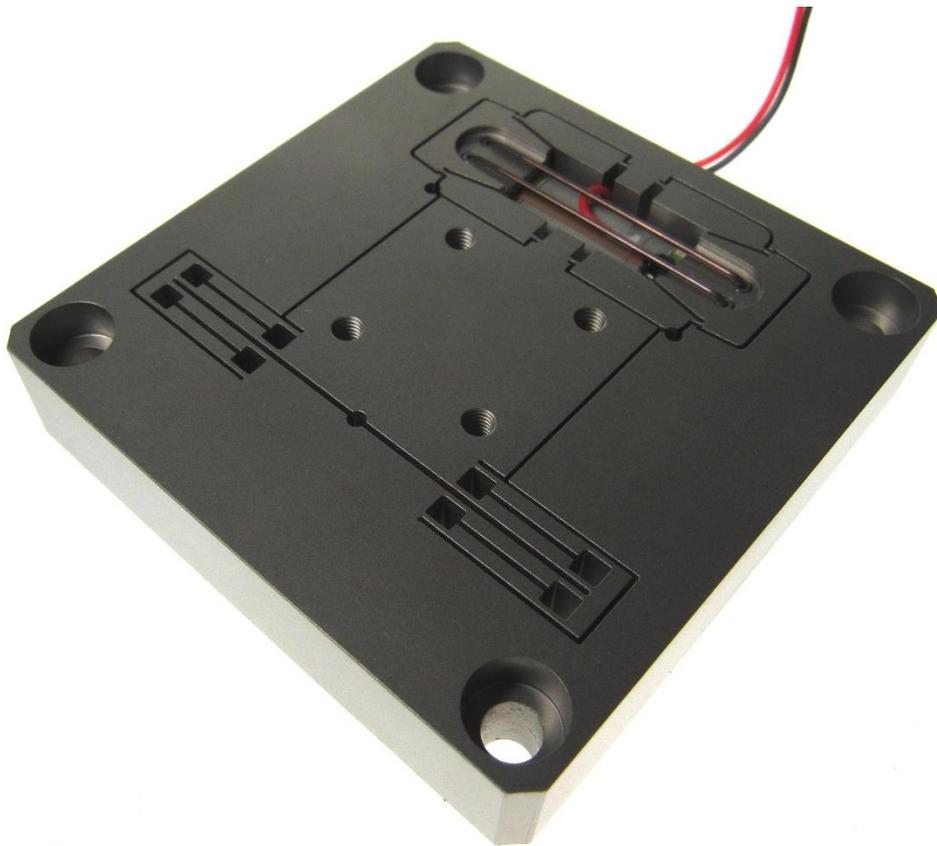**dsm**
Dynamic Structures & Materials, LLC

PIEZOELECTRIC
X-AXIS STAGE ACTUATOR (XSA)

USER MANUAL

DYNAMIC STRUCTURES AND MATERIALS, LLC
REV. 200520

Table of Contents

Appendix -   Application Notes
a) An Introduction to Piezo-Actuation
b) Design Challenges with Piezo-Actuation
c) Piezo actuators driving Spring Loads

1. PERSONAL SAFETY WARNINGS AND CAUTIONS

Please review the following points for both personal and equipment safety while operating any of DSM's piezoelectric actuator products.

Do not substitute parts or make any unauthorized modifications to the actuator. To ensure that its mechanical and electrical integrity are not compromised, please contact DSM for service and repair.

High Energy/Voltage Warnings

Exercise caution when using piezoelectric devices. High energy levels can be stored in the actuator's piezoelectric elements, which are capacitive in nature.

AC Source Grounding Warning

Ensure that the amplifier or driver used for controlling the actuator is connected to a grounded AC outlet with the recommended AC input connector configured for the available line voltage. There is a shock hazard if the amplifier chassis and cover are not connected to an electrical ground via the safety ground in the AC input connector.

CAUTION

RISK OF DANGER

In addition, the piezoelectric actuator must be mounted to a surface that is electrically grounded in order to avoid a potentially harmful voltage differential between the actuator and grounded objects.

2. OPERATING AND SERVICE PRECAUTIONS

DSM's flexure-guided piezoelectric actuators incorporate advanced materials and engineering for precision motion. The piezo actuators can easily be damaged from improper use and/or exposure to harmful environments.

Improper uses include but are not limited to applications such as the following examples:

- DO NOT: introduce static compressive loads exceeding 100% of an actuator's blocked force rating
- DO NOT: drive the actuator in a way that creates impacts between the actuator and other rigid surfaces. Strive to avoid dropping the actuator.
- DO NOT: cycle the actuator beyond 50% of the first natural frequency corresponding to the loaded condition
- DO NOT: introduce loading conditions that create bending moments in the actuator's frame
- DO NOT: drive an actuator with a step input or square wave. (If rapid response is required, DSM recommends using a half-sinusoidal transition with frequency not exceeding 50% of the actuator's first natural frequency corresponding to the loaded condition.)
- Accidental, extreme voltage changes may damage the piezo material within the actuator. Extreme voltage changes may occur if a plug power plug is pulled or a piezo amplifier overvoltages or undervoltages the actuator. DSM recommends using only DSM piezo amplifiers with DSM piezo actuators.
- DO NOT: introduce tensile loading into actuator frame. Prying or twisting of the actuator frame may damage the mechanism.
- DO NOT: allow the piezo within the actuator to come in contact with water. All water and alcohol liquid must be removed prior to operation. Humidity levels must be reduced to the level recommended in section 11. Note that isopropyl alcohol may have high levels of water and should not come in contact with the actuator.

Please contact DSM to determine the suitability of these flexure devices for your particular application's requirements.

3. PHYSICAL FEATURES OF DSM'S PIEZOELECTRIC ACTUATOR PRODUCTS

DSM has designed its flexure-guided piezoelectric actuator products to deliver reliable motion and force output. The figure below illustrates the physical features of a traditional DSM Piezoelectric X-Axis Stage Actuator. The standard mounting orientation of this type of actuator is also shown below.
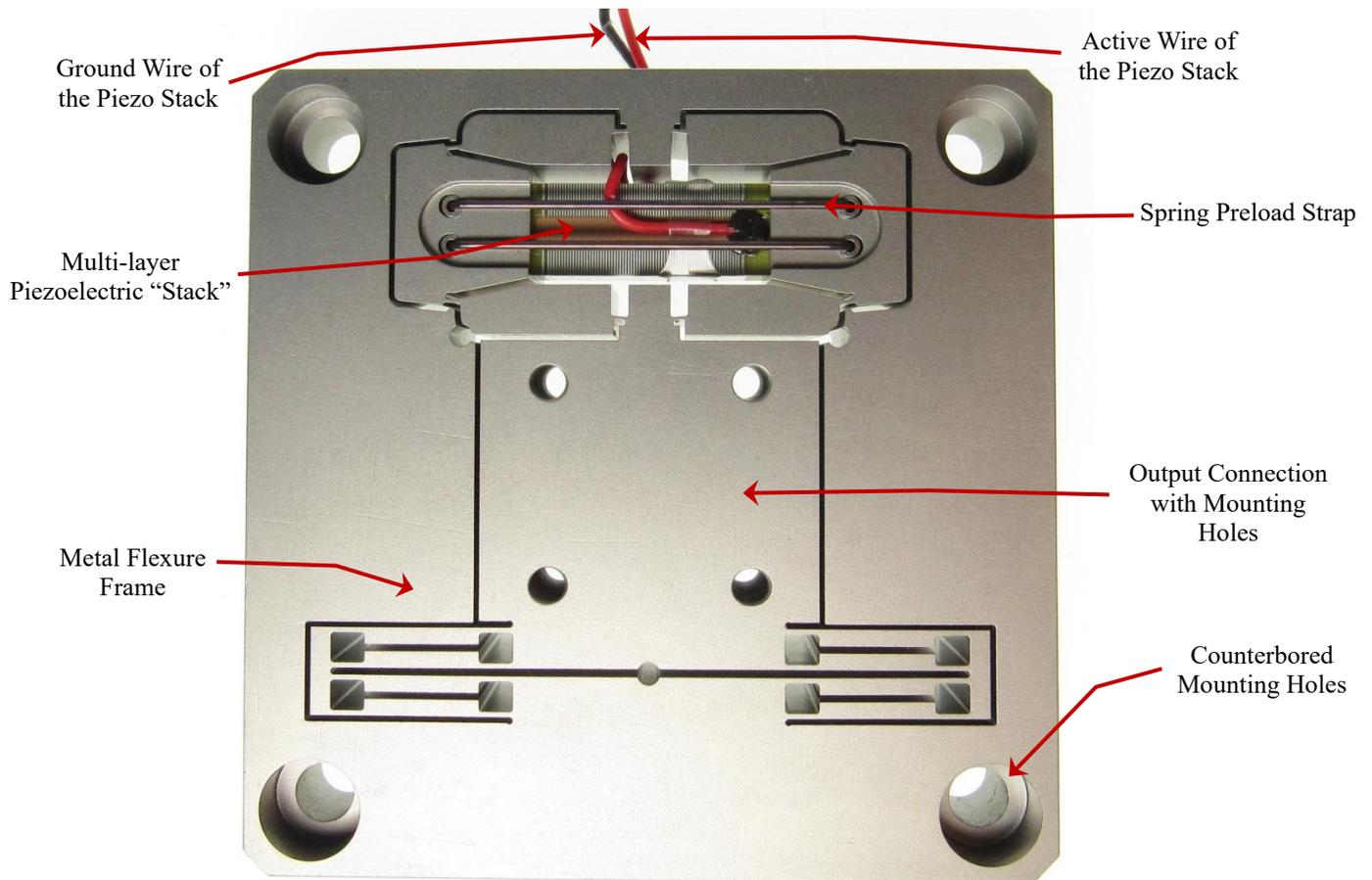
*Representative Piezoelectric X-Axis Stage Actuator*

DSM's typical Piezoelectric X-Axis Stage Actuators consists of a metal flexure frame, spring preload straps, and a piezoelectric "stack." The piezo stack is equipped with two electrical lead wires, typically red (active) and black (ground).

Customized metal frames, piezo stack elements, and preload straps are necessary for specialized applications. The metal frame material of the Piezoelectric X-Axis Stage Actuator can be made from nonmagnetic material for high magnetic field applications. Titanium frames can be used for cryogenic and/or vacuum applications.

DSM has piezoelectric actuator design experience with various extreme environments, such as high magnetic field (MRI), thermal (cryogenic or rocket), and vacuum (space) applications. Please contact DSM for application related questions or cost considerations.

4. MOTION OF AN XSA ACTUATOR

A voltage potential applied to the electrical leads of the piezo actuator results in a small physical expansion of the piezoelectric stack along its length. The lengthwise expansion of the piezo stack is amplified with a mechanical flexure frame, as shown in the figure below. As a result of the mechanical leverage created by the actuator's flexure arms, the piezo stack's lengthwise motion is translated into vertical motion of the actuator's center stage.
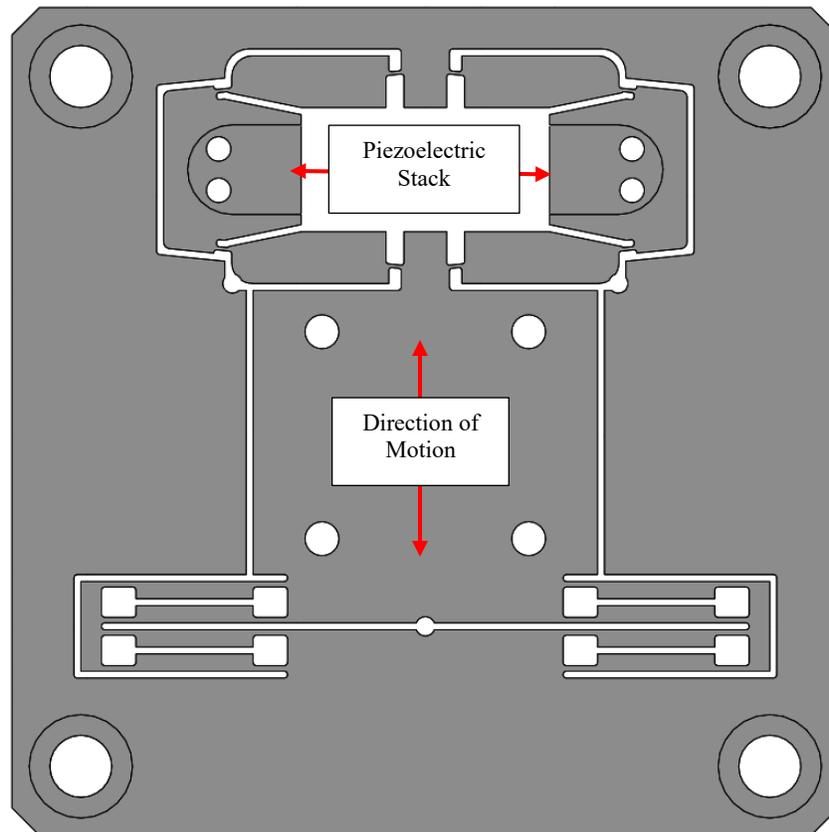
XSA Direction of Motion from Expansion of Piezoelectric Stack

When the piezoelectric stack is energized the XSA contracts towards the piezo stack. Actuators can be designed to expand or contract when voltage is applied to the piezo stack.

5. APPLIED PIEZO VOLTAGE INPUT LIMITS

The recommended voltage limit for DSM's standard piezoelectric stack is a signal operating between –30 V and +150 DC. It is preferable to drive the actuator with a sine wave as input for high frequency actuation, because the extremely high-frequency components of square waves and triangle waves will decrease the expected life of the piezo stack, eventually leading to premature stack failure. When operating a piezoelectric actuator, take care not to subject the device to voltage spikes at or near maximum voltage, (which can occur when turning on an amplifier), as these spikes can also damage the piezo stack. Piezoelectric materials are very responsive, and high frequency drive signals can cause the material to experience damaging tensile stresses.

6. ACTUATOR STATIC OPERATION

The actuator can be operated at static or near-static conditions using only a power supply and a voltmeter. The input voltage can be adjusted until the desired displacement level is achieved. Use the voltmeter to verify that the input signal is within the actuator's rated voltage range (i.e., –30V to +150V). At higher humidity levels, prolonged DC Voltage can lead to stack degradation.

7. ACTUATOR DYNAMIC OPERATION

Typical dynamic operation of a Piezoelectric X-Axis Stage Actuators involves an analog output device (e.g., function/signal generator, data acquisition card) and a piezo linear amplifier. Prior to connecting the piezo stack in the XSA actuator to the piezo linear amplifier device, DSM recommends auditing the analog signal. Use the piezo linear amplifier to drive a capacitor that is equal to the capacitance of the piezo actuator and rated for high voltage levels. Monitor the voltage applied to the capacitor from the linear amplifier with an oscilloscope to ensure that the voltage limits and waveform are appropriate for the rating of the piezo stack. Use proper caution while working with all high voltage devices and connections.

The analog output device provides the signal to the linear piezo amplifier, which in turn is electrically connected to the piezoelectric actuator. During dynamic operation, it is important that the actuator is not driven at or near the actuator's loaded resonant frequency. Operation at or near the actuator's loaded resonant frequency may cause the displacement of the mechanism to exceed the actuator's rated displacement. If an XSA actuator is driven in a dynamic manner where it exceeds its rated stroke, high cycle fatigue may occur in the flexure elements of the actuator frame. In high cycle fatigue, the flexures may snap and the piezoceramic may electrically fail as a result of unbalanced loading.

Several solutions may be considered to avoid over-stroke of the piezo actuator in dynamic applications. The XSA actuator might be linked to the applied mass load with a spring to "decouple" the mass. Another option may be a bumper or stroke limiter placed in the mechanism to prevent over-stroke. Alternatively consider driving the actuator at or near a loaded resonance condition only with a very low peak-to-peak input voltage with the actuator's

displacement monitored. Consider hiring DSM to analyze your load application to avoid damaging the actuator mechanism.

The piezoelectric stack is very responsive to electrical ripple on the input signal. If the input signal has a low-amplitude, high-frequency ripple component, the actuator frame may not dynamically respond with corresponding motion, but the piezoelectric stack may respond and vibrate or chatter within the frame. For example, if a low-resolution motion card or DAC (digital to analog conversion) card is used to produce the signal to the piezoelectric device, there might be some filtering ripple on top of the input signal. If the noise is not filtered out, it may manifest itself as a high frequency noise that can be heard emanating from the actuator. Although the actuator frame cannot respond dynamically to these signals, the piezo stack has the ability to respond and follow voltage signals up to 20 KHz.

8. ACTUATOR POSITION OUTPUT AND HYSTERESIS

Actuator motion is approximately proportional to the voltage applied to the piezo stack. Due to the solid-state nature of the device and the sensitivity of piezo material to applied voltage, the actuator's motion can be repeatable as long as things like temperature, load, and coefficients of thermal expansion are considered and controlled where possible.

When a piezoelectric actuator is cycled from one voltage level to another and then back, a path dependent behavior sometimes called hysteresis can be seen in the actuator's response. The path dependent behavior exhibited by the actuator displacement plot is a function of the piezo material, not mechanical issues. The piezo path dependent behavior is rate dependent but can be characterized with testing. The plot below depicts the displacement path dependent behavior of an XSA actuator vs. applied voltage.
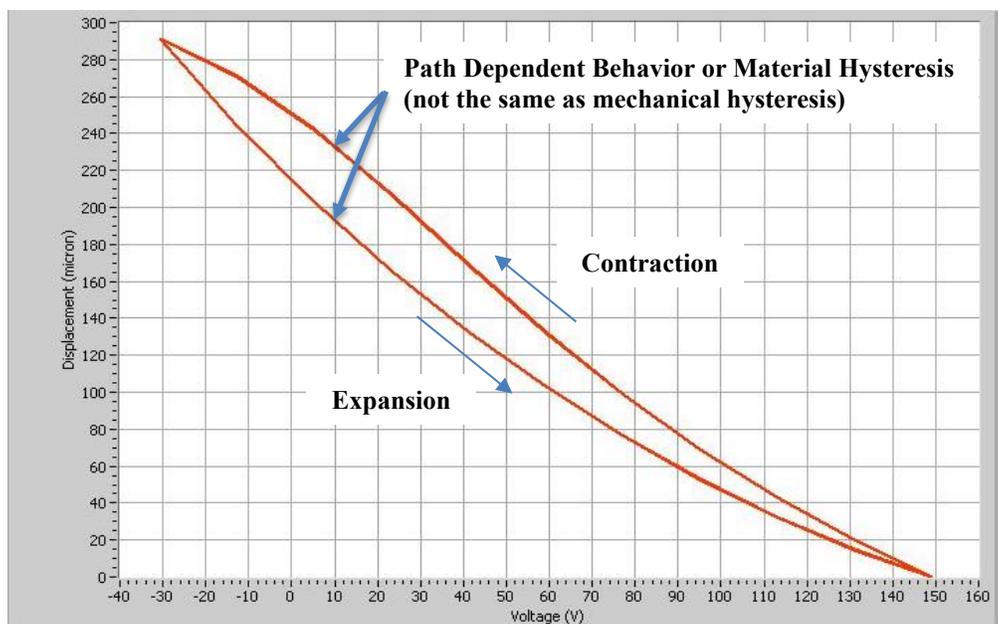

XSA actuator displacement vs. voltage and the inherent piezo hysteresis

The two curves shown in the graph are representative of the path dependent behavior at full voltage stroke, and this is quantified as 10-15% for typical piezoelectric materials. In practical application, the presence of this path dependent behavior dictates that the actuator's position at a given voltage level will be different depending upon whether the voltage was attained by increasing or decreasing the applied voltage. Also, as mentioned earlier things like temperature, load, and material coefficient of thermal expansion will play a role in open-loop position repeatability. In general, repeatable open-loop location control is possible under highly controlled conditions. DSM recommends implementing a closed-loop control system on its actuators to increase location repeatability of the actuator and reduce or eliminate path dependent behaviors. DSM can add encoders for closed-loop control on any of its actuator systems.

9. APPROPRIATE MOUNTING AND LOADING OF AN XSA ACTUATOR

XSA devices are designed to accept a balanced load on the mounting plate. The loading should be applied orthogonal to the mounting surface of the actuator output blocked (Z-axis as shown in the figure below).
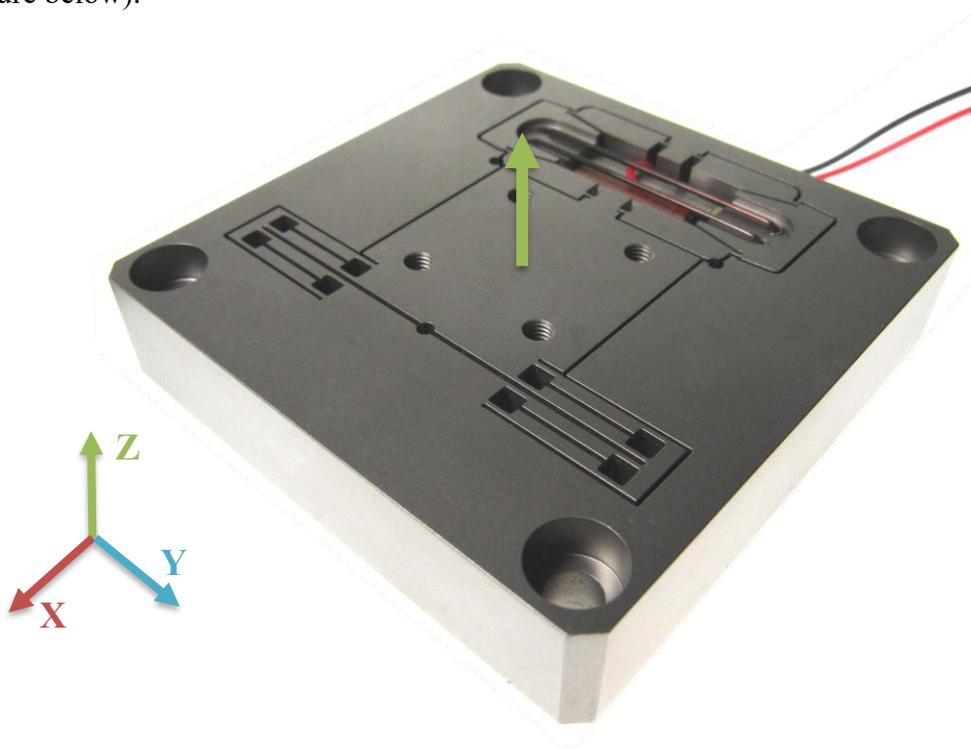
Appropriate loading condition for an XSA actuator

Large loads in X or Y direction may cause damage to the actuator frame. This limitation applies to both static and dynamic loading and any combination of the two. Care should be applied to verify that any dynamic loading (operating at high frequency with an attached mass) does not exceed the recommended load (refer to data sheet for specific model for loading information).

Actuator Force Output and Available Stroke

The magnitude of the applied load should not exceed the "blocked force" rating of the actuator. The blocked force rating is a product of the stroke and the stiffness of the actuator.

Example:
DSM's XSA-0200C-S-0718-150-SS has a rated stiffness of 0.8 N/micron and a rated displacement of 170 microns over the standard 0 to +150V range. Therefore, the maximum recommended load (blocked force) is 136 N for this model.

The blocked force is the maximum force generated by the actuator. DSM determines a piezo actuator's "blocked force" by multiplying stiffness by the travel range of the actuator when operating at 0 V to 150 V. Under a static load equal to an actuator's blocked force, the actuator will be able to move through its full range of motion and will respond rapidly to changes in the applied voltage field. The static load simply shifts the actuator's un-energized equilibrium position.

10. PIEZO SELF HEATING AND OPERATIONAL DUTY CYCLE LIMITS

Piezoelectric materials are capacitive in nature, but these materials also have some internal, losses that can lead to destructive self-heating under high dynamic operation. High levels of electrical current can flow in and out of the actuator depending upon the driving waveform and the associated rate of change of the applied voltage field. Peak current for a "straight line" voltage change is calculated as Current (Amps) = Capacitance x dV/dt (where dV/dt is the change in voltage with respect to time). The rate of change in voltage with respect to time is directly related to operational frequency. Please check the expected operational current and heat up before using the piezoelectric actuator in applications where the duty-cycle or operational frequency may cause the external stack temperature of the piezo stacks to exceed 80 C.

A smaller cross section piezo stack (e.g., 5x5 mm cross section) can likely be driven over a 0-150 V range at up to 300-350 Hz continuously without exceeding the allowable steady-state temperature of 80 °C. A large stack (e.g., 10x10 mm cross section) would be likely limited to approximately 150 Hz for 0-150 V continuous operation in order to maintain the allowable steady-state surface temperature below 80 C. These continuous operation specifications are for actuators in still air at room temperature.

The heat-up of the actuator depends on the application duty cycle among other factors. For applications where the user detects that the actuator temperature is approaching 80 °C, DSM recommends the addition of forced air convection to aid in cooling the stack.

As a result of the many factors that can affect the thermal condition of the piezoelectric stacks, please consult with DSM regarding your requirements. DSM cannot guarantee satisfactory performance under all conditions.

11. PREFERRED ENVIRONMENTAL OPERATING CONDITIONS

A standard piezoelectric actuator will be designed to operate in the following environment. Any deviation from the specified environment must be approved by DSM and may result in the voiding of any warranty.

- Environmental temperature for full stroke operation at less than 200 Hz: 15 to 50 degrees Celsius*
- Percent relative humidity: 0-50% (Non-condensing)
- Operating supply voltage: -30 to +150 V**

* NOTE: The output stroke of piezoelectric material decreases approximately linearly from room temperature (25C) down to -273C, where displacement output is assumed to be zero. With this in mind, the motion range of a standard piezoelectric actuator will be about 20% less at -40 °C than at room temperature.

** This is the typical operating voltage for the majority of DSM's actuator products, but some products are rated for up to 200V. Please see your respective quotation and/or product design data.

⚠ CAUTION: As with any electrical device, do not spill liquids on or immerse piezoelectric actuators and drive electronics. This may cause electrical shock or short circuit of the devices.

Please contact DSM for applications requiring temperature or relative humidity conditions outside of that recommended above.

Vacuum and Specialty Environments
DSM's customers have used our piezoelectric actuator designs in vacuum and specialty environments (MRI, etc) with great success. The performance of the actuator in any unique environment is the responsibility of the user.

Based on some limited experience, DSM estimates that operation of the piezoelectric actuator devices in the following environments will not cause any difficulties. Helium, Argon, Nitrogen.

12. GENERAL SOURCES FOR ADDITIONAL INFORMATION

DSM receives piezo projects from time to time that require additional piezo testing in novel environments, new electrical configurations, or innovative mounting techniques. The testing that DSM completes often yields new information that is publishable. The reader is encouraged to review DSM's website for piezo information and new products.

http://www.dynamic-structures.com

Appendix A: An Introduction to Piezo-Actuation

Using piezo actuators requires an understanding of actuator mechanical and electrical performance issues. Understanding the basic operating concepts behind piezo actuators may also be beneficial to controlling and operating the piezo actuators. The following information on piezo actuator design and performance issues can be helpful when comparing piezoelectric-based actuators to more conventional electromagnetic actuators (solenoids, motors, voice-coils) and other "induced strain actuator" materials such as electrostrictive ceramic, magnetostrictive, and shape memory alloys.

Applications for Piezo Actuators

Actuators based on piezoelectric ceramic material prime movers (or piezo actuators) find broad acceptance in applications where precision motion and/or high frequency operation is required. Piezo actuators can produce smooth continuous motion with resolution at the nanometer and sub-nanometer level. This property makes them useful in precision positioning and scanning systems. The very fast response times, wide operating bandwidth, and high specific force can also be beneficial for applications in fluid valve control, optical scanning, vibration isolation, and precision machining.

Using the Piezoelectric Effect to Generate Motion and Force

Producing Displacement: DSM uses the term "piezo actuator" for actuator or motion generating devices that use electro-expansive ceramic materials such as lead zirconate titanate (PZT), as the prime mover. Piezoelectric materials exhibit an effect whereby they expand or contract in the presence of an applied electric field. This "induced strain" or change in length occurs as electrical dipoles in the material rotate to an orientation that more closely aligns with the direction of the applied electric field. The change in length is generally proportional to the field strength as applied via the device actuation voltage. A typical value for length change might be 0.1 percent of the total material length in the direction of the applied field. For example, when actuated, a 1 mm thick layer of PZT will increase in thickness by one micrometer. A monolithic stack of PZT layers and electrodes (called a PZT stack) is most often used in DSM's piezo actuators. PZT stacks expand in the column direction as represented in Figure 1.
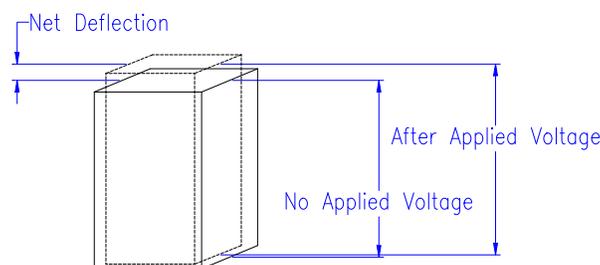

Figure 1 – Example of PZT stack expansion

PZT material fabricators supply their materials in the stack geometry to best leverage the piezoelectric effect at low voltages. A stack consists of many thin layers of PZT ceramic laminated together and electrically connected in parallel. PZT stacks come in various sizes and shapes and can be combined to produce extended motion. Useful expansions can be achieved at voltage levels as low as 10 volts, although many fabricators design their low voltage stacks for operation up to 150 volts. PZT stacks are typically available in circular or rectangular cross-sections from 1 mm to 14 mm across and in lengths as small as a few millimeters. Other form factors for PZT in actuator applications include tubes and thin patches or strips bonded to one or both sides of a substrate material.

DSM has developed many actuators that use mechanical amplification to enhance the small levels of expansion found in PZT materials. These actuator mechanisms leverage the high force and small stroke of PZT materials to create

many times greater stroke levels. Figures 2, 3, 4, and 5 represent some of the basic piezo actuator amplification concepts for PZT stacks and thin patches.
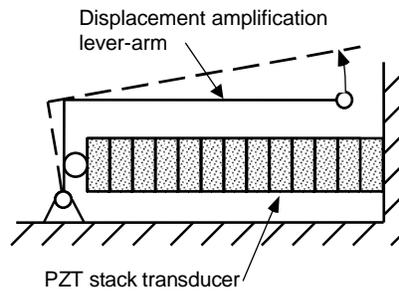

Figure 2 – Simple lever-arm mechanism

Figure 3 – DSM LPA-100 piezo actuator uses a simple lever-arm mechanical amplification. (PZT stack is green - output is in vertical direction)
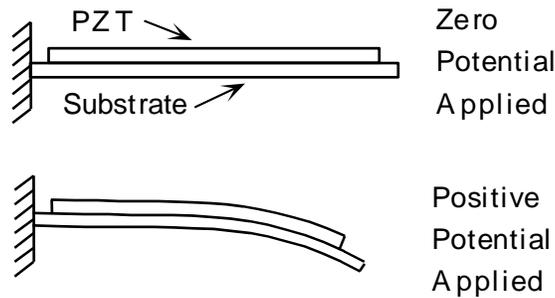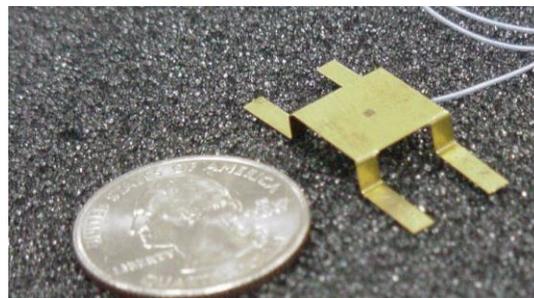

Figure 4 – PZT uni-morph patch amplification

Figure 5 - A miniature piezo actuator for a 70 um displacement switching application uses a uni-morph amplification concept.

Producing Force: PZT stacks are strain-generating devices. They expand proportionally to the applied electric field or actuation voltage. Maximum motion or expansion of the PZT occurs at maximum actuation voltage. When an external load resists the motion of the PZT expansion, the PZT stacks apply a force that is a function of the stiffness of the external load. The PZT stacks can generate a very high level of pressure against an external load if the stiffness of the external load is high enough to prevent expansion of the PZT.

Strengths of Piezo Actuators

Given the relatively small displacement that a PZT stack can develop, piezo actuators have unique design considerations. For example, piezo actuators excel in precision positioning applications where small, high-force moves are desirable. When fabricating, measuring, or testing extremely small structures or features, piezo actuators can provide very smooth and continuous motion over a range of a few microns to a few millimeters. With proper system design, piezo actuators hold the potential for high speed operation. Generally, the response time of a piezo-stack is limited by the speed of sound in the material. Therefore, natural frequency of a PZT stack may be tens of kiloHertz. Even with the added mass and lower stiffness of an amplification mechanism, the natural frequency of an amplified piezo actuator may exceed one kiloHertz.

Additionally, when designed and constructed properly, piezo actuators can exhibit the following strengths.
- solid-state construction with zero backlash, stiction, or cogging
- low or zero power position hold capability
- very high frequency response (bandwidth)
- very high force per unit area (force and stroke directly scale with size)
- little or no outgassing or particle generation as flexure-based designs have little or no friction and require no lubrication
- relatively low heat generation
- highly scalable and reliable

Summary

DSM's piezo actuators harness the small precise amount of expansion generated by the piezoelectric effect to produce a wide range of actuator solutions. With proper design, piezo actuators have performance attributes and properties that can be valuable in precision positioning, vibration control, and scanning applications. Smooth, precise motion from the sub-nanometer to multiple-millimeter level is possible with a variety of solid-state actuation/amplification mechanisms.

Appendix B: Design Challenges with Piezo-Actuation

Developing piezo actuators that feature precision motion capabilities presents an opportunity for creative solid-state mechanism design. DSM has developed strategies to deal with the challenge of short strokes and very high forces inherent to piezoelectric materials. Piezo actuator design must account for the following issues.

- Reactive energy
- Hysteresis, creep, and temperature instability
- Spring effects - available force is not constant, but dependent on position
- Energy losses from compliance in the system

Reactive Energy: Driving a piezo actuator requires sourcing sufficient current from the driver (programmable power supply or amplifier) to produce the desired electrical field or voltage level in the PZT stack. Because PZT stacks have relatively high capacitance, only a small amount of the energy delivered by the driver is used to move the load. The majority of the current applied is in the form of reactive power. Thus, the driving electronics must be able to move a relatively large amount of charge in and out of the PZT stack. This is slightly analogous to a four-quadrant drive for a DC motor with the added complication that the load is capacitive rather than resistive. In short, the drive electronics for a piezo actuator are specialized for driving capacitive loads.

Hysteresis, Creep, Temperature Instability: Path dependent behavior sometimes called dipole hysteresis in piezoelectric actuators manifests itself as a difference in displacement paths in the forward stroke compared to the return stroke. Therefore, the correlation between voltage and strain in piezoelectric materials is typically not highly linear. Open-loop hysteresis is generally around 10 to 15% of full scale, depending upon the particular piezo material. The output of the piezo actuator in a standard displacement graph reflects this variation in forward versus return path displacement (Figure 1).

To compensate for the change in position, one must drive the piezo actuator to a slightly different voltage in the return move to get back to the same starting position. The value of the stroke hysteresis is a percentage of the entire commanded stroke. For example, a 50-micron move would produce a hysteresis level of 5 to 7.5 microns.
Since PZT stack expansion occurs when electrical dipoles in the material rotate, the expansion is susceptible to temperature, time, and material resistance effects. Changes in temperature cause dipole creep or variations in dipole mobility. Dwelling at a specific dipole orientation for a period of time manifests itself as slight mechanical creep or drift in the PZT displacement. Drift or creep of 1 to 3% might be manifested; therefore, DSM recommends the use of displacement feedback to achieve the very fine resolution possible in piezo actuators.
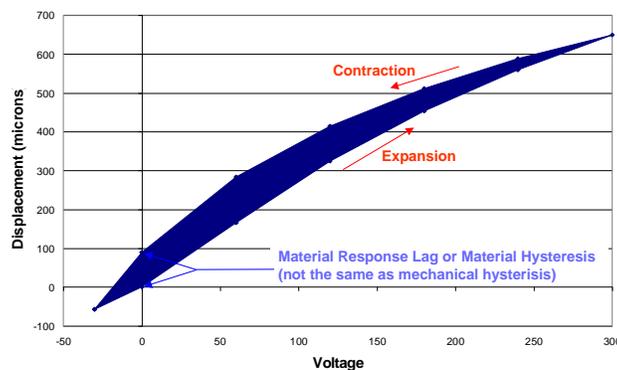

Figure 1 - Voltage-Displacement curve for one of DSM's amplified piezo actuators in open loop motion. Note the hysteresis between the expansion and contraction paths.

Spring Effects: A piezo actuator acts like a spring; the force it develops is not constant over its range of motion as might be the case for a linear motor or air cylinder device. The push force available from a piezo actuator gradually decreases as it extends. It is important to consider the stiffness of the actuator and the forces pushing against it to assure that it will operate correctly. Because the PZT stack is a strain generating device and only develops force as its expansion is resisted, the amount of displacement and remaining pushing force are dependent on the stiffness of the applied load. DSM specializes in high stiffness actuators that can deliver long travel/high force performance in compact sizes.

Energy Losses from Compliance: Since piezo actuators produce small levels of displacement, any mechanical slop, play or backlash in the actuator system or in the mechanical connecting elements reduces the available work. As a result, DSM recommends working with a competent actuator designer to develop the appropriate connections and mountings systems when incorporating piezo actuators.

Appendix C: Piezo actuators driving Spring Loads

When a piezo actuator (whether amplified or non-amplified) is actuated against a spring load, it converts electrical energy into both motion and force. This force will vary according to the amount of expansion/contraction achieved by the piezo actuator under the applied electrical field. When activated with an applied electric field, the piezo actuator moves against the spring load until it reaches a force balance condition. If at this point the spring load were to be removed, the stored potential energy within the piezo actuator would be converted completely into additional displacement. Therefore, when working against a spring load, the amount of displacement that the piezo actuator can produce is less than the piezo actuator's free zero-load displacement. The amount of displacement that the spring can be compressed or stretched is a function of the spring stiffness and the piezo actuator stiffness.

The following nomenclature will be used in this discussion:

Constants

k_{spr} : stiffness or spring constant of the applied spring load

k_{pzt} : stiffness or spring constant of the piezo actuator

$\delta_{pzt,\max}$: maximum displacement produced by the piezo actuator with no load

$F_{\max}$: maximum force capacity produced by the piezo actuator when k_{spr} is infinite (blocked force)

F_0 : Force capacity zero

Variables

δ_{pzt} : displacement produced by the piezo actuator under the applied electric field

F_{pzt} : force produced by the piezo actuator as it moves against a spring load

Piezo actuators have an inverse, linear relationship between their force capacity (for pushing against a spring-type load) and their displacement. At zero displacement, an actuator has maximum force capacity ($F_{\max}$). At maximum displacement ($\delta_{pzt,\max}$) under the maximum applied rated voltage, the force capacity is zero (F_0). Similarly, when the stiffness of the spring load (k_{spr}) is zero, the piezo actuator is able to achieve $\delta_{pzt,\max}$. When k_{spr} is infinite, the piezo actuator is not able to move against the applied spring load and instead produces its maximum

force capacity $F_{\max}$ against that load under the maximum rated voltage condition. The maximum force capacity $F_{\max}$ can be approximated by the product of $\delta_{pzt,\max}$ and the piezo actuator's stiffness k_{pzt} .

One calculates the amount of displacement that the piezo actuator can achieve when acting against a spring load using the following equations:

Equations
The linear force-displacement relationship for a piezo actuator pushing against a spring load is defined as

$$(1)\quad \delta_{pzt} = \delta_{pzt,\max} - \frac{\delta_{pzt,\max}}{F_{\max}} F_{pzt} \quad \text{or} \quad F_{pzt} = F_{\max}\left(1 - \frac{\delta_{pzt}}{\delta_{pzt,\max}}\right)$$

where δ_{pzt} is the deflection of the piezo actuator and F_{pzt} is the corresponding force capacity that can be generated by the piezo actuator at that deflection

The force-displacement relationship of the spring load is defined as:

$$(2)\quad F_{spr} = \delta_{spr} k_{spr} .$$

Recognizing that at equilibrium the force provided by the piezo actuator is equal in magnitude to the opposing force from the spring load, we can equate the expressions from (1) and (2):

$$(3)\quad F_{spr} = F_{pzt} = \delta_{spr} k_{spr} = F_{\max}\left(1 - \frac{\delta_{pzt}}{\delta_{pzt,\max}}\right)$$

At force equilibrium, the actuator has compressed the spring by a distance

$$(4)\quad \delta_{pzt} = \delta_{spr}$$

Substituting (4) into (3) yields

$$(5)\quad \delta_{spr} = F_{\max}\left(k_{spr} + \frac{F_{\max}}{\delta_{pzt,\max}}\right)^{-1} = \frac{F_{\max}}{k_{spr} + k_{pzt}} \text{ or } \delta_{pzt} = \delta_{pzt,max}\left(\frac{1}{1+\frac{k_{spr}}{k_{pzt}}}\right)$$

Consequently, if the spring stiffness exceeds the piezo actuator stiffness, less than one-half of the piezo actuator's free displacement can be achieved when acting against the spring. If the spring stiffness equals the piezo actuator stiffness, then exactly one-half of the piezo actuator's free displacement can be applied to the spring. If the spring stiffness is less than the piezo actuator stiffness, more than one-half of the piezo actuator's free displacement can be applied to the external spring. The portion of the piezo actuator's free displacement not applied to the external spring is stored in the piezo actuator as potential energy. In order to achieve full force, the piezo actuator must be in a contracted state.

Examples of a piezo actuator driving against a spring load

FPA-100 piezo actuator: nominal spring stiffness k_{pzt} = 1.0 N/micron; nominal blocked force F_{max} = 145 N. For reference, nominal displacement $\delta_{pzt,\,max}$ = 145 microns.

Case A: spring load having a stiffness of 0.25 N/micron (25% of the XSA-100 stiffness)

Using Equation (5), we determine δ_{spr} :

δ_{spr} = 145 N / [(0.25 N/µm) + 1 N/µm] = 116 µm

Case B: spring load having a stiffness of 1.5 N/micron (150% of the XSA-100 stiffness)

Using Equation (5), we determine δ_{spr} :

δ_{spr} = 145 N / [(1.5 N/µm) + 1 N/µm] = 58 µm