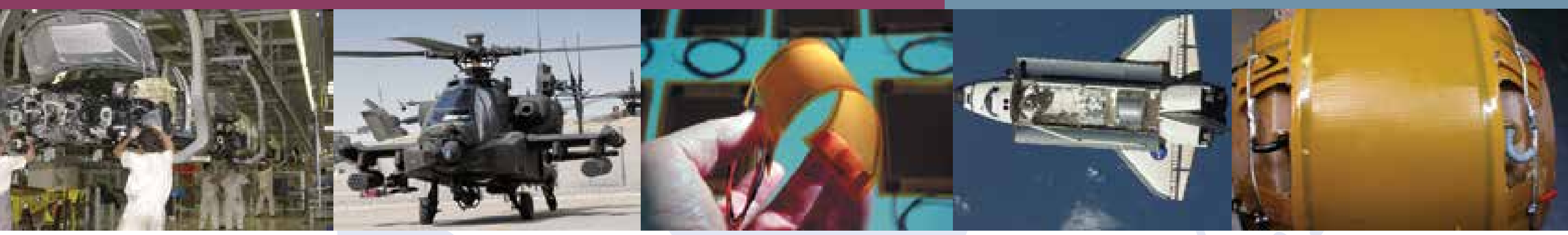


MACRO FIBER COMPOSITE - MFC

Actuator, Sensor, Energy Harvester
Energy Harvesting Systems
Piezo Powering and Instrumentation
Engineering Services

www.smart-material.com

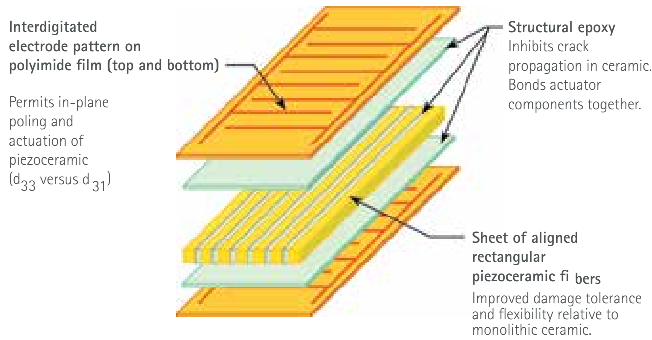
SMART MATERIAL

What is a Macro Fiber Composite (MFC)?

MFC benefits

- Flexible and durable
- Increased strain actuator efficiency
- Directional actuation / sensing
- Damage tolerant
- Available as elongator (d_{33} mode) and contractor (d_{31} mode)
- Conforms to surfaces
- Readily embeddable
- Environmentally sealed package
- Demonstrated performance
- Different piezo ceramic materials available

Schematic structure of the MFC



The Macro Fiber Composite (MFC) is the leading low-profile actuator and sensor offering high performance, durability and flexibility in a cost – competitive device. The MFC was invented and is being developed by NASA since 1996. Smart Material started commercializing the MFC in 2002 as the manufacturer and distributor. Since then, the MFC has been continuously improved and customized to fit the customers' specific needs. More than 23 standard types are currently available.

The MFC technology permits the production of perfectly aligned fiber actuators that are no thicker than a few tenths of a millimeter.

The MFC consists of rectangular piezo ceramic rods sandwiched between layers of adhesive, electrodes and polyimide film. The electrodes are attached to the film in an interdigitated pattern which tranfers the applied voltage directly to and from the ribbon shaped rods. This assembly enables in-plane poling, actuation and sensing in a sealed and durable, ready–to–use package. As a thin, surface–conformable sheet it can be applied (normally soldered) to various types of structures or embedded in a composite structure.

If voltage is applied it will bend or distort materials, counteract vibrations or generate vibrations.

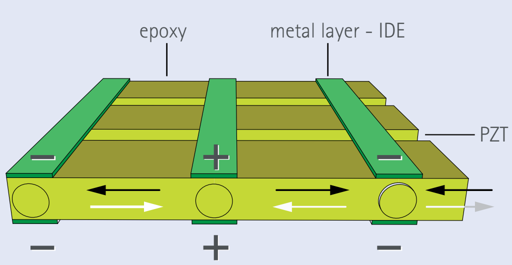
If no voltage is applied it can work as a very sensitive strain gauge, sensing deformations, noise and vibrations or harvesting energy from it.

The novel, uniquely pliable and conformable features of the MFC also allow for precise health monitoring, morphing and stiffening of structures, lambda wave generation and large area ultrasound as 2–2 composites.

The MFCs flat profile and capability of simultaneously acting as an actuator and sensor allows for its use in very critical or tight areas. The MFC is available in d_{33} and d_{31} operational mode, a unique feature of the Macro Fiber Composite.

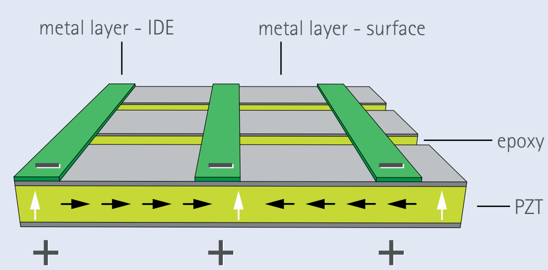
MFC P1 Type (d_{33} effect)

Elongator
- powerful actuator
- sensitive sensor



MFC P2 Type (d_{31} effect)

Contractor
- Low Impedance sensor
- energy generator



General technical information for the MFC

High–field (|E| > 1kV/mm), biased–voltage–operation piezoelectric constants:

d_{33}*	4.6E + 02 pC/N	4.6E + 02 pm/V
d_{31}**	-2.1E + 02 pC/N	-2.1E + 02 pm/V

Low-field (|E| < 1kV/mm), unbiased-operation piezoelectric constants:

d_{33}*	4.0E + 02 pC/N	4.0E + 02 pm/V
d_{31}**	-1.7E + 02 pC/N	-1.7E + 02 pm/V
Free-strain* per volt (low–field – high–field) for d_{33} MFC (P1)	~ 0.75 – 0.9 ppm/V	0.75 – 0.9 ppm/V
Free-strain* per volt (low–field – high–field) for d_{31} MFC (P2)	~ 1.1 – 1.3 ppm/V	~ 1.1 – 1.3 ppm/V
Free-strain hysteresis*	~ 0.2	~ 0.2
DC poling voltage, Vpol for d_{33} MFC (P1)	+1500 V	+1500 V
DC poling voltage, Vpol for d_{31} MFC (P2)	+450 V	+450 V
Poled capacitance @ 1kHz, room temp, Cpol for d_{33} MFC (P1)	~ 0.42 nF/cm²	~ 2.7 nF/in²
Poled capacitance @ 1kHz, room temp, Cpol for d_{31} MFC (P2)	~ 4.6 nF/cm²	~ 29 nF/in²

Orthotropic Linear Elastic Properties (constant electric field):

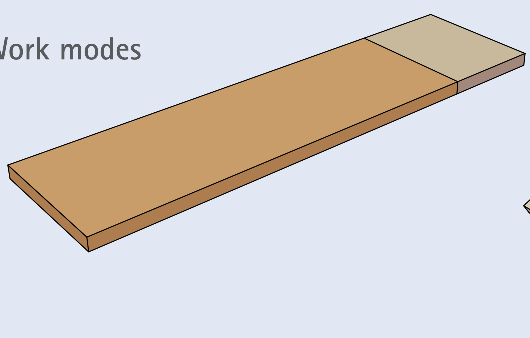
Tensile modulus, E1*	30.336 GPa	4.4E + 06 psi
Tensile modulus, E1**	15.857 GPa	2.3E + 06 psi
Poisson's ratio, v12	0.31	0.31
Poisson's ratio, v21	0.16	0.16
Shear modulus, G12 (rules-of-mixture estimate)	5.515 GPa	8.0E + 05 psi

Operational Parameters:

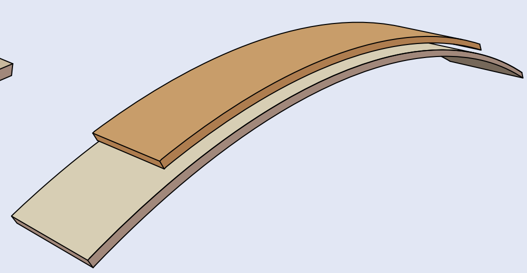
Maximum operational positive voltage, Vmax for d_{33} MFC (P1)	+1500 V	+1500 V
Maximum operational positive voltage, Vmax for d_{31} MFC (P2)	+360 V	+360 V
Maximum operational negative voltage, Vmin for d_{33} MFC (P1)	500 V	-500 V
Maximum operational negative voltage, Vmin for d_{31} MFC (P2)	-60 V	-60 V
Linear – elastic tensile strain limit	1000 ppm	1000 ppm
Maximum operational tensile strain	< 4500 ppm	< 4500 ppm
Peak work-energy density	1000 in – lb/in3	~1000 in – lb/in3
Maximum operating temperature – Standard Version	< 80°C	< 176°F
Maximum operating temperature – HT Version	< 130°C	< 266 °F
Operational lifetime (@ 1kVp–p)	> 10E + 09 cycles	> 10E + 09 cycles
Operational lifetime (@ 2kVp–p, 500VDC)	> 10E + 07 cycles	> 10E + 07 cycles
Operational bandwidth as actuator, high electric field Operational bandwidth as actuator, low electric field	0Hz to 10 kHz 0Hz to 750kHz	0Hz to 10 kHz 0Hz to 750kHz
active Area Density	5.44 g/cm³	5.44 g/cm³
Thickness for all MFC Types	approx 0.3mm	approx. 12 mil

* Rod direction
** Electrode direction

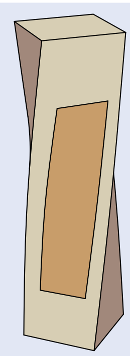
Work modes



expansion



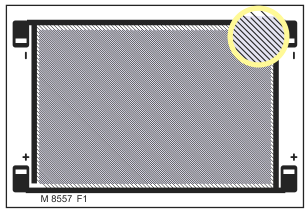
bending



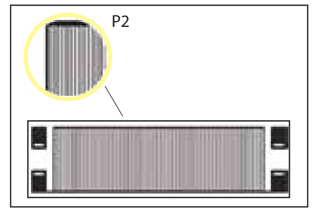
torsion

MFC Types specifications

d_{33} Actuators with expanding motion P1

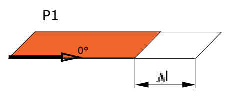


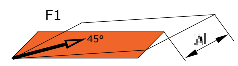
d_{33} Actuators with twisting motion F1



d_{31} Actuators with contracting motion P2

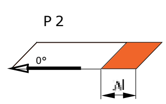
MFC P1 / F1 Types (d_{33} effect actuators)

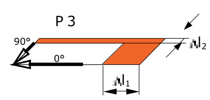




model	active length	active width	overall length	overall width	Capacitance	free strain	blocking force
	mm	mm	mm	mm	nF	ppm	N
P1–Types (0° fiber orientation)							
M-2503-P1	25	3	46	10	0.25	1050	28
M-2807-P1	28	7	40	18	0.33	1380	87
M-2814-P1	28	14	38	20	0.61	1550	195
M-4005-P1	40	5	50	11	0.64	1180	51
M-4010-P1	40	10	50	16	1.00	1400	126
M-4312-P1	43	12	60	21	1.83	1500	162
M-5628-P1	56	28	67	37	3.21	1800	450
M-8503-P1	85	3	110	14	0.68	1050	28
M-8507-P1	85	7	101	13	1.53	1380	87
M-8514-P1	85	14	101	20	3.00	1600	202
M-8528-P1	85	28	103	35	5.70	1800	454
M-8557-P1	85	57	103	64	9.30	1800	923
M-14003-P1	140	3	160	10	1.45	1050	28
F1–Types (45° fiber orientation)							
M-8528-F1	85	28	105	35	6.30	1350	485 calc.
M-8557-F1	85	57	105	64	12.70	1750	945 calc.

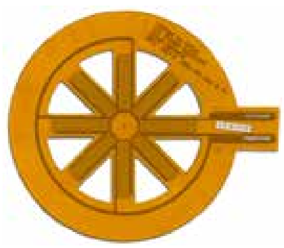
MFC P2 / P3 Types (d_{31} effect actuators)



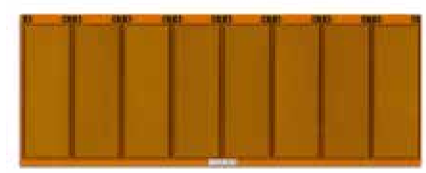


model	active length	active width	overall length	overall width	Capacitance	free strain	blocking force
	mm	mm	mm	mm	nF	ppm	N
P2–Types (anisotropic)							
M-0714-P2	7	14	16	16	6.5	-600	-85
M-2807-P2	28	7	37	10	12.4	-650	-40
M-2814-P2	28	14	37	18	25.7	-700	-85
M-5628-P2	56	28	66	31	113.0	-820	-205
M-8503-P2	85	3	113	8	12.3	-480	-13
M-8507-P2	85	7	100	10	38.4	-670	-42
M-8514-P2	85	14	100	18	89.5	-700	-85
M-8528-P2	85	28	103	31	172.0	-820	-205
M-8557-P2	85	57	103	60	402	-840	-430
M-8585-P2	85	85	103	88	605	-842	-650
M-17007-P2	170	7	186	12	91	-670	-42
P3–Types (orthotropic)							
M-2814-P3	28	14	37	18	29.5	-750	-110
M-5628-P3	56	28	66	31	121.7	-900	-265
M-8528-P3	56	28	103	31	223	-900	-265

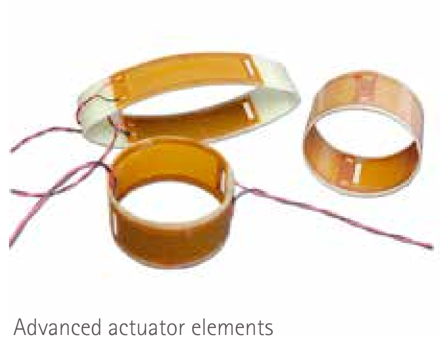
Special MFC actuators & arrays



The Star MFC



Customized layouts and arrays



Advanced actuator elements

triangular MFC for strain adaptation

sensor/actuator arrays for closed loop control

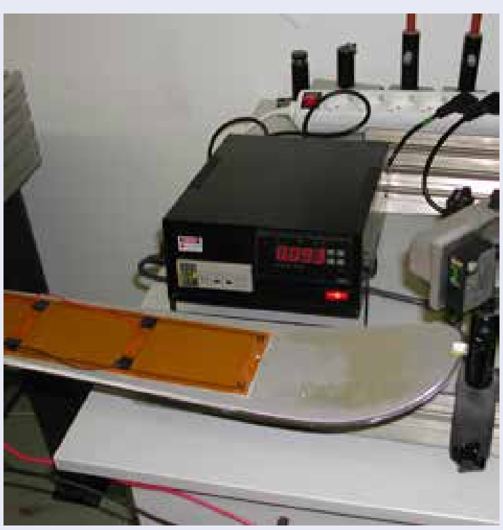
customized contact pads

In addition to manufacturing MFCs in a wide variety of standard sizes for our customers, we are also offering many specialized MFC layouts to meet our customers' needs for specialized applications.

These include for example the Star MFC, for pumps and synthetic jets, the S1 and S2 type MFCs, which consist of sensor and actuator elements for a closed loop control, as well as several other MFC arrays.

The MFC technology is highly adaptable to specific application needs. Custom designed layouts based on your own ideas and requirements have a typical lead time of 5 weeks.

Engineering and Prototyping Services



Due to our long-term experience in designing piezoelectric transducers and a well-equipped laboratory, we are able to help our customers along the whole development process so that their ideas come true.

- Analytical calculation and FEA on sensor & actuator systems
- Numerical design and simulation for ultrasonic transducers
- Prototyping and mechanical/ acoustical tests

Systems

High Voltage Amplifier and Pulser

SMART Power Amp PA05039 (made by TREK)

The design of the custom amplifier is based on the renowned Trek amplifier technology. With an output voltage of -500V to +1500V and a maximal output current of 50mA the PA05039 is designed to drive several P1 or F1 type (d_{33} effect) MFC's.

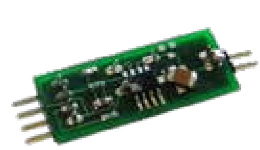
Smart Power Amp HVA 1500/50-4

This multi–cannel amplifier series, with up to 4 independent channels, was designed for precise control of single MFC actuators and MFC actuator arrays .
These amplifiers are ideal power sources for both the P1/F1 and P2/P3 MFC's. An additional audio input allows the customer to apply signals easily from their notebook's soundcard.

SMART PowerSonic 280-PW

To enable customers to perform their own tests on low frequency ultrasonic transducers this µC controlled power pulser was developed. The pulses have a voltage of +/- 280V with a frequency up to 100 KHz. Typical parameters like frequency, pulse number, refresh rate, uni–/bipolar mode and shut down time can be programmed via the RS 232 serial interface.

Data Acquisition Systems and Energy Harvesting



SMART Charge

The MFC is capable of sensing strain based on the reverse piezo effect. Compared to a resistive strain gauge the MFC generates much higher output levels. This special preamplifier was developed to make strain measurements down to the static state possible. In contrast to typical channel amplifiers, no significant drift can be observed with this outstanding module.

SMART Logger

Equipped with 4 independent input channels (high impedance voltage preamps) this module can be used to monitor dynamic events on the flight measured with MFC sensors from milliseconds up to some hours. All parameters for the SMART Logger can be programmed via USB.
A software allows to display the input signals and save the data as CSV–file.

SMART Energy Harvester Development Kit

Generating energy form environmental vibrations is one of the current challenges for engineers. This development kit consists of a simple on–desk shaker with suitable power amp unit, several MFC generator structures and 3 electronic modules with different measurements circuits.
It enables scientists from mechanical engineering and electronics to study causal relations between mechanical input parameters and electrical outputs.

Q: Which adhesives are you recommending to bond MFCs to a structure?

A: We recommend two component adhesives like 3M's DP 460 Epoxy or Loctite's E120 HP Epoxy. Best results are obtained if the adhesive is cured at 50°– 60°C for 2 hours and the MFC is pressed against the structure with a fixture during curing.

Q: I want to use the MFC as a strain sensor but it seems I can not get any reading?

A: Make sure you have attached the MFC to a structure that is actually inducing a strain into the patch, i.e. stretching or compressing the fibers.

Q: What is the max force that an MFC can produce?

A: The MFC will expand at 1800 ppm over the length of the actuator (free strain). The blocking force is about 4kN/cm² for the active cross section of the MFC.

Q: Is the MFC porous or non–porous?

A: The MFC is non-porous due to its environmentally sealed packaging.

Q: What type of force does a standard MFC generate, including displacement?

A: The M8557P1 is generates about 900N blocking force and ~150µm displacement (free strain).

Q: What is the typical density of an MFC?

A: Typical areal density is 0.16g/cm² or volume density of 5.44 g/cm³

Q: What is the mechanical efficiency of an MFC, meaning electrical energy transformed into mechanical energy?

A: This question requires a little more in depth analysis:

a) In general a PZT 5A1 material used in the MFC has an effective coupling coefficient (k_{33}) of about 0.69. That is its first order electrical – to – mechanical energy conversion efficiency. k_{33} is a measure of efficiency, but not the actual efficiency

b) $k33^2$ is the ratio of stored mechanical energy to input electrical energy (= 0.48), but this is not the same as output work energy efficiency, since one can not actually use all of the stored energy to do useful work.

c) Max. output work energy efficiency (under optimum loading condition) for the MFC will work out to about 0.16, so max 16% of input electrical energy can be converted into useful output work with an MFC.

d) Max. output – work energy efficiency is not the same as output – work to consumed electrical energy efficiency! Most (may be 97 – 99%, depending on dielectric loss of the package) of the electrical energy not converted to work is actually stored electrostatically, i.e., like in a capacitor. You can recover that energy, in principal, with a clever drive electronic design.

Q: How tight a radius of curvature can you bend the MFC before cracking? For example the standard size 3.4" x 2.2" MFC M8557P1.

A: Max. mechanical tensile strain the ceramics can endure is approx. 2500 ppm before fracturing. The package is still functional, although elastic properties will change. For 7– mil ceramic, this works out to a minimum curvature diameter of the actuator of about 3.5 inches (curled in fiber direction) and 3 inches curled perpendicular to the fiber direction.

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