Modeling and Characterization of Piezoelectric and Magnetostrictive Induced Strain Actuators

Victor Giurgiutiu and Radu Pomirleanu
Mechanical Engineering Department, University of South Carolina
Columbia, SC 29208, 803-777-8018, victorg@sc.edu

ABSTRACT

This paper presents the results of theoretical modeling and experimental characterization of PiezoSystems Jena P-177-00 large stroke piezoelectric actuator and of Etrema AA-140J025-ES1 large stroke/large power magnetostrictive actuator. An improved smart-material actuators measurement method suited for static and low frequency actuation was devised. Analytical and finite element modeling (ANSYS) of the experimental setup to determine stiffness component characteristics was performed. The output displacements of the active material actuators were recorded in quasi-static and dynamic regimes, under varied pre-stress level, voltage and frequency values. The measurements indicated a strong dependence of the actuator stiffness and piezoelectric properties on the electromechanical loading conditions. The study also identified and calculated the parameters of the induced strain actuators electro-mechanical model. These parameters are necessary for performing design optimization to achieve maximum energy transfer and minimum power requirements. Experimentally verified data characterizing piezoelectric and magnetostrictive actuators in the full stroke/full power regime required for designing an effective airborne induced strain activated aerodynamic control system for air and space vehicles is provided.

Keywords: piezoelectric, magnetostrictive, induced-strain actuators, solid-state actuators, electro-mechanical loading

1. INTRODUCTION

Fundamental research for the application of smart-material actuators is currently being pursued in a number of areas, including flow control, precision positioning, vibration suppression, noise control, and mesoscale actuator devices. The intrinsic properties the of stack actuators - large bandwidth and high forces – make them ideally suited for the above-mentioned areas. Moreover, the very low parts count, high energy density and potentially high reliability extend the active material use to applications involving control of aircraft/helicopter/missile aerodynamic surfaces, dynamic space structures and automotive industry, the only major challenge needed to be overcome being the inherent small strain capabilities of the smart materials themselves (piezoelectric ceramics are capable of 0.15% maximum strains under no-load condition).

Practice has shown that whenever a smart material actuator was used for structural activation, the designer had to test it for establishing the useful correlations governing the actuator behavior. Hence, sustained efforts for characterizing the active material response under combined electro-mechanical load have been pursued, in order to facilitate their optimal use in actuation applications. For the piezoceramic sheet actuators, besides recording the force-voltage-displacement-frequency correlations, other characteristics like power consumption, drift under DC bias field, and depolarization behavior were investigated^{1, 2}. The behavior of the piezoceramic stack actuators intended for rotorcraft applications was evaluated at University of Maryland³, University of California, LA^{4, 5}, Boeing⁶, 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 weight³, MTS machine⁴, variable impedance by the means of a variable stiffness spring⁶ or variable aluminum plates bonded to piezoceramic plate⁷, and constant stiffness spring mounted in series with the smart material actuator⁸. We have chosen the last of the above-mentioned methods because most of the applications offer spring-like reactive load. The method of applying the mechanical load was further developed to allow for the measurements of the data points situated below the external spring curve characteristic. The experimental data was then processed to yield information about the smart material behavior, namely the force and displacement influence on the compliance and piezoelectric coefficients. Useful experimental work, data processing and modeling were performed upon magnetostrictive actuators as well^{8, 9}. For actuator power consumption estimation, of special interest is the evaluation of impedance spectrum variation with force and magnetic field. This study addresses this issue by experimental evaluation of the Etrema AA140J025 magnetostrictive actuator impedance for currents approaching maximum allowed values. The results indicate impedance changes of up to 80% for a given frequency, depending on the magnitude of the applied current.

2. MEASUREMENTS

Measurements of actuator force, displacement and dynamic response were made on two actuators: (a) piezoelectric PiezoSystems Jena P-177-00; (b) magnetostrictive Etrema AA-140J025-ES1. These actuators, with a fairly large total stroke (120-140 μm), are typical for mechanical design applications.

2.1. PIEZOSYSTEMS JENA P-177-00 (PAHL 120/20)

The active component of the PiezoSystems Jena 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 useful when static tensile forces are expected to occur or for general dynamic applications. Although not specifically indicated by the manufacturer, the material piezoelectric coefficient and the compliance values (Table 1) suggest a soft piezoceramic-type material.

Table 1 PiezoSystems Jena actuator properties

Maximum displacement	120 μm
Voltage range	-10 – 150V
Temperature range	-20 – 80 $^{\circ}\text{C}$
Actuator internal stiffness	30 kN/mm
Maximum tensile force	350 N
Maximum blocked force	3500 N
Capacitance (for small strength electrical fields)	42 μF
Resonance frequency	5 kHz
Length	126 mm
Diameter	20 mm
Piezoelectric coefficient d_{33} ($10^{-12} \times \text{m/V}$)	700
Compliance s_{33}^E ($10^{-12} \times \text{m}^2/\text{N}$)	20.8
Coupling factor κ_{33}	0.65

Figure 1 PiezoSystems Jena P-177-00

The piezoelectric PiezoSystems Jena actuator (Figure 1) measurements were taken in static and quasi-static regimes, because the maximum output current of the amplifier used is 50mA, insufficient for harmonically driving the actuator at frequencies in excess of 1.25 Hz, at maximum voltage. We have 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. This signal was further tapped and sent to the Tektronix TDS 210 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 stack tip was recorded using the Philtec D100 optical displacement transducer. The signal coming from the optical displacement transducer had to be offset to facilitate its display on the digital oscilloscope. If needed, the signals on the oscilloscope were downloaded into a laptop computer (Figure 2b).

Figure 2 Experimental set-up for the piezoelectric PiezoSystems Jena actuator; a) no-load configuration; b) in-phase electro-mechanical loading measurements; c) compression machine

For the no-load condition, the optical transducer was placed directly against the top of the stack (Figure 2a). For the loaded case, the force was applied using a LongYear compression machine, provided with a proving ring with a force dial gauge having a calibrated accuracy of $\pm 7.2\text{N}$ (Figure 2c). The load applied in this way has a spring-like behavior, due to the presence of the proving ring, calling for a different measuring procedure than the one used in the case of dead weight machine³ or the one using a MTS machine⁶.

First, the free displacements for positive voltage were recorded, to verify the experimental apparatus and the compliance with the manufacturer information. Then, the blocked force as function of applied voltage was recorded, using two different methods:

Method 1: apply first the voltage and then the load. The following steps were applied: a) discharge the stack; b) set to zero the voltage going into the stack and turn on the amplifier; c) bring on the oscilloscope display the signals from the sensor and the one that goes 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 cylinder; e) adjust the cursor on the oscilloscope to superimpose on the signal coming from the displacement transducer; f) adjust the voltage on the DC power source until the desired value – the stack will expand and the proving ring will compress; g) compress the assembly until the signal coming from the sensor superimposes on the cursor. When this step is completed the stack has recovered 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).

Figure 3 Blocked force variation with voltage

Method 2: apply first a pre-stress level, and then adjust 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 volts, 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 on the dial gauge and the voltage supplied to the actuator. Comparison of the two methods showed consistency for voltages up to 70% of the maximum voltage, but the results diverged for higher voltages, with a 14% difference for 150V (Figure 3).

Figure 4 Generic Force-voltage-displacement diagram

Finally, to completely describe the piezoelectric actuator behavior under quasi-static conditions, we recorded the variation of the actuator displacement under the combined effect of applied force and voltage. 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 curve (Figure 4). For the points situated above the line, the following steps were taken when recording the displacement response under combined electromechanical load:

- set the bottom of the cylinder in contact with the top of the actuator and slightly compress them, up to 10 – 15N(1-2 divisions on the force dial gauge);
- superimpose the first cursor on the displacement transducer signal (v_1);
- 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;
- apply voltage V_k : the stack expands and the proving ring further compresses;
- superimpose the second cursor on the current transducer signal on the oscilloscope display (v_2);
- 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;
- repeat steps for the next voltage $V_{k+1} > V_k$;
- repeat steps a) to g) for the next initial level of pre-stress $F_{i+1} > F_i$.

Data points evaluated through 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. For points below the external stiffness curve, the following procedure was used:

- discharge the stack;
- apply the voltage V_i on the unloaded stack;
- bring the top of the actuator in contact with the bottom of the cylinder and slightly compress the entire assembly (10-15N), to ensure the contact;
- apply the voltage $V_k > V_i$ and record the force on the dial gauge and the displacement from the oscilloscope
- repeat step d) for the rest of the voltages up to the maximum voltage;
- 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 5).

Figure 5 PiezoSystems Jena PAHL 120/20 behavior described by the force-displacement-voltage correlation

2.2 ETREMA AA-140J025

The magnetostrictive actuator measurements were taken at frequencies higher than 1kHz, due to the limitations of the Compact Power MAC01 amplifier. The ETREMA actuator (Figure 6) 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. 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 linear strain-magnetic field characteristic. This is especially needed for magnetostrictive actuators, which show high hysteretic behavior.

Table 2 Etrema AA-140J025 magnetostrictive actuator properties

Displacement	$\pm 70 \mu\text{m}$
Current range	0 – 3A RMS
Temperature range	$-20 - 100 ^\circ\text{C}$
Maximum dynamic force	$\pm 890 \text{ N}$
Maximum blocked force	1740 N
Axial stiffness	24.9 kN/mm
DC Resistance	2.3 Ω
Inductance	3.5 mH
Natural frequency	2.4 kHz
Length	198 mm
Diameter	47 mm

Figure 6 ETREMA AA-140J025

Figure 7 Experimental set-up for determining the magnetostrictive actuator impedance variation with input current

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. In determining the necessary power consumption one has to accurately know the frequency and current variation of the actuator impedance. Usually, information released by vendor refers to the frequency variation under the conditions of very small currents. In this study, we have focused on the bi-variation of the magnetostrictive actuator impedance with both current and frequency. So far, the measurements did not take into account the mechanical load influence on the impedance variation.

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 7). 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 the entire series circuit were displayed on the Tektronix TDS 210 oscilloscope allowing for the measurement of phase lag induced by the magnetostrictive actuator. For the case of small currents, the magnetostrictive actuator impedance was directly measured using the HP 4914A impedance/gain analyzer.

3. MODELING AND DATA PROCESSING

Since data processing and actuator electro-mechanical modeling are closely interrelated, these two activities were done together, as presented next.

3.1 External stiffness for the PiezoSystems Jena actuator measurements

The external stiffness in the case of quasi-static applications refers to the stiffness of the external structure, as seen by the actuator. The external stiffness is needed if a model describing the piezoelectric material quasi-static behavior is sought. An equivalent stiffness model of the test rig was built, containing all the known spring-like elements (Figure 8a). Particularly, the stiffness of the proving ring k_{PR} , cylindrical spacer k_C , columns and upper beam k_{CB} were evaluated. Although the calculation could not yield the exact value of the external stiffness due to the unknown compression mechanism stiffness k_{CM} , an upper bound approximation was determined. This value was used to validate the external stiffness value determined from the experimental data.

Figure 8 a) Quasi- static stiffness model of the test rig; b) ANSYS simulation of proving-ring deformation under a 600N radial load with the deformed and undeformed geometry shown

The stiffness of the columns and the cylindrical spacer were calculated using $k = EA/L$, employing the appropriate values for the geometrical and material parameters: For the proving ring, the theory of curved beams¹² predicts the stiffness when subjected to a radial load as:

$$k_{PR}^{(r)} = \frac{4EA}{\pi R} \frac{1}{1 + \frac{12(\pi^2 - 8)}{\pi^2} \left(\frac{R}{h}\right)^2}$$

where R is the mid-radius, h is the ring width and A is the cross-sectional area in a radial plane. With a 212GPa Young's modulus, the above formula yields 14.39 kN/mm for the proving ring stiffness.

These calculations were further checked against an ANSYS proving ring radial loading simulation (Figure 8b). The computer modeling indicated the same stiffness within 3% error. Without the compression mechanism stiffness estimation, the series system defined by k_{ST} , k_C , and k_{CB} has the stiffness 12.7 kN/mm; this value should be regarded as an upper value for the actual external stiffness.

Another approach for determining the external stiffness is to use the experimental data, noting that parallel straight lines correspond to different pre-stress level sets of data points (Figure 9). The slope of these lines gives a value of approximately 6.3 kN/mm for the external stiffness, below the estimated upper bound value of 12.7 kN/mm. The difference comes from the finite stiffness of the compression mechanism, placed in series with the other spring elements.

Figure 9 External stiffness estimation from experimental data

3.2 Quasi-static linear model for the PiezoSystems Jena actuator

Modeling the PiezoSystems Jena piezoelectric actuator implied assumptions on the geometry of the device and on the behavior of the active material. The geometry was simplified (Figure 10) to account for the following active material stack geometric parameters: cross-sectional area, layer thickness, and number of layers. 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 given in Table 1, as provided by the manufacturer. We have used the linear piezoelectric equations for describing the active material behavior:

$$S_{ij} = s_{ijkl}^E T_{kl} + d_{kij}^E E_k \quad D_i = d_{ikl} T_{kl} + \epsilon_{ik}^T E_k$$

These equations were further simplified for the case where only the 3-direction effects were considered non-negligible. 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, the piezoelectric equations simplify to:

$$S_3 = s_{33}^E T_3 + d_{33}^E E_3 \quad D_3 = d_{33}^T T_3 + \epsilon_3^T E_3$$

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, the quasi-static model considered the loading of the active material stack in 3 steps:

- apply the pre-stress force F_0 by the means of an internal spring k_{SP} – the active material stack and the internal spring will be compressed;
- apply a force $F_e^{(1)}$ by compressing the series assembly made of the actuator and an external spring k_e – both the stack and the external spring will be compressed, while the internal spring will expand;
- apply a positive voltage – the stack will expand, 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. With this hypothesis in place, the stress and strain in the active material stack under combined electro-mechanical load would then be described by:

$$S_3 = \left(1 + \frac{k_{SP}}{k_{ST}}\right) \frac{F_0 + F_e^{(1)}}{(k_{ST} + k_{SP}) L_i^{(0)}} + \frac{d_{33}}{t} k_{ST} \frac{V}{k_e + k_{SP} + k_{ST}} \quad T_3 = \frac{F_0}{A} + \frac{F_e^{(1)}}{A} \cdot \frac{k_{ST}}{k_{ST} + k_{SP}} - \frac{d_{33} \cdot V}{t \cdot s_{33}} \frac{k_e + k_{SP}}{k_{ST} + k_e + k_{SP}}$$

where t is the active material layer thickness, A and $L_i^{(0)}$ are the cross sectional area and the initial length of the stack. The internal active stack stiffness k_{ST} was evaluated based on the material compliance value reported by the manufacturer. Due to the presence of the internal spring, the force exerted on the actuator and read on the dial gauge $F_e^{(2)}$ will differ from the force manifested in the active material stack. The external force $F_e^{(2)}$ can be directly compared with the experimental data, and thus its estimation is useful:

Figure 10 Idealized geometry of the PAHL120

$$F_e^{(2)} = \frac{k_{SP}}{k_{ST}} F_0 + F_e^{(1)} \frac{k_{ST}}{k_{ST} + k_{SP}} - A \frac{d \cdot V}{t \cdot s_{33}} \frac{k_e}{k_e + k_{SP} + k_{ST}}$$

These formulae show a poor accuracy when compared to the experimental data (Figure 12). The possible sources for errors are: a) geometry and boundary conditions simplification assumptions consisting mainly in neglecting the effects due to the electrodes and resin; b) material non-linearity.

Figure 12 Comparison of the PiezoSystems Jena actuator linear model prediction with the experimental data

Figure 11 Comparison of bivariate regression (smooth curves) with the experimental data points

3.3 Actuator stiffness estimation

In one of the first stages of every actuation process design, one has to check whether the actuator meets the energy and power requirements of the activated structure. In this step, knowing the actuator stiffness as function of input voltage and force is extremely useful when deciding the smart material actuator energy capabilities and demands for quasi-static activation.

Without any simplification assumptions on the geometry or the material behavior, the actuator bulk compliance, defined as $\partial(\text{Displacement})/\partial(\text{Force})$, can be determined from the experimental data. The only element of arbitrary is introduced by the bivariate cubic regression that was applied to the actuator displacement with respect to applied voltage and external force. Thus, the derivatives of the regression function may not exactly follow the correspondent physical quantities, as they would be measured, because the bivariate regression approximates the function and not its derivatives. 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 11).

The bivariate cubic regression retained all but the free term, because the displacement of the active material actuator under no electro-mechanical loading must be zero:

$$u = C_0 F^3 + C_1 F^2 V + C_2 F V^2 + C_3 V^3 + C_4 F^2 + C_5 F V + C_6 V^2 + C_7 F + C_8 V$$

Having determined all the C_i coefficients, the bulk actuator stiffness was then easily modeled as the inverted partial derivative of u with respect to F .

Figure 13 Actuator bulk stiffness: a) variation with external force; b) variation with voltage at 1kN; c) variation with voltage at 2kN

The results (Figure 13) indicate that the bulk stiffness of the piezoelectric actuator significantly increases with the level of applied mechanical load, while the voltage dependence is negligible.

3.4 Piezoelectric and compliance coefficients estimation

The actuator displacement under electro-mechanical loading contains additional information besides the particular behavior of the piezoelectric material because of 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 given, if electrodes, resin and non-uniformity of the electric field are assumed to be higher order parameters when characterizing the actuator measured behavior. In this case, the force manifested within the active material stack is the sum of the measured force and the force exerted by the pre-stress spring, which further depends on the actuator displacement:

$$F_{ST} = F_E + F_0 - k_{sp} \cdot u$$

where F_0 is the initial pre-stress force, k_{sp} is the internal spring stiffness, F_E is the measured external force and u is the corresponding measured actuator displacement. Replacement of the external force from the previous equation into the regression equation provides the full description of the active material behavior, in terms of force in the active material, voltage and actuator displacement. The resulting equation is cubic in F_{ST} , V and u , evading an explicit formulation and calling for more mathematic manipulations before a numeric relation of the form $u_{ST} = u_{ST}(F_{ST}, V)$ is determined (Figure 14).

Figure 14 Piezoelectric stack displacement as function of force and voltage, relative to the initial deformation due to the internal spring pre-load

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 constants such that they hold the dimensions of piezoelectric coefficient d_{33} and compliance s_{33} , respectively:

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

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:

$$\frac{A}{L_i^0} \frac{\partial u}{\partial F} = s_{33} + F \frac{\partial s_{33}}{\partial F} + \frac{A}{t} V \frac{\partial d_{33}}{\partial F} \quad \frac{t}{L_i^0} \frac{\partial u}{\partial V} = \frac{t}{A} F \frac{\partial s_{33}}{\partial V} + V \frac{\partial d_{33}}{\partial V} + d_{33}$$

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 negligible quantities unless more hypotheses based on experiments are made. Without these 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. One 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.

One previously used⁶ method of reducing the problem is to neglect all terms but s_{33} in the $u_{ST,F}$ expression in search of qualitative results. A similar assumption can be made for estimating the piezoelectric coefficient¹³. With all these implied assumptions, the compliance is seen to decrease with the increasing stress (Figure 15a) and not to vary significantly with the

applied electric field. Similar qualitative analysis reveals that the piezoelectric coefficient is displaying a maximum value for approximately half the maximum electric field, and that its dependence on stress is not negligible (Figure 15b).

3.5 Magnetostrictive actuator impedance

The Etrema magnetostrictive actuator was electrically modeled as a series RL circuit, and thus the entire electrical circuit could be simply represented in the phasors space (Figure 16a). The impedance of the actuator can then be generically written as $Z = U_E / I$, where U_E is the voltage across magnetostrictive actuator. The current I was read directly as the voltage drop across the constantan-wire resistor, due to its 1Ω current-independent resistance. Due to resolution problems in directly reading U_E , the phase lag between U and U_I was measured instead, allowing for estimation of the φ angle between current and voltage across the entire circuit (Figure 16b). With U , U_I and φ measured for each given frequency, the impedance of the magnetostrictive actuator was modeled using:

$$Z_E = \frac{U_E}{I} = \frac{\sqrt{U^2 + U_I^2 - 2U_I U \cos(\varphi)}}{U_I \cdot 1}$$

Figure 16 a) Phasors diagram for the Etrema actuator measurement circuit; b) Etrema AA140J250 impedance for high currents

The magnetostrictive actuator modeled impedance departs from the low current impedance values with more than 80%. This change will be seen in both the active and the reactive power required from the power supply. The actuator impedance can be further broken down into real and imaginary parts: $\text{Re}(Z_E) = U \cos(\varphi) - U_I$; $\text{Im}(Z_E) = U \sin(\varphi)$ (Figure 17).

Figure 17 Impedance spectrum change with current; a) imaginary impedance; b) real impedance

4. CONCLUSIONS

This research investigated the quasi-static behavior of the piezoelectric actuator PiezoSystems Jena PAHL120/20 under electro-mechanical loading and the dynamic response of the magnetostrictive actuator Etrema AA140J025 under high currents operation. A measuring procedure involving a spring element was used to test the piezoelectric actuator under combined in-phase electro-mechanical loading. The measured data was further processed to yield design-oriented information about actuator stiffness and active material properties. For the particular piezoelectric actuator under study, the estimated active material compliance variation with voltage was found to be insignificant. This dependence on force only was previously encountered when evaluating the actuator stiffness. The qualitative estimation of the piezoelectric coefficient showed an optimal operating point, corresponding to half of the maximum allowed voltage. The magnetostrictive actuator impedance under high currents operation was estimated using a series RL circuit as electrical model of the actuator. Previously reported deviations from low currents characteristics specific to impedance analyzer measurements were recorded (up to 80%), for the chosen frequency range (1kHz-2kHz). The data presented in this paper is valuable for the design of induced-strain actuators for military and civilian applications.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Army Research Office, Grant No. DAAD 19-00-1-0017, Dr. Gary Anderson, Program Manager.

REFERENCES

- [1] Sirohi, J., Chopra, I., "Fundamental behavior of piezoceramic sheet actuators", *Proceedings SPIE Conference on Smart Structures and Integrated Systems*, #3329, pp 626-646, San Diego, CA, 1998
- [2] Lin, C.-Y., Hagood, N. W., "Compression depolarization of PZT piezoelectric materials under high electromechanical driving levels", *Proceedings SPIE Conference on Smart Structures and Materials*, #3992, pp. 115-125, Newport Beach, CA, 2000
- [3] Lee, T., Chopra, I., "Development and validation of a refined piezostack-actuated trailing edge flap actuator for a helicopter rotor", *Proceedings SPIE Conference on Smart Structures and Integrated Systems*, #3668, pp. 22-36, Newport Beach, CA, 1999
- [4] Mitrovic, M., Carman, G. P., Straub, F. K., "Durability characterization of piezoelectric stack actuators under combined electro-mechanical loading", *41st AIAA/ASME/ASCE/AHS/ASC Conference Structures, Structural Dynamics, and Materials*, Paper # AIAA 2000-1500, Atlanta, 2000
- [5] Mitrovic, M., Carman, G. P., Straub, F. K., "Electromechanical characterization of piezoelectric stack actuators", *Proceedings SPIE Conference on Smart Structures and Integrated Systems*, #3668, pp. 586-601, Newport Beach, CA, 1999
- [6] Straub, F. K., Ngo, H. T., Domzalski, D. B., "Development of a piezoelectric actuator for trailing edge flap control of rotor blades", *Proceedings SPIE Conference on Smart Structures and Integrated Systems*, #3668, pp. 2-13, Newport Beach, CA, 1999
- [7] Yoshikawa, S., Farrell, M., Warkentin, D., Jacques, R., Saarmaa, E., "Monolithic piezoelectric actuators and vibration dumpers with interdigital electrodes", *Proceedings SPIE Conference on Smart Structures and Integrated Systems*, #3668, pp. 578-585, Newport Beach, CA, 1999
- [8] Pan, M.-J., Rehrig, P. W., Kucera, J. P., Park, S.-E., Hackenberger, W. S., "Comparison of actuator properties for piezoelectric and electrostrictive materials", *Proceedings SPIE Conference on Smart Structures and Materials*, #3992, pp. 80-90, Newport Beach, CA, 2000
- [9] Dapino, M., J., Calkins, F., T., Flatau, A. B., "On identification and analysis of fundamental issues in Terfenol-D transducer modeling", *Proceedings SPIE Conference on Smart Structures and Materials*, #3329, pp. 185-197, San Diego, CA, 1998
- [10] Flint, E. M., Rogers, C. A., "Electro-dynamic transduction equations for piezoelectric stack actuators", *Adaptive Structures and Composite Materials: Analysis and Application*, AD-Vol. 45/MD-Vol. 54, pp. 201-210, New York, 1997
- [11] Ikeda, T., *Fundamentals of piezoelectricity*, Oxford University Press, 1996
- [12] ANSI/IEEE, *IEEE Standard on piezoelectricity*, IEEE, New York, 1987, Std. 176
- [13] Boresi, A. P., Schmidt, R. J., Sidebottom, O. M., *Advanced Mechanics of Materials*, John Wiley & Sons, Singapore, 1993