INDUCED STRAIN ACTUATORS
FOR SMART-STRUCTURES APPLICATIONS

by
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I would like to acknowledge the guidance and support of Dr. Victor Giurgiutiu, throughout my research and academic preparation. I would also like to thank all the professors who have passed bits of wisdom to me, throughout my education.

In addition, I would like to sincerely thank my colleagues JingJing “Jack” Bao, Adrian Cuc, Paulette Goodman, Florin Jichi, Greg Nall, and Andrei Zagrai who were always helpful and taught me many useful lessons.

Last but not least, I would like to express my sincere gratitude to my parents and my wife, without whom none of this would have been possible.
ABSTRACT

The present research proposed a method for investigating the smart materials actuators performances in quasi-static and low frequency dynamic regimes, using a general-to-specific approach. A brief review of the state of the art accounts for current methods of testing linear actuators and active material characterization. With an assumed linear behavior for the smart materials, an extensive review of active materials linear actuators was conducted among actuators manufacturers with the goal of identifying the current attainable specific energy levels. The response of a piezoelectric actuator under large electro-mechanical excitation was modeled using the linear smart material behavior assumption. The thorough quasi-static and dynamic actuator characterization through measurements indicated a strong dependence of the actuator stiffness and piezoelectric properties on the electromechanical loading conditions. The comparison of the model with the measured behavior was discussed and it provided further useful information as to the actuation systems design incorporating active materials actuators. The comparison also allowed the identification of key parameters of the induced strain actuator electro-mechanical model. These parameters were necessary to perform design optimization towards maximum mechanical energy transfer and minimum power requirements.
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1. BACKGROUND

1.1 SMART STRUCTURES AND SMART MATERIALS

From the design point of view (Spillman, 1996), a smart structure is a non-biological physical structure having the following attributes: a) a definite purpose; b) means and imperative to achieve that purpose; c) a biological pattern of functioning. Given this definition, a smart sub-system must present beside structural functionality other type of functions e.g. health monitoring, actuation, control. In order to achieve this goal the system must incorporate smart (adaptive, intelligent) materials that present coupling between the mechanical field of strain/stresses and another field, let that be electric, magnetic or thermal.

Smart materials can be classified based on the type of the coupled fields and internal structure as follows: piezoelectric ceramics (PZT, PMN), magnetostrictive materials (Terfenol-D), shape memory alloys (NiTiNol), and piezoelectric polymers.

A comparison of the traditional actuation and smart materials technologies (Table 1) reveals the small strain capabilities of the latter category. The shape memory alloys and the contractile polymer make exception, although they have the drawback of a low bandwidth. The piezoelectric and the magnetostrictive actuators display a significantly
larger bandwidth, when compared with traditional actuation technologies, that translates in a higher power density.

Table 1 Comparison of traditional and solid-state actuators

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Property</th>
<th>Stress (MPa)</th>
<th>Strain</th>
<th>Bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td></td>
<td>0.02</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Hydraulic</td>
<td></td>
<td>20</td>
<td>0.5</td>
<td>4</td>
</tr>
<tr>
<td>Pneumatic</td>
<td></td>
<td>0.7</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>Shape memory alloy</td>
<td></td>
<td>200</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td></td>
<td>35</td>
<td>0.002</td>
<td>5000</td>
</tr>
<tr>
<td>Electrostrictive</td>
<td></td>
<td>50</td>
<td>0.002</td>
<td>5000</td>
</tr>
<tr>
<td>Magnetostrictive</td>
<td></td>
<td>35</td>
<td>0.002</td>
<td>3500</td>
</tr>
<tr>
<td>PZN-PT Single crystal</td>
<td></td>
<td>300</td>
<td>0.017</td>
<td>5800</td>
</tr>
<tr>
<td>Contractile polymer</td>
<td></td>
<td>0.3</td>
<td>0.5</td>
<td>10</td>
</tr>
</tbody>
</table>

1.1.1 Shape memory alloys

The actuation mechanism for the shape memory alloys (SMAs) arises from a phase transformation in the microstructure, which is controlled by temperature. These materials have been shown to exhibit extremely large, recoverable strains (10%) (Liang et al., (1990)). Macroscopically, the observed mechanical response of SMAs can be separated into two categories: the shape memory effect, in which the specimen exhibits large residual strains after loading and unloading that can be fully recovered upon rising the temperature, and the pseudo-elastic effect, in which a specimen achieves a very large strain upon loading, that is then fully recovered in a hysteresis loop upon unloading. The capability of recovering large strains is due to a martensite phase transformation occurring in the SMA material according to certain environmental and boundary conditions. In a stress-free state, a SMA material at high temperatures exists in the parent
phase (austenitic phase, body-centered cubic crystal), and upon decreasing the temperature, the crystal undergoes a self-accommodating crystal transformation into martensite (faced-centered cubic) (Brinson, 1993)).

Since temperature is the activation driver for SMAs, the actuation bandwidth for these materials is restricted by how fast the heating/cooling of these devices can be accomplished. Maximum actuation frequencies run up to approximately 1-2 Hz.

1.1.2 Piezoelectric materials

The piezoelectric materials exhibit induced-strain actuation under the action of an electric field. They are primarily of two types:

- PZT - Lead Zirconate Titanate (PbZrO$_3$ : PbTiO$_3$) - A ferroelectric ceramic material with piezoelectric properties and reciprocal behavior that converts electrical energy into mechanical energy and vice-versa. A variety of PZT formulations have been developed to suit a wide range of signal transmission and reception qualities. PZT-5 is one of the most widely used compositions for actuator applications. It is convenient to classify the ceramic materials according to their coercive field in the field-induced strain. The material with a coercive field larger than 10 kV/cm is called a “hard” piezoelectric, which shows a wide linear drive region, but relatively small strain magnitude. The material with a coercive field between 1-10kV/cm is called a “soft” piezoelectric, which shows a large field induced strain, but relatively large hysteresis. The “hard” or “soft” character of ferroelectrics is achieved with the use of dopants.
PMN - Lead Magnesium Niobate (PbMg\(_{1/3}\)Nb\(_{2/3}\)O\(_3\))- An electrostrictive ceramic material with piezoelectric properties and reciprocal behavior that converts electrical energy into mechanical energy and vice-versa. Numerous PMN formulations have been developed to suit a wide range of signal transmission and reception qualities.

A comparison of soft PZT, hard PZT, and electrostrictive (PMN) material properties is given in Table 2.

Table 2 Mechanic and dielectric properties for piezoelectric and electrostrictive materials.

<table>
<thead>
<tr>
<th>Property</th>
<th>PZT 5A (soft)</th>
<th>PZT 8 (hard)</th>
<th>PMN EC-98</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho) (kg/m(^3))</td>
<td>7600</td>
<td>7600</td>
<td>7850</td>
</tr>
<tr>
<td>(k_{31})</td>
<td>0.36</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>(k_{33})</td>
<td>0.71</td>
<td>0.61</td>
<td>0.72</td>
</tr>
<tr>
<td>(k_{15})</td>
<td>0.67</td>
<td>0.54</td>
<td>0.67</td>
</tr>
<tr>
<td>(d_{31}) (x10(^{-12})m/V)</td>
<td>-270</td>
<td>-100</td>
<td>-312</td>
</tr>
<tr>
<td>(d_{33}) (x10(^{-12})m/V)</td>
<td>550</td>
<td>220</td>
<td>730</td>
</tr>
<tr>
<td>(d_{15}) (x10(^{-12})m/V)</td>
<td>720</td>
<td>320</td>
<td>825</td>
</tr>
<tr>
<td>(g_{31}) (x10(^{-3})Vm/N)</td>
<td>-9.0</td>
<td>-11.3</td>
<td>-6.4</td>
</tr>
<tr>
<td>(g_{33}) (x10(^{-3})Vm/N)</td>
<td>18.3</td>
<td>24.9</td>
<td>15.6</td>
</tr>
<tr>
<td>(g_{15}) (x10(^{-3})Vm/N)</td>
<td>23.9</td>
<td>36.2</td>
<td>17</td>
</tr>
<tr>
<td>(s_{11}^{\varepsilon}) (x10(^{-12})m(^2)/N)</td>
<td>15.9</td>
<td>10.6</td>
<td>16.3</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.31</td>
<td>0.31</td>
<td>0.34</td>
</tr>
<tr>
<td>(s_{33}^{\varepsilon}) (x10(^{-12})m(^2)/N)</td>
<td>20.2</td>
<td>13.2</td>
<td>21.1</td>
</tr>
<tr>
<td>Curie Temp. (°C)</td>
<td>200</td>
<td>350</td>
<td>170</td>
</tr>
<tr>
<td>Mechanical (Q_m)</td>
<td>75</td>
<td>900</td>
<td>70</td>
</tr>
</tbody>
</table>
The constitutive equations for piezoelectric ceramics are (Ikeda, 1989):

\[
S_{ij} = s_{ijkl}T_{kl} + d_{ikj}E_k \quad D_i = d_{ikl}T_{kl} + \varepsilon_{ik}^T E_k
\]  

(1)

where \(S_{ij}\) is the strain tensor, \(T_{kl}\) is the stress tensor, \(E_k\) is the electric field vector, \(D_i\) is the electric displacement vector, \(s_{ijkl}\) is the compliance tensor, \(\varepsilon_{ik}\) is the electric permittivity tensor and \(d_{ikj}\) is the piezoelectric coupling tensor. The electric displacement is defined by, \(\text{div}(D) = \rho\), where the \(\rho\) is the free charge density.

The PZT crystal at room temperature can be found in either of the following phases: cubic, tetragonal or rombohedral. In its cubic phase (Figure 1a), the titanium ion is in the center of the PZT crystal unit cell, and thus there is no net polarization. This is called the unpoled or paraelectric state. If the titanium ion Ti\(^{4+}\) is off center (tetragonal or rombohedral states), the crystal behaves as a dipole, and a polarization vector can be defined (Figure 1a). In the same time, the crystal elongates in the direction of the polarization vector. Due to this electro-mechanical coupling, the crystal structure responds to both mechanical and electrical stimuli.

If an electric field is applied, the titanium ion will move, changing the polarization vector, and also the dimension of the unit cell. If the field applied against the remnant polarization vector is strong enough, the Ti\(^{4+}\) will be brought back to the center of the unit cell, and the crystal becomes cubic, losing its polarization (Figure 1b). Such a field is called the coercive field \((E_c)\). If the field is further increased, the crystal will re-polarize in the opposite direction (Figure 1c). This is called 180\(^0\)-polarization switch. Conversely, on the application of a mechanical load, the unit cell will compress, changing the dipole
length. For a given value of stress (coercive stress), the potential energy of the crystal structure will find a minimum for the position shown in Figure 1d. This is called $90^0$ polarization (ferroelastic) switch, in the case of the tetragonal phase. The energetic levels for ferroelastic switching in the rombohedral phase correspond to $75^0$ and $105^0$ polarization switch.

![Figure 1](image1.png)

**Figure 1**  a) Cubic (paraelectric) and tetragonal (ferroelectric) phases of the lead titanate crystal; b) Depolarization under coercive field $E_c$; c) $180^0$ polarization switch for $E > E_c$; d) $90^0$ polarization switch for stresses higher than the coercive stress (Lynch, 1996)

The properties of the PZT crystal can be modified by doping the PZT crystal. The “hard” or “soft” character of a PZT composition is explained by Uchino (2000) through the type of vacancy created by various dopants.

![Figure 2](image2.png)

**Figure 2** PZT Doping: a) Undoped PZT; b) Acceptor doping (hard PZT); c) Donor doping (soft PZT) (Uchino, 2000)

For example, acceptor ions doping (Fe$^{3+}$) introduce oxygen vacancies (Figure2b) that are mobile enough to not allow easy switching (“domain pinning”). Acceptor doping creates
“hard” PZTs. In the case of donor ions doping (Nb\(^{5+}\)), Pb deficiency is introduced, leading to ineffective domain pinning, because the Pb ion cannot easily move to an adjacent vacancy (Figure 2c). This will create “soft” PZTs.

Another cause for the polarization change within a PZT crystal is the phase change, because the piezoelectric crystals are usually found near the morphotropic boundary between rombohedral and tetragonal phases.

1.1.3 Magnetostrictive materials

TERFENOL - TER (Terbium) FE (Iron) NOL (Naval Ordinance Laboratory) - A magnetostrictive alloy consisting primarily of Terbium, Dysprosium, and Iron. This magnetostrictive material does not exhibit reciprocal behavior since it only converts electro-magnetic energy into mechanical energy. Various TERFENOL formulations have been developed. A commonly used formulation is TERFENOL-D.

1.1.5 New active materials

The inherent small strain capabilities and the hysteresis behavior of the above-presented ceramic materials prompted more research. Park et al. (1997) reported strain levels of up to 1.5% for single crystals of relaxor pervoskite Pb(Zn\(_{1/3}\)Nb\(_{2/3}\))O\(_3\) – PbTiO\(_3\), maintaining in the same time a reduced hysteresis (Figure 3a). Single crystal material characteristics as reported by TRS are given in Table 3. The design of the actuators that use the PZN-PT material must take into account the strong dependence of the piezoelectric properties on the crystal orientation (Figure 3b).
Table 3 Single crystal properties (TRS Ceramics Inc.)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{33} )</td>
<td>5000</td>
</tr>
<tr>
<td>( T_{\text{max}} ) (°C)</td>
<td>152</td>
</tr>
<tr>
<td>( d_{33} ) (pC/N)</td>
<td>2000</td>
</tr>
<tr>
<td>( d_{31} ) (pC/N)</td>
<td>-950</td>
</tr>
<tr>
<td>( s_{33} ) ((10^{-12}) m²/N)</td>
<td>120</td>
</tr>
<tr>
<td>( s_{31} ) ((10^{-12}) m²/N)</td>
<td>65</td>
</tr>
<tr>
<td>( k_{33} )</td>
<td>0.91</td>
</tr>
<tr>
<td>( k_{31} )</td>
<td>0.50</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Although this fact can be regarded as an optimization criterion in the design of actuators, it implies a reduced versatility when compared with piezoceramic materials. With this PZN-PT new material, TRS Ceramics Inc. reports building a prototype actuator with a maximum strain around 0.3%. Although no commercial version of this actuator is available at the moment, the PZN-PT material holds potential that is likely to be used in
the future. The uncertain reliability of PZN-PT single crystals is still a concern. Yield when manufacturing single crystals devices typically is 10%. Of the 10%, 90% will fail if the transducer is to perform significant work, as in the case of actuation applications (Uchino, 2000).

Figure 4  a) Changes of magnetostrictition vs. magnetic field curves with increasing temperature in melt-spun Fe-29.6at%Pd alloy thin plate (roll speed 28.3 m/s, 900°C, 1h annealed, phase transformation temperature 163°C); b) The cyclic strain response of rapidly solidified Fe-Pd foil and Fe-C foil as a reference at H=0.3 kOe at 10Hz in solenoid-type coil (Furuya et al., 1998).

Another interesting research direction is to drive the shape memory alloys with other fields than temperature. The advantage consists mainly in the increase of the actuation speed.

Furuya et al. (1998) proposed a rapidly solidified ferromagnetic shape memory Fe-29.6at%Pd alloy that shows magnetostrictition of up to 1800 microstrain at an applied magnetic field of 8x10^5 A/m. The material also holds its dependency on temperature (Figure 4). Furuya et. al. (1998) also investigated the dynamic response under the alternative magnetic field and have confirmed that the magnitude of striction of the Fe-Pd foil is at least ten times greater than that of the conventional Fe-based magnetostrictive
materials at 10 Hz. The response signal can be confirmed up to 100 Hz, which is 20 times faster than that of thermal SMA actuator material.

Another shape memory alloy displaying ferromagnetic properties is Ni-Mn-Ga (Murray et al., 2000). The mechanism of field-induced deformation is the rearrangement of the variant structure of a twinned martensite through the motion of twin boundaries to accommodate the applied field and/or load. Field-induced twin boundary motion can result in deformation of several percent (Figure 5).

**Figure 5** Magneto-mechanical response of Ni-Mn-Ga at various constant stress levels (Murray et al., 2000)

1.2 ACTUATORS

1.2.1 Piezoelectric stack actuators

An electroactive solid-state actuator consists of a stack of many layers of electroactive material (PZT or PMN) alternatively connected to the positive and negative terminals of a high voltage source (Figure 6). Such a PZT or PMN stack behaves like an electrical capacitor. When activated, the electroactive material expands and produces output displacement. Typical strains for electroactive materials are in the range 750-1200 µm/m.
Figure 6  (a) Small-size piezoelectric stacks. (b) Larger-size piezoelectric stacks (EDO Corporation); c) Induced strain actuator using a PZT or PMN electroactive stack

PZT or PMN stacks are constructed by two methods. In the first method, the layers of active material and the electrodes are mechanically assembled and glued together using a structural adhesive. The adhesive modulus (typically, 4-5 GPa) is at least one order of magnitude lower than the modulus of the ceramic (typically, 70-90 GPa). This aspect may lead to a stack stiffness that is significantly lower than the stiffness of the basic ceramic material. In the second method, the ceramic layers and the electrodes are assembled in the "green" state, and then fired together (co-fired) and, possibly, subjected to a high isostatic pressure (HIP process) to increase density. This process ensures a much stiffer final product and, hence, a better actuator performance. However, the processing limitations, such as oven and press size, etc., limit the applicability of this process to small size stacks only. The PZT and PMN stacks are surrounded by a protective polymeric or elastomeric wrapping. Lead wires protrude from the wrapping for electrical connection. Steel washers, one at each end, are also provided for distributing the load into the brittle ceramic material. When mounted in the application structure, these stacks must be handled with specialized knowledge. Protection from accidental impact damage must be provided. Adequate structural support and alignment are needed. Mechanical connection to the application structure must be such that tension stresses
are not induced in the stack since the active ceramic material has very low tension strength. Hence, the load applied to the stack must always be compressive and perfectly centered. If tension loading is also expected, adequate pre-stressing must be provided through springs or other means.

1.2.2 Magnetostrictive actuators

A magnetoactive solid-state actuator consists of a TERFENOL bar inside an electric coil and enclosed into an annular magnetic armature (Figure 7). When the coil is activated, the TERFENOL expands and produces output displacement. The TERFENOL material has been shown to be capable of strains up to 2000 mm/m, but with highly nonlinear and hysteresis behavior. Practical strains employed by the manufacturers of TERFENOL actuators are in the quasi-linear behavior range of 750-1000 mm/m.

The TERFENOL-D bar, the coil, and the magnetic armature, assembled between two steel-washers and put inside a protective wrapping, form the basic magnetoactive induced-strain actuator.
1.3 PREVIOUS WORK ON ACTUATORS MODELLING AND CHARACTERIZATION

The initial approach towards modeling the piezoelectric material response regarded the piezoelectric material as a continuum, whose constitutive equations are governed by 3 tensors: the compliance, the piezoelectric and the permittivity tensors through Equation (1). The electro-mechanical linear model can accurately describe only a fraction of the full operating range of the smart material actuators. The nonlinear behavior influences not only the design force and displacement of active material actuator, but also the maximum available mechanical energy and the required electrical energy. The hysteresis of the stress-strain and electric displacement-electric field characteristics relates to the electro-mechanical energy loss and the subsequent temperature increase of the material, with further influence on the strain capabilities. The first sustained attempts to characterize the non-linear behavior of piezoelectric materials under high-stress conditions were related to naval transducer applications (Krueger and Berlincourt, (1961)). They related the deviations from a linear behavior to macroscopic quantities such as dielectric permittivity, piezoelectric coefficient, loss factor and coupling coefficients. Although this approach could not lead to efficient modeling of the material behavior due to exclusive consideration of macroscopic effects, it was extremely useful in recognizing and separating the basic responses of hard PZTs from that of soft PZTs. This early experiments showed that the tensor components from the constitutive equations varied significantly with the electro-mechanical boundary conditions and that the material presents time-history effects related to the previous loading conditions. This was explained later through the evolution of the remnant polarization vector associated
with each domain inside the poly-crystal structure. The tensors mentioned earlier had thus to be carefully defined in terms of experimental set-up conditions, failing to provide a comprehensive characterization of the material behavior.

From the required electrical energy/power point of view, early studies pointed out the strong dependence of dielectric permittivity on the stress and AC field amplitude applied (Krueger, (1967), (1968)). The same dependence of permittivity on the magnitude of the applied electric field was later noticed by Brennan et al. (1997) and Jordan et. al (2000). They measured the capacitance values of PZT wafers for different frequency and driving fields and found an almost linear increase with voltage. The capacitance variation further affects the power requirements of the piezoelectric actuator.

A different approach considered the microstructure through the concept of domain switching when explaining the non-linear behavior of PZT material. The domains inside a piezoelectric material crystal are defined as regions with the same direction of the remnant polarization vector. The polarization vector changes its direction (switches) under electro-mechanical loading. Carefully conducted experiments have been pursued to determine the polarization switch behavior under high electric fields and compressive stresses for differently doped PZT ceramics (Zhang et al., (1997), Lynch, (1996), Fan et al., (1999), Lin et al., (2000), Yang et al., (2000)). It was shown that while the ferroelectric switching can be reversed through the application of an electric field bigger than the coercive field (Figure 1c), the ferroelastic switching (Figure 1d) could not be reversed through further application of stress. The depolarization through $90^0$ domain motions can be viewed as a depolarization softening followed by a saturation hardening
Fan et al. (1999) explained this behavior through domain switching dynamics within the material. Accordingly to their work, the switching is initiated locally and then propagates throughout the crystal. The stress-induced 90° domains switching for hard PZT compositions occur at higher stresses than in the case of soft PZT (Zhang et al., (1997), Fan et al., (1999)).

Several attempts have been made to cross the bridge from the micro-mechanics of the crystal structure to the macroscopic properties of piezoceramics under high electromechanical driving conditions (Chen et al., (1997), Fan et al., (1999), Hwang et al., (2000), Huber et al., (2001)). The modeling effort so far was confined to the case of piezoelectric bulk material subjected to precisely known electro-mechanical excitation, or away from any applied boundary conditions, such that their influence is negligible. The modeling of stacked smart material actuators using micro-mechanics considerations is more complex because the electro-mechanical boundary conditions for every layer are not precisely known. Consequently, the actuators characterization was performed through measurement and data fitting rather basic modeling. Moreover, the thorough actuator characterization is usually performed by the end-user due to the scarcity of experimental data from the smart materials and actuators manufacturers regarding the non-linear switching behavior (Lee et al., (1999), Straub et al., (1999), Mitrovic et al., (1999), Pan et al., (2000)). The behavior of the piezoceramic stack actuators intended for rotocraft applications was evaluated at University of Maryland (Lee et al. (1999)), University of California, LA (Mitrovic et al., (1999), (2000)), Boeing (Straub et al., (1999)), etc. Additionally, important design-oriented information regarding the mechanical stiffness,
energy density and load amplitude, temperature effects and durability was retrieved. Several solutions have been proposed in literature for the application of the mechanical load: dead weight (Lee et al., (1999)), MTS machine (Mitrovic et al., (1999), (2000)), variable impedance by the means of a variable stiffness spring (Straub et al., (1999)) or variable, and constant stiffness spring mounted in series with the smart material actuator (Pan et al., (2000)).

1.4 PRESENT INVESTIGATION

Recognizing the scarcity of experimental data of engineering significance provided by active material actuators manufacturers, the present research proposed a method for investigating the smart materials actuators performances in quasi-static and low frequency dynamic regimes, using a general-to-specific approach. In the first phase, an extensive review was conducted among active materials linear actuators manufacturers with the goal of identifying the current state-of-the-art of the smart material actuation technology. With an assumed linear behavior for the smart materials behavior, the survey employed energy-specific, efficiency and price metrics to evaluate the current state of the smart materials actuators market. Throughout this survey, data from manufacturers was used to perform calculations. The second phase considered modeling and characterization of high stroke/ high force smart materials actuators. During this task the PiezoSystems Jena PAHL 120/20 piezoelectric and the Etrema AA140J025 magnetostrictive actuators were modeled and thoroughly characterized using quasi-linear models. Although the simple linear model of the piezoelectric direct and converse effects is able to provide a first-order estimate for the behavior of the smart materials actuators as used in the survey,
measurements shown that the intrinsic non-linearity associated with the response of the material under high level driving fields cannot be neglected. Using the gathered experimental data, the quasi-static models were tuned, revealing consistent active material behavior patterns, when subjected to varying frequency, pre-stress level and applied electric field. Current microstructure theories relating the observed piezoelectric actuator behavior to the dynamics of polarization domains inside the active material ceramic were used to explain the observations. The last phase detailed the design steps and the optimization issues that must be considered when actuation systems employing smart material technology are considered.
2. CRITICAL SURVEY OF COMMERCIALLY AVAILABLE ACTUATORS

2.1 INTRODUCTION

The development of solid-state induced-strain actuators has entered the production stage, and actual actuation devices based on these concepts are likely to reach the applications market. An increasing number of vendors are producing and marketing solid-state actuation devices based on induced-strain principles. However, the performance of the basic induced-strain actuation materials used in these devices, and the design solutions used in their construction, are found to vary from vendor to vendor. This variability aspect presents a difficulty for the application engineer who simply wants to utilize the solid-state induced-strain actuators as prime movers in their design, and does not intend to detail the intricacies of active materials technology.

Recognizing this need, this survey set out to perform a comparison of commercially-available induced-strain actuators based on a common criterion: the amount of energy that they can deliver, and the density of this energy per unit volume, unit mass, and unit cost. Additionally, this survey also compares the efficiency with which various induced-strain actuators convert the input electrical energy into output mechanical energy for use in the application. The comparison is done using vendor-supplied information. This
survey is the continuation of the effort to evaluate the smart materials actuators market using an engineering approach, initiated at Virginia Tech (Giurgiutiu et al., (1995)).

2.2 SIMPLIFIED DESCRIPTION OF A SOLID-STATE ACTUATOR

In order to compare solid-state actuators of various material types and different operation principles, two overall performance parameters were selected: ISA displacement, $u_{ISA}$, measured in mm; and internal stiffness, $k_i$, measured in kN/mm or N/µm. The ISA displacement, $u_{ISA}$, is the result of the induced-strain effect, which is the basic property of the active material.

Due to actuator compressibility, the external load, $F(u_e), F(0)=0$, produces an elastic displacement, $F/k_i$, where $k_i$ is the internal stiffness (Figure 8). From the point of view of actuator effectiveness, the elastic compressibility displacement represents a loss. Since the internal stiffness of the actuator is finite, the application of an external load will always be accompanied by a compressibility loss. Hence, an induced-strain actuator under load $F$ will output only a fraction of its induced-strain displacement, $u_{ISA}$. Under load, $F$, the actuator output displacement, $u_e$, is given by:

$$u_e = u_{ISA} - \frac{F}{k_i}$$

(2)
When the external reaction load, $F$, is zero, the actuator output displacement, $u_e$, is maximum since no compressibility losses take place. The actuator displacement under zero external load is commonly known as "free stroke". Measurement of the actuator free stroke gives the value of the induced-strain actuator displacement, $u_{ISA}$. For nonzero external load, the actuator displacement, $u_e$, is always less than the induced-strain displacement, $u_{ISA}$. As the external load increases, the actuator displacement gets progressively smaller. Eventually, a point is reached where the external load is such that the compressibility loss balances the induced-strain displacement, and the resulting output displacement is zero. In other words, the actuator is "blocked". The actuator blocked load is given by

$$F_{\text{blocking}} = k_i \cdot u_{ISA}.$$ \hfill (3)

Consider now that the external load, $F$, varies linearly with the output displacement, $u_e$, as for example in the presence of an external spring, $k_e$, as shown in Figure 8. Thus:

$$F = k_e \cdot u_e.$$ \hfill (4)

Note that, in this case, the external load is entirely reactive, i.e., it takes place only in response to the actuator output displacement, $u_e$. If the actuator output displacement is zero, then the external load is also zero. After substitution and simplification, one gets an expression for the output displacement, $u_e$, in terms of the stiffness ratio, $r = k_e/k_i$, i.e.,

$$u_e = \frac{1}{1 + r} u_{ISA}.$$ \hfill (5)
As the external stiffness, $k_e$, increases, the reaction force, $F$, also increases, and compressibility losses lead to diminishing output displacement. As the external stiffness tends to infinity, the whole induced-strain displacement, $u_{ISA}$, is consumed internally, and the output displacement vanishes. This corresponds to the previously discussed "blocked" condition. Beyond this point, no further increase in the reaction force is possible. Thus, the maximum force of the actuator is realized when the actuator is blocked, i.e.,

$$F_{\text{max}} = k_i \cdot u_{ISA}$$  \hspace{1cm} (6)

2.3 ENERGY CONSIDERATIONS

2.3.1 Output energy

Under quasi-static conditions, the output energy is half the product between the force and the output displacement, i.e.,

$$E_e = \frac{1}{2} k_e \cdot u_e^2$$  \hspace{1cm} (7)

Substitution of Equation (5) into Equation (7) yields the expression of output energy in terms of stiffness ratio, $r$, as:
The variable part of Equation (8) is the output energy coefficient:

\[ E'_e(r) = \frac{r}{(1+r)^2} \left( \frac{1}{2} k_i u_{ISA}^2 \right) \]

(9)

A plot of \( E'_e(r) \) as a function of \( r \) is given in Figure 9. The function \( E'_e(r) \) is zero for both "free" \( (r=0) \) and "blocked" \( (r \to \infty) \) conditions, and has a maximum at \( r = 1 \). The \( r = 1 \) condition when \( k_e = k_i \), is called "stiffness match". Thus, the maximum value of the output energy that can be delivered by an induced-strain actuator under the most favorable conditions is \( E_{e,max} = \frac{1}{4} k_i u_{ISA}^2 \).

2.3.2 Example

An actuator produces a free stroke \( u_{ISA} = 120 \, \mu m \), and has an internal stiffness \( k_i = 370 \) kN/mm. Under the most favorable conditions (i.e. at stiffness match), the output energy is

\[
E_{e,max} = \frac{1}{4} \left( \frac{1}{2} \right) 370 \, kN/mm \times (120 \, \mu m)^2 = 0.666 \, J
\]

2.3.3 Output Energy Densities

In order to compare the output performance of induced-strain actuators of different shapes and sizes, allowance must be made for their differences in volume and mass. This study uses two output energy densities: the specific output energy per unit volume and
the specific output energy per unit mass. They are computed by simply dividing the maximum output energy by the volume and the mass of the actuator, respectively.

2.3.4 Energy Conversion Efficiency

The output mechanical energy delivered at the output end of an induced-strain actuator is the result of electromagnetic energy applied at the input end of the induced-strain actuator. The conversion of electromagnetic energy into mechanical energy that takes place inside the actuator is a highly coupled process (Giurgiuțiu et al., 1996). However, using simplified electric and magnetic energy expressions, one can derive first order approximations for the energy transformation efficiency that can serve as a basis for comparison between various actuators.

A first order approximation of the input electrical energy of solid-state induced-strain actuators based on electroactive materials (PZT and PMN), is given by:

\[ E_{cl} = \frac{1}{2} CV^2, \]  \hspace{1cm} (10)

where \( C \) is the capacitance, and \( V \) is the voltage.

For solid-state induced-strain actuators based on magnetoactive materials (TERFENOL), a first approximation to the input electrical energy is given by:

\[ E_{cl} = \frac{1}{2} LI^2, \]  \hspace{1cm} (11)

where \( L \) is the inductance and \( I \) is the current.
2.4 DATA COLLECTION

A large variety of induced-strain actuators are presently available in the commercial market. During the survey, we collected as much data as possible by directly contacting the vendors and manufacturers of these products. A template of relevant input data was drafted. The template contained data entries for the induced-strain actuator and for the active material inside the actuator. Data entries regarding the induced-strain actuator were grouped under two headings: "General Data of the ISA Device" and "Data about the Active Material (PZT, PMN, TERFENOL, etc.)". These were detailed as follows:

"General Data of the ISA Device"

- Manufacturer (name, address, FAX/Phone, contact point)
- Device identification
- Description (10 word max.)
- Maximum (free stroke) displacement, mm
- Maximum force, N
- Stiffness, kN/mm
- Length, mm
- Outside diameter, mm (or width \(\infty\) thickness, for rectangular cross-section, mm \(\infty\) mm)
- Mass, kg
- Volume, cm\(^3\)
- Voltage, V, or current, A, as appropriate.
- Capacitance, \( \mu F \), or inductance, mH, as appropriate
- Price, $

"Data about the Active Material (PZT, PMN, TERFENOL, etc.)"

- Active material diameter, mm (or width and thickness, for rectangular cross-section, mm\(^2\))
- Active material length, mm
- For stacked actuators, the layer thickness, mm, and the number of layers
- Nonlinearity index, or a representative curve of the output displacement against electrical input

Table 4 Basic data for selected induced strain actuators.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Type</th>
<th>Max. Free Expansion</th>
<th>Max. Force</th>
<th>Price</th>
<th>Active Material Outside Diameter</th>
<th>Active Material Inside Diameter</th>
<th>Active Material Area</th>
<th>Active Material Length</th>
<th>Stiffness</th>
<th>Active Material Volume</th>
<th>Active Material Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polytet PI</td>
<td></td>
<td>uISA (( \mu )m)</td>
<td>F (N)</td>
<td>($)</td>
<td>( D_o ) (mm)</td>
<td>( D_i ) (mm)</td>
<td>A (mm(^2))</td>
<td>ki (kN/mm)</td>
<td>VISA (mm(^3))</td>
<td>mISA (g)</td>
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<tr>
<td>PZT (P-245.70)</td>
<td>HVPZT</td>
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<td>2000</td>
<td>2010</td>
<td>10</td>
<td>78.5</td>
<td>101</td>
<td>32.0</td>
<td>7929</td>
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<td>PMN (E100P-4)</td>
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<td>265</td>
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<td>60</td>
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<td>HVPZT</td>
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<td>28000</td>
<td>4530</td>
<td>31.75</td>
<td>791.3</td>
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<td>28000</td>
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<td>791.3</td>
<td>180.34</td>
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<td>TOKIN</td>
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<td>3500</td>
<td>366</td>
<td>11.5X11.5</td>
<td>N/A</td>
<td>132.3</td>
<td>20</td>
<td>190.217</td>
<td>2000</td>
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<tr>
<td>ASB171C801</td>
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<td>588</td>
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<td>N/A</td>
<td>25</td>
<td>200</td>
<td>5.5</td>
<td>50000</td>
<td>40.0</td>
</tr>
</tbody>
</table>

Based on the above data, we set out to calculate the following comparative data:

- Apparent free strain, %:
• Apparent volume, cm³:
• Apparent density, 10^3 \( \text{kg/m}^3 \):
• Maximum deliverable energy per unit mass J/kg:
• Maximum deliverable energy per unit volume, J/cm³
• Maximum deliverable energy per unit cost, J/$1000

The data template was sent to several prominent manufacturers of ISA materials and devices. The manufacturers contacted in our survey are listed below in alphabetical order. Underlined are the manufacturers from which data has been received to date.

1. **Burleigh Instruments, Inc.,** Burleigh Park, Fishers, NY 14453
2. **EDO Corporation,** 2645 South 300 West, Salt Lake City, Utah 84115
3. **Etrema Products, Inc.,** 2500 North Loop Drive, Ames, Iowa 50010
4. **Piezo Kinetics, Inc.,** P. O. Box 756, Pine St. & Mill Rd., Bellefonte, PA 16823
5. **Piezo Systems, Inc.,** 186 Massachusetts Ave., Cambridge, MA 02139
6. **TRS Ceramics Inc.,** Suite J, 2820 E. College Avenue, State College, PA 16801
7. **Polytec PI, Inc.,** 3001 Redhill Ave., Bldg. 5-102, Costa Mesa, CA 92626
8. **Tokin America, Inc.,** 155 Nicholson Ln, San Jose, CA 95134
9. **Kinetic Ceramics, Inc.,** 26242 Industrial Blvd., Hayward, CA 94545

The response of the manufacturers was extensive. Out of the large number of entries, we selected 12 representative actuators. These include the actuators with the most outstanding performance from each vendor. For comparison, some actuators with lower performance were also included. Table 4 presents the basic data for the 12 selected actuators. The length, diameter, volume and mass data in Table 4 only refers to the active
material contained inside the actuator. For actuators without casing, these data is practically all that is required.

Table 5 Basic data and mechanical performance of six induced strain actuators with casing and pre-stress mechanism

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>μ ISA (μm)</td>
<td>(mm)</td>
<td>(mm)</td>
<td>% V (mm³)</td>
<td>m (g)</td>
<td>kg/m³</td>
<td>Eₔ (J)</td>
<td>Eₑ/V ISA (J/dm³)</td>
<td>Eₑ/m ISA (J/kg)</td>
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<tr>
<td>Polytec PI</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-245.70</td>
<td>HVPZT</td>
<td>120</td>
<td>18</td>
<td>125</td>
<td>0.096</td>
<td>31793</td>
<td>154</td>
<td>4844</td>
<td>0.05760</td>
<td>1.8117</td>
<td>0.3740</td>
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<tr>
<td>P-246.70</td>
<td>HVPZT</td>
<td>120</td>
<td>39.8</td>
<td>140</td>
<td>0.086</td>
<td>174086</td>
<td>830</td>
<td>4768</td>
<td>0.36000</td>
<td>2.0679</td>
<td>0.4337</td>
</tr>
<tr>
<td>P-247.70</td>
<td>HVPZT</td>
<td>120</td>
<td>50</td>
<td>142</td>
<td>0.085</td>
<td>276675</td>
<td>980</td>
<td>3517</td>
<td>0.72000</td>
<td>2.5837</td>
<td>0.7347</td>
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<tr>
<td>P-844.60</td>
<td>LVPZT</td>
<td>90</td>
<td>20</td>
<td>137</td>
<td>0.066</td>
<td>43018</td>
<td>215</td>
<td>4998</td>
<td>0.06581</td>
<td>1.5299</td>
<td>0.3061</td>
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<td></td>
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<td></td>
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<tr>
<td>D125160</td>
<td>HVPZT</td>
<td>160</td>
<td>38.1</td>
<td>185.42</td>
<td>0.086</td>
<td>211289</td>
<td>1450</td>
<td>6683</td>
<td>0.49034</td>
<td>2.3207</td>
<td>0.3382</td>
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<td>HVPZT</td>
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<td>38.1</td>
<td>218.44</td>
<td>0.092</td>
<td>248915</td>
<td>1163</td>
<td>4672</td>
<td>0.61290</td>
<td>2.4623</td>
<td>0.5270</td>
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<tr>
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<td></td>
<td>170</td>
<td>19.6</td>
<td>213</td>
<td>0.080</td>
<td>64233</td>
<td>500</td>
<td>7784</td>
<td>0.01987</td>
<td>0.3093</td>
<td>0.0397</td>
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Table 6 Mechanical performances of selected induced strain actuators.

<table>
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<tr>
<th>Identification</th>
<th>Apparent Density</th>
<th>Free Strain</th>
<th>Apparent Young's Modulus</th>
<th>Maximum Output Energy</th>
<th>Output Energy per Active Material Volume</th>
<th>Output Energy per Active Material Mass</th>
<th>Output Energy per Unit Cost</th>
<th>Cost per Unit of Energy</th>
<th>Price/Eₑ ($)/mJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polytec PI</td>
<td></td>
<td></td>
<td>E (GPa)</td>
<td>Eₑ (J)</td>
<td>Eₑ/V ISA (J/dm³)</td>
<td>Eₑ/m ISA (J/kg)</td>
<td>Eₑ/Price (mJ / $1000)</td>
<td>Price/Eₑ ($)</td>
<td></td>
</tr>
<tr>
<td>PZT (P-245.70)</td>
<td>7800</td>
<td>0.119</td>
<td>41.2</td>
<td>0.0576</td>
<td>7.265</td>
<td>0.931</td>
<td>28.7</td>
<td>$ 34.90</td>
<td></td>
</tr>
<tr>
<td>PZT (P-246.70)</td>
<td>7800</td>
<td>0.120</td>
<td>40.8</td>
<td>0.3600</td>
<td>7.338</td>
<td>0.941</td>
<td>72.4</td>
<td>$ 13.82</td>
<td></td>
</tr>
<tr>
<td>PZT (P-247.70)</td>
<td>7800</td>
<td>0.120</td>
<td>41.6</td>
<td>0.7200</td>
<td>7.487</td>
<td>0.960</td>
<td>91.1</td>
<td>$ 10.97</td>
<td></td>
</tr>
<tr>
<td>PZT (P-844.60)</td>
<td>7800</td>
<td>0.082</td>
<td>71.4</td>
<td>0.0658</td>
<td>5.988</td>
<td>0.768</td>
<td>14.1</td>
<td>$ 70.88</td>
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</tr>
<tr>
<td>EDO Corp.</td>
<td></td>
<td></td>
<td>E (GPa)</td>
<td>Eₑ (J)</td>
<td>Eₑ/V ISA (J/dm³)</td>
<td>Eₑ/m ISA (J/kg)</td>
<td>Eₑ/Price (mJ / $1000)</td>
<td>Price/Eₑ ($)</td>
<td></td>
</tr>
<tr>
<td>PMN (E100P-4)</td>
<td>7850</td>
<td>0.092</td>
<td>41.1</td>
<td>0.0108</td>
<td>4.373</td>
<td>0.557</td>
<td>39.3</td>
<td>$ 25.46</td>
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<tr>
<td>PMN (E300P-3)</td>
<td>7850</td>
<td>0.098</td>
<td>24.9</td>
<td>0.0485</td>
<td>2.969</td>
<td>0.378</td>
<td>89.0</td>
<td>$ 11.23</td>
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</tr>
<tr>
<td>PMN (E400P-1)</td>
<td>7850</td>
<td>0.096</td>
<td>21.6</td>
<td>0.0279</td>
<td>2.506</td>
<td>0.319</td>
<td>105.2</td>
<td>$ 9.50</td>
<td></td>
</tr>
<tr>
<td>PMN (E400P-4)</td>
<td>7850</td>
<td>0.100</td>
<td>20.4</td>
<td>0.0630</td>
<td>2.548</td>
<td>0.325</td>
<td>112.5</td>
<td>$ 8.89</td>
<td></td>
</tr>
<tr>
<td>Kinetic Ceramics</td>
<td></td>
<td></td>
<td>E (GPa)</td>
<td>Eₑ (J)</td>
<td>Eₑ/V ISA (J/dm³)</td>
<td>Eₑ/m ISA (J/kg)</td>
<td>Eₑ/Price (mJ / $1000)</td>
<td>Price/Eₑ ($)</td>
<td></td>
</tr>
<tr>
<td>D125160</td>
<td>7000</td>
<td>0.111</td>
<td>28.0</td>
<td>0.4903</td>
<td>4.280</td>
<td>0.611</td>
<td>108.2</td>
<td>$ 9.24</td>
<td></td>
</tr>
<tr>
<td>D125200</td>
<td>7000</td>
<td>0.111</td>
<td>27.9</td>
<td>0.8129</td>
<td>4.295</td>
<td>0.614</td>
<td>112.9</td>
<td>$ 8.86</td>
<td></td>
</tr>
<tr>
<td>TOKIN</td>
<td></td>
<td></td>
<td>E (GPa)</td>
<td>Eₑ (J)</td>
<td>Eₑ/V ISA (J/dm³)</td>
<td>Eₑ/m ISA (J/kg)</td>
<td>Eₑ/Price (mJ / $1000)</td>
<td>Price/Eₑ ($)</td>
<td></td>
</tr>
<tr>
<td>ASB171C801</td>
<td>8000</td>
<td>0.085</td>
<td>44.0</td>
<td>0.0199</td>
<td>3.974</td>
<td>0.497</td>
<td>33.8</td>
<td>$ 29.59</td>
<td></td>
</tr>
</tbody>
</table>
For actuators with casing and pre-stress mechanism, more data is required. The survey showed that many commercially available induced-strain products are delivered as basic units, without casing and pre-stress mechanism. We could identify three manufacturers that offer induced-strain products with casing and pre-stress mechanism. These manufacturers are Polytec PI, Tokin, and Kinetic Ceramics.

The vendor Polytec PI produces a large variety of induced-strain actuators based on PZT electroactive material. Their products usually contain a pre-stressing spring. The piezoceramic actuators developed by Tokin and Kinetic Ceramics does not commonly include pre-stressing spring, and hence, care must be taken to ensure that only compressive load is applied. This precaution comes from the small strength in tension that is common to all ceramic materials. A number of seven actuators that can be delivered with casing and pre-stress mechanism were included in our study. For these actuators, the basic data must also include the overall length, diameter, volume and mass of the actuator. For the seven actuators included in our study, these data is given in Table 5. Note that the overall dimensions, volume and mass of the complete actuators are considerably larger than those for the active material alone. It is expected that this aspect will make the energy density of the actuator with casing and pre-stress mechanism sensibly lower than that of the active material alone.
2.5 Survey Results

2.5.1 Data Reduction

The collected data was processed to yield the following entries:

- Maximum output energy, defined as $E_{\text{max}} = \frac{1}{4} \left( \frac{1}{2} k_i \cdot u_{\text{ISA}}^2 \right)$, where $k_i$ is the internal stiffness of the actuator and $u_{\text{ISA}}$ is the maximum displacement (free stroke).

- Volume-based energy density, defined as reference energy per unit volume.

- Mass-based energy density defined as reference energy per unit mass.

- Cost-based energy density defined as reference energy per unit cost.

- Energy-based price defined as the cost of a unit of reference energy.

- Energy transformation efficiency.

Table 7 Comparison of mechanical and electrical performance of selected induced strain actuators

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Polytec P1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZT (P-245.70)</td>
<td>0.05760</td>
<td>1000</td>
<td>0.5</td>
<td>183</td>
<td>0.500</td>
<td>0.2500</td>
<td>23.0%</td>
</tr>
<tr>
<td>PZT (P-246.70)</td>
<td>0.36000</td>
<td>1000</td>
<td>3.28</td>
<td>178</td>
<td>0.500</td>
<td>1.6400</td>
<td>22.0%</td>
</tr>
<tr>
<td>PZT (P-247.70)</td>
<td>0.72000</td>
<td>1000</td>
<td>6.56</td>
<td>178</td>
<td>0.500</td>
<td>3.2800</td>
<td>22.0%</td>
</tr>
<tr>
<td>PZT (P-844.60)</td>
<td>0.06581</td>
<td>100</td>
<td>43.00</td>
<td>999</td>
<td>0.110</td>
<td>0.2150</td>
<td>30.6%</td>
</tr>
<tr>
<td><strong>EDO Corp.</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMN (E100P-4)</td>
<td>0.01080</td>
<td>800</td>
<td>0.09</td>
<td>14</td>
<td>0.500</td>
<td>0.0288</td>
<td>37.5%</td>
</tr>
<tr>
<td>PMN (E300P-3)</td>
<td>0.04851</td>
<td>800</td>
<td>1.10</td>
<td>46</td>
<td>0.500</td>
<td>0.3520</td>
<td>13.8%</td>
</tr>
<tr>
<td>PMN (E400P-1)</td>
<td>0.02789</td>
<td>800</td>
<td>0.50</td>
<td>28</td>
<td>0.500</td>
<td>0.1600</td>
<td>17.4%</td>
</tr>
<tr>
<td>PMN (E400P-4)</td>
<td>0.06300</td>
<td>800</td>
<td>1.25</td>
<td>28</td>
<td>0.500</td>
<td>0.4000</td>
<td>15.8%</td>
</tr>
<tr>
<td><strong>Kinetic Ceramics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D125160</td>
<td>0.49034</td>
<td>1000</td>
<td>8.20</td>
<td>178</td>
<td>0.500</td>
<td>4.1000</td>
<td>12.0%</td>
</tr>
<tr>
<td>D125200</td>
<td>0.61290</td>
<td>1000</td>
<td>10.50</td>
<td>178</td>
<td>0.500</td>
<td>5.2500</td>
<td>11.7%</td>
</tr>
<tr>
<td><strong>TOKIN</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>AE1010D16</td>
<td>0.00805</td>
<td>150</td>
<td>5.4</td>
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<td>N/A</td>
<td>0.0608</td>
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<tr>
<td>ASB171C801</td>
<td>0.01987</td>
<td>150</td>
<td>15</td>
<td>N/A</td>
<td>N/A</td>
<td>0.1688</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

29
The maximum output energy, \( E_{\text{max}} = \frac{1}{4} \left( \frac{1}{2} k_i u_{\text{max}}^2 \right) \), was obtained directly from the data provided by the manufacturers. The energy densities per unit volume and unit mass were obtained by dividing by the relevant volume and mass.

2.5.2 Results Based on Active Material Volume and Mass

Table 6 presents the mechanical performance of all the 12 selected induced strain actuators based on active material volume and mass. The maximum output energy and the output energy densities based on active material volume and mass are given. Also given in Table 6 are the output energy per unit cost, and its inverse, the cost of a unit of output energy.

2.5.3 Results Based on Actuator Volume and Mass

Table 5 presents, in its last two columns, the mechanical performance energy indicators based on volume and mass. By comparing the entries in Table 5 and in Table 6 for the same actuator, it can be seen that the addition of casing and pre-stress mechanism significantly lowers the energy density of the device.

2.5.4 Results Based on Energy Conversion Efficiency

A comparison of the mechanical and electrical performance of the actuators is given in Table 7. The maximum output mechanical energy, and the electrical energy necessary to produce this output are given. Division of the output mechanical energy by the input electrical energy yields the energy conversion efficiency of the induced-strain actuator. The energy conversion efficiency is given in the last column of Table 7.
Table 8 Ranking of 12 induced-strain actuators in terms of maximum output energy, energy densities with respect to active-material volume and mass, cost, and with respect to actuator volume and mass for the actuators with a casing and pre-stress mechanism.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Maximum Output Energy</th>
<th>Output Energy per Active Material Volume</th>
<th>Output Energy per Active Material Mass</th>
<th>Output Energy per Unit Cost</th>
<th>Output Energy per Actuator Total Volume</th>
<th>Output Energy per Actuator Total Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polytec PI</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PZT (P-245.70)</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>PZT (P-246.70)</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>PZT (P-247.70)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PZT (P-844.60)</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>6</td>
<td>6</td>
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<td><strong>EDO Corp.</strong></td>
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<td></td>
</tr>
<tr>
<td>PMN (E100P-4)</td>
<td>11</td>
<td>5</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMN (E300P-3)</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMN (E400P-1)</td>
<td>9</td>
<td>12</td>
<td>12</td>
<td>4</td>
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<tr>
<td>PMN (E400P-4)</td>
<td>6</td>
<td>11</td>
<td>11</td>
<td>2</td>
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<td></td>
</tr>
<tr>
<td><strong>Kinetic Ceramics</strong></td>
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<tr>
<td>D125160</td>
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<td>7</td>
<td>6</td>
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<td>4</td>
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<tr>
<td>D125200</td>
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<td>6</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<tr>
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<td>12</td>
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<td>9</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASB171C801</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

2.5.5 Ranking of the Induced-Strain Actuators

Table 8 presents the ranking of the 12 induced-strain actuators considered in the study. The ranking is done in decreasing order. The actuators with the best performance are ranked first, while those with the less desirable performance are ranked last. Examination of Table 8 indicates that some rank variations exist that can be related to the type of criteria used. However, a clear distinction can be drawn between actuators with high performance, and actuator with low performance. It is interesting to note that actuators of widely different performance ranking exist within the product line of the same manufacturer, as for example under the entries for Polytec PI. The ranking is just a first-order comparison of the considered actuators, since every specific application will have its own requirements.
2.5.6 Consistency Checks

To impair increased credibility to the numerical results, and to filter out any inadvertent discrepancies, a number of consistency checks were performed. First, it was noticed that our study computed the energy density of active material by simply dividing the maximum output energy by the active material volume and mass provided by the manufacturer. However, the energy density could also be correlated with other basic material data, such as: free strain, $e_{ISA}$, defined as the ratio between the free displacement, $u_{ISA}$, and the length, $L$, and the apparent Young's modulus, $E$, defined from the stiffness formula $k_i = EA/L$, where $A$ is the cross-sectional area of the stack.

The free strain was calculated by dividing the free displacement by the active material length. The apparent Young's modulus was calculated from the formula $k_i = EA/L$ when the active material stiffness was available. This is especially the case with glued stacks, where the compliance of the adhesive layer lowers significantly the stiffness of the stack. In certain situations, the active material stiffness was not available. Then, general values of the material Young's modulus as available from the manufacturer were used to calculate the active material stiffness.
It should be noted that the volume-based energy density can also be calculated by the well-known formula \( E_{\text{max}} / V = \frac{1}{4} \left( \frac{1}{2} E \varepsilon_{\text{MA}}^2 \right) \). A further division by the equivalent material density, \( \rho \), yields the mass-based energy density, \( E_{\text{max}} / m = \frac{1}{\rho} \frac{1}{4} \left( \frac{1}{2} E \varepsilon_{\text{MA}}^2 \right) \). Based on these observations we performed consistency checks on our results.

### 2.6 Discussion of Survey Results

The results presented in Tables 4 through 8 were used to construct comparative charts presented in Figures 10 through 13.

![Comparison of output energy per active material volume](image)

![Comparison of output energy per active material mass](image)

**Figure 11**  
(a) Comparison of output energy per active material volume;  
(b) Comparison of output energy per active material mass

These charts give a quick visual perception of the relative performance of the actuators in terms of maximum output energy, output energy densities, and energy conversion efficiency.
Figure 10 presents a comparison of the maximum output energy that can be extracted from the commercially available induced-strain actuators currently on the market. It seems that, at present, only two companies, Polytec PI, Inc. and Kinetic Ceramics, have products with large energy capability (P-254-70, D125200, D125160, and P246-70). When this aspect was discussed with the other vendors, it was argued that they can also manufacture products with similar output energy, but on special order.

Figure 11a compares the energy density per unit volume. For high-performance induced-strain actuators, a mid-range value of around 6-7.5 J/dm³ seems to be common.

Figure 11b compares the energy density per unit mass of active material. For high-performance induced-strain actuators, a mid-range value of around 0.7-0.9 J/kg seems to be common.

Figure 12  a) Comparison of output energy density per unit volume for 7 induced-strain actuators with casing and pre-stress mechanism, b) comparison of output energy density per unit mass for 7 induced-strain actuators with casing and pre-stress mechanism
Figure 12 compares the energy densities per unit volume and unit mass for the seven actuators that can also be delivered with casing and pre-stress mechanism. The energy densities based on active material volume and mass are contrasted with the energy densities based on total actuator volume and mass. It can be noticed that the addition of casing and pre-stress mechanism greatly reduces the energy density of the device. This reduction is more pronounced in terms of energy density per unit volume than in terms of energy density per unit mass.

![Figure 12](image)

**Figure 13**

- a) Comparison of output energy per unit cost for commercially available induced strain actuators
- b) Comparison of electrical into mechanical energy conversion efficiency

For applications where volume and mass are essential, as for example in the aerospace industry, the direct incorporation of the induced-strain actuator without casing and pre-stress mechanism in the host structure is highly desirable since it leads to important volume and mass savings.
Figures 13a compares energy density based on unit cost in mJ/$1000. Examination of this chart indicates that some companies are capable of marketing products with remarkably lower specific energy cost than others. This observation does not seem to be influenced by the processing method, since it equally affects adhesively-bonded and co-fired actuator products.

Finally, Figure 13b presents a comparison of the energy conversion efficiency from input electrical energy into output mechanical energy. It should be mentioned that the formulae used to estimate the required input electrical energy are only first order approximations since they ignored the variation or capacitance and inductance in the presence of an applied external load. Also, the energy dissipation in internal electric resistance and in hysteresis is, for the moment, ignored. Figure 13b shows that, for high-performance induced-strain actuators based on electroactive materials the energy transformation efficiency is around 20%. This does not mean that the remaining 80% of energy is lost, but that it simply does not get converted into mechanical energy and is sent back to the power source.
3. MODELING OF ACTIVE MATERIAL ACTUATORS

BEHAVIOR

3.1 MODELING OF PIEZOELECTRIC ACTUATORS

3.1.1 Quasi-static model

The piezoelectric actuator consists of an active material stack with geometry similar to the one shown in Figure 6c, which is pre-stressed at 350N inside the steel casing with the use of an internal spring (Figure 14). The space between the steel casing and the piezoelectric stack is filled with an epoxy resin that protects the stack from shocks. The piezoelectric stack the force/displacement through a steel pushing-rod.

The quasi-static model assumes that the application of electrical and mechanical loads to the actuator constitutes as an equilibrium process. Consequently, the static super-position of loads can be applied.

Modeling the PiezoSystems Jena piezoelectric actuator implied assumptions on the geometry of the device and on the behavior of the active material. The following active
material stack geometric parameters: (a) cross-sectional area, $A$, (b) layer thickness, $t$, and (c) length of the stack, $L$. The effect of the pre-stress spring was taken into account through the value of the pre-stress force and the spring stiffness. The piezoelectric material used is a soft PZT, with the characteristics provided by the manufacturer. We have used the linear piezoelectric equations (Equation (1)) for describing the active material behavior.

These equations were simplified for the case were only the 3-direction effects (in the direction of remnant polarization) were considered significant. With this assumption, we have neglected the effects that take place in the plane perpendicular to the 3-direction (e.g. interaction with the resin layer, non-uniform distribution of the electric field through the active material, etc.). Consequently, using the contracted notation, the simplified piezoelectric equations are:

$$ S_3 = s_{33}^E T_3 + d_{33} E_3 \quad D_3 = d_{33} T_3 + \varepsilon_3^T E_3 $$

Consistent with the above equations, the convention of positive displacements in the $x_3$ direction (expanding the stack) and negative compressive forces was assumed.

We have also neglected the influence of the finite stiffness of the electrodes placed between the active material layers. Assuming the principle of electrical and mechanical loads superposition, we developed the quasi-static model considering that the loading of the active material stack in was applied in 3 steps:

a) Apply the pre-stress force $F_0$ through the internal spring $k_{SP}$. During this
process, the active material stack and the internal spring are compressed;

b) Apply a force $F_e^{(1)}$ by compressing the series assembly made of the actuator and an external spring $k_e$. During this process, both the stack and the external spring are compressed, while the internal spring expands;

c) Apply a positive voltage $V$. The stack expands, remaining in compression.

The loads superposition principle is valid if the active material stack piezoelectric and stiffness properties are assumed to remain constant throughout the entire process. After the first step, the stack displacement, strain, and stress and are given by:

$$\Delta L^{(a)} = \frac{L}{k_{ST}^{(E)}} \quad S_{3}^{(a)} = \frac{1}{L} k_{ST}^{(E)} F_0 \quad T_{3}^{(a)} = \frac{F_0}{A}$$  \hspace{1cm} (13)$$

The internal active stack stiffness $k_{ST}^{(E)}$ was evaluated based on the closed loop material compliance value reported by the manufacturer:

$$k_{ST}^{(E)} = \frac{A}{s_{33}^{(E)} L}$$ \hspace{1cm} (14)$$

The application of an external mechanical load $F_e$ (step (b)) leads to the following force equilibrium (Figure 15):

$$F_{ST}^{(b)} = F_e^{(b)} + F_{SP}^{(b)}$$ \hspace{1cm} (15)$$
Consequently, the displacement increment from equilibrium state (a) is \( \Delta L^{(b)} = \frac{F_e^{(b)}}{k_{ST}^{(E)} + k_{SP}} \), and the strain and the stress follows as:

\[
S_3^{(b)} = \left(1 + \frac{k_{SP}}{k_{ST}^{(E)}}\right) \frac{F_0 + F_e}{L \left(k_{ST}^{(E)} + k_{SP}\right)}
\]

\[
T_3^{(b)} = \left(1 + \frac{k_{SP}}{k_{ST}^{(E)}}\right) \frac{F_0 + F_e}{A \left(1 + \frac{k_{SP}}{k_{ST}^{(E)}}\right)}
\] (16)

The application of the voltage (step (c)) does not change the free-body diagram (Figure 15), but adds an positive offset to the stack displacement, given by:

\[
\Delta L^{(c)} = \frac{Ad}{t} \frac{V}{k_{e} + k_{SP} + k_{ST}^{(E)}}
\] (17)

The corresponding strain and stress are:

\[
S_3^{(c)} = \left(1 + \frac{k_{SP}}{k_{ST}^{(E)}}\right) \frac{F_0 + F_e^{(c)}}{L \left(k_{ST}^{(E)} + k_{SP}\right)} + \frac{d_{33}}{t} \frac{k_{ST}^{(E)}}{k_{e} + k_{SP} + k_{ST}^{(E)}} V
\]

\[
T_3^{(c)} = \frac{F_0}{A} + \frac{F_e^{(c)}}{A \left(k_{ST}^{(E)} + k_{SP}\right)} - \frac{d_{33} \cdot V}{t \cdot s_{33}^{(E)}} \frac{k_{e} + k_{SP}}{k_{ST}^{(E)} + k_{e} + k_{SP}}
\] (18a)

\[
T_3^{(c)} = \frac{F_0}{A} + \frac{F_e^{(c)}}{A \left(k_{ST}^{(E)} + k_{SP}\right)} - \frac{d_{33} \cdot V}{t \cdot s_{33}^{(E)}} \frac{k_{e} + k_{SP}}{k_{ST}^{(E)} + k_{e} + k_{SP}}
\] (18b)

Due to the presence of the internal spring, the external force will differ from the force manifested in the active material stack (Equation (17)). The external force \( F_{e}^{(c)} \) can be directly compared with the experimental data:

\[
F_{e}^{(c)} = F_{e}^{(b)} - A \frac{d_{33} \cdot V}{t \cdot s_{33}^{(E)}} \frac{k_{e}}{k_{e} + k_{SP} + k_{ST}^{(E)}}
\] (19)
3.1.2 Dynamic linear model

The dynamic model describes the response of the piezoelectric actuator under in-phase electro-mechanical loading. The wave equation can model the response of an elastic medium under harmonic excitation. This approach, initially used by Liang et al., (1994) in conjunction with thin PZT wafers modeling, was later expanded to piezoelectric and magnetostrictive actuators by Giurgiutiu et al., (1994), and Ackerman et al., (1996). The one-dimensional wave equation is used as the start-up point:

$$\frac{\partial^2 u}{\partial \tau^2} = c^2 \frac{\partial^2 u}{\partial x_3^2}$$  \hspace{1cm} (20)

where $\tau$ is the time, $x_3$ is the coordinate perpendicular on the electrodes, and $c$ is the complex wave speed, defined by:

$$c^2 = \frac{1}{\rho \cdot s_{33}^{(E)} (1 - i\eta)}$$  \hspace{1cm} (21)

The parameter $\eta$ accounts for averaged mechanical losses, including active material damping, for losses that take place in the bonding between electrodes and piezo-material, and for losses in the surrounding resin. The term $s_{33}^{(E)*} = s_{33}^{(E)} (1-i\eta)$ will be further used as a complex compliance.

It should be noted from the beginning that, although the piezoelectric stack is not homogeneous, the material between two consecutive electrodes could be considered as such. Moreover, the non-uniformity associated with the electric field distribution within
the dielectric material is expected to yield second order terms in the low frequency regime in which the actuator was tested. Based on this hypothesis, the stack is further modeled as a homogeneous structure, with no electrodes in between. The electric field throughout this homogeneous body is taken equal with the one developed within a single piezoelectric layer subjected to a given voltage: \( E_3 = V / t \). This model is valid as long as the excitation circular frequency is much smaller than the ratio of the active material wave speed to the stack length.

If the origin of the coordinate system is taken as the bottom of the stack (Figure 14) the boundary conditions associated with Equation (20) are:

\[
\begin{align*}
  u(x = 0, \tau) &= 0 \tag{22a} \\
  A \cdot T_3(x = L, \tau) &= F_{ST}(\tau) \tag{22b}
\end{align*}
\]

where \( F_{ST} \) is the force exerted by the active material stack on the internal spring and the external structure. \( F_{ST} \) is made up of two components: (i) a bias force \( F_b \) given by the internal spring pre-stress \( F_0 \), external pre-load \( F_e \) and the bias voltage; (ii) an oscillatory component \( F_\tau(\tau) \) that can be related to the velocity of the top of the stack through:

\[
F_\tau(\tau) = -Z_{EXT} \left( \frac{\partial u}{\partial x_3} \right)_{x_3=L} \tag{23}
\]

where \( Z_{EXT} \) is the impedance of the structure external to the piezostack.

The excitation voltage has the form:
\[ V(\tau) = V_0 + V_a e^{i\omega \tau} \]  
(24)

Denote \( \gamma = \omega / c \) and assume a displacement solution of the form:

\[ u(x_3, \tau) = \left( C_1 \sin(\gamma x_3) + C_2 \cos(\gamma x_3) \right) e^{i\omega \tau} - C_3 x_3 \]  
(25)

Apply the first boundary condition (Equation (22a)) to yield \( C_2 e^{i\omega \tau} = 0, \forall \ \tau \). Then, \( C_2 = 0 \). The strain at \( x_3 = L \):

\[ S_3(x_3 = L, \tau) = \left( \frac{\partial u_3}{\partial x_3} \right)_{x_3=L} = \gamma C_1 \cos(\gamma L) e^{i\omega \tau} - C_3 \]  
(26)

Use the strain written above and apply the hypothesis of uniform electric field distribution between the electrodes to rewrite the first Equation (12) at \( x_3 = L \) as

\[ \gamma C_1 \cos(\gamma L) e^{i\omega \tau} - C_3 = s_{33}^{(E)} T_3(L, \tau) + \frac{d_{33}^*}{t} \left( V_0 + V_a e^{i\omega \tau} \right) \]  
(27)

where \( V_0 \) and \( V_a \) are the bias and the amplitude voltages respectively, and \( d_{33}^* = d_{33} (1-i\lambda) \), where \( \lambda \) accounts for the imperfect piezoelectric energy conversion (Holland, 1967).

Replace the stress \( T_3 \) at \( x_3 = L \) with the sum of the bias and oscillatory force (Equation (23)), using the displacement given by Equation (25) to obtain:

\[ \gamma C_1 \cos(\gamma L) e^{i\omega \tau} - C_3 = s_{33}^{(E)} T_3(L, \tau) + \frac{d_{33}^*}{t} \left( V_0 + V_a e^{i\omega \tau} \right) \]  
(28)

Since Equation (28) must hold for any time \( \tau \), the constants \( C_1 \) and \( C_3 \) result as:
The bias force $F_b$ in Equation (28) can be written using the stress given by Equation (18b) for $V=V_0$:

$$F_b = F_0 + F_e^{(b)} \cdot \frac{k^{(E)}_e}{k^{(E)}_e + k_{SP}} = \frac{d^{\ast}}{t} \cdot \frac{V_0}{s_{33}^{(E)} t \cdot s_{33}^{(E)}} \cdot \frac{k^{(E)}_e + k_{SP}}{k^{(E)}_e + k_{SP} + k_e}$$

With this, the displacement can be further expressed as:

$$u(x,t) = \frac{d^{\ast}_3 V_a e^{i\omega t}}{t \left(1 + \frac{s_{33}^{(E)} \cdot i\omega Z_{EXT} \tan (\gamma L)}{A} \gamma \right)} \frac{\sin(\gamma x)}{\gamma \cos(\gamma L)}$$

$$\quad + x \left[ \frac{s_{33}^{(E)} A}{F_0 + F_e^{(b)} k^{(E)}_e + k_{SP}} + \frac{d^{\ast}_3 V_0}{k^{(E)}_e + k_{SP} + k_e} \right]$$

For the generic mass-spring-damper external load sketched in Figure 14, the mechanical impedance can be written as:

$$Z_{EXT} = i m \frac{\omega^2 - \omega_n^2}{\omega} + c_d \quad \text{with} \quad \omega_n = \left(\frac{k_{SP}}{m}\right)^{1/2}$$

Then, at $x_3=L$, the displacement of the actuator becomes:

$$u_{ST} = \frac{d^{\ast}_3 V_a \tan (\gamma L) e^{i\omega t}}{t \gamma \left(1 + \frac{s_{33}^{(E)} A \cdot i\omega Z_{EXT} \tan (\gamma L)}{\gamma} \right)} + \frac{F_e^{(1)}}{k^{(E)}_e + k_{SP}} + \frac{L d^{\ast}_3 V_0}{k^{(E)}_e + k_{SP} + k_e}$$
Although the impedance $Z_{EXT}$ is singular at $\omega = 0$, the denominator in the first term of Equation (30) is not singular as frequency goes to zero. If numerical errors are expected to appear (e.g. the case of small frequency), the impedance expression can be replaced in Equation 30 by the equivalent formulation of dynamic stiffness through

$$k_d = i\omega Z_{EXT} = -m\left(\omega^2 - \omega_n^2\right) + i\omega c_d$$

(33)

For the tested frequencies (1-5 Hz), the formulations with impedance and dynamic stiffness were numerically equivalent.

The force exerted in the piezostack follows from the first part of Equation 12, after replacing the strain by the displacement derivative with respect to $x_3$ ($S_3 = \partial u / \partial x_3$):

$$F_{ST}(x_3 = L, \tau) = -F_{block} \frac{V_a}{V_0} e^{i\omega \tau} \left( \frac{1}{1 + \frac{S_{33}^{(E)p}}{A} \frac{\omega Z_{EXT}}{\gamma} \tan(\gamma L)} + F_0 + F_e^{(b)} \frac{k_{ST}^{(E)p}}{k_{SP} + k_{ST}^{(E)p}} + F_{block} \left( \frac{k_e + k_{SP} + k_{ST}^{(E)p}}{k_e + k_{SP} + k_{ST}^{(E)p}} + \frac{V_a}{V_0} e^{i\omega \tau} \right) \right)$$

(34)

where $F_{block}$ is the blocked force for the bias voltage, given by

$$F_{block} = -\frac{d^*}{S_{33}^{(E)p}} \frac{A}{l} V_0$$

(35)

The external force can be expressed as:

$$F_e(\tau) = F_{ST}(\tau) - k_{SP} u_{ST}(\tau) - F_0$$

(36)
The second part of Equation (12) relates the electric displacement to the stress and electric field intensity. Electric losses (through conduction) can be modeled as $\varepsilon_{33}^* = \varepsilon_{33}(1 - i\delta)$. Since we are interested in the electric current modeling, the second part of Equation (12) will be re-written as:

$$D_3 = d_{33}^* \frac{F_{ST}(\tau)}{A} + \frac{\varepsilon_{33}^*}{t} \left( V_0 + V_d e^{i\omega t} \right) \quad (37)$$

where the electric field was replaced by the linear approximation $E = V / t$.

The electric displacement $D$ is related to the free charge distribution $\rho_f$ by the equation (Maxwell, 1891): $\text{div } D = \rho_f$. For one-dimensional geometry, the equation reduces to:

$$Q = D_3 A \quad (38)$$

where $Q$ is the free charge accumulated on the electrodes. The instantaneous current, written as the partial derivative of the free charge with time takes the form:

$$i_{ST}(\tau) = \frac{dQ}{d\tau} = \frac{L}{i\omega V_a e^{i\omega t}} \left[ d_{33}^* F_{\text{block}} \left( \frac{1}{1 + i \frac{S_{33}^{(E)} Z_{\text{EXT}}}{A} \frac{\omega}{\gamma} \tan(\gamma L)} - 1 \right) \frac{\varepsilon_{33}^* A}{t} \right] \quad (39)$$

The instantaneous power is given by $p(\tau) = i_{ST}(\tau) \cdot v(\tau)$, and the average active power per cycle can then be written as:

$$P_a = f \cdot \int_{\text{cycle}} p(\tau) d\tau \quad (40)$$
3.2 MODELING OF MAGNETOSTRICTIVE ACTUATOR IMPEDANCE

Analysis of a magnetostrictive actuator follows closely the development of piezoelectric actuator, shown in Equations (12)-(40), if linear behavior for the Terfenol-D material is assumed. The biased one-dimensional linearized constitutive equations for Terfenol-D (Butler, 1998) define the mechanical strain and magnetic flux as:

\[
\begin{align*}
S_3 &= s_{33}^{(H)} T_3 + d_M H \\
B_3 &= d_M T_3 + \mu_3^{(T)} E_3
\end{align*}
\]  

(41)

where \(d_M\) is the piezomagnetic coefficient relating applied magnetic field to induced strain, \(H\) is the applied magnetic field, \(B\) is the magnetic flux density, and \(\mu_3^{(T)}\) is the magnetic permeability. Similarly with the piezoelectric material case, magnetic and mechanical losses inside the magnetostrictive material can be modeled using complex compliance \(s_{33}^{(H)*}\), complex magnetic permeability \(\mu_3^{*}\), and complex piezomagnetic coefficient \(d_M^{*}\):

\[
\begin{align*}
s_{33}^{(H)*} &= s_{33}^{(H)} (1 - i\eta_M) \\
\mu_3^{(T)*} &= \mu_3^{(T)} (1 - i\delta_M) \\
d_M^{*} &= d_{33} (1 - i\lambda_M)
\end{align*}
\]  

(42)

According to Ackerman (1996), the electrical impedance of a magnetostrictive actuator could be written as:

\[
Z_M = \frac{i\omega N^2 A_M}{L_M} \left[ \frac{(d_M^{*})^2}{s_{33}^{(H)\nu} Z_{\text{EXT}}} + \frac{1}{i\omega k_M^{(H)\nu}} \frac{\tan(\gamma L_M)}{\gamma L_M} + \left( \frac{\mu_3^{(T)*}}{s_{33}^{(H)\nu}} \right)^2 \right] + R
\]  

(43)

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where \( A_M \) and \( L_M \) are the cross-sectional area and the length of the magnetostrictive rod, \( k_M^{(H)^*} \) is the complex static stiffness, \( N \) is the total number of turns in the actuator coil, and \( R \) is the resistance of the actuator coil.
4. EXPERIMENTAL EVALUATION OF INDUCED STRAIN ACTUATORS

4.1 PiezoSystems Jena PAHL 120/20 EXPERIMENTAL SET-UP

The active component of the PAHL 120/20 actuator is a piezoelectric stack, which is pre-stressed at approximately 350N by an internal spring located inside the steel casing. The mechanical bias is needed to prevent tensile stresses in the stack during static and dynamic applications. Although not specifically indicated by the manufacturer, the material piezoelectric coefficient and the compliance values (Table 9) suggest a soft piezoceramic-type material.

The piezoelectric PAHL 120/20 actuator (Figure 16) measurements were taken in quasi-static and dynamic regimes. The maximum current capability of the power supply limits the maximum frequency when operating a capacitive load (Figure 17). Given the 0.1 A maximum current of the TREK amplifier, for a voltage duty-cycle
from 0 to 150 V, the PAHL 120/20 piezoelectric actuator can be driven at frequencies smaller than $f_C \approx 5$Hz.

Table 9 PiezoSystems Jena actuator properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum displacement</td>
<td>120 $\mu$m</td>
</tr>
<tr>
<td>Voltage range</td>
<td>-10 – 150V</td>
</tr>
<tr>
<td>Actuator internal stiffness</td>
<td>30 kN/mm</td>
</tr>
<tr>
<td>Maximum tensile force</td>
<td>350 N</td>
</tr>
<tr>
<td>Maximum blocked force</td>
<td>3500 N</td>
</tr>
<tr>
<td>Capacitance (for small strength electrical fields)</td>
<td>42 $\mu$F</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Length</td>
<td>126 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>Piezoelectric coefficient $d_{33}$ ($10^{-12}$ m/V)</td>
<td>700</td>
</tr>
<tr>
<td>Compliance $s_{33}^E$ ($10^{-12}$ m²/N)</td>
<td>20.8</td>
</tr>
<tr>
<td>Coupling factor $\kappa_{33}$</td>
<td>0.65</td>
</tr>
<tr>
<td>Stack length $L$</td>
<td>118 mm</td>
</tr>
<tr>
<td>Stack area $A$</td>
<td>64 mm²</td>
</tr>
<tr>
<td>Layer thickness $t$</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

We performed static measurements in both loaded and no-load conditions, using different set-ups. In both cases, the active material stack received the signal from the Hewlett Packard HP 3312A function generator, amplified by the high-voltage TREK 750/50 amplifier (Figure 18). This signal was further tapped and sent to the HP5460B digital oscilloscope. A parallel second circuit consisting from a resistor and a normally open switch was added for discharging the stack. The displacement of the actuator was recorded using the Philtec D100 optical displacement transducer. The signal coming from the optical displacement transducer conditioning circuit had to be offset to facilitate its display on the Tektronix TDS210 digital oscilloscope (Figure 19a). For the test under no-load condition, the optical transducer was placed directly against the top of the actuator.
For the dynamic case, the current going through the actuator had to be measured for a full characterization. This was accomplished by measuring the voltage drop across a calibrated $1\,\Omega$ resistor placed in series with the actuator. This signal was passed through a low-pass filter and then displayed on the HP5460B.

![Experimental set-up for dynamic testing of PAHL 120/20](image)

Figure 18

---

For the tests under the loaded condition, the load was applied using a LongYear compression frame. A proving ring with a dial gauge were used to measure the force.

![Schematic for the experimental set-up for the piezoelectric PAHL 120/20 actuator](image)

(b) compression frame

Figure 19

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to a calibrated accuracy of +/-7.2N (Figure 19b). The load applied in this way has a spring-like behavior, due to the presence of the proving ring. The force was transformed into displacement by the proving ring, readily read on the dial gage. For the dynamic measurement, the proving ring was instrumented with strain gages placed in full bridge. The strain gage bridge was calibrated using the calibration sheet of the proving ring. The signal from the bridge was filtered using a low-pass filter and then displayed on the TDS210 oscilloscope. For the dynamic case, all four waveforms were synchronized using the input signal from the function generator and applying the same trigger settings to the two oscilloscopes. The synchronized waveforms were downloaded into a PC, using the serial communication and the GPIB interfaces.

4.2 MEASUREMENTS PROCEDURES AND RESULTS FOR PAHL 120/20

4.2.1 Introduction

The purpose of the experiments was to evaluate the blocked force, the characteristic loops, and the mechanical and electrical envelopes for the piezoelectric actuator, in quasi-static and dynamic regimes. The characteristic loops can be force-displacement, current-voltage, and voltage-displacement correlations. The mechanical envelope for a given frequency is a triple correlation between extreme values for voltage, displacement and force (Figure 20). Likewise, the electrical envelope correlates force and voltage with the maximum or the active power.

First, measurements were taken for the unloaded condition (free displacements), in order to verify the experimental apparatus and compliance with the manufacturer information.
For these measurements, no special procedure needed to be devised, because no significant ferroelastic switching was expected to occur.

The load applied with the compression frame has a spring-like behavior, due to the presence of the proving ring, calling for a different measuring procedure than the ones used in the case of dead weight machine (Lee et al., 1999) or MTS machine (Mitrovic et al., 2000).

For dynamic characterization, the electric current information is also important, since in correlation with voltage provides the actuator power consumption. Besides, the direct piezoelectric effect (the second part of the Equation (1)) can be used for tuning and checking the model.

4.2.2 Blocked force

The blocked force is the force generated by the actuator when the displacement is completely impeded. This condition is ideally achieved when the actuator has to push against a body of infinite stiffness, because all the induced-strain is consumed internally, and no displacement is recorded externally. Since the compression frame has a finite stiffness, two methods were devised to simulate the condition of zero external displacement. Although defined for the static case, the methods were extended to the dynamic case as well.

Method 1 Apply first the voltage $V_1$ that generates a tip displacement and then load
the stack in quasi-static regime until the tip displacement is brought back to zero. The following steps were applied: a) discharge the stack; b) set to zero the voltage going into the stack and turn on the amplifier, with zero voltage drop on the actuator; c) capture on the oscilloscope display the signal from the sensor and the signal into the actuator; d) compress the entire assembly until the dial gauge indicates 1-2 divisions – this is for ensuring the contact between the top of the stack and the bottom of the spacer; e) adjust the cursor on the oscilloscope to superimpose on the signal coming from the displacement transducer; f) increase the voltage on the DC power source until the voltage equals $V_i$; during this step, the stack expands and the proving ring compresses; g) compress the assembly until the signal coming from the sensor superimposes on the cursor. When this step is completed the stack recovers its initial length and the material is in compression. The force dial gauge indicates now the blocked force for the voltage set in step f).

**Method 2** applies first a pre-stress level, and then adjusts the voltage until the initial length of the stack is recovered. This method required the following steps: a) ensure that the stack is discharged; b) with the amplifier switched on, zero the voltage, match the cursor on the oscilloscope with the sensor signal; c) set a pre-stress level, by compressing the entire assembly; d) increase the voltage until the sensor signal on the oscilloscope display superimposes on the cursor and read the blocked force and the voltage.

**Method 3** is a modification of the first method for the dynamic case. The steps are as follows: a) discharge the unloaded stack, with the amplifier switched off and bring the stack and the external load in contact until strain gage signal is zero; b) set the desired
voltage cycle and turn on the amplifier – the voltage, displacement and force will harmonically cycle between zero and a maximum value; place one of the oscilloscope cursors on the minimum value of the displacement; c) compress the assembly until the maximum value of the displacement waveform coincides with the cursor set at step b); d) record the blocked force value as the minimum value of the force cycle.

Figure 21 Blocked force variation with voltage: theory and experiment

Figure 21 shows a comparison of results obtained with the three methods. Consistency between the three methods is observed for voltages up to 50% of the maximum value. At higher voltages the results diverged, with a 14% maximum difference observed at 150V. The theoretical blocked force can be readily obtained from Equation (12a) by setting \( S_3 = 0 \), with the expression given in Equation 35. As seen from Figure 21, the linear theory over-predicts the quasi-static blocked force values.
4.2.3 Static measurements

To completely describe the piezoelectric actuator behavior under quasi-static conditions, the variation of the actuator displacement under the combined effect of applied force and voltage was recorded. Due to the spring-like character of the load, distinction had to be made between the measurement procedures for the points situated above and respectively below the external stiffness line (Figure 20). For the points situated above the external stiffness line, the following steps were taken when recording the displacement response under combined electromechanical load:

a) set the bottom of the spacer in contact with the top of the actuator and apply a slight compression force, up to 10 – 15N (1-2 divisions on the force dial gauge);
b) move the first cursor until it superposes on the displacement transducer signal (v1);
c) compress the whole assembly up to a given pre-stress level $F_i$, indicated on the force dial gauge: both the actuator and the proving ring compresses;
d) apply voltage $V_k$: the stack expands and the proving ring further compresses;
e) move the second cursor until it superposes on the displacement signal on the oscilloscope display (v2);
f) read the compressive force on the dial gauge; the displacement of the stack is given by the signed difference $v_2-v_1$, times a scaling factor;
g) repeat steps for the next voltage $V_{k+1} > V_k$;
h) repeat steps a) to g) for the next initial level of pre-stress $F_{i+1} > F_i$.

Data points evaluated using the above mentioned procedure lie on curves parallel to and located above the external stiffness curve. It follows that the experimental procedure
cannot be used for the determination of the points situated below the external stiffness curve, because this would imply the application of tensile force to the active material actuator.

![Graph](image)

**Figure 22** PiezoSystems Jena PAHL 120/20 behavior described by the force-displacement-voltage correlations

For points below the external stiffness curve, the following procedure was used:

a) discharge the stack;

b) apply the voltage $V_i$ on the unloaded stack;

c) bring the top of the actuator in contact with the bottom of the spacer and apply a slight compression (10-15N), to ensure mechanical contact;

d) apply the voltage $V_k > V_i$ and record the force on the dial gauge and the displacement from the oscilloscope

e) repeat step d) for the rest of the voltages up to the maximum voltage;

f) repeat from step a), changing $V_i$ with $V_{i+1} > V_i$ at step b).
Again, the data points will lie on curves parallel to the external stiffness curve, but situated below it (Figure 20).

4.2.4 Dynamic measurements

The procedure for dynamic measurements resembles the one used for quasi-static measurements, although some modifications had to be done, to account for the dynamic character of the actuation, with the excitation voltage of the form given in Equation 24, when $V_a = V_0$. Particularly, the points situated below the external stiffness curve in the mechanical envelope (Figure 20) could not be measured with a procedure similar to the one used in static testing, because this would have implied either a tensile force on the actuator, or a bias voltage different from the voltage amplitude. While the first scenario would have damaged the piezoelectric stack, the data obtained with a bias voltage different from the amplitude voltage did not fit on the same characteristic curves with the points above the external stiffness curve in the mechanical envelope. This is due to the significant variation of the $d_{33}$ with the bias voltage, consistent with the static measurements results.

In order to account for points below the external stiffness curve, the dynamic data was complemented with no-load measurements of the piezoelectric actuator for each frequency.

For the points situated above and on the external stiffness curve, the following procedure was used for each tested frequency:

a) set the desired level of pre-stress $F_i$;
b) set-up the biased voltage signal on the function generator and turn on the amplifier; the voltage should cycle between zero and \( V_k \), while the force will cycle between \( F_i \) and a maximum value;

c) apply identical trigger settings for the two oscilloscopes, such that the waveforms for displacement, force, current and voltage are synchronized, and download the waveforms into the PC system;

d) repeat step for the next voltage cycle (from zero to \( V_{k+1} > V_k \)), until the maximum allowable voltage;

e) repeat b) and c) for the next pre-stress level \( F_{i+1} > F_i \), until the pre-stress corresponds to the blocked force for maximum voltage, measured previously.

4.3 ETREMA AA-140J025 EXPERIMENTAL SET-UP

The power consumption is a major concern when the design targets the optimal functioning of the entire system, composed by the active material actuator, power supply and the actuated structure. To determine the power consumption one has to accurately know the variation of the actuator impedance with frequency and current. Usually, information released by vendor refers to the frequency variation under the conditions of very small currents. In this study, we covered the full range of currents, and investigated the variation of the magnetostrictive actuator impedance with both current and frequency.

The ETREMA AA-140J025 actuator (Figure 23a) consists of a Terfenol-D rod surrounded by a coil that applies a magnetic field oriented along the rod axis when the current passes through the windings (Figure 7a). Since the magnetostriction is optimized
when is both mechanically and magnetically biased, the ETREMA actuator employs disc springs and permanent magnets.

The mechanical pre-stress orients the magnetic domains normal to the compression axis, thus maximizing the displacement. The role of the bias magnetic field is to bring the zero-point operation within the middle of the quasi-linear strain-magnetic field characteristic. This is especially needed for magnetostrictive actuators, which pronounced non-linearity and significant hysteresis behavior.

The magnetostrictive actuator was driven with a signal generated by the HP3312A function generator and then amplified by the Compact Power MAC-01 amplifier (Figure 23b). Since the gain of the amplifier was found to vary with the input voltage, calibration measurements had to be taken, in order to ensure the actuator was not driven at higher than acceptable currents. For the actual impedance measurements, a series circuit containing the magnetostrictive actuator and a 1Ω calibrated resistor was built. The
series resistor was built using constantan wire, due to its low resistance dependency with temperature, and thus on current. Its purpose was to allow direct reading of the instantaneous current through the circuit. The harmonic voltage signals across the 1Ω resistor and across the entire series circuit were simultaneously displayed on the Tektronix TDS 210 oscilloscope. This allowed for the independent measurement of the voltage, electric current and relative phase lag induced by the magnetostrictive actuator. Thus, the magnetostrictive actuator impedance could be measured. For small currents, the magnetostrictive actuator impedance was also measured using the HP 4914A impedance/gain analyzer.

Table 10  
Etrema AA-140J025 magnetostrictive actuator properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>±70 μm</td>
</tr>
<tr>
<td>Current range</td>
<td>0 – 3A RMS</td>
</tr>
<tr>
<td>Temperature range</td>
<td>-20 – 100 °C</td>
</tr>
<tr>
<td>Maximum dynamic force</td>
<td>±890 N</td>
</tr>
<tr>
<td>Maximum blocked force</td>
<td>1740 N</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>24.9 kN/mm</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>2.3 Ω</td>
</tr>
<tr>
<td>Inductance</td>
<td>3.5 mH</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>2.4 kHz</td>
</tr>
<tr>
<td>Length</td>
<td>198 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>47 mm</td>
</tr>
<tr>
<td>Number of turns in the coil</td>
<td>1070</td>
</tr>
<tr>
<td>Length of the Terfenol-D rod</td>
<td>152.4 mm</td>
</tr>
<tr>
<td>Area of the Terfenol-D rod</td>
<td>126.45 mm²</td>
</tr>
<tr>
<td>Density of Terfenol-D</td>
<td>9183 kg/m³</td>
</tr>
</tbody>
</table>
4.4 ETREMA AA-140J025 TESTING PROCEDURE

The magnetostrictive actuator measurements were taken at frequencies higher than 1kHz, due the following factors: a) actuator integrity, because the actuator electrical impedance is expected to be proportional with the frequency, and thus at lower frequencies one gets higher currents (Figure 17); b) the MAC01 amplifier has a minimum input voltage of 300mVRMS, that translates into a minimum output voltage of 43VRMS. The minimum output voltage combined with the 3A maximum allowable current for the magnetostrictive actuators restricts the operation above 700Hz.

The testing procedure consisted of:

a) Set an input voltage $U_k$, such that the current at 1kHz would not exceed 3A RMS;

b) Sweep the frequency between 1 kHz and 2 kHz in steps of 100Hz and record the voltage across the entire circuit $U$, the voltage across the $1\Omega$ calibrated resistor $U_1$, and the phase lag between these two signals

c) Calculate a new maximum input voltage $U_{k+1}$ using the impedance calculated with the data recorded in step b). Then, repeat steps a) and b), until $U_{k+1}$ would induce a current greater than 3A RMS, at 1kHz.
5. DATA PROCESSING AND COMPARISON WITH THEORETICAL PREDICTIONS

5.1 PiezoSystems Jena PAHL 120/20 QUASI-STATIC DATA

Comparison of the piezoelectric linear static model with experimental data shows acceptable results for zero force (Figure 24). However, the static model fails though to predict the quasi-static behavior under high force condition.

![Figure 24](image.png)

Figure 24 Comparison of the PiezoSystems Jena actuator static linear model prediction with experimental data

This may be attributed to the $90^\circ$ domain switching that occurs at high forces and which is not completely reversed upon return to zero. These deviations from the linear model were addressed through coefficient tuning, using a bivariate cubic regression method. The details of this process are presented in the follow-on section.
5.1.1 Actuator static stiffness

In the first stages of actuation process design, one has to check whether the actuator meets the energy and power requirements of the activated structure. In this step, the variation of the actuator stiffness with the input voltage and force is a key-parameter when deciding the smart material actuator energy capabilities and demands for quasi-static activation.

Without any simplifying assumptions on the geometry or the material behavior, the actuator bulk compliance, defined as the ratio displacement/force, could be determined from the experimental data. The only element of arbitrariness was introduced by the bivariate cubic regression that was applied to the actuator displacement with respect to applied voltage and external force. Since the bivariate regression was an approximation of the displacement, the derivatives of the regression function may not exactly follow the correspondent physical quantities, as they would be measured. Nevertheless, quantitative and especially qualitative statements can be inferred as to the behavior of the piezoelectric actuator, given the good accuracy of the regression (Figure 25).
In the bivariate cubic regression all but the free term were retained. The free term is not needed because the displacement of the active material actuator must be zero under no electro-mechanical loading. Thus:

\[ u = C_0 F^3 + C_1 F^2 V + C_2 FV^2 + C_3 V^3 + C_4 F^2 + C_5 F + C_6 V + C_7 F + C_8 V \]  \hspace{1cm} (44)

After determining all the \( C_i \) coefficients, the bulk actuator stiffness was modeled as the inverse of the partial derivative of \( u \) with respect to \( F \), i.e. \( k = (\partial u/\partial F)^{-1} \).

The results (Figure 26) indicate that the bulk stiffness of the piezoelectric actuator increased significantly with the level of applied mechanical load. The variation of the bulk stiffness with voltage is negligible.

5.1.2 Quasi-static piezoelectric and compliance coefficients

Besides the intrinsic behavior of the piezoelectric material under electro-mechanical loading, the actuator displacement also contains the influence of the pre-stress spring, electrodes and resin on the overall characteristics of the actuator. The non-uniform distribution of the electric field inside the active material layer also adds non-linearity to
the overall actuator behavior. Nevertheless, an approximate description of the smart material characteristics under electro-mechanical loading can be obtained, if we ignore the effect of electrodes, resin and electric field non-uniformity as higher order parameters. Under this assumption, the force in the active material stack $F_{ST}$ is simply the sum of the measured force and the force exerted by the pre-stress spring, which also depends on the actuator displacement, i.e.

$$F_{ST} = F_E + F_0 - k_{sp} \cdot u$$  \hspace{1cm} (45)$$

where $F_0$ is the initial pre-stress force, $k_{sp}$ is the pre-stress spring stiffness, $F_E$ is the external force, and $u$ is the actuator displacement. Substitution of Equation (45) into the regression equation (44) provided the full description of the active material actuator, in terms of the force in the active material, voltage and actuator displacement.

![Graph showing correlation between force, voltage, and stack displacement](image)

**Figure 27** Correlation between force, voltage and stack displacement relative to the initial deformation due to the internal spring pre-load
The resulting equation was cubic in $F_{ST}, V$ and $u$, evading an explicit formulation. Consequently, a numeric solution of the form $u = u(F_{ST}, V)$ was determined (Figure 27). The resulting formulation is still incomplete because the initial deformation of the stack due to the internal pre-load under short-circuit electrodes conditions is unknown. This initial deformation must be subtracted from $u$ to get the true active material stack deformation. However, this is not an impediment if the partial derivatives of the stack displacement are to be evaluated. Denote by $u_{ST,V}$ and $u_{ST,F}$ the partial derivatives of the stack displacement with voltage and force, pre-multiplied with appropriate constants such that the dimensions of piezoelectric coefficient $d_{33}$ and compliance $s_{33}$ are obtained, respectively:

$$u_{ST,V} = \frac{t}{L^0} \left( \frac{\partial u}{\partial V} \right)$$
$$u_{ST,F} = \frac{A}{L^0} \left( \frac{\partial u}{\partial F} \right) \quad \text{(46)}$$

If we assume that the piezoelectric material behavior is sufficiently well described by the law $S_{33} = s_{33}(V,F) \cdot F + d_{33}(V,F) \cdot V$, the displacement derivatives can also be written as:

$$u_{ST,F} = s_{33} + F \frac{\partial s_{33}}{\partial F} + A \frac{V}{t} \frac{\partial d_{33}}{\partial F}$$
$$u_{ST,V} = \frac{t}{A} F \frac{\partial s_{33}}{\partial V} + V \frac{\partial d_{33}}{\partial V} + d_{33} \quad \text{(47)}$$

It is apparent now that the voltage and force derivatives $u_{ST,F}$ and $u_{ST,V}$ differ from the compliance $s_{33}$ and piezoelectric coefficient $d_{33}$ by additive functions that cannot be reduced to zero or neglected unless more hypotheses are made, based on experiments. Without such hypotheses, the problem of finding the material coefficients under combined electro-mechanical load cannot be solved, as two functions are to be retrieved from one equation. A useful particular case is that of mechanically unloaded stack. In this
case, the variation of $d_{33}$ coefficient with voltage can be determined, since the term containing the compliance vanishes, and $d_{33} = u_{ST} / V$.

![Figure 28 Derivatives of displacement with force and voltage, approximating the material coefficients: a) $u_{ST,F}$; b) $u_{ST,V}$](image)

Another way of simplifying the problem (Mitrovic, 1999) is to neglect all terms but $s_{33}$ in the $u_{ST,F}$ expression. This would give qualitative results. A similar assumption was proposed for the estimation of the piezoelectric coefficient (ANSI/IEEE Std.176, (1987)). Under these assumptions, the compliance is seen to decrease with the increasing stress (Figure 28a) and not to vary significantly with the applied electric field. The qualitative analysis reveals that the piezoelectric coefficient is displaying a maximum value at approximately half the maximum electric field, and that its dependence on stress is not negligible (Figure 28b).

5.2 PIEZOSYSTEMS JENA PAHL 120/20 DYNAMIC DATA

5.2.1 Data processing

With no *a priori* knowledge regarding the piezoelectric actuator behavior under high-field in-phase electromechanical loading, a 3-dimensional test matrix (Figure 29)
covering the entire allowable operational envelope (frequency, voltages, and pre-stress level was devised.

<table>
<thead>
<tr>
<th>Voltage range</th>
<th>0 - 20 V</th>
<th>0 - 40 V</th>
<th>0 - 60 V</th>
<th>0 - 80 V</th>
<th>0 - 100 V</th>
<th>0 - 120 V</th>
<th>0 - 140 V</th>
<th>0 - 150 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>1150</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>1700</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>2300</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>2900</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Figure 29 Test matrix for dynamic measurements of the piezoelectric actuator PAHL 120/20

For each frequency/pre-stress/voltage case, four waveforms were recorded and further processed (displacement, force, current, voltage), except for the no external load case, when the force waveform was omitted. The raw data was processed in several stages as shown in Figure 30.

Figure 30 Data processing logic flow
After downloading the waveforms from the oscilloscopes into the PC, the data was processed using Matlab™ software. The first stage of data processing consisted of:

a) adjust the current and force related signals to account for the phase and amplitude change introduced by the analog low-pass filter, using the filter calibration;

b) filter out the spikes from the electric current, force and displacement related waveforms using a cascaded algorithm for outliers elimination;

c) apply a high-order Butterworth filter to all four waveforms. The phase introduced by the digital filter (the same phase for all waveforms) needs not to be accounted for, (Figure 31)
Figure 32. Comparison of experimental data with the model prediction for 5Hz, 1150 pre-stress and 0-100 V:

a) displacement waveform; 

b) force waveform; 

c) electric current waveform; 

d) instantaneous power waveform; 

e) displacement-force loop; 

f) electric current-voltage loop; 

g) voltage-displacement loop.
d) Use the calibration data for the proving ring, strain gages full-bridge, and the 1Ω resistor to convert electrical waveforms into force, electric current and displacement waveforms.

For illustration of how the dynamic data was processed, the following case will be presented in detail (Figure 31): frequency=5Hz; voltage range = 0-100V; pre-stress=1150N.

The next processing stage built the characteristics loops by first synchronizing the waveforms and then pairing them as follows: displacement vs. force, current vs. voltage, and displacement vs. voltage (Figure 32e, f, g). These characteristics loops for each frequency/pre-stress/voltage range were used for tuning the actuator dynamic model.

Finally, the mechanical and electrical envelopes were synthesized using the extreme values of the characteristic loops (Figure 33). Complete envelopes are given in Figures A1, A2 and A3, in APPENDIX. These envelopes give a general view of actuator capabilities and point to its usefulness when considered for specific applications.

![Figure 33 Piezoelectric PAHL 12/20 envelopes (5Hz): a) mechanical; b) peak power](image-url)
5.2.2 Model tuning and improvement

The model tuning was performed by comparison of the experimental data with the displacement, force, and power waveforms, and the force-displacement, displacement-voltage, and current-voltage characteristic loops (Figure 32). The influence of the model coefficients on the shape of the above-mentioned curves is summarized in Table 11.

Table 11 Correlation between tuning coefficients and experimental curves

| $d_{33}$ | proportional to the amplitude of the displacement waveform and the secant slope of the force-displacement characteristic loop; |
| $s_{33}^{(E)}$ | influences amplitudes of the force and displacement waveforms; the ratio of the stack stiffness $k_{ST}$ to the external dynamic stiffness $k_d$ influences the slope of the force-displacement loop |
| $\varepsilon_{33}$ | controls current amplitude on the loading path; |
| $\lambda$ | proportional with the hysteresis in the displacement-voltage characteristic loop |
| $\eta$ | no significant influence; |
| $\delta$ | global tilt of the current-voltage characteristic loop. |

For the chosen case-study, the numerical values of the eight tuning coefficients are given in Table 12.

Table 12 Model parameters tuned for operation at 5Hz, 1150N pre-stress, 0-100V

| $d_{33}$ | $680 \cdot 10^{-12}$ [m/V] |
| $s_{33}^{(E)}$ | $17 \cdot 10^{-12}$ [m²/N] |
| $\varepsilon_{33}$ | $7.3 \cdot 10^{-8}$ [F/m] |
| $\lambda$ | 0.16 |
| $\eta$ | 0.01 |
| $\delta$ | 0.25 |

The dynamic model as presented yields sinusoidal current waveforms, while the experimental results deviate from the harmonic form on the unloading path, as shown in Figures 32c and 32d. Particularly, during unloading, the measured current lags behind the model prediction. For a specific combination of frequency, voltage cycle and initial mechanical pre-stress, the instantaneous minimum current is smaller in absolute value...
than the maximum current. In order to account for these phenomena, the following numerical adjustments were applied to the dielectric permittivity and loss coefficients:

\[
\varepsilon = \varepsilon_0 \left[ 1 - 0.5(k_e - 1)f_e(t)(H(t_{\text{end}}) - H(t_{\text{start}})) \right] \tag{48a}
\]

\[
\delta = \delta_0 \left[ 1 + 0.5(k_e - 1)f_e(t)(H(t_{\text{end}}) - H(t_{\text{start}})) \right] \tag{48b}
\]

where \(k_\delta\) and \(k_e\) account for the current phase shift and amplitude reduction respectively on the unloading path, \(H(t)\) is the Heaviside function with \(t_{\text{start}}\) and \(t_{\text{end}}\) being the start and the end of the electro-mechanical unloading. The error function \(f_e\) must ensure a smooth transition from the initially assumed values of \(\varepsilon_0\) and \(\delta_0\) on the loading half-cycle to the corresponding peak values on the unloading half-cycle, \(\varepsilon_0(1-k_\delta)\) and \(\delta_0(1+k_\delta)\), respectively. For the present model, \(f_e\) was chosen such that the product \(0.5 f_e(t)(H(t_{\text{end}}) - H(t_{\text{start}}))\) is a Hanning window, with non-zero values on the unloading half-cycle (Figure 34).

![Figure 34](image-url)  
**Figure 34** Error function \(f_e\) acting on the unloading path

Retaining the model coefficients values given in Table 12, and taking \(k_e = 1.07\) and \(k_\delta = 2\), improved the current and the active power predictions as shown in Figure 35.
Thus, 8 parameters for model tuning were identified: \(d_0, \lambda, s_{33}^{(E)}, \eta, \varepsilon_0, \delta_0, k_\delta, k_\varepsilon\). Except for \(k_\delta\) and \(k_\varepsilon\), the other parameters act as average values per cycle. All eight coefficients are expected to change as the frequency, pre-stress level, and voltage range are varied. This variation is presented in tabular form in Table A1, in APPENDIX. The elastic energy losses coefficient \(\eta\) was not listed in Table A1, because it showed no significant influence on the actuator modeling. Thus, a generic value of \(\eta=0.01\) was used throughout the tuning process.

5.3 ETREMA AA-140J025 IMPEDANCE DATA

In order to determine the electrical impedance from the experimental data, the Etrema magnetostrictive actuator was electrically modeled as a series RL circuit. The entire electrical circuit could be simply represented in the phasors space as shown in Figure 36a. The impedance was determined as:

\[
Z_E = \frac{U_E}{I} = \frac{\sqrt{U^2 + U_I^2 - 2U_IU \cos(\phi)}}{U_I} \cdot 1
\]

(49)
With the available model parameters $s_{33}^{(H)}, \mu_3^{(T)}, d_M, \eta_M, \delta_M,$ and $\Lambda_M,$ the model was tuned using the experimental data shown in Figure 36b.

![Phasors diagram for the Etrema actuator measurement circuit; b) Etrema AA140J250 impedance for high currents](image)

Figure 36 a) Phasors diagram for the Etrema actuator measurement circuit; b) Etrema AA140J250 impedance for high currents

The upward shift of the impedance spectrum can be modeled through the variation of the $s_{33}^{(H)}, \mu_3^{(T)},$ and $d_M$ parameters.

### Table 13 Relative magnetic permeability tuning using the experimental impedance value for the magnetostrictive actuator

<table>
<thead>
<tr>
<th>Voltage across actuator [VRMS]</th>
<th>$\kappa_M = \frac{\mu_M}{\mu_0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\approx 0$</td>
<td>3.6</td>
</tr>
<tr>
<td>45.3</td>
<td>4.5</td>
</tr>
<tr>
<td>68.6</td>
<td>5.0</td>
</tr>
<tr>
<td>95.5</td>
<td>5.5</td>
</tr>
<tr>
<td>123</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Previous studies (Goodfriend, 1992) as well as manufacturer data, placed the compliance coefficient between $28 \cdot 10^{-12}$ and $47 \cdot 10^{-12} \text{ m}^2/\text{N},$ the relative magnetic permeability $\kappa_M = \frac{\mu_M}{\mu_0}$ between 3 and 10, and the piezomagnetic coefficient between 8 and 20 nm/A. The cycle-averaged values used by the magnetostrictive actuator model fall within these
ranges (Table 13).

The actuator impedance can be further broken down into real and imaginary parts. While this follows naturally for the model, since the impedance is written in complex form (Equation (43)), the equivalent real and imaginary impedance can be extracted from the experimental data as (Figure 37):

\[
\text{Re}(Z_E) = U \cos(\phi) - U_1; \quad \text{Im}(Z_E) = U \sin(\phi) \quad (50)
\]

Figure 37  Measured real (a) and imaginary (b) impedance of the magnetostrictive ETREMA actuator
6. DESIGN GUIDELINES FOR OPTIMAL ENERGY TRANSFER

6.1 USING THE DYNAMIC MODEL OF THE PIEZOELECTRIC ACTUATOR

Suppose the PiezoSystems Jena PAHL 120/20 is used to work against a one degree of freedom spring-mass-damper system, with the following characteristics: mass $m_e=10\text{kg}$; natural frequency $\omega_n=150\text{Hz}$, and a damping ratio $\zeta=0.05$. The requirements are for a 5 Hz frequency harmonic excitation and a 0.5 mm maximum relative displacement. The power supply specifications can be given in terms of maximum current or reactive power.

Since the actuator is capable of only 120$\mu$m maximum free displacement, the use of a displacement amplification mechanism (DAM) is required. At this stage of design, the DAM is considered as a black box, with the following characteristics: gain $G=7$, average

Figure 38 Actuation of a spring-mass-damper system with the PAHL 120/20 piezoelectric actuator through a displacement amplification mechanism

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power efficiency \( \eta_p = 0.8 \), and a phase lag between the input and output displacements \( \varphi_a \), such that:

\[
u_e(\tau) = G u'_e(\tau) e^{i \varphi_a}
\]

(51)

First, the external dynamic stiffness is determined in order to check whether the actuator is capable of meeting the requirements at the maximum allowed voltage. The balance of mechanical power through the DAM can be written as:

\[
F_e' \dot{u}_e' \eta_p = F_e \dot{u}_e
\]

(52)

where the \( F_e' \), \( u_e' \), and \( \dot{u}_e' \) are the force, displacement and velocity of the piezoelectric actuator tip, and \( F_e \), \( u_e \), and \( \dot{u}_e \) are the corresponding quantities acting at the external structure level. Combination of Equations (51) and (52) and use of the definition of impedance as the ratio of force to velocity yield:

\[
Z_{EXT} = \frac{G^2}{\eta_p} Z_e \ e^{i \varphi_e}
\]

(53)

where \( Z_e \) is the impedance of the actuated structure (Equation 31) and \( Z_{EXT} \) is the external impedance. The dynamic stiffness can be calculated as:

\[
k_d = i \omega Z_{EXT} = m_e \left( \omega_n^2 - \omega^2 \right) \ e^{i \varphi_e} \frac{G^2}{\eta_p}
\]

(54)

Using numerical values, \( \text{Re}(k_d) = 9.6 \cdot 10^6 \) N/m. Taking the mechanical envelope for 5 Hz and drawing a line with the slope equal to the external stiffness curve of 9.6 N/\( \mu \)m
(Figure 39), and intersecting this line with the 120 V force-displacement curve, yields an actuator displacement in excess of 75μm. If we multiply this value by the DAM gain, the available displacement of the structure will be higher approximately 525 μm, in excess of the required 500μm.

Figure 39   Find the design point by intersecting the external stiffness curve with the local linear interpolation of the force-displacement curve

The next step is to check whether the operating point lies within the electrical capabilities of the power supply. If the specifications of the available power supply are given in terms of maximum power, the designer should check whether the peak power for the given voltage cycle exceeds the power supply capability, using the corresponding electrical envelope (Figure A3d, in APPENDIX). If the specifications are given in terms of maximum current, a safe estimation of the peak current required from the actuator can be given:

\[ i_{\text{max}} = \omega C V_a = 2\pi f \left( \frac{L}{t} \frac{E}{A} \right) V_a = 0.103 \text{ A} \]  \hspace{1cm} (55)
For this calculation, the actuator properties listed in Table A1 in APPENDIX and a linear interpolation method were used

6.2 Optimal Quasi-Static Energy Transfer

The impact of the actuator stiffness on the design process is manifested not only in meeting the structure actuation requirements, but also in optimization algorithms. Optimal design for direct structural actuation with smart material devices usually implies the maximization of the energy transfer between the actuator and the activated structure by matching their impedances, for a given combination of frequency and electromechanical loading. The small strains capabilities of the smart materials actuators make necessary the use of an amplification mechanism, to achieve the required displacements in excess of hundreds of micrometers. The amplification mechanism itself represents an addition of mass and complexity to the entire assembly. Moreover, it is safe to assume that the size, weight and/or complexity of the amplification mechanism increase with the required gain. An optimal actuation design will thus have to consider also a minimization of the required gain, besides the maximization of the transfer energy.

Off-the-shelf smart material actuators generally display the same classes of output displacement, but various stiffnesses within each group (e.g. PiezoSystems Jena PAHL120/20, Physik Instrumente P 247-70 and Kinetic Ceramics D125120 actuators all have $u_{ISA} = 120\mu m$ free displacement output, but the manufacturers reported stiffness are ranging from 30kN/mm to 400 kN/mm). Before choosing the smart material actuator and designing the displacement amplification mechanism, one has to investigate whether
optimal structural behavior towards maximum transfer energy and minimum gain can be achieved, with the given structural stiffness, $k_\delta$, maximum required output displacement, $\delta$, and maximum free displacement of the active material actuator, $u_{ISA}$ and varying actuator internal stiffness, $k_i$. 

![Displacement amplification mechanism](image)

Figure 40 Quasi-static structural actuation of an aerodynamic load through a displacement amplification mechanism

The external structure is assumed to display a spring-like behavior, as for example in the case of flight control surfaces quasi-static actuation for relatively small deflections, where the hinge moment is found to vary linearly with the control surface deflection. For completeness of the design schematic (Figure 40), a hinge radius $r_0$ is used to transform the linear motion of the actuator into angular motion required by the control surface. As $r_0$ is just a geometric feature, it will not influence the mechanical energy transfer from the actuator to the activated structure. The gain will vary linearly with $r_0$, and thus a minimal technological value for the hinge radius is found to be optimal from the standpoint of the energy transfer and required gain criteria. The displacement amplification mechanism efficiency $\eta_m$ is defined as the ration of the input and output mechanical work and the gain $G$ simply as the ratio of input and output displacements:

$$\eta_m = \frac{F_e \cdot u_e}{F_e \cdot u_e} \quad G = \frac{u_e}{u_e}$$

(56)
where $F_e'$ and $u_e'$ are the output force and displacement of the actuator, and $F_e$ and $u_e$ are the output of the amplification mechanism. With the kinematical gain defined as $\eta = \delta r_0 / u_{ISA}$, and the non-dimensional stiffness ratio $r = k_i / (k_\delta r_0^2)$ the required displacement amplification mechanism gain results as:

$$G = \eta_m \frac{1 + \sqrt{1 - 4 r \eta^2}}{2 r \eta}$$

(57)

The gain from the above formula takes real values only if $1 - 4 r \eta / \eta_m > 0$, which translates into a critical condition for the internal actuator stiffness $k_i$ if amplification mechanism efficiency $\eta_m$ is given:

$$k_i \geq k_i_{cr} = \frac{4 k_\delta}{\eta_m u_{ISA}}$$

(58)

The output energy is defined as $E_{out} = k_\delta \delta^2 / 2$ and can be further expressed as $E_{ref} E_e'$, where $E_{ref} = k_i u_{ISA}^2 / 2$ is the reference input energy and $E_e'$ is the transfer energy coefficient:

$$E_e' = \eta^2 r = \frac{r G^2}{1 + r \frac{G^2}{\eta_m^2}}$$

(59)

### Table 14  
Actuation system parameters

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<tr>
<th>Required angular deflection, $\delta$</th>
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<td>Aerodynamic stiffness, $k_\delta$</td>
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<td>Hinge radius, $r_0$</td>
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<tr>
<td>Free induced displacement, $u_{ISA}$</td>
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</table>
The case study assumed the quasi-static actuation of a small aspect ratio wing, with integral movement (e.g. missile fin), at zero angle of attack. The corresponding aerodynamic stiffness and other pertinent parameters are given in Table 14.

![Figure 41](image1)

**Figure 41** Variation of the (a) required gain and (b) energy transfer coefficient with the actuator internal stiffness

For fixed displacement amplification efficiency both the required gain and the transfer energy coefficient are shown to decrease with the increased internal stiffness (Figure 41).

This suggests that for a given amplification efficiency, there exists an optimal actuator stiffness. Since an optimum is sought following two independent criteria – energy transfer maximization and required gain minimization – a metric must be defined, that would capture both desired trends. The choice of such a metric is not unique and depends on the designer interest in optimization of either gain or transfer energy.

![Figure 42](image2)

**Figure 42** The metric $R$ for the case of equal optimum criteria weights ($p=1, q=1$)
A possible general form for this metric is:

$$R_p^q = \frac{(E_x)^p}{(G)^q}$$  \hspace{1cm} (60)

where $p$ and $q$ are the weights attributed to the two optimum criteria – maximum transfer energy and minimum required gain. Before solving for the metric maximum, introduce $x = 4r\eta^2/\eta_m$, a non-dimensional positive quantity, smaller than unity. Then, $R_p^q$ can be written as:

$$R_p^q = \eta_m^p\eta^{-q}2^{-(p+q)}\frac{x^{p+q}}{(1+\sqrt{1-x})^q}$$ \hspace{1cm} (61)

The maximum of the optimal metric $R_p^q$ with respect to $x$ occurs for

$$x = 4\frac{p(p+q)}{(2p+q)^2}$$ \hspace{1cm} (62)

Since $x$ correlates the actuator internal stiffness and the amplification efficiency, the above equation defines an optimal correlation between $k_i$ and $\eta_m$ (Figure 42) that can be used in the design process for the choice of an optimal off-the-shelf actuator. For example, suppose the designer has to choose between the Physik Instrumente P247-70, Kinetic Ceramics D125120 and PiezoSystems Jena PAHL120/20 in order to actuate an aerodynamic control surface with the set of requirements from Table 14. Also assume that the actuators stiffness provided by the manufacturer are accurate for the level of force and voltage required by maximum control surface deflection. Then, for an ideal
amplification efficiency $\eta_m$ of one, the critical actuator stiffness is $k_i,cr = 145.4$ kN/mm. From Table 9, PAHL120/20 has a stiffness of 30kN/mm, well below the critical stiffness. Results that this actuator cannot be used for the above mention project. Further on, assuming a generic displacement amplification efficiency of 0.8, the corresponding optimal actuator stiffness for equal weighted optimum criteria ($p=q=1$) would be approximately 200 kN/mm. The P247-70 and the D125120 have internal stiffness of 400 kN/mm, and 205 kN/mm respectively and thus, the Kinetic Ceramics actuator for this case would represent a mechanically optimal choice. Once the optimal actuators are selected, experimental data focusing on the behavior under desired operational conditions (e.g. actuator stiffness, dielectric losses, etc.) are needed to further justify the selection.
7. DISCUSSION

7.1 PIEZOELECTRIC ACTUATOR BEHAVIOR

The experimental and modeling effort concerning the PiezoSystems Jena PAHL 120/20 piezoelectric actuator yielded two basic results:

a) The actuator mechanical capabilities and its electrical requirements

b) The evaluation of the model parameters over a wide range of voltage cycles, pre-stress levels, and frequencies.

The modeling of the piezoelectric actuator behavior was performed in a cycle-average sense, and thus the numerical values obtained for the tuning parameters should be regarded as equivalent values that hold significance for the cycle used to tune the model. Nevertheless, interpolation of the data in Table A1 can be performed to evaluate cases that were not tested, since most of the parameters variations display a consistent pattern when frequency, voltage range and pre-stress level are varied.

The mechanical envelopes for the tested frequencies (Figure A1) show that the blocked force, as defined in Section 4.2.2, remains constant with frequency. It is worthwhile to mention that the maximum attained force will increase with the excitation frequency, as its value is related to the frequency-dependant dynamic stiffness of the external structure.
As shown in Equation 33, the dynamic stiffness decreases with frequency up to resonance.

The relative displacement of the stack slightly decreases with frequency (Figure A12). This can be explained by the switching process time-history, as the ferroelastic switching does not occur instantaneously, but rather it nucleates in one area and then propagates throughout the domain. If the actuation frequency is increased, then some domains will not have time to switch, and less induced strain will result. Consequently, a decrease in the cycle-equivalent piezoelectric coefficient $d_{33}$ with increased frequency is expected.

Data presented in Table A1 in APPENDIX suggests that the cycle-equivalent value of the $d_{33}$ coefficient increases with the voltage. This trend can be also observed in Figures A8 through A12, as the slope of the voltage-displacement correlation increases with the voltage range. This can be explained through the increased number of domain ferroelastic switching when the voltage is cycled up to a higher value. The cycle-equivalent values of $d_{33}$ are consistent with the corresponding static data (Figure 28b), taken for the bias voltage.

The electrical envelopes for the maximum peak power show a consistent dependence on frequency, force, and voltage cycle (Figures A2, in APPENDIX), qualifying the peak power as a useful indicator when evaluating a piezoelectric actuator for a specific application. Hence, besides the expected proportionality with the applied voltage and frequency, the peak power is seen also to increase with force (Figure A2). This increase (up to 10%), cannot be explained by the change in capacitance due to variable-layer geometry, as this factor can account for less than 0.15% change in the capacitance.
Instead, the explanation resides in the increased dielectric permittivity along a direction no longer aligned with the dipole axis of the PZT crystal, due to inherent crystal anisotropy (Du et al., 1997). As force increases, more ferroelastic switches will occur, leading to more domains having their electric dipoles misaligned from the $x_3$ axis, and thus an increased permittivity at the poly-crystallite level. The cycle-equivalent electrical permittivity $\varepsilon_{33}$ that resulted after the model tuning correlated well with the above-mentioned trend. Moreover, its variation with voltage for a given frequency at low pre-stress level suggest the existence of a maximum within the tested voltage range. As the pre-stress level increases, the point of maximum permittivity seems to occur at higher and higher voltages. However, the difference between the maximum and minimum values does not exceed 10% (Table A1).

The second set of the electrical envelopes (Figure A3) represents the average active power per cycle through the actuator. Although the data scatter is non-negligible, there appears to be a trend towards decreasing active power per cycle with increasing pre-stress level, and a significant increase with the voltage cycle. These characteristics can be both explained through domain switching: for a given voltage cycle, increasing the pre-stress level is equivalent to impeding more domains to perform ferroelastic switching, while with a given pre-stress level, an increased voltage cycle will help more domains to perform $90^0$ switching. In all these, the ferroelastic switching is associated with the energy loss, as shown by Kessler et al. (2001). These observations correlate with the model coefficients mostly through the variation of the $\delta_0 \cdot k_S$ product (Table A1), that represents the peak dielectric loss on the unloading cycle. It is worthwhile to notice that

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this quantity represents a better modeling parameter than $k_\delta$, since it captures both the above-mentioned measured trends seen in the active power envelopes, and variation is contained within a narrower range. For example, for the 0-150 V duty cycle, the numerical value of $k_\delta$ is found to vary between 6 and 35, depending on the frequency and pre-stress level, but the variation of the $\delta_0 \cdot k_\delta$ product lies between 0.4 and 0.6.

The piezoelectric actuator dynamic model tuning coefficients have shown limitations when characterizing the high pre-stress level load cases, especially the average slope of the force-displacement correlation. This could be attributed to the non-linear external stiffness, associated with the loading structure (proving ring, and the compression mechanism) and most probably the internal spring.

7.2 MAGNETOSTRICTIVE ACTUATOR BEHAVIOR

The full-power magnetostrictive actuator impedance departs from the low current impedance values with more than 80%. This behavior cannot be explained based only on the linear theory alone (Equation 43). Model tuning using experimental data was based exclusively on the magnetic permeability coefficient, as all the other parameters involve mechanical characteristics (i.e. force and displacement) that could not be measured within the project time frame.

The real part of the impedance spectrum (Figure 37a) departs from the model prediction, because the resistance of the coil varies significantly with frequency. This variation is probably induced by the increase of temperature with frequency and of resistance with temperature. Likewise, the imaginary part of the impedance (Figure 37b) shows less
pronounced increase with frequency above 1.5kHz for high current operation, a trend that cannot be captured with a frequency-constant magnetic permeability coefficient. As a result, the active and reactive powers are expected to be of the same order of magnitude, as suggested by the experimentally determined real and imaginary impedance curves. More testing of the bulk Terfenol-D would be needed to capture the strong dependence of magnetostrictive material with frequency.
8. CONCLUSIONS

This thesis has presented a consistent engineering approach for smart materials technology implementation into actuation systems, in a general-to-specific fashion. The review of the state of the art and an extensive review of manufacturers resources revealed that while methods for smart materials and actuators characterization and microstructure theories exist, there is a scarcity in the data provided by manufacturers that impedes the knowledge-based choice of smart materials actuators. However, the survey has pointed out energy, price and efficiency metrics that can be used to map the current active material actuators market. These metrics can be further used for a first order analysis, when the choice of an actuator for a specific application is made.

The thorough characterization of the piezoelectric PiezoSystems Jena PAHL 120/20 actuator comprised the determination of the correlations between output force, displacement, and input electrical current and voltage over a wide range of voltages, pre-stress levels and frequencies. The quasi-linear dynamic model employed in this analysis permitted the evaluation of cycle-averaged parameters influencing the smart material behavior, giving a quantitative insight into optimization opportunities arising from varying pre-stress level or frequency. For example, the increased pre-stress level for a fixed frequency and voltage cycle leads to a higher stack stiffness, which in turn means a higher energy density. Since the decrease in compliance can be as much as 24% when the
pre-stress changes from 1.1kN to 2.8kN, the elastic modulus and actuator static stiffness increases with 30%. However, an increased pre-stress level will also require more electrical power to drive the actuator (up to 10% increase in peak power) due to dielectric permittivity increase. Comparison of the experimental data with the model predictions allowed the improvement of the model through the consideration of increased dielectric losses on the unloading path. A good metric for these losses was found to be the peak dielectric loss on the unloading path. This parameter was found to increase with voltage cycle and decrease with the level of applied pre-stress, leading to reduced active power required by the piezoelectric actuator. The microstructure theory of polarization domain switching correlates qualitatively with the observed behavior of the piezoelectric stack.

The evaluation of the electrical properties of the magnetostrictive Etrema AA140J025 actuator revealed important variations (up to 80%) of the full-power electrical impedance from the low-power impedance spectrum. A theoretical model of the electrical impedance was constructed and tuned using the experimental data.

Practical steps towards the design and optimization of actuation systems integrating smart materials technology were also given.

At the present, the smart materials actuators have already formed a market, but the possible applications are still limited due to inherent small strain capabilities. The areas where smart materials technology targets its applications spans from optical systems, where the nanometric resolution is utilized, to vibration reduction, stability augmentation, and aerodynamic surfaces control projects, where the high energy density of active materials actuators and their reduced parts count can prove advantageous over
traditional actuators. In this context, the present work proposed an engineering approach to the design of actuation systems incorporating smart materials actuators.
BIBLIOGRAPHY


Giurgiutiu, V., Chaudhry, Z., Rogers, C.A., (1995), "Effective Use of Induced-strain


Material Systems and Structures, Vol. 3, No. 2, pp. 245-254


materials under high electromechanical driving levels”, Proceedings SPIE Conference on Smart Structures and Materials, Newport Beach, CA, #3992, pp. 115-125


APPENDIX

Table A 1  Piezoelectric actuator tuning coefficients – variation with frequency, voltage and pre-stress level

<table>
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<tr>
<th>Voltage Range</th>
<th>$\lambda$ \times 10^{-12}</th>
<th>$d_0$ \times 10^{-9}</th>
<th>$s_E$ \times 10^{-12}</th>
<th>$\kappa_{33}$</th>
<th>$\delta_0$</th>
<th>$k_\delta$</th>
<th>$\delta_0 \cdot k_\delta$</th>
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<td></td>
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<td></td>
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<tr>
<td>0-60V</td>
<td>0.03</td>
<td>650</td>
<td>7.1</td>
<td>20.8</td>
<td>0.29</td>
<td>0.13</td>
<td>2.0</td>
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<td>0-100V</td>
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<td><strong>4Hz, \approx 1100N pre-stress</strong></td>
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<td>6.6</td>
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<td>22</td>
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<td>22</td>
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<td>0.46</td>
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Figure A 1  Mechanical envelopes for the piezoelectric actuator PiezoSystems Jena PAHL 120/20 under dynamic testing a) 1Hz; b) 2Hz; c) 4Hz; d) 5Hz
Figure A 2  Electrical envelopes for the PiezoSystems Jena PAHL 120/20: peak power: a) 1Hz; b) 2Hz; c) 4Hz; d) 5Hz
Figure A 3 Electrical envelopes for the PiezoSystems Jena PAHL 120/20: active power: a) 1Hz; b) 2Hz; c) 4Hz; d) 5Hz
Figure A 4  Force-displacements correlations for 1Hz, with different pre-stress levels:  
a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A 5  Force-displacements correlations for 2Hz, with different pre-stress levels:
a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A.6  Force-displacements correlations for 4Hz, with different pre-stress levels:
a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A 7 Force-displacements correlations for 4Hz, with different pre-stress levels:

a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N; f) 2840N
Figure A 8 Displacement-voltage correlations for 1Hz, with different pre-stress levels: a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A 9  Displacement-voltage correlations for 2Hz, with different pre-stress levels:
  a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A.10  Displacement-voltage correlations for 4Hz, with different pre-stress levels: 
a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A 11  Displacement-voltage correlations for 5Hz, with different pre-stress levels: a) 0N; b) 550N; c) 1100N; d) 1650N; e) 2275N f) 2840N
Figure A 12  Displacement-voltage correlations with no external load: a) 1Hz; b) 2Hz; c) 4Hz; d) 5Hz