Title: Power And Energy Characteristics Of Solid-State Actuators

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ABSTRACT

A method has been developed to predict the apparent material constants, the input and output power and energy, and the electro-mechanical energy conversion efficiency of electro-active induced-strain actuators under full-stroke, quasi-linear dynamic operation. The effect of the piezo-electric counter electro-motive force on the apparent input admittance is included. The non-symmetric expansion-retraction behavior of the electro-active material under full-stroke dynamic operation is symmetrized using a bias-voltage component and a superposed dynamic voltage amplitude that produce, in the actuator, a static position and a dynamic stroke amplitude, respectively. It is shown that the presence of the bias-voltage operation increases significantly the reactive power amplitude, and a simple formula for estimating this increase is provided. Reactive power values up to three times larger than those for unbiased operation were found.

The secant linearization method and vendor data were used to evaluate the full-stroke piezoelectric strain coefficient, $d$, elastic compliance, $s$, electrical permittivity, $\varepsilon$, and electro-mechanical coupling coefficient, $\kappa$, of the electro-active actuator. Consistency with the basic active-material values was checked, and a correction of the actuator full-stroke electro-mechanical coupling coefficient was applied, when required. Maximum power and energy delivery under optimal dynamic conditions (dynamic stiffness match) were studied, and the dynamic energy output capability of several commercially-available actuators were computed. Output energy densities per unit volume, mass, and cost were also calculated. The best electro-mechanical conversion efficiency, which was shown to take place at stiffness ratios slightly different from the dynamic stiffness match, was also computed.

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INTRODUCTION

The present study presents the performance of induced-strain actuators under a dynamic regime. Since the behavior of induced-strain actuators under expansion and contraction regimes is strongly non-symmetrical, the dynamic performance cannot be directly extrapolated from the static results. This paper shows how the bias position and the dynamic displacements are computed from vendor data, and points out that the presence of bias voltage can increase the actuator reactive power requirements by up to three times. The theoretical approach uses a complete dynamic model for the external load (mass, stiffness, damping), accounts for the dynamic losses in the stack through complex stiffness and complex permittivity representation, and includes the piezo-electric counter electro-motive force effect on the apparent input capacitance of the actuator. The study derives prediction formulae for the effective full-stroke electromechanical coupling coefficient of the actuator, and for the power and energy conversion efficiency. The maximum output energy and the best conversion efficiency under dynamic conditions are derived. It is shown that the dynamic stiffness ratio match condition ensures maximum output energy, but does not ensure best conversion efficiency, which happens at a slightly higher stiffness ratio value.

THEORETICAL BACKGROUND

BASIC EQUATIONS OF LINEAR ELECTRO-ACTIVE MATERIAL BEHAVIOR

The general constitutive equations of linear electro-active material behavior, given by ANSI/IEEE Standard 176-1987, describe a tensorial relation between mechanical and electrical variables (mechanical strain $S_{ij}$, mechanical stress $T_{ij}$, electrical field $E_i$, and electrical displacement $D_i$) in the form:

$$
S_{ij} = s_{ijkl} T_{kl} + d_{kj} E_k \\
D_i = d_{ijkl} T_{kl} + \varepsilon_{jk}^T E_k,
$$

where $s_{ijkl}$ is the mechanical compliance of the material measured at zero electric field ($E = 0$), $\varepsilon_{jk}^T$ is the dielectric permittivity measured at zero mechanical stress ($T = 0$), and $d_{kj}$ is the piezo-electric coupling between the electrical and mechanical variables.

![Diagram](image)

**Figure 1** Schematic representation of a solid-state induced-strain actuator (PZT stack) operating against a mechanical load.

Typical electro-active induced-strain actuators are stacks of thin active-material layers, alternatingly charged (Figure 1). In such an electro-active material stack, mechanical stress and electric field act...
only in the 3-direction (the stack axis), and the transverse effects can be neglected in a first-order analysis. The one-dimensional equivalent of Equation (1) is, simply,

\[
S = s \cdot T + d \cdot E
\]
\[
D = d \cdot T + \varepsilon \cdot E,
\]

where the subscripts "3", "33", "333", and "3333" are implied, as appropriate, and \( s \) is the compliance measured at zero electric field, while \( \varepsilon \) is the permittivity, is measured at zero stress.

**ELECTRO-MECHANICAL DESCRIPTION OF AN INDUCED-STRAIN ACTUATOR OPERATING A MECHANICAL LOAD**

Most commercially-available induced-strain actuators are rated for voltage and displacement values that ensure quasi-linear behavior. This allows us to use a linear electro-mechanical model in our analysis. A dynamic-stiffness representation of a solid-state induced-strain actuator (PZT stack) operating a mechanical load of parameters \( k_e \), \( m_e \), and \( c_e \) is shown in Figure 1. The PZT stack is energized by a voltage source, \( v(t) \), which sends a current, \( i(t) \), that builds up the internal charge. As the charge is built up, the voltage and the electric field increase. Under the action of the electric field, the electro-active material expands and produces an output displacement, \( u(t) \), which generates a reaction force from the mechanical system, \( F(t) \). The reaction force, \( F(t) \), acting on the PZT stack, induces loss of output displacement through the stack compressibility and through the counter electric motive force (emf) due to the piezo-electric effect. Hence, an actuator under load always has a lower output displacement than a load-free actuator energized by the same voltage. For operation frequencies below 100 Hz, the wave propagation effects can be ignored, and the equivalent input admittance was found to be:

\[
Y(\omega) = i\omega C \left( 1 - \frac{d^2}{s\varepsilon} \frac{\bar{R}(\omega)}{1 + \bar{R}(\omega)} \right),
\]

where \( C \) is the zero-load capacitance of the stack, \( d \) is the zero-load induced-strain coefficient, \( s \) is the open-circuit (zero-field) complex mechanical compliance of the stack, and \( \varepsilon \) is the zero-load complex electrical permittivity (dielectric constant) of the active material, i.e.,

\[
s = s(1 - i\eta)
\]

\[
\varepsilon = \varepsilon(1 - i\delta),
\]

with \( \eta \) being the hysteresis internal damping coefficient, and \( \delta \) the dielectric loss coefficient. The coefficient \( \bar{R}(\omega) \), is the complex stiffness ratio:

\[
\bar{R}(\omega) = \overline{k_e(\omega) / \overline{k_i}},
\]

where the complex stiffness expressions are:

\[
\overline{k_i} = \frac{A}{sI} \quad \text{(complex internal stiffness),}
\]

\[
\overline{k_e(\omega)} = (k_e - \omega^2 m_e) + i\omega c \quad \text{(complex external stiffness)}.
\]
Apparent electro-mechanical coupling coefficient of an induced-strain actuator

Apparent electro-mechanical constants of an electro-active induced-strain actuator can be defined using the overall performance data available in the vendor catalogues. Using the secant linearization method, apparent values of the piezo-electric strain coefficient, \( d \), elastic compliance, \( s \), electrical permittivity, \( \varepsilon \), and electro-mechanical coupling coefficient, \( \kappa \), are derived:

\[
d = \frac{\hat{u}_{ISA}}{V} \frac{t}{l} \quad \text{(apparent piezo-electric strain coefficient)} \tag{8a}
\]

\[
\varepsilon = \frac{C}{A} \frac{t^2}{l} \quad \text{(apparent zero-stress electrical permittivity)} \tag{8b}
\]

\[
s = \frac{A}{lk_i} \quad \text{(apparent zero-field elastic compliance)} \tag{8c}
\]

where \( l \) is the stack length, \( t \) is the layer thickness, \( A \) is the stack cross-sectional area, and \( \hat{u}_{ISA} \) is the dynamic free stroke. According to the IEEE Standard on Piezoelectricity (ANSI/IEEE Std 176-1987), the electro-mechanical coupling coefficient, relevant to the 33-direction in which the induced-strain actuator operates, is:

\[
\left( k_{33}^l \right)^2 = \frac{d_{33}^2}{s_{33}^E \varepsilon_{33}^T} \tag{9}
\]

Consistent with the linearization scheme, the constants \( d_{33}, \varepsilon_{33}^T, \) and \( s_{33}^E \), are given by expressions (8a)-(8c) as \( d, \varepsilon, \) and \( s \). Denoting \( k_{33}^l \) by \( \kappa \) (to avoid confusion with the notation, \( k \), already used for the mechanical stiffness) we arrive at the following simple expression for the full-stroke electro-mechanical coupling coefficient of the actuator:

\[
\kappa^2 = \frac{d^2}{s \varepsilon} = \frac{k_i \hat{u}_{ISA}^2}{CV^2} \tag{10}
\]

Upon substitution, Equation (3) becomes:

\[
Y(\omega) = i\omega C \left( l - \kappa^2 \frac{\tilde{F}(\omega)}{I + \tilde{F}(\omega)} \right) \tag{11}
\]

*Figure 2* Dynamic operation of Polytec PI P247.70 induced-strain actuator: (a) applied voltage, \( v(t) \), has bias and dynamic components, \( V_0 \) and \( V \); (b) the corresponding induced-strain displacement, \( u_{ISA}(t) \).
**ELECTRICAL POWER WITH BIAS VOLTAGE**

Electro-active solid-state induced-strain actuators do not have a symmetrical behavior when the polarity of the applied voltage is reversed under full-stroke operation. Hence, dynamic operation takes place about a mid-range position, which is achieved by superposing a bias component onto the dynamic component. For biased operation, the applied voltage is:

$$v(t) = V_0 + V \sin \alpha t,$$

where $V_0$ is the bias voltage, and $V$ is the dynamic voltage amplitude. The corresponding induced-strain displacement has the expression:

$$u_{ISA}(t) = u_0 + \hat{u}_{ISA} \sin \alpha t,$$

where, $u_0$ is the bias position, and $\hat{u}_{ISA}$ is the dynamic displacement amplitude (Figure 2). By definition, electrical power = voltage $\times$ current, and hence,

$$P(t) = v(t) \cdot i(t) = (V_0 + V \sin \alpha t) \cdot I \sin(\alpha t - \phi).$$

Expansion of Equation (14) gives:

$$P(t) = \frac{1}{2} VT \cos \phi - \frac{1}{2} VT \cos(2 \alpha t - \phi) + V_0 I \sin(\alpha t - \phi)$$

$$= P_{active} + P_{reactive}(t).$$

Note that the active component of power is not influenced by the bias voltage and has the expression $P_{active} = \frac{1}{2} VT \cos \phi$, while the reactive component of power has the modified expression:

$$P_{reactive}(t) = -\frac{1}{2} VT \cos(2 \alpha t - \phi) + V_0 I \sin(\alpha t - \phi).$$

The complex power amplitude, $|\bar{P}| = \frac{1}{2} VT$, can be factored out of Equation (15), and hence,

$$P_{reactive}(t) = |\bar{P}|(- \cos(2 \alpha t - \phi) + 2V_0 \sin(\alpha t - \phi))^1,$$

where,

$$V_0 = V_0 / V,$$

is the bias voltage coefficient. Electro-active induced-strain actuators are mainly capacitive, and their phase angle is close to $-90^0$. For $\phi = -90^0$, Equation (17) becomes:

$$P_{reactive}(t) = |\bar{P}|(\sin(2 \alpha t) + 2V_0 \cos(\alpha t)).$$

Figure 3a presents the time-variation of the normalized reactive power for various values of the bias voltage coefficient, $V_0$. Note that, for $V_0 < 1$, the reactive power curve shows a pair of local maxima, of which only one is also global maximum, i.e., the peak value of the reactive power per cycle. For $V_0 = 1$, the curve has a horizontal-tangent inflection point at $3\pi/2$. For $V_0 > 1$ the reactive power curve presents only one maximum since its behavior is dominated by the bias-voltage component.
Figure 3  Variation of normalized reactive power for piezo-stacks \( (\phi = -90^0) \): (a) time-trace of reactive power flow; (b) reactive power correction coefficient, \( \chi(v_0) \).

The peak reactive power takes place at the critical angle, \( \omega t_{cr} \). A reactive power correction coefficient, \( \chi(v_0) \), defined as

\[
\chi(v_0) = \left| P_{\text{reactive}} \right| / \left| P \right|.
\]

is plotted in Figure 3b. For a limited range of \( v_0 \), the curve shown in Figure 3b is almost linear, though its algebraic expression (not given here for brevity) is quite elaborate. A reasonable approximation for the reactive power correction coefficient in the range \(-1.5 < v_0 < 1.5\) is given by the formula:

\[
\chi(v_0) \approx 1 + 1.62|v_0|.
\]

**ELECTRICAL POWER INPUT TO AN INDUCED-STRAIN ACTUATOR**

Since the induced-strain actuator operates under biased voltage, \( v(t) = V_0 + V \sin \omega t \), the peak reactive power per cycle is given by:

\[
P_{\text{peak}}^{\text{reactive}} = \chi(v_0)|P_{\text{elecr}}|,
\]

where \( P_{\text{elecr}} = \frac{1}{2} \bar{V}^2 \) is the complex electrical power and \( \chi(v_0) \) is given by Equation (21).

Substitution of Equation (11) into Equation (22), gives the peak input power per cycle of an electro-active induced-strain actuator:

\[
P_{in} = \frac{1}{2} \chi(v_0) \omega C \left( I - \kappa^2 \frac{\bar{f}(\omega)}{1 + \bar{f}(\omega)} \right) V^2.
\]

The power input varies with the frequency-dependent complex stiffness, \( \bar{f}(\omega) \). For a low-damping mechanical system, driven well below the mechanical resonance frequency, the complex stiffness ratio is predominantly real, i.e., \( \bar{f} \approx r \). Thus, the peak value per cycle of the electrical power input takes the simpler form:

\[
P_{in} = \omega \cdot \chi(v_0) \left( I - \kappa^2 \frac{r}{I + r} \right) \left( \frac{1}{2} CV^2 \right).
\]
MECHANICAL POWER OUTPUT FROM AN INDUCED-STRAIN ACTUATOR

By definition, mechanical power = force × velocity. For harmonic motion, the expression of the complex power is \( \overline{P} = \frac{1}{2} \overline{F} \cdot \overline{v}^* \), where \( \overline{v}^* \) is the complex conjugate of \( \overline{v} \), and \( \overline{v} = i \omega \overline{u} \). Using the output displacement amplitude

\[
\overline{u} = \frac{1}{1 + \overline{F}(\omega)} \hat{u}_{ISA},
\]

we write the output mechanical power as:

\[
\overline{P}_{out} = \frac{1}{2} k_e \overline{u} (i \omega \overline{u})^* = -i \omega \frac{\overline{F}(\omega)}{(1 + \overline{F}(\omega))(1 + \overline{F}(\omega))} \left[ \frac{1}{2} k_i \hat{u}_{ISA}^2 \right] \]  \( \text{(26)} \)

The power output varies with the complex stiffness, \( \overline{F}(\omega) \) which depends strongly on frequency. For low-damping mechanical systems, driven well below the mechanical resonance frequency, the complex stiffness ratio is predominantly real, i.e., \( \overline{F} \approx r \). Thus, the power output amplitude takes the simpler form:

\[
P_{out} = \omega \frac{r}{(1 + r)^2} \left[ \frac{1}{2} k_i \hat{u}_{ISA}^2 \right].
\]  \( \text{(27)} \)

The output power increases linearly with frequency. Equation (27) contains a modifier that accounts for the external loading conditions through the stiffness ratio, \( r \). As the stiffness ratio increases, the output power increases at first, and then decreases (Figure 4). The maximum output power is obtained at \( r = 1 \), and its value is:

\[
P_{out}^{\max} = \omega \frac{1}{4} \left( \frac{1}{2} k_i \hat{u}_{ISA}^2 \right).
\]  \( \text{(28)} \)

Similarly, the maximum output energy is given by:

\[
\hat{E}_{out}^{\max} = \frac{1}{4} \left( \frac{1}{2} k_i \hat{u}_{ISA}^2 \right).
\]  \( \text{(29)} \)

The quantity \( \hat{E}_{out}^{\max} \) is a frequency-independent metric that can be effectively used in comparing the static and dynamic performance of various active-material stacks.

![Figure 4](image_url)  
**Figure 4** Variation of output power with dynamic stiffness ratio, \( r \), has a peak at \( r = 1 \).
ELECTRO-MECHANICAL POWER CONVERSION EFFICIENCY OF AN INDUCED-STRAIN ACTUATOR

The electro-mechanical conversion efficiency of the system consisting of the electro-active induced-strain actuator and the mechanical load can be defined as the ratio between the output mechanical power and the input electrical power, i.e.,

\[
\eta = \frac{\hat{P}_m}{\hat{P}_em} = \frac{\frac{\omega}{\left(1 + \bar{\tau}(\omega)\right)(1 + \bar{F}(\omega))} \left(\frac{1}{2} k_i^2 \bar{u}_{i1A}^2\right)}{\omega \chi(v_0) \left(1 - \kappa^2 \bar{\tau}(\omega) + \frac{\bar{F}(\omega)}{1 + \bar{F}(\omega)}\right) \frac{1}{2} CV^2} = \frac{\kappa^2 \bar{F}(\omega)}{\chi(v_0) \left[1 + \left(1 - \kappa^2 \bar{F}(\omega)\right)\right]} \left[1 + \bar{F}(\omega)\right]^*.
\]  

(30)

The electro-mechanical conversion efficiency varies with the frequency-dependent complex stiffness, \(\bar{F}(\omega)\). For low-damping mechanical systems, driven well below the mechanical resonance frequency, the complex stiffness ratio is predominantly real, i.e., \(\bar{r} \approx r\). Thus, the conversion efficiency takes the simpler form:

\[
\eta = \frac{\kappa^2 r}{\chi(v_0) \left[1 + (1 - \kappa^2)r\right] (1 + r)}.
\]  

(31)

As the stiffness ratio increases, the conversion efficiency, \(\eta\), increases at first, and then decreases (Figure 5a). The conversion efficiency has a peak at stiffness ratio values, \(r_\eta\), that are close to \(r = 1\), but not exactly equal to 1. This optimal stiffness value, \(r_\eta\), that maximizes the conversion efficiency, can be found by setting to zero the derivative of the conversion efficiency with respect to \(r\). Hence,

\[
r_\eta(\kappa) = \frac{1}{\sqrt{1 - \kappa^2}}.
\]  

(32)

Substitution of Equation (32) into Equation (31) gives the best conversion efficiency, \(\eta_{max}\), in terms of the electro-mechanical coupling coefficient, \(\kappa\) and the bias voltage coefficient, \(v_0\), i.e.,

\[
\eta_{max}(\kappa, v_0) = \frac{1}{\chi(v_0) \left[2 \sqrt{1 - \kappa^2} + 2 - \kappa^2\right]}.
\]  

(33)

Figure 5  
Variation of electro-mechanical power conversion efficiency with \(r\), \(v_0\) and \(\kappa\):  
(a) Plots at \(v_0 = 0\); (b) best conversion efficiency for various \(\kappa\) and \(v_0\).
Plots of Equation (33) are given in Figure 5b. For \( v_0 = 0 \), (operation without bias voltage) the best conversion efficiency may vary between 11% and 17%. As bias voltage is applied, the conversion efficiency decreases. For the \( v_0 = 1 \) case (bias voltage equals dynamic voltage amplitude), the electro-mechanical conversion efficiency may vary between 3% and 5%.

**NUMERICAL RESULTS**

Figure 6 presents a number of charts comparing the performance of the electro-active induced-strain actuators considered in this study. The apparent electro-mechanical coupling coefficient, \( \kappa \), can serve as a first indicator of the actuator performance. The variation of the apparent electro-mechanical coupling coefficient is shown in Figure 6a. Values as low as 0.45 are observed in some cases, but the majority of the commercially-available induced-strain actuators seem to claim a very good electro-mechanical coupling performance.

A comparison of the maximum dynamic energy output that can be extracted from the commercially-available induced-strain actuators is given in Figure 6b. It seems that, at present, only one company, Polytec PI, Inc., has off-the-shelf induced-strain actuator products with large dynamic energy output capability (0.260 J peak for P-247.70). However, similar high-output energy products may also be available from other manufacturers, by special order. Figure 6c compares the energy density per unit volume, which is found to vary from 0.7 to 3.7 J/dm\(^3\). For many induced-strain actuators, a mid-range value of around 2 J/dm\(^3\) seems to be common. The high end values, around 3.7 J/dm\(^3\), are reached by the Polytec PI and AVX products. Figure 6d compares the energy density per unit mass, which varies from 0.091 to 0.482 J/kg. For many induced-strain actuators, a mid-range value of around 0.2 J/kg seems to be common. The high-end value of 0.482 J/kg is reached only by one Polytec PI product (P-247.70). Figure 6e gives an energy density comparison based on energy per unit cost in mJ/$1000. Examination of this chart indicates that some companies are capable of marketing products with specific energy costs remarkably lower than others. This observation does not seem to be influenced by the processing method, since it affects adhesively-bonded and co-fired products equally.

Figure 6f presents a comparison of the best energy conversion efficiencies that can be expected from these induced-strain actuators under the most favorable stiffness ratio conditions. This coefficient represents the ratio between the output mechanical energy and the input electrical energy. These energies are predominantly reactive (capacitance in the electrical energy, and spring in the mechanical energy), and hence the efficiency coefficient is defined as the ratio between their peak values. Note that the peak value per cycle of the reactive electrical energy is strongly influenced by the presence of the bias voltage. The energy conversion efficiency is also influenced by the electro-mechanical coupling coefficient, \( \kappa \), as shown in Equation (33). Figure 6f indicates that the energy conversion efficiency seems to vary from 2.90% to 10.33%, with the high-end products also having high values of conversion efficiency.
Figure 6  Charts of predicted behavior under dynamic operation calculated using vendor data for 14 commercially-available induced-strain actuators.
CONCLUSIONS

The dynamic power and energy capabilities of commercially-available induced-strain actuators operating against an external mechanical load have been considered. The mechanical load was modeled by a spring-mass-damping system of equivalent dynamic stiffness ratio, $\bar{F}(\omega)$. In the beginning of the study, clarification of some fundamental concepts regarding the active and reactive components of power and energy specific to the dynamic operation of electro-active induced-strain actuators was done. It was found that for lightly-damped systems, the reactive power and energy are dominant, and this aspect was found to be fundamentally different from the conventional analysis of electric motors and other traditional electro-mechanical devices.

A number of specific concepts were introduced and/or clarified in the present study: The apparent electro-mechanical coupling coefficient, $\kappa$, of an electro-active induced-strain actuator was introduced by Equation (10) via a secant-method linearization procedure. The reactive power amplification coefficient, $\chi(\nu_0)$, was defined through Equation (20) in terms of the complex power magnitude, $|\bar{P}|=|\bar{P}|V^2$, and the bias-voltage coefficient, $\nu_0 = V/\nu V$. A linearized expression for the reactive power amplification coefficient, $\chi(\nu_0)$, was given in Equation (21) for the range $-1.5 < \nu_0 < 1.5$. Hence, the reactive input power requirements for an electro-active induced-strain actuator were expressed by Equation (24) in terms of the reference electrical energy, $\frac{1}{2}CV^2$, the reactive power amplification coefficient, $\chi(\nu_0)$, the apparent electro-mechanical coupling coefficient, $\kappa$ and the stiffness ratio, $r$.

The output power and energy were expressed in terms of the reference mechanical energy, $\frac{1}{2}k\hat{u}_{ISA}^2$, and an extraction factor that depends on the stiffness ratio and has its maximum value equal to $\frac{1}{2}$. Hence, the maximum output energy was identified as $\hat{E}_{\text{out}}^{\max} = \frac{1}{2} \left( \frac{1}{2}k\hat{u}_{ISA}^2 \right)$, while the corresponding output power was found to be, simply, $\hat{P}_{\text{out}}^{\max} = \omega \hat{E}_{\text{out}}^{\max}$. Finally, the ratio between the output and input power was used to define the electro-mechanical conversion efficiency, $\eta$, of the electro-active induced-strain actuator operating the mechanical load. The maximum possible value, $\eta_{\text{max}}$, of the electro-mechanical conversion efficiency was calculated in terms of $\nu_0$ and $\kappa$ and given as a simple formula in Equation (33). Remarkably, the stiffness ratio value at which the best conversion efficiency is attained does not coincide with the stiffness match value at which maximum energy output is obtained. However, the difference between the two optimal stiffness ratios (for best energy conversion and for maximum energy output) was not found to be very large.

The study is accompanied by extensive numerical data, shown in tables and charts. It was found that that maximum dynamic output energy of commercially-available electro-active induced-strain actuators can be as high as 0.260 J. The corresponding energy density values per unit volume and unit mass were found in the range 0.7-3.7 J/dm$^3$, and 0.091-0.482 J/kg, respectively. Not surprisingly, these values are lower than those for static operation (Giorgiutti, Rogers, and Chaudhry, 1996) since, due to the asymmetric behavior of the induced-strain actuators, the dynamic displacement amplitude, $\hat{u}_{ISA}$, is much lower (typically $\frac{1}{2}$) than the static stroke, $u_{ISA}$. Electro-mechanical energy conversion efficiency was found to be in the range 2.9% to 10.3%, while the optimal stiffness ratio for best energy conversion was found in the range 1.12 to 1.51.
The present study offers useful dynamic performance data that can be directly incorporated in the design of mechanical and hydraulic devices utilizing off-the-shelf induced-strain actuators. The linearization procedure used in this study to model the full-stroke dynamic behavior ensures that all the important parameters (input power, output power, conversion efficiency, and electro-mechanical coupling coefficient) are expressed in terms of standard vendor information and do not require insight into the intimate behavior of the active material used inside the induced-strain actuator. For these reasons, the analysis is general and can be readily applied to other similar products. It can also lead directly to formulation of industry standards that will greatly facilitate the development, use, and marketing of this novel class of actuators.

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