FACE®

FACE® INTERNATIONAL CORPORATION

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THUNDER® WHITE PAPER

CONTENTS

Thunder® devices are manufactured and sold by Face® International Corporation under licenses from NASA. Thunder® devices are protected under US Patent Nos. 5,6324,841 and 5,639,850 and other patents pending.

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Thunder®

THE TECHNOLOGY

Thunder® is a revolutionary device that is a member of a family of products containing "smart" materials. These materials are most commonly used in actuators, sensors, and acoustic sound generators. Based on a patented NASA invention, and only commercially available through Face® International Corporation, Thunder is a unique, extremely rugged, and highly adaptable member of the "smart" materials group of products. Thunder is a ferroelectric device made of multiple layers of material, typically stainless steel, aluminum and PZT piezoceramic. The individual material layers are held together in a "sandwich-like" package using a NASA patented high temperature polyimide adhesive called LaRC™-SI. The bonding strength of the adhesive allows the manufacturing process to induce a "pre-stress" or "pre-load" in the device and enables Thunder to have exceptional ruggedness and performance capability.

PZT Piezoceramic and Piezoelectricity

At the heart of every Thunder device is a PZT piezoceramic wafer which enables Thunder to act as either a sensor or transmitter/actuator, or both. Piezoelectricity[1] is a phenomenon that occurs in a certain class of naturally occurring crystalline materials such as quartz, Rochelle salt, and tourmaline. Piezoelectric materials change their geometry or dimensions when an electrical charge (voltage) is applied to them, and, conversely, they produce an electrical charge (voltage) when mechanical pressure is applied to them. However, these materials exhibit such a small amount of this very useful behavior that other materials have been created that have improved piezoelectric properties. Piezoelectric ceramics made of polycrystalline ferroelectric materials such as $BaTiO3$ and Lead Zirconate Titanate (PZT) have been manufactured with improved piezoelectric properties.

[1] Jaffe, B., Cook, W.R., Jaffe, H., *Piezoelectric Ceramics*, Academic Press, New York, 1971.

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Thunder Construction

Thunder is a layered composite in which individual materials are layered on top of each other to form a "sandwich." The bottom layer is stainless steel, the middle layer PZT ceramic, and aluminum the top layer; LaRC™-SI adhesive is applied between the layers. The entire assembly is placed into an autoclave for processing. During the autoclave cycle, the "sandwich" is heated and squeezed, allowed to cook and then cooled to room temperature. During the cool down cycle, the mismatch in coefficients of thermal expansion cause the metal and ceramic layers to contract at different rates, and they begin to work against one another, putting the ceramic in compression at room temperature. However, the strength of the adhesive bond holds everything together. The result is a "pre-stress" internal to the individual layers, which results in the characteristic bend or curvature of the finished product.

The bond between layers is essential because it makes possible the induced pre-stress. This pre-stress keeps the ceramic in compression and allows Thunder to be deflected far more than standard piezoceramics without cracking. The pre-stress also yields Thunder's unique, natural "pumping" motion. Depending on the polarity of the applied voltage, the radius of curvature will either increase or decrease, creating a pumping motion with relatively large displacements. This motion is one of the reasons why Thunder is constantly being considered as a solution for applications where traditional piezoceramic benders or stacks are limited.

Thunder's Advantages

Powerful, rugged, and reliable, Thunder actuators and sensors represent a significant advancement in piezoceramic technology. Lab demonstrations have shown displacements more than 30 times[2] the thickness of the device. No other actuator in its class -- certainly nothing in this low-cost, high-efficiency category -- exhibits Thunder's extraordinary mechanical output under load.

[2] Displacement values are dependent on factors such as applied voltage, drive frequency, load and mounting. This figure is based on cantilever mounting, high driving field, tip displacement, no load, and 1 Hz or quasi-static frequency laboratory conditions.

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Thunder devices can be manufactured in a wide variety of useful configurations -- disks, squares, and strips -- from a few millimeters to many centimeters in size. Depending upon the application, thickness is nominally less than a millimeter. And thanks to Thunder's simple design, solid-state construction, and efficient energy conversion, its reliability is extremely high, even under substantial load or pressure.

APPLICATIONS

Thunder technology introduces a versatile new family of rugged, robust, reliable piezoelectric actuators and sensors. Because of their unique composite structure, these powerful solid-state devices offer exceptional performance in a durable package, with the promise of significant benefits to a variety of applications.

Thunder actuators are relatively small, quite economical and flexible in design. Many exhibit very large mechanical displacement; the output amplitude for certain designs is an order of magnitude greater than conventional devices. Actuators can be operated using a broad spectrum of voltage frequencies from dc to kilohertz. They also demonstrate unusually high force, strength, durability and life expectancy. Certain models have reached 50 million cycles in life testing under restricted conditions, with no identifiable failure modes. Reliability testing is on-going by Face International and other research organizations. And Thunder packs all this performance into compact devices that demonstrate both low power consumption and high energy conversion efficiency.

Sensors in the Thunder family exhibit the ability to measure very small to very large displacements and forces. They also generate relatively high voltage outputs, thus simplifying system design and packaging. Both sensors and actuators can be manufactured in a variety of geometries. A novel fabrication process produces tough, durable, solid-state devices that can achieve and maintain wide-bandwidth performance even in harsh environments.

The breakthrough technology caused *R&D* magazine to name Thunder as one of the top 100 most technologically significant research developments in 1996.

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Figure 1 lists specifications for standard configuration Thunder products. Compared to other unimorphs, bimorphs, direct extension devices, flex tension actuators, benders, and multi-layer transducers, Thunder is superior. Figure 2 provides approximate force-displacement operational ranges for these devices compared to Thunder.

In general, Thunder is superior to other piezoelectric actuators and sensors because it…

- Exhibits Greater Flexibility
- Is Tougher & More Durable
- Exhibits Exceptional Load Capacity
- Operates with High Efficiency
- Provides Higher Performance at a Lower Cost
- Measures Large Forces & Displacements
- Can Operate in Harsh Environments and Over a Wide Temperature Range

As a result of the manufacturing process, the basic piezoceramic material is strengthened and protected with the internal pre-stresses and by the addition of metallic top and bottom layers. The metallic layers not only act to protect the ceramic and improve its ruggedness but also provide a place for electrical connection.

One of the exciting things about piezoceramic technology is that useable mechanical and electrical energy is generated from a lightweight, low power, and versatile material. As an actuator, the mechanical deformation of the ceramic can perform work when voltage is applied across its surfaces. This is accomplished by using the motion of the ceramic to vibrate or to move in step increments, depending on the type of input voltage. These movements usually are accomplished by using the actuator as a simple bender or a multilayered stack.

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When used in the cantilever position as a bender for applications in the fields of switching, flow control, positioning, or pointing, Thunder actuators should be firmly clamped or fastened at one end of the substrate material. Slots can be provided for ease of mounting. When used as a simple beam to generate force or create "pumping motion" for applications in flow control, positioning, vibration damping, or on-off control, Thunder actuators should be secured at both ends. One end should be completely fixed while the other end is free, or more free, to move. Rigidly fixing both ends of the Thunder device in this application will significantly limit the full use of its capabilities. There is also a method to extract work by utilizing the force produced from changes in the effective length of the unit. In this application, both ends are fixed. There are also several stacking configurations and changes to basic materials and processes that can be used to modify performance or to magnify certain performance characteristics.

Specific Applications.

Thunder actuators and sensors are being used in a vast variety of applications. Businesses, government laboratories, and researchers see tremendous potential for such devices. Listed below are just a few examples of specific applications being considered and actively researched.

Energy Harvesting

Thunder elements have been integrated into the design of conventional footwear in an attempt to harvest a useful amount of energy "parasitically" from the weight transfer which occurs during walking[3]. Thunder was able to generate peak values of 150 volts and 80 miliwatts with net energy transfers of 2 millijoules per step. These values were two to four times that generated by a multilayer laminate of PVDT foil used in the same experiment. A Thunder-based electrical generating system could produce an equivalent 150 cc of lithium-based battery energy in two years of average use and Thunder is rugged and lightweight. Human energy conversion research has direct application in DOD energy harvesting programs to power individual soldier systems.

[3] Kymissis, John, *et. al.* "Parasitic Power Harvesting in Shoes," *Physics and Media Group*, Massachusetts Institute of Technology Media Laboratory, August 1998.

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Precision Positioning

Thunder elements have been integrated into the design of a Self-Contained Actuator (SCA)[4] system used for precision machine tool positioning and chatter suppression and a Single Axis Piezoelectric Gimbal[5] used on spacecraft for data gathering instrumentation.

The SCA, designed by Dynamic Structures & Materials, L.L.C, was developed for high speed machining in the automobile industry. The system, built with stacked Thunder actuators, is used for custom profile turning at machine speeds in excess of 10,000 RPM, providing 60-100 lb tool feed force and up to 0.02 inches of stroke control. Singly or in combination, Thunder based actuators can be customized as to size, stroke, force, configuration, material, and mounting.

The piezoceramic gimbal, which can provide rotational motion without the moving parts normally found in conventional designs, has shown promise as a high frequency scanner for sampling or surveillance-type instruments on spacecraft. The gimbal constructed using Thunder was determined to be simple in design, inexpensive to manufacture, had no parts to wear out, and was lightweight.

Performance Enhancing Shape Control

Thunder is being investigated for use in changing the shape and geometry of airfoil bodies and space-based antennas.

NASA has conducted a feasibility study that incorporates Thunder into the upper surface of a sub-scale airfoil[6]. Displacement of the actuator is used to alter the upper surface geometry to enhance performance under aerodynamic loads. Thunder provided up to 13 times the out-of-plane displacement demonstrated by another type of piezoelectric actuator used in the study.

[4] Dynamic Structures & Materials, L.L.C. www.dynamic-structures.com
[5] Horner, Garnett and Taleghani, Barmac. "Single Axis Piezoceramic Gimbal," NASA Langley Research Center, Hampton, VA, 1998.
[6] Pinkerton, Jennifer L. and Moses. Robert W. "A Feasibility Study to Control Airfoil Shape Using Thunder®," NASA Langley Research Center, Hampton, VA, November 1997.

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Thunder is also being considered in the design of active reflectors for an aperture antenna for use on space-based satellites[7]. Thunder actuators are designed into the reflector surfaces of the antenna. Displacement of the actuators in a reduced gravity environment will deform the antenna, creating the ability to beam shape and scan without using gimbals or expensive phased array technology.

Active Noise Control

Thunder piezoelectric actuators were used in speakers for active control of noise in aircraft interiors at the University of Delaware[8]. The benefits Thunder provided in this application were its light weight and low power consumption. It was especially identified to be superior to other types of piezoelectric actuators because of its ruggedness and reliability.

GENERAL CATEGORIES OF POTENTIAL APPLICATIONS

Potential Actuator Applications

Motors	Valves	Pumps & Compressors
Positioners	Switches	Vibrating Elements
Agitation/Mixing	Separation/Filtration	Humidifier/Mister/Atomizers
Ultrasonic Transducers	Ultrasonic Cleaning	Ultrasonic Welding
Ultrasonic Cutting	Noise Cancellation	Jitter Suppression
Panel Stiffening	Air Flow Control	Electro-Optical Scanning
Sonar		Smart Structures

Potential Sensor Applications

Smart Structures	Pressure Sensors	Force Sensors
Flow Sensors	Shock Sensors	Level Sensors
Motion Sensors	Position Sensors	Accelerometers
Hydrophones		Non-Destructive Evaluation

[7] Washington, Gregory, PhD and Granger, Rich, “Reduced G Testing of a Mechanically Active Reflector for an Active Aperture Antenna,“ Department of Mechanical Engineering, Ohio State University, June, 1999.
[8] Jayachandran, V., *et. al*. “Piezoelectrically Driven Speakers for Active Aircraft Interior Noise Suppression,“ Department of Mechanical Engineering, University of Delaware, September, 1998.

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THUNDER® SPECIFICATIONS

Model	Weight	Dimensions L x W x H	Ceramic Thickness	Dome/Arch Height[1]		Capaci-tance	Max Applied Volts[2]	Resonant Frequency[3]		Typical Cantilevered Displacement[4]		Block Force[5]	
	(gms)	(inches)	(inches)	(mm)	(in)	(nF)	(Vpp)	(c)	(ss)	(mm)	(in)	(N)	(lbf)
TH 5-C	2.6	1.25 diam. x 0.019	0.007	1.29	0.051	39	424	NAp	532	NAp	NAp	133	30
TH 6-R	16.3	3.00 x 2.00 x 0.031	0.015	4.24	0.167	77	905	60	NA	3.12	0.123	>133	>30
TH 7-R	18.0	3.80 x 2.80 x 0.023	0.010	9.57	0.377	166	595	31	106	7.62	0.300	133	30
TH 8-R	2.1	2.50 x 0.50 x 0.019	0.008	3.83	0.151	30	480	65	177	1.98	0.078	67	15
TH 9-R	1.0	0.88 x 0.38 x 0.021	0.008	0.61	0.024	7	480	3479	NA	0.12	0.005	31	7
TH 10-R	1.0	1.00 x 0.50 x 0.022	0.008	0.64	0.025	10	480	2854	NA	0.20	0.008	36	8
TH 11-R[6]	0.9	3.00 x 0.10 x 0.029	0.015	NA	NA	4	905	NA	NA	1.98	0.078	NA	NA
TH 12-R[6]	19.5	3.80 x 2.80 x 0.022	0.010	5.49	0.216	139	600	NA	NA	NA	NA	NA	NA

Notes:

[1] Dome / Arch Height: Considered to be the highest point of the Thunder® device when measured with the device resting on a flat surface.

[2] Maximum Voltage: The maximum allowable input voltage at which a Thunder® device may be operated is dependent upon the thickness of the piezoceramic element: max peak-to-peak 60 V/mil; max negative 30 V/mil; max positive 60 V/mil.

[3] Resonant Frequency: Typical values in Hz with device cantilevered (c), or simply supported (ss), no load, generally driven at 20% of maximum voltage. "NA" denotes values not available as yet; "NAp" denotes values not applicable.

[4] Typical Displacement: The amount of displacement or stroke achieved by Thunder® devices is dependent upon factors such as applied voltage, drive frequency, load and mounting. The displacements indicated above are typical bi-directional values for the various models when driven at maximum allowable input voltage under 1 Hz, no-load, cantilevered (for "R" models) laboratory conditions. Actual displacement in specific applications may be greater or less than indicated.

[5] Block Force: The force or load required to restrict the displacement of a Thunder® device to approximately 10% of the ceramic thickness while the device, simply supported, is driven at maximum voltage.

[6] These models are special order only and not carried in inventory. TH 12-R is designed with a 0.25" center mounting hole between two piezoceramic elements.

Note: Thunder® devices can be manufactured in a wide variety of useful configurations -- disks, squares and strips -- from a few millimeters to many centimeters in size. Depending upon the application, thickness can range down to less than a millimeter. Device configurations detailed above are not intended to suggest current or future restrictions or limitations in dimensions or performance. Characterization and performance information provided is based upon tests believed to be accurate and reliable. Inasmuch as Face® International Corporation has no control over the manner in which others may use this information or Thunder® devices, the Company does not guarantee results to be obtained, nor does the Company make any express or implied warranty of fitness for any particular purpose concerning the effects, results or consequences of such use.

Figure 1

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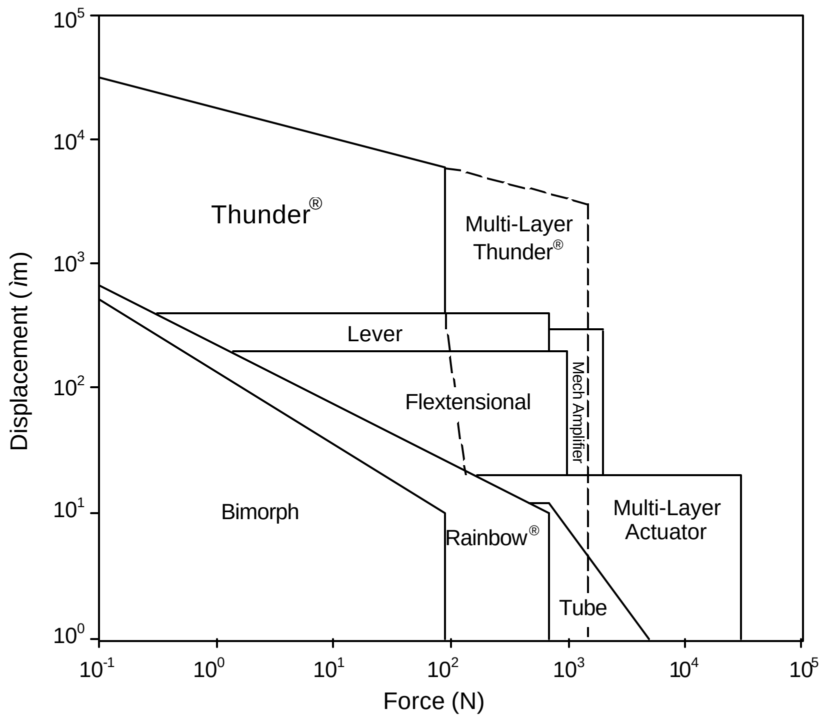
FORCE-DISPLACEMENT OPERATIONAL RANGES

FOR STATE-OF-THE-ART PIEZOELECTRIC ACTUATORS

All Data Except Thunder® Data is taken from Craig D. Near, *Piezoelectric Actuator Technology*, Presented at SPIE Smart Structures and Materials Conference, February 27, 1996.



Thunder® performance values are based on representative Thunder® device data from measurements using simply supported actuators.

PLEASE NOTE
These preliminary test results represent typical performance values of selected Thunder® devices and are intended to offer a general understanding of significant capabilities of this technology. Application-specific performance may be greater or less and will very depending upon factors such as mounting, load, applied voltage and drive frequency. Dashed lines indicate projected data.

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Figure 2