magnetic flux density.

The equation coupling strain to magnetic filed strength can be obtained from thermodynamic potential functions, and according to equation [4] it has the following form:

$$S = c_1 H + c_2 H^2 \qquad [5]$$

In equation [5], c_1 defines the piezomagnetic effect. In order for a material to exhibit piezomagnetism, the crystal structure must me anisotropic. However, all ferromagnetic materials exhibit magnetostriction, i.e. $c_2 \neq 0$. Therefore, the phenomenological description of piezomagnetism and magnetostriction is equivalent to the phenomenological description of piezoelectricity and electrostriction. The typical strain versus applied magnetic field curve for magnetostrictive materials is depicted in figure 1. It shows the quadratic dependance of strain on magnetic field strength.

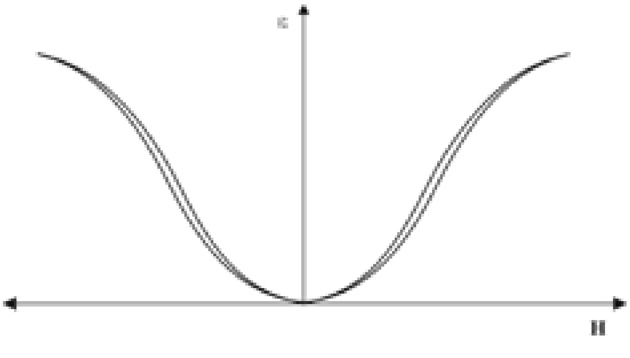

Fig. 1- Quadratic functional relation between strain and magnetic field intensity in magnetostrictive materials.

Carrying on with the analogy between electrical and magnetic domains, for a pure magnetostrictive material (exhibiting crystal symmetry and thus no piezomagnetism), the magneto-mechanical coupling will be described by:

$$S_{ij} = m_{ijkl} H_k H_l \qquad [6]$$

which, for the direction of imanation, reduces to:

$$\Delta S = 2 m H_0 \Delta H \qquad [7]$$

Notice that equation [6] represents a quadratic dependence of strain on magnetic field strength. Once the magnetostrictive coefficients are defined for a particular material, equation [6] indicates that the magnetostrictive material will contract or expand when either positive or negative magnetic fields are applied.

Consequently, equation [7] describes a way of converting unidirectional displacements in a magnetostrictive domain into two-directional displacements by means of a bias magnetic field strength, H_0, a technique widely adopted in the design of magnetostrictive actuators.

The process is schematically depicted in figure 2. Due to the quadratic relationship between strain and magnetic field, the driving frequency presents non-linearity and the rate of the strain is twice the rate of the applied magnetic field (black lines in figure 2). When a bias DC magnetic field, H_0, is applied, the strain becomes quasi-linear around the bias magnetic field and the non-linearity in the frequency is eliminated (grey, dashed lines in figure 2).

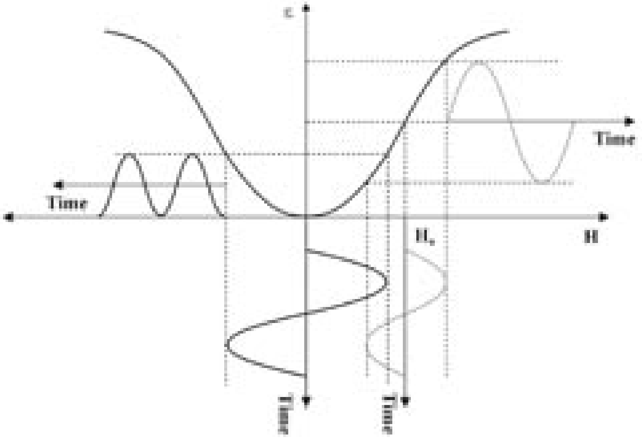

Fig. 2- Linearization and two-directional operation with magnetostrictive materials.

3. CONTROL OF STIFFNESS IN PZ AND MS ACTUATORS

In the application of emerging actuators in smart structures, a common approach is to use the controllable change of stiffness of embedded actuators as a means of stiffening the structure and change its resonance characteristics. Both PZ and MS materials can result in programmable stiffness systems. This section describes the ability of PZ and MS actuators in controlling the stiffness.

3.1 Programmable stiffness in PZ materials

In normal, passive materials the mechanical stiffness, K, is defined as the ratio of applied force to deformation:

$$K = \frac{dF}{dl} \qquad [8]$$

In the case of PZ actuators, because of the active nature of the material, there is the possibility of programmable stiffness. The force-deformation ratio for piezoelectric actuators is highly dependent on the electrical boundary conditions applied to the actuator electrodes.

In this context, there are three possible situations depending on the electrical boundary conditions:

1. Short circuited or voltage controlled actuators. In this situation, a ``low” stiffness is achieved. Under deformation, the charge generated by the piezoelectric effect is free to flow and equilibrate.
2. Open circuit or charge/current controlled actuators. In this situation, the charge is blocked at the electrodes of the actuator when a force is applied. Blocking of the charge (either because the circuit is open or because the control fixes its value) results in an electric field that will oppose the force. The outcome of this situation is greater stiffness (twice as much as in case 1).
3. Impedance controlled actuators. In this case the control loop applied to the piezoelectric actuator sets the reference mechanical impedance for the piezoelectric actuator, i.e. the reference charge/current is increased as a result of changes in actuator’s strain. At the upper limit, when the reference impedance is very high, the control strategy is equivalent to a position control of the piezoelectric motor, and the apparent stiffness of the actuator is virtually infinite.

3.2 The ΔY-effect in MS materials

The Young’s modulus, Y, in structural materials is a parameter used to define the material’s stiffness. It is calculated as the ratio of change in stress to the corresponding change in strain in a given material.

In transducing materials, and in particular in magnetostrictive materials, there is a coupling between the stiffness (Young’s modulus) and the imanation state of the material. As a consequence, the Young’s modulus for magnetostrictive materials is not constant but rather is a function of the imanation state.

A change in the Young’s modulus of a magnetostrictive material is commonly to be expected. Giant magnetostrictive materials undergo strains of the order of 1500-2000 ppm in response to changes in the imanation state. The strains that these materials can exhibit when a pure mechanical load is applied are much lower that those produced by magnetostriction. Consequently, we may expect the effective elastic modulus, as the ratio of stress to strain, to be considerably affected by imanation.

The so-called ΔY-effect is defined as the relative change in Young’s modulus upon application of an external magnetic field, H, with respect to Young’s modulus at zero magnetic field, H=0, (10):

$$\Delta Y = \frac{Y_H - Y_0}{Y_0} \qquad [9]$$

It is worth noting that Young's modulus undergoes a change even where the strength of the magnetic field is higher than the saturation imanation. This indicates that the ΔY-effect cannot be convincingly explained only on the basis of the reorientation of magnetic domains due to external fields.

The maximum reported magnitude of the ΔY-effect (11) is of the order of 1, that is Young's modulus is doubled as a consequence of the change in the imanation state of the magnetostrictive material. Moreover, since the resonance frequency of a magnetostrictive rod is:

$$f_r \propto \sqrt{Y} \qquad [10]$$

it follows that the change in Young's modulus is related to the change in the resonant frequency squared. It can be seen that this property of magnetostrictive materials can be used in tunable vibration absorbers based on this technology.

Table 1 shows the properties of three magnetostrictive and electrostrictive materials. The table shows mechanical, thermal and electrical as well as electrostrictive and magnetostrictive properties.

A piezoelectric actuator establishes a flow of energy from the electrical to the mechanical domain according to the constitutive equations of the piezoelectric effect. When no external load is applied to a piezoelectric stack actuator, the displacement (strain) will be a non-linear, hysteretic function, $S_1(V)$, of the voltage applied at the input port. Wherever an external force is applied to the actuator, it will act as a disturbance to the output displacement. The complete relationship between strain, voltage and load will take the form of equation [11] and is commonly called an operator-based actuator model of the piezoelectric stack transducer (12).

$$S(t) = S_1(V) + kf(t) \qquad [11]$$

where *k* is the piezoelectric stack stiffness.

Similarly, the charge developed in the piezoelectric stack, Q(t), will be a direct function of the load applied to the transducer, f(t). This time, the voltage-induced charge during operation will act as a disturbance to the operator-based sensor model described by equation [12].

$$Q(t) = df(t) + Q_1(V) \qquad [12]$$

where d is the piezoelectric coefficient and $Q_1(V)$ is a non-linear hysteretic function of the voltage.

Again, even though the PZ stack cannot be used to impose a displacement (strain) and to concomitantly sense it, the sensor model of equation [12] can be used to estimate the load on the actuator: i.e. the piezoelectric stack is being used concomitantly to impose a displacement and to sense the load. The estimated load can then be used to compensate for its disturbing effect on the displacement of equation [11] (12).

TABLA I. MAGNETOSTRICTIVE AND ELECTROSTRICTIVE PROPERTIES OF SOME MATERIALS

Property	**Units**	**Terfenol-D**	**Hiperco**	**PZT-2**
Mechanical Properties				
Density	Kgm^{-3}	9.25•10^{3}	8.1•10^{3}	7.5•10^{3}
Young's modulus, H=0	GPa	26.5	206	110
Young's modulus, B=0	Gpa	55.0	-	60
Speed of sound	ms^{-1}	1690	4720	3100
Electrical properties				
Resistivity	10^{-6} Ω cm	60.0	0.23	0.01
Magnetoestrictive and Electrostrictive Properties				
Permeability	-	9.3	75	1300
Curie Temperature	C	387	1115	300
Maximum strain	ppm	1500-2000	40	400
Coupling factor	-	0.72	0.17	0.68
d_{33}	mA^{-1}, mV^{-1}	1.7•10^{-9}	-	300•10^{-12}
Energy density	Jcm^{-3}	14-25•10^{-3}	-	10^{3}

4. CONCOMITANT SENSING AND ACTUATION WITH PZ AND MS ACTUATORS

When dealing with the application of actuators in smart structures, the ability to perform both as a sensor and as an actuator is of paramount importance. In this section, we will introduce a discussion on how Piezoelectric and Magnetostrictive actuators can be used concomitantly as sensors and actuators.

Piezoelectric actuators are suitable to adopt various different configurations, basically stacks and cantilevers for direct actuation. On the other hand, MS actuators adopt always the configuration in which a rod of magnetostrictive material is subject to the magnetic field. Therefore, only Piezoelectric stacks can be compared to Magnetostrictive actuators, since stroke and stiffness are of the same order.

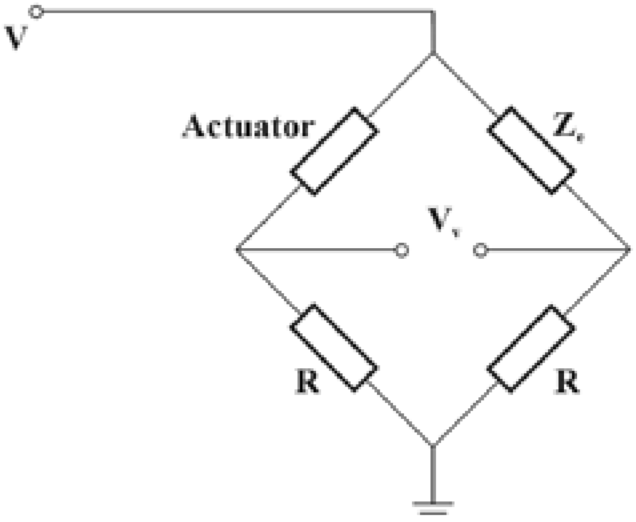

Fig. 3- Bridge circuit for producing a signal proportional to the actuator's velocity in concomitant sensing and actuation: while the actuator is driven by means of voltage V, the bridge unbalance, V_v, is proportional to the actuator's velocity U.

A model of the transduction process can be used to implement both functions (sensing and actuation) at a time. Before discussing this possibility in detail, let us introduce here equation [13], which describes the relationship between effort and flow variables in the electric-circuit analogy:

$$V = Z_e I + T_{em} v \quad \text{and} \quad F = T_{me} I + Z_m v \qquad [13]$$

The first equation describes the transducer as an actuator, i.e. the application of a voltage, V, leads to a current drawn, I, and to an output velocity, v. The Laplace transform of this first equation is:

$$V(j\omega) = Z_e I(j\omega) + T_{em} U(j\omega) \qquad [14]$$

The overall electrical voltage includes a term dependant on the current drawn, $Z_e I(j\omega)$, and a term related to the output velocity, $T_{em} U(j\omega)$. This equation indicates that the output velocity could be estimated by measuring the overall voltage, V, and subtracting the voltage drop, VZ_e across the actuator's blocked impedance, $VZ_e = Z_e\ I(j\omega)$.

The above result provides the basis for estimation of the actuator's motion from a *Bridge Circuit configuration*, as shown in figure 3. This result is important in that it could lead to: (i) modification of the actuator's behavior (for instance its damping characteristics) through the implementation of feedback control loops based on the estimation of the velocity, and (ii) collocated and concomitant sensing and actuation.

If a copy of the actuator's blocked impedance is used in the bridge circuit branch as depicted in figure 3, the voltage across the bridge, V_v, is proportional to the actuator's velocity.

The first approach, i.e. modification of the actuator's damping properties, has been studied in the context of voice coil loudspeakers (13). In this case, the feedback from the unbalanced bridge voltage is utilized to increase damping around the resonance frequencies. The second approach has been implemented in collocated and concomitant position and velocity feedback in PZ actuators, see (14) and (8).

The main problem in this approach is measurement of the actuator's blocked impedance. It has been found that in most implementations, the blocked impedance, rather than being constant and independent of the actuator's motion, is a non-linear function of the current drawn.

Ideally, if output velocity could be estimated from the voltage across the bridge, V_v, the sensing part of the electric-circuit analogy (see equation [13]) could then be used to produce an estimate of the mechanical conjugate variable (the force).

In the context of concomitant sensing and actuation based on magnetostrictive materials, let us recall here the linearized version of the constitutive equations for the magnetostrictive effect:

$$\begin{aligned} S &= c^H T + dH \\ B &= \bar{d} T + \mu^T H \end{aligned} \qquad [15]$$

Equation 15 describes the coupling between magnetic and mechanical variables in the direct and converse magnetostrictive effect. The first equation describes the transducer as an actuator, that is, the resulting displacement is a function of the applied magnetic field strength. It further includes the coupling between mechanical variables, i.e. the displacement resulting from mechanical load.

The second part of the constitutive equation describes the transducer in the role of sensor, relating the mechanical load to the magnetic induction. Again, this part includes the coupling between the magnetic field variables: i.e. the applied magnetic field strength results in magnetic induction.

The two equations can be combined by solving the first part for H and substituting it in the second part to yield:

$$B = T\left[\bar{d} - \frac{\mu^T c^H}{d}\right] + \frac{\mu^T}{d} S \qquad [16]$$

Equation [16] describes the sensor model for the magnetostrictive transducer. It formulates the relationship between the resulting magnetic induction in the magnetostrictive material, B, and the applied force, T, and displacement, S. Faraday's law can be used to determine the magnetic induction in the material. This states that the voltage induced in a coil wrapped around the magnetostrictive material is:

$$V = NA\frac{dB}{dt} = NA\frac{dT}{dt}\left[\bar{d} - \frac{\mu^T c^H}{d}\right] + NA\frac{dS}{dt}\frac{\mu^T}{d} \qquad [17]$$

where N is the number of turns in the coil and A is the cross sectional area.

Equation [17] indicates that the voltage in such a sensor configuration is proportional to the rate of change of force (jerk) and to the rate of change of displacements (velocity) in the magnetostrictive material. It can be demonstrated (5) that the magnetostrictive process is fully reversible and $\bar{d} = d$ and that the term in equation [17] corresponding to the velocity is one order of magnitude smaller than the terms relating to force. Therefore, for harmonic excitations, a model for the force measured by the transducer would be:

$$T = \frac{V}{NA\omega}\left[\frac{1}{\bar{d} - \frac{\mu^T c^H}{d}}\right] \qquad [18]$$

The design of magnetostrictive transducers as sensors is equivalent to their design as actuators. Moreover, as we assumed that $\bar{d} = d$, this implies that if the transducer is designed for efficient operation as an actuator, it will be a high-sensitivity sensor. These are commonly used in sonar transducers where a transducer designed as an efficient emitter also yields the best results as a receiver.

For combined sensor and actuation operation of Magnetostrictive actuators, the Bridge Circuit configuration can be implemented. To do this, the linearized constitutive equations for the Magnetostrictive effect, equation [15], must be rewritten in line with the electric-circuit analogy.

We commence the process by multiplying the sensing part of equation [15] by the actuator's cross sectional area A. Considering that $\Phi = B \cdot A$, it follows that:

$$\Phi = \bar{d}TA + \mu^T HA \qquad [19]$$

Now, if we take the time derivative of equation [19], multiply the equation by N (the number of turns in the MS actuator coil) and note that $V(t) = N d\Phi/dt$ and , $H = I(t)N$ we obtain:

$$V(t) = N\bar{d}\frac{dT}{dt}A + \mu^T N^2 \frac{A}{l}\frac{dI}{dt} \qquad [20]$$

The Laplace transform of equation [20] can now be developed. In addition, if we take into account low frequency excitation of the transducer, we can assume that the material's deformation obeys Hooke's law (T=Y ε). Given these assumptions, we can write:

$$V(j\omega) = N\bar{d}\frac{AY}{l}U(j\omega) + j\omega L I(j\omega) \qquad [21]$$

where Y is the Young's modulus, l is the length of the Magnetostrictive actuator and L is the inductance of the MS actuator coil.

A simple inspection of equations [21] and [14] will show that $Z_e = j\omega L$, that is, the blocked impedance of the Magnetostrictive actuator (which is required to complete the second branch of the Bridge Circuit) is simply the inductance of the solenoid (with the MS material as the core) used to drive the MS actuator (see figure 4).

A similar approach can be used to derive the second part of equation [13]. It can be shown, (2), that this produces:

$$F(j\omega) = \frac{AY}{l}\frac{1}{j\omega}U(j\omega) + AYdNI(j\omega) \qquad [22]$$

If the solenoid inductance is used in the second branch of the Bridge Circuit, the voltage across the bridge ought to be proportional to the actuator's velocity. However, this is not the case, and the reason is that the blocked impedance is non-linearly dependent on the current drawn. Consequently, concomitant sensing and actuation with MS actuators is difficult to achieve, although some authors, (2), have reported positive results in narrow frequency bands around the actuator's mechanical resonance.

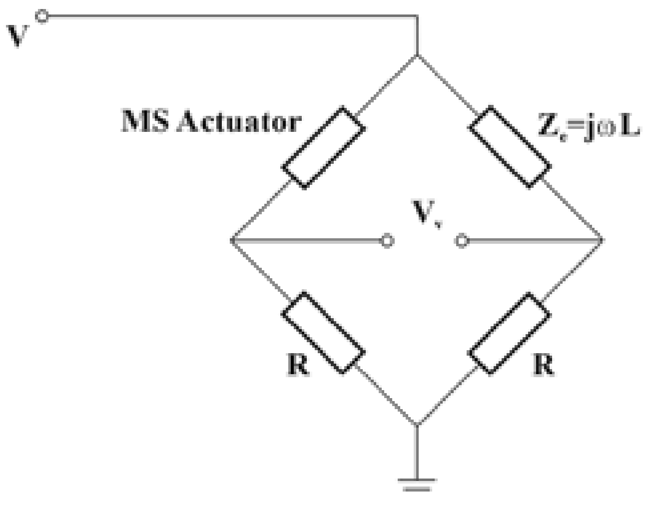

Fig. 4- Bridge circuit configuration for concomitantly using a MS actuator as a sensor.

5. PZ AND MS ACTUATORS IN SMART STRUCTURES

5.1 PZ actuators in smart structures

As we discussed in the introduction, most of the emerging actuator technologies can perform both as sensors and as actuators. Amongst them, MS, PZ and Shape Memory Actuators, SMA, are the most appropriate to be integrated in active structures. Like SMA actuators, MS and PZ actuators can perform also as sensors. Unlike SMA actuators, PZ and MS actuators cannot be used to concomitantly impose and sense the same output variable, but they can sense the conjugate variable to the imposed one.

When discussing piezoelectric actuators, it can be pointed out that current drawn, i, is in principle proportional to the actuator's velocity, v_p. In this material, the following approximate relationships hold:

$$\Delta l \propto \Delta Q \qquad [23]$$

$$v_p \propto i \qquad [24]$$

$$a_p \propto di/dt \qquad [25]$$

where Δl is the actuator change in length, ΔQ is the change in charge and a_p is the actuator's acceleration.

According to the above equations, if control is achieved by feeding the current drawn directly back in a negative control loop, the result is equivalent to a direct velocity feedback approach. Direct velocity feedback, in a collocated sensor/actuator pair (the condition of collocated sensors and actuators indicates that the sensor directly measures the action of the actuator, condition that will be always met in actuators acting concomitantly as sensors), leads to stable active damping control schemes, see (15). Therefore, since a piezoelectric smart actuator is intrinsically collocated, this approach greatly facilitates the implementation of active vibration control in smart structures.

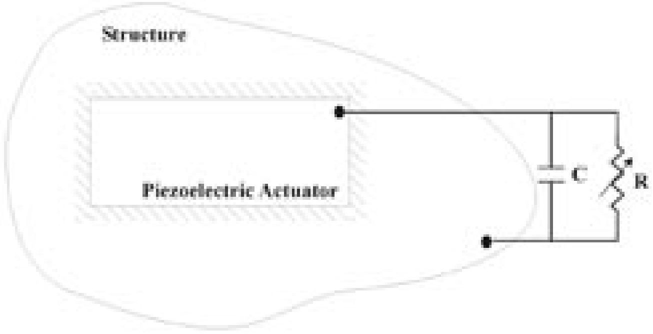

Fig. 5- Piezoelectric actuator bonded to a structure and connected to a RCL circuit for passive damping.

In the previous section, we discussed how the electrical boundary conditions applied to a piezoelectric actuator can result in programmable actuator stiffness. Programmable stiffness can be applied for voluntary stiffening in response to monitoring functions.

Two actuation approaches can be envisaged for piezoelectric actuators:

1. As linear actuators. In this approach, they replace conventional actuators in controlling structure parameters. As noted earlier, this actuation approach is not suitable for development of the smart structure concept as sensor and actuator functions are lumped rather than distributed.

2. As surface bonded actuators. The piezoelectric material is laminated and bonded in thin layers to the structure (see figure 5). This can serve for the application of either axial or bending loads.

Both actuation approaches are most commonly used to enhance the damping characteristics of the structure to which they are attached (first case) or embedded (second approach). As regards surface bonded actuators, in controlling damping, again there are two possible strategies:

1.Passive damping. In this approach, the actuator is bonded to the structure and is electrically connected to a passive RLC circuit. The actuator acts as a voltage source when driven by the structural vibrations through the direct piezoelectric effect. The electrical energy is dissipated at the resistor. This results in an apparent increase of structural damping.

Some selectivity in the damping process can be achieved by tuning the RLC characteristics of the passive circuit to the target frequency (see figure 5).

2.Active damping. In this mode, the piezoelectric actuators are integrated in a feedback control strategy, in an active control strategy or in a feed-forward control strategy. In any of these control algorithms, the piezoelectric actuator can perform as a smart actuator, i.e. sensing and actuating concomitantly.

5.2 MS actuators in smart structures

Magnetostrictive actuators are best suited for active vibration control of structures. Moreover, they are a typical example of a smart actuator. However, they are not suitable for integration in any type of structure.

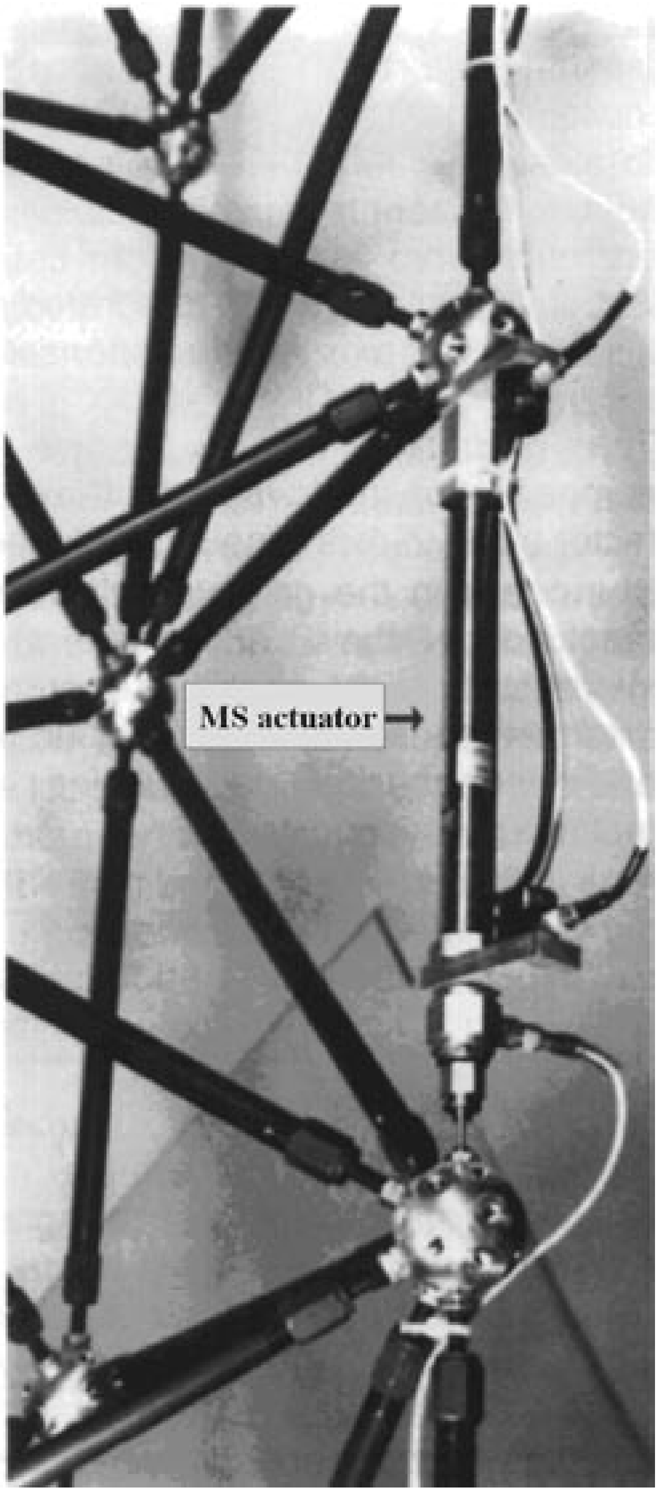

Fig. 6- 3D truss in which a linear MS actuator is integrated for active vibration isolation.

In particular, planar configurations (similar to bonded laminate piezoelectric actuators (see figure 5) are not ideal for magnetostrictive actuators. This is due to the difficulty of creating a uniform magnetic field for such a planar configuration.

Magnetostrictive actuators are more suitable for integration in discrete structures like three-dimensional trusses (see figure 6) and structures with structural cables (bridges or buildings). There, they can take the place of passive structural elements and thus offer the possibility of cancelling out structural vibrations, see (7).

The issue of active control of truss structures has been comprehensively studied by (15). We will not go into more detail here; for more details the reader is referred to (1).

Magnetostrictive actuators can be used in the context of vibration suppression in smart structures, in three different modes:

1. Stiffeners.
2. Dampers.
3. Active elements.

Stiffeners make use of the ΔY-effect, which allows a two-fold increase in the actuator's stiffness. By changes induced in the structural stiffness of the structure in which they are integrated, the resonance frequency can be modified to prevent resonance amplification following external excitation.

Magnetostrictive actuators can also be used as dampers in active damping control approaches. The role of the actuator in this control scheme is to enhance the structural damping by means of direct velocity feedback or similar approaches.

Finally, they can be applied in active vibration cancellation control schemes, both feed-forward and feedback. In this approach the MS actuator will provide the necessary secondary disturbance to cancel out vibrations. As in the case of piezoelectric or Shape Memory actuators, both sensing and driving functions can be implemented concomitantly. This is discussed in more detail in the next section.

6 OPERATIONAL CHARACTERISTICS OF PZ AND MS ACTUATORS

This section analyzes the performance characteristics of Piezoelectric and Magnetostrictive actuators. The reader is referred to (1) for a comprehensive comparative analysis of all emerging actuator technologies, but here we pay particular attention to a comparative analysis of MS and Piezoelectric actuators since these have the closest figures of merit. In this comparison we will mainly focus on PZ stack actuators since they best resemble the operation of MS linear actuators. Other Piezoelectric actuators, i.e. cantilever or multimorph actuators, could be included but their operational characteristics differ too much from MS actuators to be directly compared.

6.1 Static performance

Magnetostrictive and Piezoelectric stack actuators can be classified together as high force devices. The absolute value of force in these actuators is in the kilonewton range ($F \geq 1$ kN).

Relative forces for MS actuators (for instance as compared to cross sectional area or size) nevertheless become several orders of magnitude lower than relative forces in Piezoelectric actuators. This is mainly due to the accompanying components required to set up bias magnetic fields or to prestress the Magnetostrictive actuator. While Piezoelectric stack actuators can be directly applied to drive the load, MS actuators require coils to set up the magnetic field and in most implementations permanent magnets to apply bias fields.

Stroke in MS actuators is of the order of 1500-2000 ppm for static applications and close to 4000 ppm where resonance amplification is used in dynamic applications. In absolute value, the displacement is limited in practice to some tenths of a mm. Stroke is higher in MS actuators than in Piezoelectric stack actuators (which is of the order of 1000 ppm in static conditions), but the performance of Piezoelectric stack and MS actuators is very similar in terms of the relative stroke (for instance with respect to the length of the actuator).

6.2 Dynamic performance

The energy density of Magnetostrictive actuators is in the range of $W_V \leq 10^{-3}$ J/cm^3 and must therefore be considered low. If only the magnetostrictive material were considered, the energy density would be closer to that of Piezoelectric actuators, but here again, the bulky accompanying elements cause reduced work density.

The bandwidth of MS actuators is high, $f \geq 1$ kHz. Together with Piezoelectric stack actuators and some Piezoelectric Multimorph drives, they have the highest frequency bandwidth of all emerging actuator technologies. MS drives are driven at lower frequencies than Piezoelectric stack actuators. There are two main reasons for this:

1. Lower Young's modulus. MS materials exhibit a lower Young's modulus than Piezoelectric materials (two to three times lower). This results in lower resonance frequency of MS materials, which in turn limits the maximum driving frequency for actuators based on this technology.

2. Eddy currents. Changing magnetic fields induce electrical currents (eddy currents) in the magnetostrictive materials, and these lead to material heating and lost efficiency; the higher the frequency of the magnetic field, the stronger are the currents induced. This imposes a practical limit on the maximum frequency attainable with MS actuators, otherwise efficiency is highly reduced.

Power density in MS actuators is a result of the two previous figures of merit. Since both energy density and bandwidth are lower in MS actuators than in Piezoelectric drives, absolute power density values are low, of the order of 1 W/cm^3, which is up to three orders of magnitude lower than in Piezoelectric stack actuators.

6.3 Other performance characteristics

The temperature range of operation for MS actuators is limited in practice by the material's Curie temperature. The Curie temperature for Terfenol-D is close to 380 C, which is higher than the Curie temperature for PZT materials.

Driving voltages for MS actuators are lower than they are for Piezoelectric stack actuators. Power supply for this technology is readily available from several manufacturers. Unfortunately, the MS material itself is much less readily available. While PZT materials can be found in several grades, the only available MS material grade is Terfenol-D.

7. CONCLUSIONS

This paper has introduced a comparative analysis of PZ (stacks) and MS actuators with regard to their application as smart actuators in active structures. As such, the concomitant sensing and actuation, their ability to change material parameters (stiffness) and their operational characteristics have been studied and compared.

PZ and MS actuators have been pointed out as two of the most relevant and well established emerging actuators. As to their ability to perform both as sensors and actuators this is based on the direct piezoelectric effect and on the Villari and Matteuci effects. These phenomena allow the sensing of the conjugate variable, i.e. if the actuator is establishing a displacement, concurrent estimation of the force can be accomplished. Furthermore, this paper has introduced the estimation of both conjugate variables based on models of the electrical circuit analogy for PZ and MS actuators.

Something similar can be said of their ability of modifying the actuator stiffness. This is of importance when the actuator is integrated in smart structures as a means of changing their resonance characteristics.

PZ (stack) and MS actuators exhibit similar static operational properties, in particular stroke and force. In what they differ the most is in the dynamic operational characteristics. The resonance frequency of MS actuators is lower than the one of PZ actuators. This affects the maximum driving frequency and is closely related to the lower Young's modulus of MS actuators and to the limits due to eddy currents.

Both actuators are suitable to be embedded in smart structures, but PZ actuators can be easily bonded in thin laminar structures while MS actuators are more suited to be included in truss like structures. One of the most limiting factors for MS actuators in comparison with PZ actuators is in the low availability of materials and grades.

REFERENCES

1. J.L. Pons, Emerging Actuator Technologies: a Micromechatronic Approach, John Wiley & Sons Ltd., Chichester, England, 2005.
2. J. Pratt, Design and analysis of a self-sensing Terfenol--D magnetostrictive actuator, M. Sc. Thesis, Iowa State University, Ames, 1993.
3. P. Ochoa, M. Villegas, J.L. Pons, M.A. Bengochea, J.F. Fernández, Piezocomposites metal-cerámica como elementos activos en acelerómetros, Bol. Soc. Esp. Cerám. V., 41, 1, pp. 126-130, 2002.
4. J.C. Moreno, J.F. Fernáández, P. Ochoa, R. Ceres, L. Calderón, E. Rocon, J.L. Pons, Aplicación de sensores electrocerámicos a la caracterización biomecánica, Bol. Soc. Esp. Cerám. V., 43 (3), pp. 670-675, 2004.
5. M.J. Dapino, R.C. Smith, F.T. Calkins, A. Flatau, A Coupled Magnetomechanical Model for Magnetostrictive Transducers and its Application to Villari-effect Sensors, Journal of Intelligent Material Systems and Structures, 13, 737-747, 2002.
6. D. Mesonero-Romanos, J.F. Fernández, M. Villegas, R. Ceres, E. Rocon, J.L. Pons, Comparación entre excitación resonante y forzada de motores electrocerámicos, Bol. Soc. Esp. Cerám. V., 43 (3), pp. 725-731, 2004.
7. P.A. Bartlett, S.J. Eaton, J. Gore, W.J. Matheringham and A.G. Jenner, High-power, low frequency magnetostrictive actuation for anti-vibration applications, Sensors and Actuators A, 91, 133-136, 2001.
8. N.W. Hagwood, E.H. Anderson, Simultaneous sensing and actuation using piezoelectric materials, Active and Adaptive Optical Components, SPIE, 1543, 409-421, 1991.
9. C.Z. Rosen, B.V. Hiremath, R. Newnham eds., Piezoelectricity, American Institute of Physics, New York, 1992.
10. A.B. Flatau, M.J. Dapino, F.T. Calkins, High bandwidth tunability in a smart vibration absorber, SPIE Smart Structures and Materials Conf., San Diego, CA, 463-473, 1998.
11. A.E. Clark, H.T. Savage, Giant magnetically induced changes in the elastic moduli in Tb(0.3)Dy(0.7)Fe(2), IEEE Transactions on sonics and ultrasonics, 50-52, 1975.
12. K. Kuhnen, H. Janocha, Compensation of the Creep and Hysteresis Effects of Piezoelectric Actuators with Inverse Systems, Actuator'98, 309-312, 1998.
13. E. de Boer, Theory of motional feedback, IRE Transactions on Audio, 15-21, 1961.
14 J.J. Dosch, D.J. Inman, E. García, A self-sensing piezoelectric actuator for collocated control, Journal of Intelligent Material Systems and Structures, 3, 166-185, 1992.
15. A. Preumont, Vibration control of active structures, Kluwer Academic Publishers, 1997.

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