Title: Energy-Based Comparison of High-Power Commercially Available Induced-Strain-State Actuators

Authors: Dr. Victor Giurgiutiu, Research Professor
         Dr. Craig A. Rogers, Professor and Director

Center for Intelligent Material Systems and Structures,
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0261, USA
Phone 540 231-2900, FAX 540 231-2903
ABSTRACT
A study of published literature and information from piezoelectric, electrostrictive, and magnetostrictive actuator vendors has been undertaken to establish the mechanical and electrical operating characteristics of the actuators, and to compare them using output energy density criteria. Output energy values of up to 0.666 J can be achieved with off-the-shelf actuators. Energy density per unit volume was found in the range 1.816-7.280 J/dm³. Energy density per unit mass was found in the range 0.233-0.900 J/kg. In one isolated case, higher energy densities of 11.9 J/dm³ and 1.09 J/kg were identified for a small co-fired PMN stack of 0.00481 J total energy. Energy transformation efficiency between input electric energy and output mechanical energy was found to be: 17-27% for adhesively-bonded PZT and PMN stacks, 5-20% for co-fired PZT and PMN stacks, and 67.1% for TERFENOL-D devices. The overall performance of induced-strain actuators based on output energy density criteria was found to vary widely from vendor to vendor, and even from one model to another within the same vendor catalogue list. These variations are attributed to progress being made currently in both the active material technology and in the detailed mechanical construction of induced-strain actuators based on these materials.

INTRODUCTION
The use of solid-state induced-strain actuators has experienced a great expansion in recent years. Initially developed for high-frequency, low-displacement acoustic applications, these revolutionary concepts are currently expanding in their field of application in many other areas of mechanical and aerospace design. Compact and reliable, induced-strain actuators directly transform the input electrical energy into output mechanical energy. One application area in which solid-state induced-strain devices have a very promising perspective is that of linear actuation. At the moment, the linear actuation market is dominated by hydraulic and pneumatic cylinders, and by electromagnetic solenoids and shakers. Hydraulic and pneumatic cylinders offer reliable performance, with high force and large displacement capabilities. When equipped with servovalves, the hydraulic cylinders can deliver variable stroke output over a relatively large frequency range. Servovalve-controlled hydraulic devices are the actuator of choice for most aerospace, automotive, and robotic applications. However, a major drawback in the use of conventional hydraulic actuators is the need for a separate hydraulic power unit equipped with large electric motors and hydraulic pumps that send the
high-pressure hydraulic fluid to the actuators through hydraulic lines. These features can be a major drawback in certain applications; for example, in the actuation of a servo-tab placed at the tip of a rotating blade, the high-g environment, and the fact that the blade rotates, prohibit the use of conventional hydraulics. In such situations, an electro-mechanical actuation that directly converts electrical energy into mechanical energy is preferred. Conventional electro-mechanical actuator devices, that are based on electric motors, either deliver only rotary motion or require gearboxes and eccentric mechanisms to achieve linear motion. This route is cumbersome and leads to additional weight being added to that of the device, thus reducing its design effectiveness. Linear-action electro-mechanical devices, such as solenoids and electrodynamic shakers, exist, but are known for their typical low-force performance. The use of solenoids or electrodynamic shakers to perform the actuator duty-cycle of a hydraulic cylinders is not presently conceivable.

Solid-state induced-strain actuators offer a viable alternative. Though their output displacement is relatively small, they can produce remarkably high force. Through the use of well-architected displacement amplification, induced-strain actuators can achieve dynamic output strokes similar to those of conventional hydraulic actuators. Additionally, unlike conventional hydraulic actuators, solid-state induced-strain actuators do not require separate hydraulic power units and long hydraulic lines, and use the much more efficient route of direct electric supply to the actuator site.

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 in the next few years. 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, the present paper sets 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 paper 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 collected in an extensive survey performed over approximately a one-year period.

**BASIC ASPECTS OF INDUCED-STRAIN ACTUATORS**

**ELECTROACTIVE AND MAGNETOACTIVE MATERIALS**

Active materials exhibit induced-strain actuation (ISA) under the action of an electric or magnetic field. They are primarily of three types:

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1 The acronym ISA is used to signify either an induced-strain actuator, or the induced-strain actuation principle
Figure 1  Typical construction of induced-strain actuators: (a) induced strain actuator using a PZT or PMN electroactive stack; (b) induced strain actuator using a TERFENOL magnetoactive rod.

- **PZT** - Lead Zirconate Titanate - 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 formulation for actuator applications.

- **PMN** - Lead Magnesium Niobate - 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.

- **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.

**CONSTRUCTION OF A PZT OR PMN STACK ACTUATOR**

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 1a). 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.

The 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 an 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) under a high isostatic pressure (HIP process) in the processing oven. 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.

CONSTRUCTION OF A TERFENOL ACTUATOR

A magnetoactive solid-state actuator consists of a TERFENOL bar inside an electric coil and enclosed into an annular magnetic armature (Figure 1b). 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 µm/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 µm/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.

ACTUATORS WITH CASING AND PRE-STRESS MECHANISM

Some commercially-available solid-state actuators are just the drive units described above and shown in Figures 1 and 2. Other commercially-available solid-state actuators also include a protective casing and a pre-stress mechanism. The casing provides protection for the active material and its electrical connections. It also facilitates the mechanical connection between the actuator and the application structure. The pre-stress mechanism is necessary to ensure that the active material is loaded in only compression, even when a moderate tension load is applied to its output rod. This issue is especially important with ceramic active materials (PZT and PMN) which are very weak in tension. When a pre-stress mechanism is incorporated, the protective casing also acts as a return path for the spring load, which usually makes the casing larger and heavier. The actuators with casing and pre-stress mechanism can be directly fixed into the application structure, and do not require specialized knowledge from the user. However, the use of a spring has disadvantages from an energy output point of view, since some amount of energy will be stored in the spring and hence not delivered externally.

THEORETICAL BACKGROUND

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 µm; 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.
Figure 2a shows that, due to actuator compressibility, an external load, $F$, produces an elastic displacement, $F/k_i$, where $k_i$ is the internal stiffness. 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:

$$u_e = u_{ISA} - \frac{F}{k_i}. \quad (1)$$

When the external 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 blocking load is given by

$$F_{blocking} = k_i \cdot u_{ISA}. \quad (2)$$

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 2b. Thus:

$$F = k_e \cdot u_e. \quad (3)$$

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.,

$$u_e = \frac{1}{1+r} u_{ISA}. \quad (4)$$

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.,

\[ F_{\text{max}} = k_i \cdot u_{ISA} \cdot \]  

(5)

**OUTPUT ENERGY**

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

\[ E_e = \frac{1}{2} k_e \cdot u_e^2 \cdot \]

(6)

Substitution of Equation (4) into Equation (6) yields the expression of output energy in terms of stiffness ratio, \( r \), as:

\[ E_e(r) = \frac{r}{(1+r)^2} \left( \frac{1}{2} k_i u_{ISA}^2 \right). \]

(7)

The variable part of Equation (7) is the output energy coefficient:

\[ E'_e(r) = \frac{r}{(1+r)^2}. \]

A plot of \( E'_e(r) \) as a function of \( r \) is given in Figure 5. 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:

\[ E_{e\text{max}} = \frac{1}{4} \left( \frac{1}{2} k_i u_{ISA}^2 \right) \]

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 will be \( E_{e\text{max}} = \frac{1}{4} \left( \frac{1}{2} 370 \text{ kN/mm} \cdot (120 \mu m)^2 \right) = 0.666 \text{ J} \).

Figure 3 Stiffness match principle for peak energy delivery from an induced strain actuator
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.

ENERGY CONVERSION EFFICIENCY

The output mechanical energy delivered at the output end of an induced-strain actuator is the result of electro-magnetic energy applied at the input end of the induced-strain actuator. The conversion of electro-magnetic energy into mechanical energy that takes place inside the actuator is a highly-coupled process that will not be detailed here. 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:

\[ E_{el} = \frac{1}{2} CV^2, \]

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:

\[ E_{el} = \frac{1}{2} LI^2, \]

where \( L \) is the inductance and \( I \) is the current. The energy conversion efficiency is:

\[ \eta = \frac{E_{output}}{E_{input}} = \frac{E_{mechanical}}{E_{electrical}}. \]

DATA COLLECTION

A large variety of induced-strain actuators are presently available in the commercial market. In our study, we proposed to collect 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"

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2 A detailed account of power delivery mechanism in an induced strain actuator is given by Giurgiutiu, Chaudhry and Rogers (1994c).
• Manufacturer (name, address, FAX/Phone, contact point):
• Device identification:
• Description (10 word max.):
• Maximum (free stroke) displacement, µm:
• Maximum force, N:
• Stiffness, kN/mm:
• Length, mm:
• Outside diameter, mm (or width × thickness, for rectangular cross-section, mm × mm):
• Mass, kg:
• Volume, cm³:
• Voltage, V, or current, A, as appropriate:
• Capacitance, µF, or inductance, mH, as appropriate:
• Price, $:

"Data about the Active Material (PZT, PMN, TERFENOL, etc.)"
• Active material diameter, mm (or width × thickness, for rectangular cross-section, mm × mm):
• 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:

Based on the above data, we set out to calculate and then to disseminate among the survey participants, the following comparative data:
• Apparent free strain, %:
• Apparent volume, cm³:
• Apparent density, 10⁳ × kg/m³:
• 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. Atochem Sensors, Inc., P. O. Box 799, Valley Forge, PA 19428
2. AVX Corporation, Myrtle Beach, SC 29577
4. EDO Corporation, 2645 South 300 West, Salt Lake City, Utah 84115
5. Etrema Products, Inc., 2500 North Loop Drive, Ames, Iowa 50010
6. Morgan Matroc, Electroceramics Division, 232 Forbes RD., Bedford, Ohio 44146
7. Piezo Kinetics, Inc., P. O. Box 756, Pine St. & Mill Rd., Bellefonte, PA 16823
8. Piezo Systems, Inc., 186 Massachusetts Ave., Cambridge, MA 02139
9. Polytec PI, Inc., 3001 Redhill Ave., Bldg. 5-102, Costa Mesa, CA 92626
10. Stavely Sensors, Inc., 91 Prestige Park Circle, East Hartford, CT 06108
11. Tokin America, Inc., 155 Nicholson Ln, San Jose, CA 95134
The response of the manufacturers was extensive. Out of the large number of entries, we selected 15 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 1 presents the basic data for the 15 selected actuators. Note that the length, diameter, volume and mass data in Table 1 only refers to the active material contained inside the actuator. For actuators without casing, these data is practically all that is required. 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 only three manufacturers that offer induced-strain products with casing and pre-stress mechanism. These manufacturers are Polytec PI, Burleigh Instruments, and ETREMA. 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. Burleigh Instruments produces one small induced-strain actuator based on the PZT electroactive material. This product does not contain a pre-stressing spring and hence, when used, care must be taken to ensure that only compressive loading is applied. ETREMA produces a range of actuators with and without casing and pre-stress mechanism. These actuators are based on the TERFENOL-D magnetoactive material. A number of six 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 six actuators included in our study, these data is given in Table 3. 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.

RESULTS

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.
The maximum output energy, $E_{r\text{max}} = \frac{1}{4} \left( \frac{1}{2} k_i \cdot u_{t\text{ISA}}^2 \right)$, 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.

**RESULTS BASED ON ACTIVE MATERIAL VOLUME AND MASS**

Table 2 presents the mechanical performance of all the 15 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 2 are the output energy per unit cost, and it inverse, the cost of a unit of output energy.

The following explanation is necessary regarding the ETREMA magnetostrictive products included in the study. Since these products also include an energizing coil, it was necessary to decide whether or not to include the volume and weight of the coil in the volume and mass of active material. Eventually, it was decided not to include the volume and weight of the coil in the active material volume and mass, and only to use the volume and mass of the TERFENOL bar. Though this subjective choice might be criticized as giving an unfair advantage to the ETREMA products, we did not find that it lead to a clear discrepancy in the energy densities as presented in the comparison tables and charts.

**RESULTS BASED ON ACTUATOR VOLUME AND MASS**

Table 3 presents, in its last two columns, the mechanical performance energy indicators based on volume and mass. By comparing the entries in Table 2 and in Table 3 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.

**RESULTS BASED ON ENERGY CONVERSION EFFICIENCY**

A comparison of the mechanical and electrical performance of the actuators is given in Table 4. The maximum output mechanical energy, and the electrical energy necessary to produced 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 4.

**RANKING OF THE INDUCED-STRAIN ACTUATORS**

Table 5 presents the ranking of the 15 induced-strain actuators considered in the study. The ranking is done in decreasing order. The actuators with the best performance are ranked first, while the actuator with the worst performance are ranked last. Examination of Table 5 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.
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, $\varepsilon_{ISA}$, defined as the ratio between the free displacement, $u_{ISA}$, and the length, $L$.
- 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. For example, the stiffness of the TERFENOL-D bar was calculated using a Young's modulus value $E_{\text{TERFENOL-D}} = 35$ GPa. Similarly, for co-fired stacks, the stiffnesses of the AVX products were calculated using the values $E_{\text{PMN-AVX}} = 91$ GPa and $E_{\text{PZT-AVX}} = 70$ GPa, as suggested by the manufacturer. For the Morgan Matroc products, we used $E_{\text{PZT-5}} = 48$ GPa. The fact that AVX moduli had much higher values than the rest of the data was discussed with the company representative. It was concluded that this is to be expected since the co-fired stacks have an equivalent modulus similar to the basic ceramic material. (The only other constituent existing between the ceramic layers of the stack seems to be the electrodes made of metallic material with modulus values equal to, or higher than those of the ceramics).

It should be noted that the volume-based energy density can also be calculated by the well-known formula $E_{\text{e max}}/V = \frac{1}{4}\left(\frac{1}{2} E\varepsilon_{ISA}^2\right)$. A further division by the equivalent material density, $\rho$, yields the mass-based energy density, $E_{\text{e max}}/m = \frac{1}{\rho}\frac{1}{4}\left(\frac{1}{2} E\varepsilon_{ISA}^2\right)$. Based on these observations we performed consistency checks on our results.

DISCUSSION OF RESULTS

The results presented in Tables 2 through 5 were used to construct comparative charts presented in Figures 6 through 12. 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 6 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 one company, Polytec PI, Inc., has products with large energy capability (P-247-
70 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 7 compares the energy density per unit volume. For high-performance induced-strain actuators, a mid-range value of around 6-7 J/dm$^3$ seems to be common. In one isolated case, AVX-PMN, a much larger energy density value of 11.9 J/dm$^3$ was observed. However, this value has still to be validated by experiment.

Figure 8 compares the energy density per unit mass. For high-performance induced-strain actuators, a mid-range value of around 8-9 J/kg seems to be common. The AVX-PMN performance is again higher, but not as much as for the energy density per unit volume.

Figures 9 and 10 compare the energy densities per unit volume and unit mass for the six actuators that can also be delivered with casing and pre-stress mechanism. The energy density 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. 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 11 compares energy density based on unit cost in mJ/$1000. In this comparison, we did not include the Burleigh Instruments model PZL-060, due to its higher-than-usual relative cost, which would upset the vertical axis scale. Examination of this chart indicates that some companies are capable of marketing product 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 12 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 12 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. For induced-strain actuators based on magnetoactive materials the energy transformation efficiency is around 60%. From this point of view, the TERFENOL base products seem to have a clear advantage. However, more research needs to be put into the energy transformation efficiency estimation and measurement before a definite conclusion can be drawn.

CONCLUSIONS

An energy-based comparison of commercially-available induced-strain actuators (ISA) was presented. The data was collected from a survey of prominent manufacturers of ISA materials and devices, who responded with enthusiasm to our request for information.
The comparison, presented in the accompanying tables and charts, shows that output energy values of up to 0.666 J can be achieved with off-the-shelf commercially-available actuators. Energy density per unit volume was found in the range 1.816-7.280 J/dm³. Energy density per unit mass was found in the range 0.233-0.900 J/kg. In one isolated case, higher energy densities of 11.9 J/dm³ and 1.09 J/kg were identified for a small co-fired PMN stack of 0.00481 J total energy. Energy transformation efficiency between input electric energy and output mechanical energy was found to be: 17-27% for adhesively-bonded PZT and PMN stacks, 5-20% for co-fired PZT and PMN stacks, and 67.1% for TERFENOL-D devices.

The overall performance of induced-strain actuators, when compared on the basis of output energy density, was found to vary widely from vendor to vendor, and even from one model to another within the same vendor catalogue list. The variations from vendor to vendor may be attributed to architectural differences in the detailed mechanical construction of the induced-strain actuators. The variations between products offered by the same vendor may be explained by recent progress in the active material technology that has only been incorporated in the latest products.

It was observed that the addition of casing and pre-stress mechanism greatly reduces the energy density of an induced-strain actuator. This reduction is more pronounced in terms of energy density per unit volume than in terms of energy density per unit mass. For applications where volume and mass are essential, it is highly desireable to incorporate directly the induced-strain actuator in the host structure and to avoid the unnecessary addition of casing and pre-stress mechanism by proper design architecture of the local structure.

This study presented here went beyond simply comparing the properties of various active materials exhibiting the induce-strain actuating effect. In this study, assembled induce-strain actuators, directly available on the commercial market, were considered and compared. The advantage of our approach is that it offers data that can be directly incorporated in the design of mechanical and hydraulic devices utilizing off-the-shelf induced-strain actuators.

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