REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
10-03-20 16	Final Report	01 Jan 2013 - 31 Dec 2015

4. TITLE AND SUBTITLE
Macro-Fiber Composite Based Transduction

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N000-14-13-1-0212

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Richard J. Meyer, Jr.

5d. PROJECT NUMBER
20667

5e. TASK NUMBER

5f. WORK UNIT NUMBER
09700

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Research Laboratory
The Pennsylvania State University
PO Box 30
State College, PA 16804

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Code 321MS
875 Randolph Street
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A; Approved for Public Release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this project was to develop a family of inexpensive hydrophone and/or projector designs utilizing Macro Fiber Composite (MFC) patches. The MFC is a low profile (0.0 12") actuator and sensor invented by NASA in 1996 and manufactured by Smart Material Corporation. The MFC utilizes a layer of rectangular piezo ceramic rods that are encapsulated between layers of adhesive, polyimide film and interdigitated electrodes. The MFC is assembled in a sealed package, which makes them durable, highly flexible, inexpensive and easily applied. The patch has high actuation authority and can be stacked to provide improved force characteristics. The MFC has been used to bend and twist structures for NASA and Air Force applications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Richard J. Meyer, Jr.
U	U	U	UU	32	19b. TELEPHONE NUMBER *(Include area code)* 814-865-9607

Macro-Fiber Composite Based Transduction

Grant: N00014-13-1-0212
Start Date: 01 Jan 2013
End Date: 31 Dec 2015
Principal Investigator: Richard J. Meyer Jr.

Final Report

PENNSTATE
Applied Research Laboratory

Submitted to:

Jan Lindberg and Mike Wardlaw
ONR Code 321MS
875 N Randolph Street
Arlington, VA 22203

Submitted by:

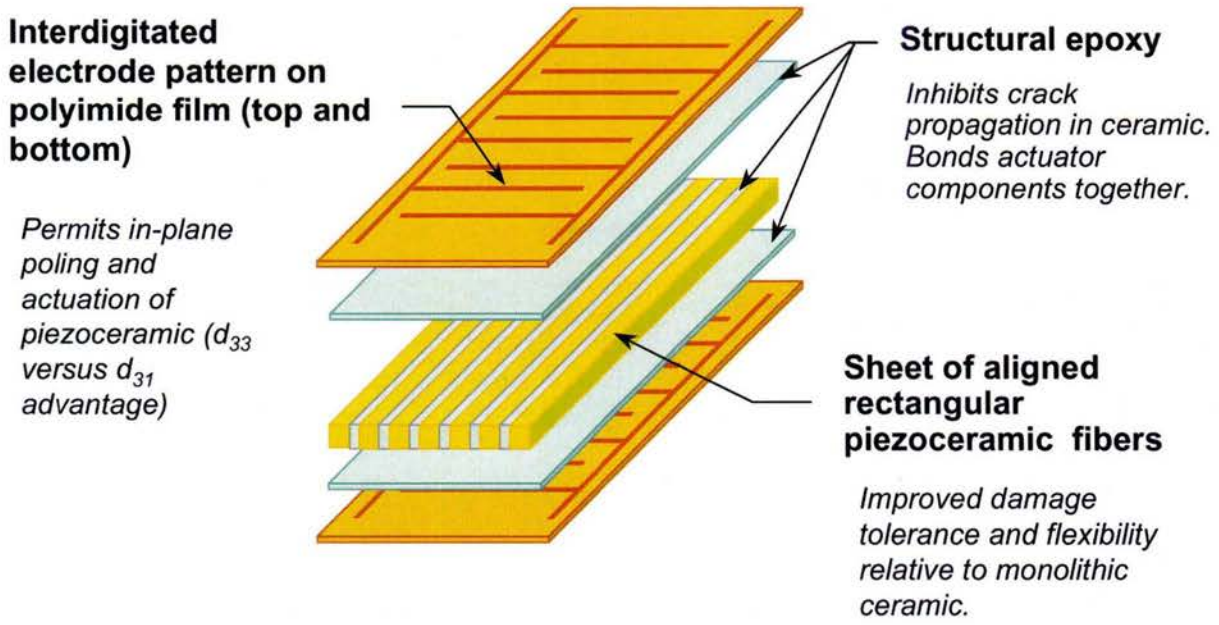
The Pennsylvania State University
Applied Research Laboratory
P.O. Box 30
State College, PA 16804-0030
R. J. Meyer Jr.
(814) 865-9607
rjm150@arl.psu.edu

Macro-Fiber Composite Based Transduction

Award Number: N00014-13-1-0212

LONG-TERM GOALS

The goal of this project was to develop a family of inexpensive hydrophone and/or projector designs utilizing Macro Fiber Composite (MFC) patches. The MFC is a low profile (0.012") actuator and sensor invented by NASA in 1996 and manufactured by Smart Material Corporation. The MFC utilizes a layer of rectangular piezo ceramic rods that are encapsulated between layers of adhesive, polyimide film and interdigitated electrodes. The MFC is assembled in a sealed package, which makes them durable, highly flexible, inexpensive and easily applied. The patch has high actuation authority and can be stacked to provide improved force characteristics. The MFC has been used to bend and twist structures for NASA and Air Force applications.



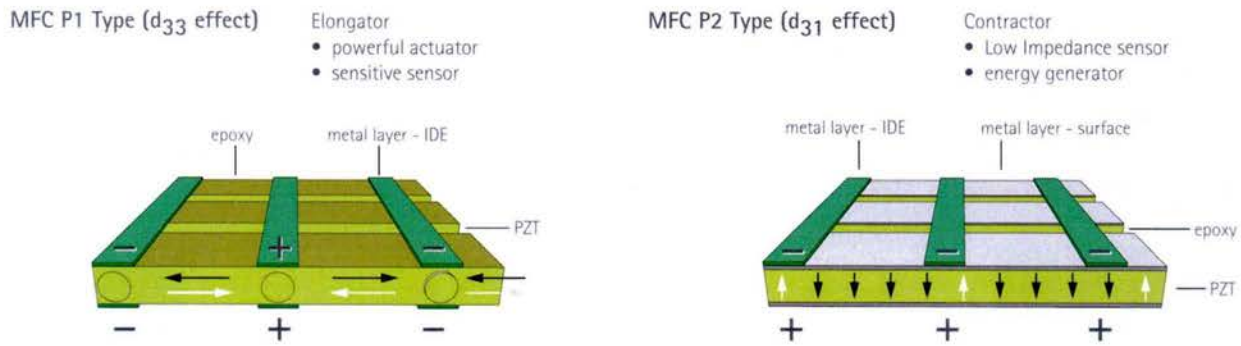


Image from Smart-Material.com

OBJECTIVES

The first objective was to develop a model that accurately predicts the MFC performance. Once the model was working, it was used to simulate the MFC in various structures and configurations. Prototypes were then developed and measured. Performance was compared to prediction. Hydrophones and projector concepts were explored as well as using the MFC to morph an existing structure to alter stiffness or shape to demonstrate the ability to tune the resonance frequency of the device.

APPROACH

This basic research effort considered both hydrophone and projector applications. For projector applications, integration of harder piezoelectric ceramics was done to decrease the loss characteristics. Performance tradeoffs were conducted both in simulation and in experimental testing.

MFCs can easily be incorporated into traditional transducer structures. One simple example would be a ring. The approach in year one was to study these simple geometries by developing a model, fabricating a test unit and electroacoustic testing. In year two, model input material properties were refined using direct calculation from impedance spectra and PolyTec Laser Doppler Vibrometry (LDV). With input from Smart Materials, work was done to explore the changes in these materials with increasing voltage. Experiments were also conducted to determine the ability of the MFC patches to influence the performance of flextensional transducers by imparting tensile or compressive strains to the elastic members of the flextensionals. Models of some novel transducer designs were constructed.

This effort is in conjunction with two partnerships. The Applied Research Laboratory provided stipend and tuition for Master candidate Bradley Golder as part of an Eric Walker Fellowship. In addition, a teaming arrangement was formed with Smart Material, Inc. Smart agreed to supply MFC patches and tailor their product with hard piezoceramic compositions at a reduced cost.

WORK COMPLETED

MFC patches were procured from Smart Materials, Inc. Several different sizes and geometries were delivered. Patches containing PZT5A and PZT8 were each procured. Examples of these patches are shown in Figure 1. These patches were incorporated into cylindrical transducers and into simple bender bars. These shapes were then characterized in air and in water to determine displacements, resonance frequencies, and acoustic performance.

In addition to the experimental work, ATILA++ finite element models were developed and used to predict performance. Several code iterations were required to troubleshoot the patch function to calculate impedances and displacements properly. In addition, tangential polarization was added to the code to allow for modeling of cylindrical geometries.

Initial material property inputs for the models were calibrated through comparison with measured results, followed by iteration of properties in the models to yield matching results. This

worked fairly well. However, these values have been refined through direct measurement of MFC edge displacements using a PolyTec Scanning Laser Doppler Vibrometer and calculations from impedance spectra.

Bender bars and rings were measured in water for TVR and FFVS data and drive linearity.

SMC reported that MFC properties are improved when driven at high voltage (>300VAC). Samples were subjected to increasing voltage drive to characterize this effect. As-received patches and bender bars were tested in air, and a bender bar was tested in water.

The merits of using MFC's to affect the performance of flextensional transducers was tested. An MFC patch was bonded to the outside of a slotted-cylinder transducer and across the span of a ClassIV flextensional and the impedance spectra were recorded for increasing positive or negative DC voltage applied to the MFC.

An extensive literature survey was conducted to generate a bibliography of references on theory, materials and applications for MFCs.

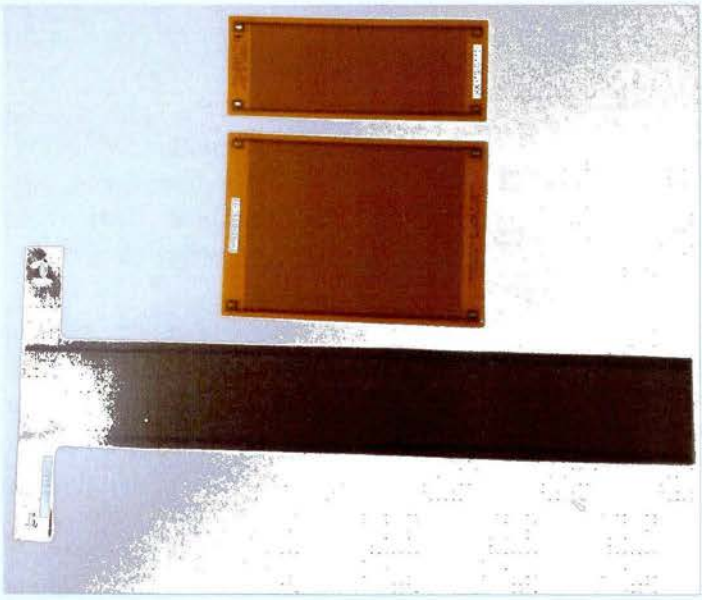


Figure 1 MFC patches produced by Smart Materials, Inc.

RESULTS

Material Properties for Atila++ Entry

Measured in-air complex impedance data from all available samples was averaged to yield values for calculating elastic and dielectric constants and losses. The calculations used are shown in Table 1. Sample masses were used to calculate densities for the modeling inputs. Measurements were made of the displacements at the ends and sides of samples using a PolyTec

Scanning LASER Doppler Vibrometer system (LDV). These displacements were used to calculate piezoelectric dXX coefficients as shown in Table 2.

Table 1 Elastic and Dielectric Formulas

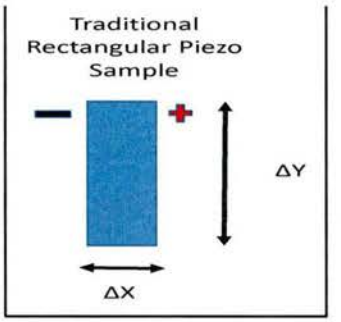
• $1/S_{33}^{D} = 4*dens*(f_r^2*L^2)$
• $1/E3 = S_{33}^{D}/(1-k_{33}^2)$
• $K^T = (Cap.*elctrode\ gap)/(Area*\varepsilon_0*n)$

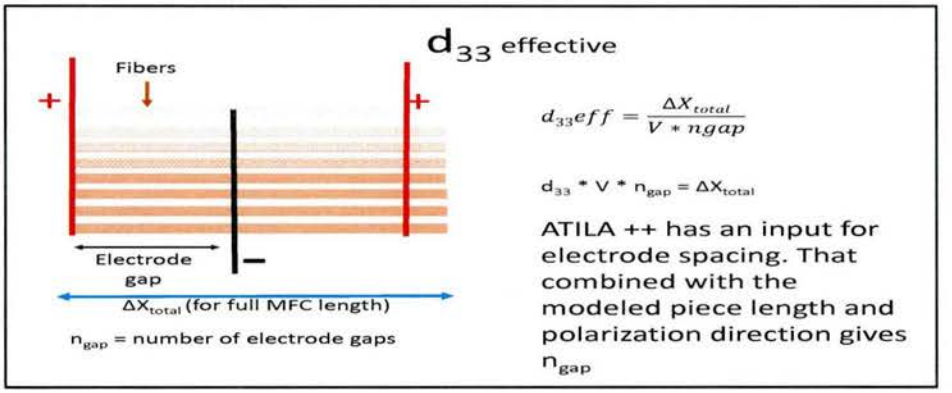
Table 2 Calculation Methodology for Piezoelectric Coefficients

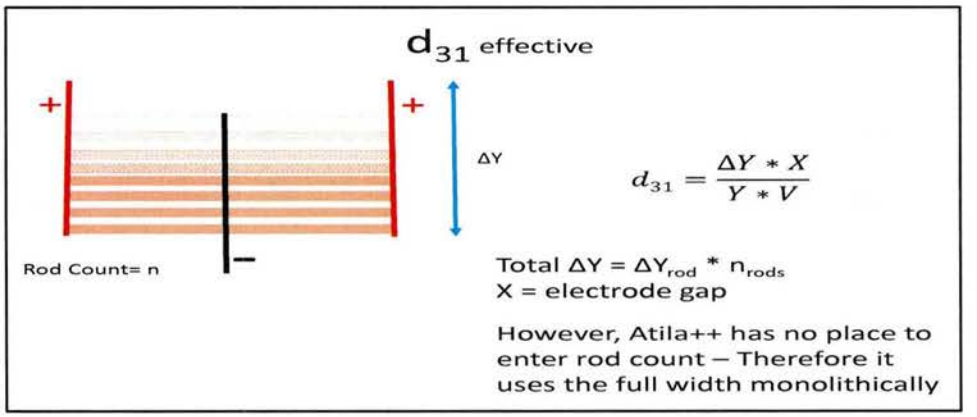
$$d = \frac{Strain}{Field}$$

$$d_{33} = \frac{\frac{\Delta X}{X}}{\frac{V}{X}} = \frac{\Delta X * X}{V * X} = \Delta X/V$$

$$d_{31} = \frac{\frac{\Delta Y}{Y}}{\frac{V}{X}} = \frac{\Delta Y * X}{Y * V}$$



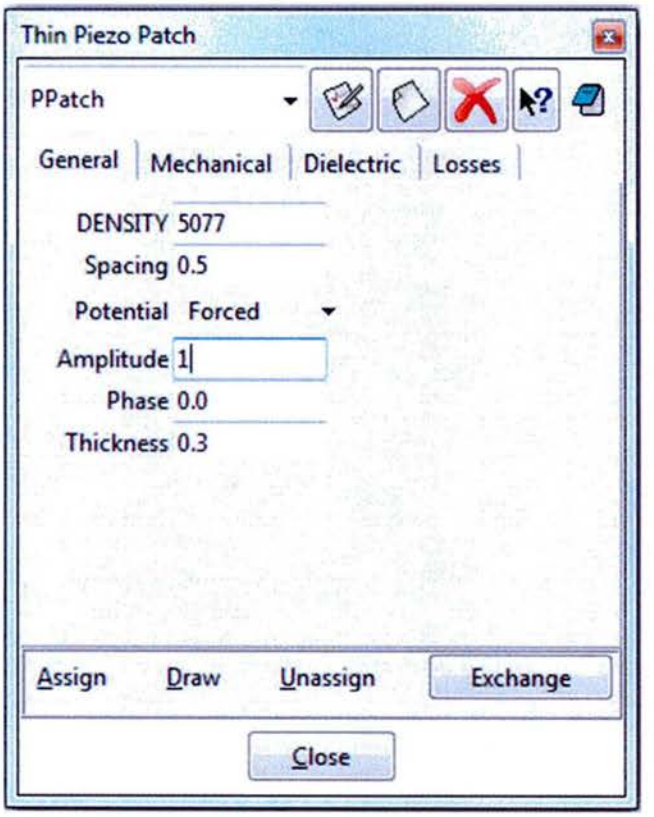




The refined Atila input material properties (1-volt properties) are listed in Table 3.

Table 3 MFC Atila "Thin Piezo Patch" Material Property Inputs

General		PZT5A (P1)	PZT8 (SP8)	
	Density	5077	5612	Average Measured
	Spacing	0.5	0.5	
	Thickness	0.3	0.3	
Mechanical				
	E1	14745E+6	20217E+6	Width Mode
	E3	51938E+6	50535E+6	Length Mode
	NU13	0.16	0.16	SMC Datasheet
	NU12	0.31	0.31	SMC Datasheet
	G13	5.52E+09	5.52E+09	SMC Datasheet
	D31	-046.0E-12	038.9E-12	LASER Edge Measurements
	D33	82.0E-12	86.1E-12	LASER Edge Measurements
Dielectric				
	E33T/E0	310	273	Measured Average
Losses				
	DELTA M	0.022	0.023	Measured Average
	DELTA P	0.000	0.000	
	DELTA D	0.018	0.010	Measured Average



Patch Modeling

In-Air models of the different sizes of MFC patches were run using the above input properties. Results showing comparisons of measured and modeled values for as-received patches are shown in Figure 2 through Figure 6. The measured curves are averages with the number of samples shown in the figure captions. The M-8528 and M-25528 model results are in good agreement with measured. For the M-8557-P1 test, only one sample was available, and its second peak appears to be dampened, perhaps by proximity of some spurious mode.

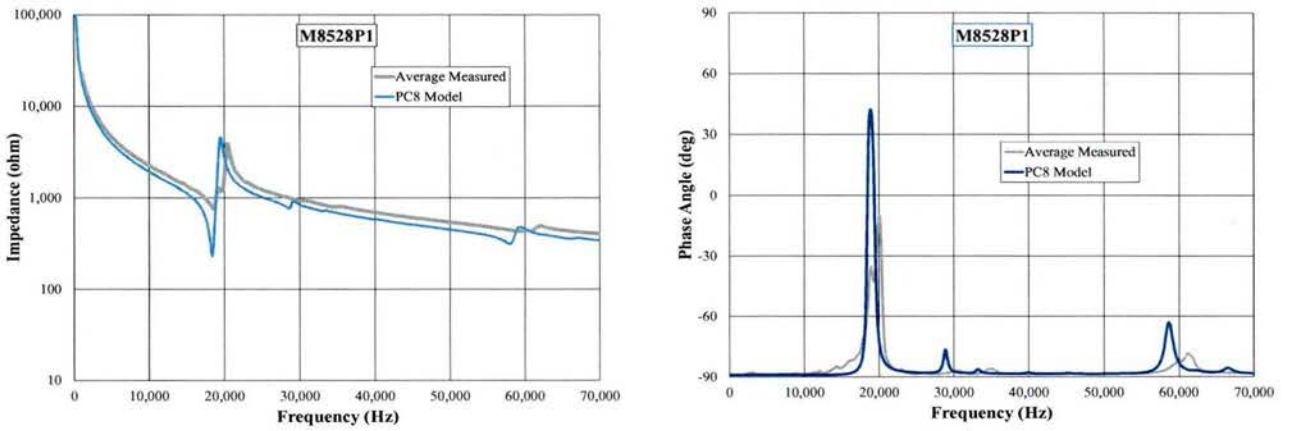


Figure 2 M-8528-P1 sized PZT5 patch modeled and measured impedance and phase (average of 12 samples)

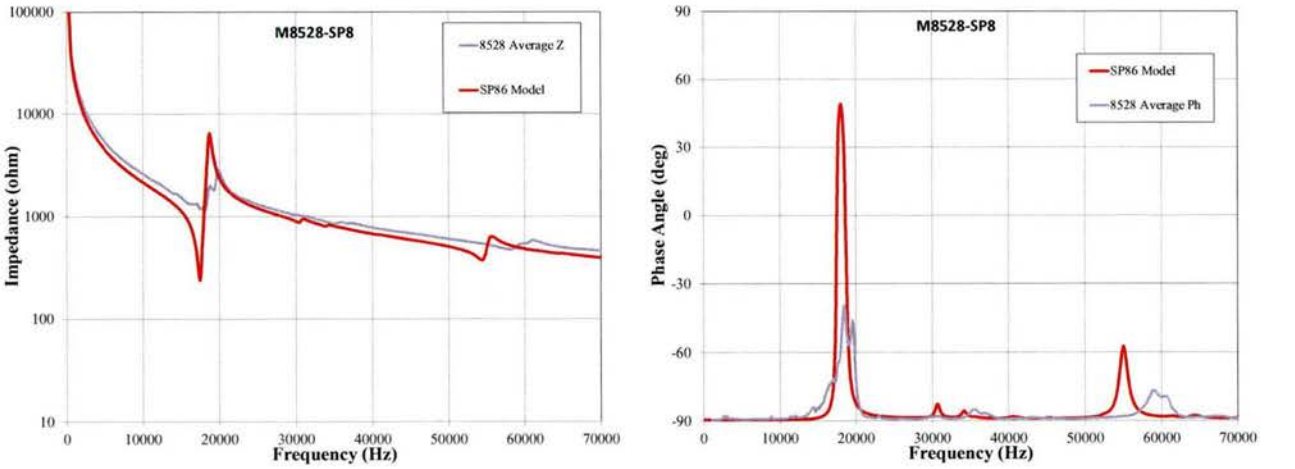


Figure 3 M-8528_SP8 sized PZT8 patch modeled and measured impedance and phase (average of four samples)

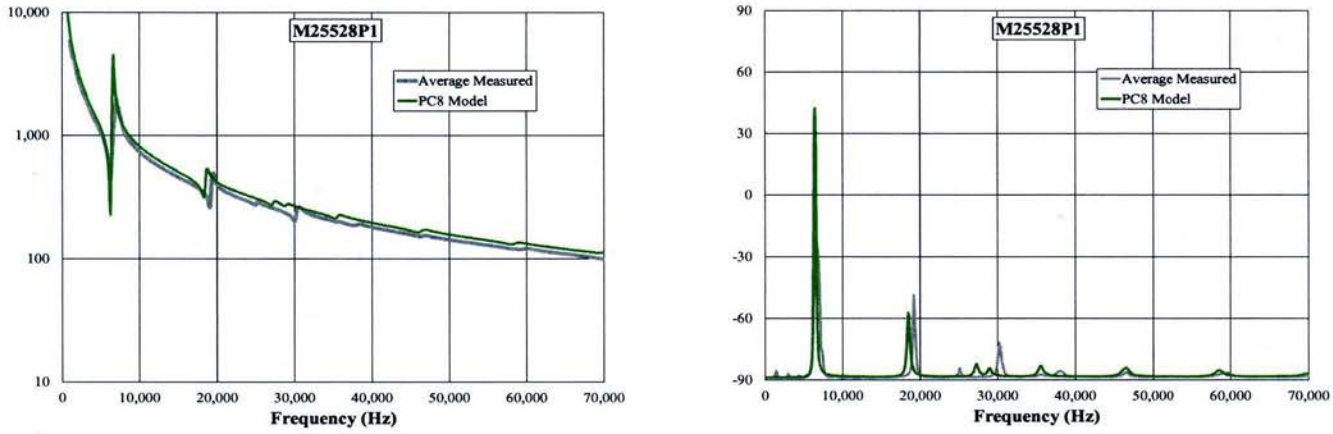


Figure 4 M-25528-P1 sized PZT5 patch modeled and measured impedance and phase (average of nine samples)

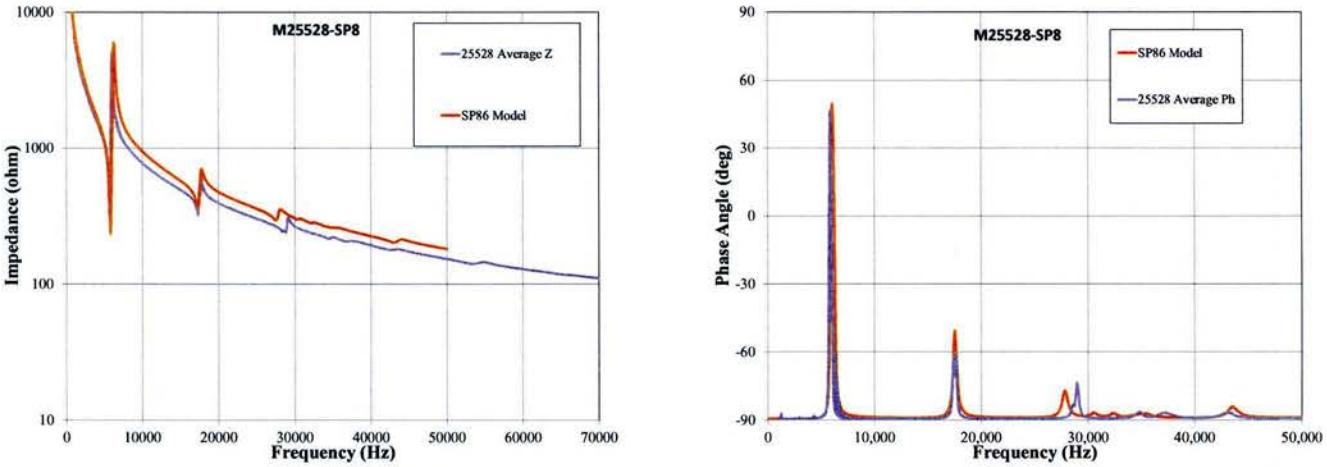


Figure 5 M-25528-SP8 sized PZT8 patch modeled and measured impedance and phase (average of four samples)

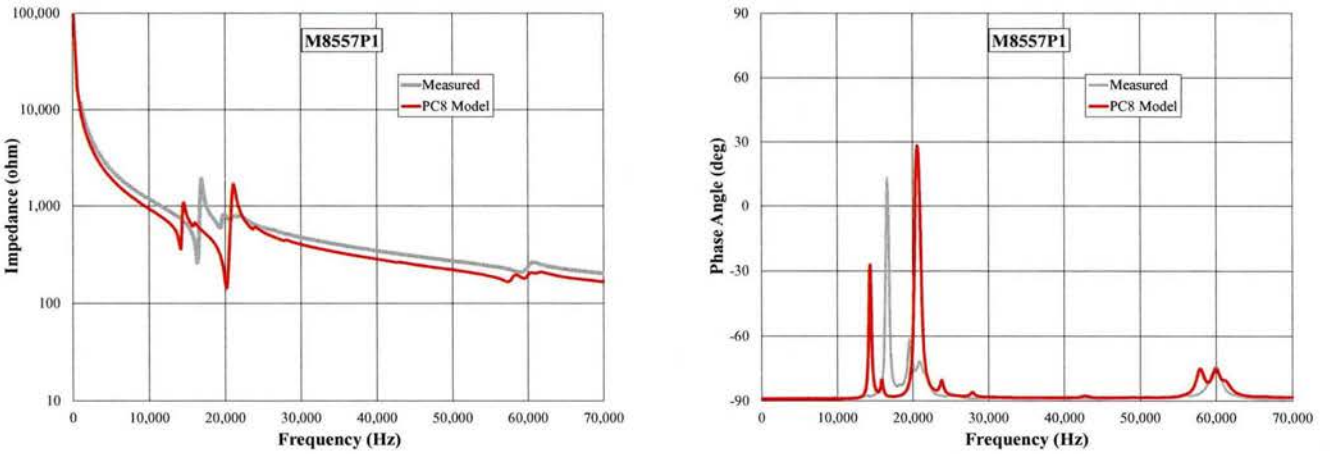


Figure 6 M-8557-P1 sized patch modeled and measured impedance and phase (single sample)

Bender Bars

Additional models were run with P1 type patches bonded to steel plates to produce bender bars. Steel thicknesses of 0.8mm and 3.0mm were used and measured results are shown compared to the models in Figure 7 and Figure 8. The model results are in good agreement with the measured data. These bars employed single patches. Multiple layers of patches or higher voltage driving may improve coupling.

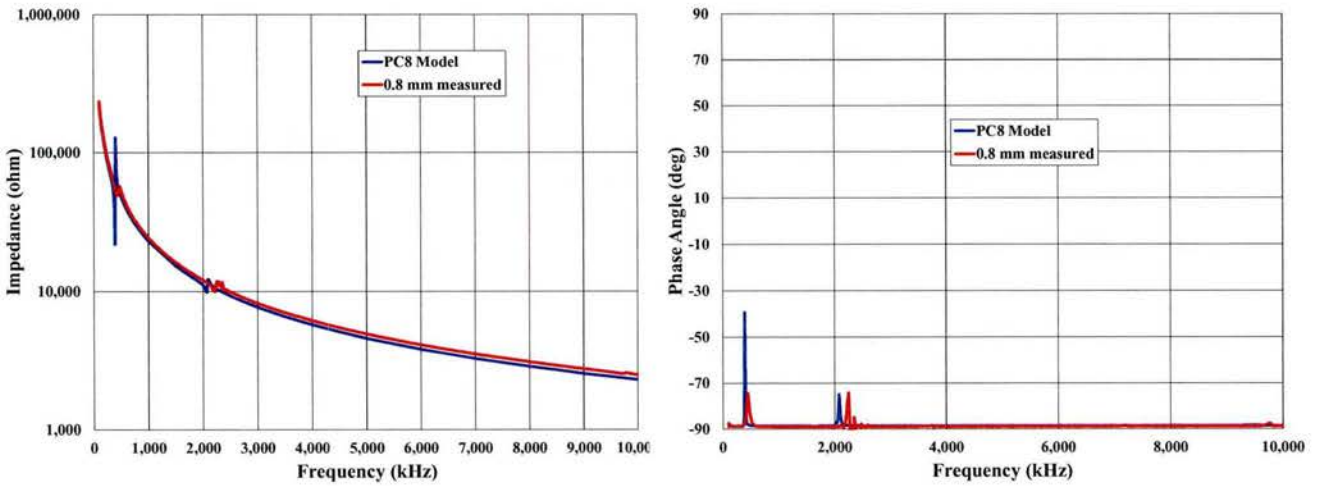


Figure 7 M-8528-P1 patch on 0.8mm thick steel plate modeled and measured impedance and phase

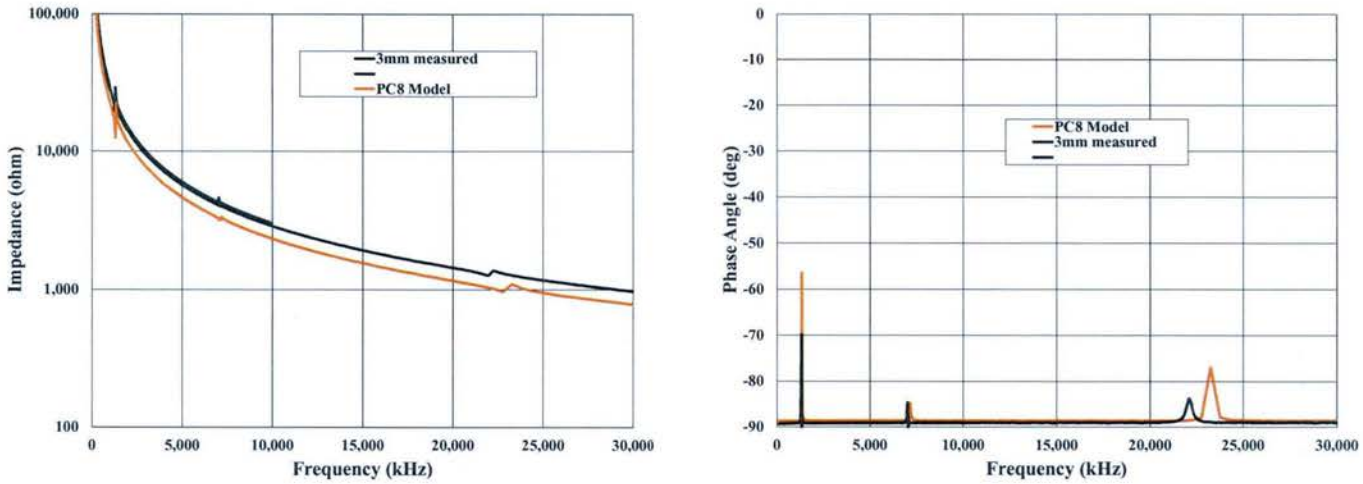


Figure 8 M-8528-P1 patch on 3mm thick steel plate modeled and measured impedance and phase

Figure 9 compares measured and modeled deflection shapes and displacements for an MFC patch bonded to a 3mm steel plate. Measured results were obtained using a PolyTec Scanning LASER Doppler Vibrometer. The measured and modeled results agree to within 3 percent in frequency. The center point displacement in the model is exaggerated by about 40 percent (more on the ends), indicating a possible need for additional loss considerations in the model such as accounting for the glue joint.

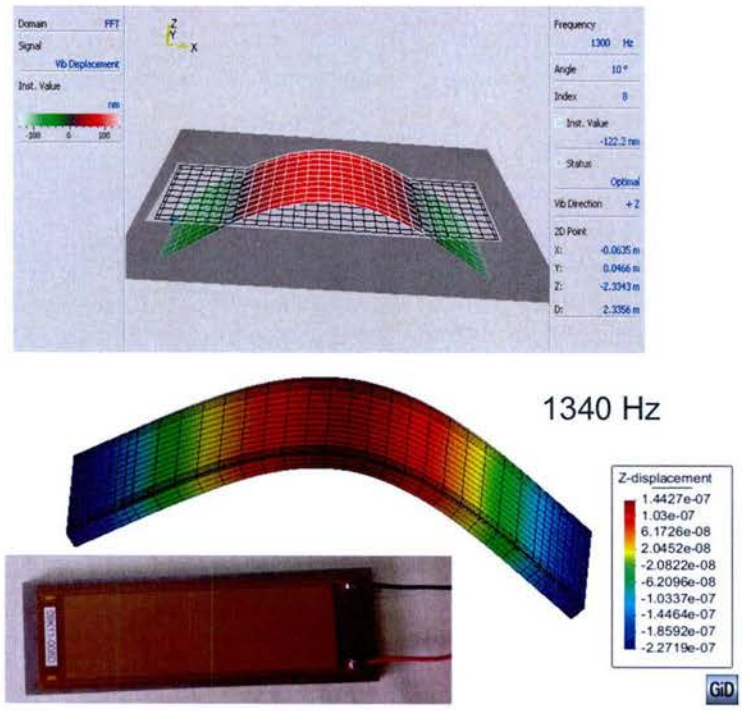


Figure 9 LDV measured (top) and modeled (bottom) results for an M-8528-P1 patch bonded to a 3mm steel plate showing the deflection shape and displacement (real part)

In-Water measurements of the 3mm-steel bender bar are shown in Figure 10 with measured and modeled TVR results. The model predicts the principle resonances. This sample was measured in water at increasing voltage drive levels to investigate the linearity. Figure 10B shows the resulting TVR when the sample was driven with 600Vrms. The simple difference between this result and the 32Vrms level is shown in Figure 11, and reveals an increase in TVR of about 4.3dB averaged from 10 kHz – 40 kHz.

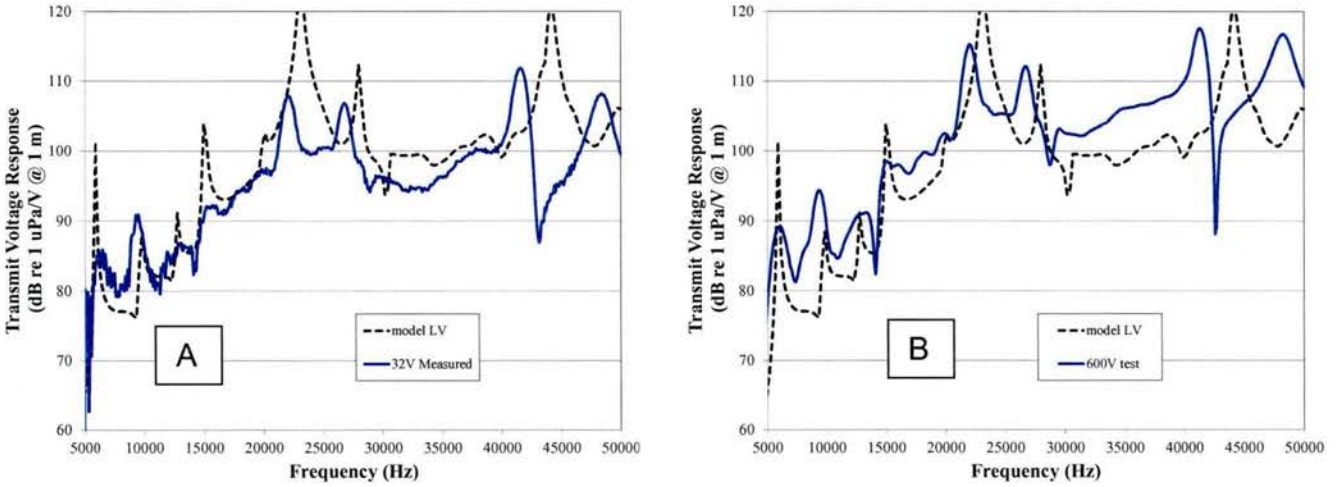


Figure 10 TVR of an M-8528-P1 3mm-steel bender bar at 32V and 600V

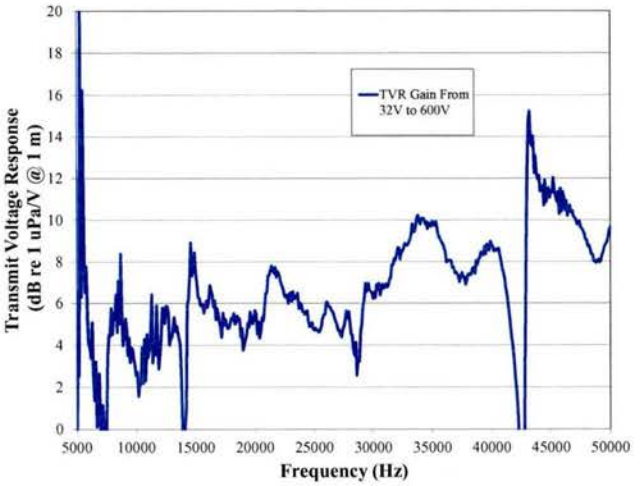


Figure 11 The gain in TVR produced by increasing voltage from 32V to 600Vrms on a M-8528-P1 3mm-steel bender bar

Ring Configurations

Figure 12 shows an MFC ring made by wrapping four nested MFC M25528-P1patches around a mandrel. Each MFC patch covers the entire circumference of the ring. Their electrical-connection tabs are staggered around the circumference. The layers were bonded together with Loctite – Hysol E-120HP epoxy. This configuration was tested in air and in water for both P1 (PZT5A) and SP8 (PZT8) materials. The in-water tests were done free flooded and with a simulated air backing made from a foam core (a weight was suspended below the device for negative buoyancy). Figure 13 and Figure 14 illustrate the comparison between in-air modeled and measured complex impedance. The model does not account for glue joints between the layers, therefore the model resonance frequency is high by 5%.

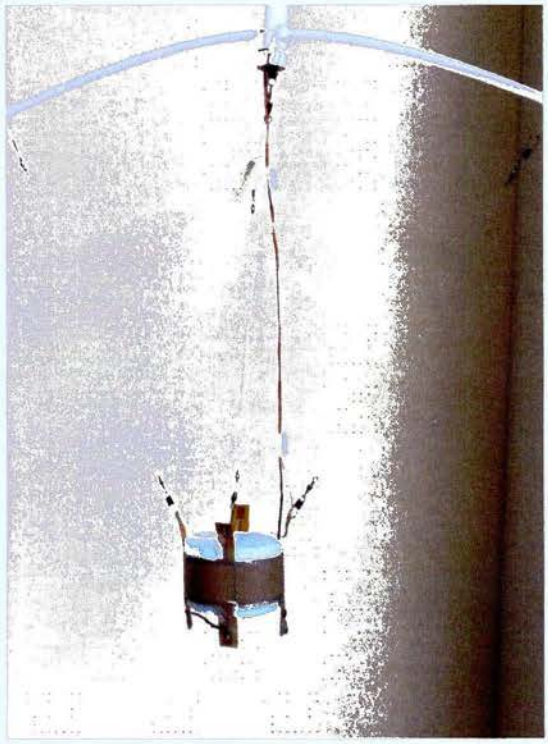


Figure 12 Cylindrical geometry made from four M-25585-P1 MFCs

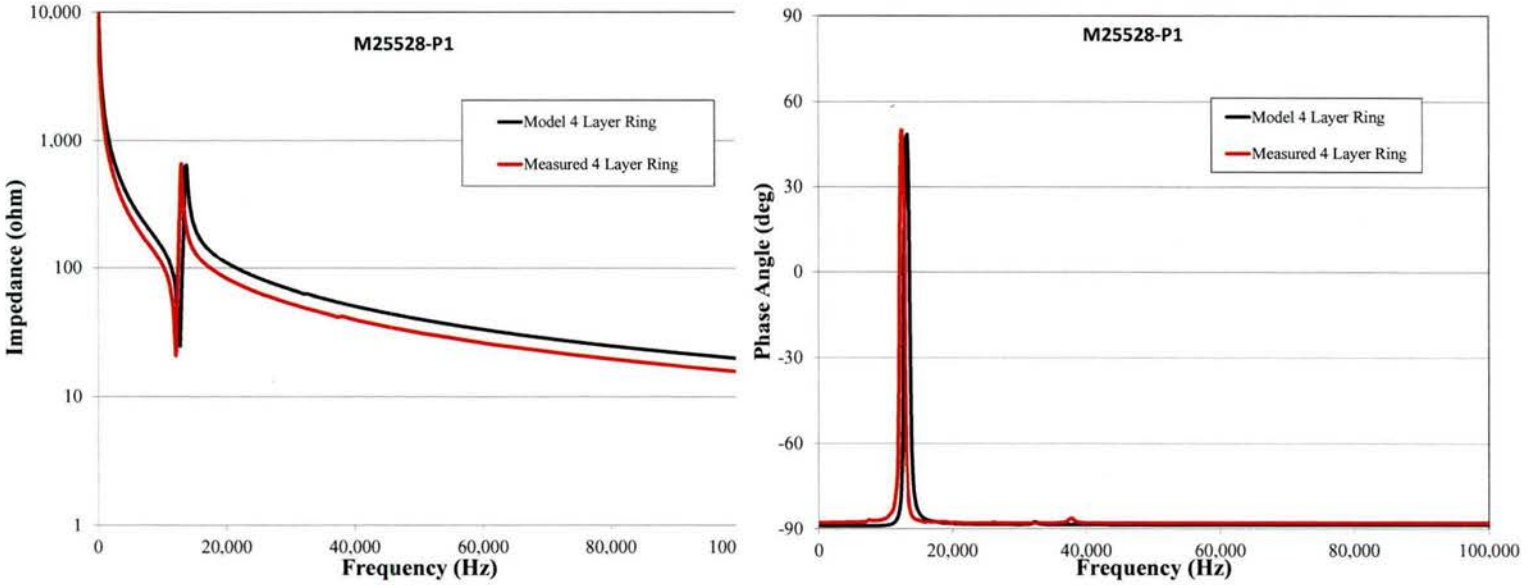


Figure 13 In-Air Impedance and Phase of a Ring of four PZT5 MFCs

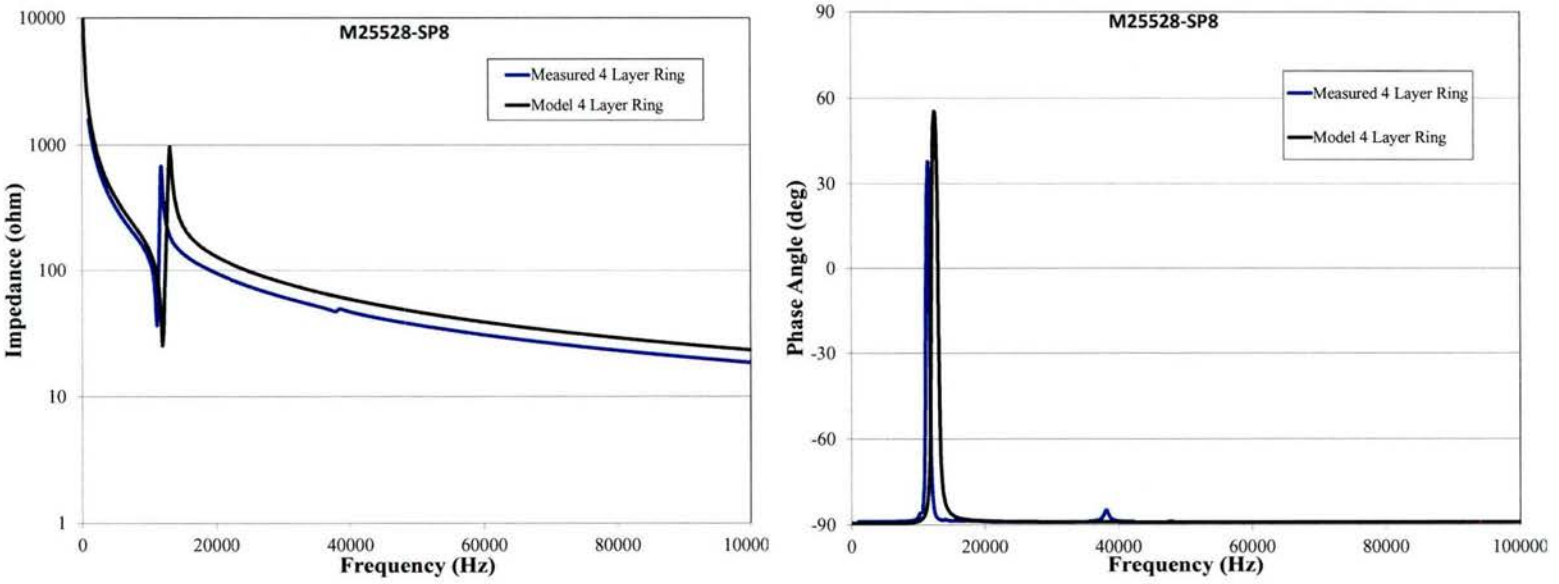


Figure 14 in-Air Impedance and Phase of a Ring of four PZT8 MFCs

Figure 15 shows the TVR and phase of the MFC cylinder in-water with an air backing (foam core). The wide-band response and flat phase indicate a possible use as a hydrophone. The low phase angle might be adjustable with tuning inductors to bring much of the TVR band into serviceable power ranges. (The model loses accuracy at the high frequency end due to mesh coarseness.) Figure 16 shows the effect of increasing the drive voltage (with DC bias to keep the peaks within the -500V limit). In this case, the TVR gain appears to be frequency dependent. Figure 17 shows measured FFVS and model results. The basic model matches the measured well. Another model with a single MFC layer and 5X electrode spacing shows FFVS gain of 5-20 dB. Discussions are underway with SMC to produce some MFC samples with custom electrode spacings. The TVR of same device with no foam core and, in effect, water-backed does not have as flat a response, as seen in Figure 18. The TVR and beam patterns for the PZT8 ring, air-backed, are shown in Figure 19 and Figure 20. This device is effectively omnidirectional.

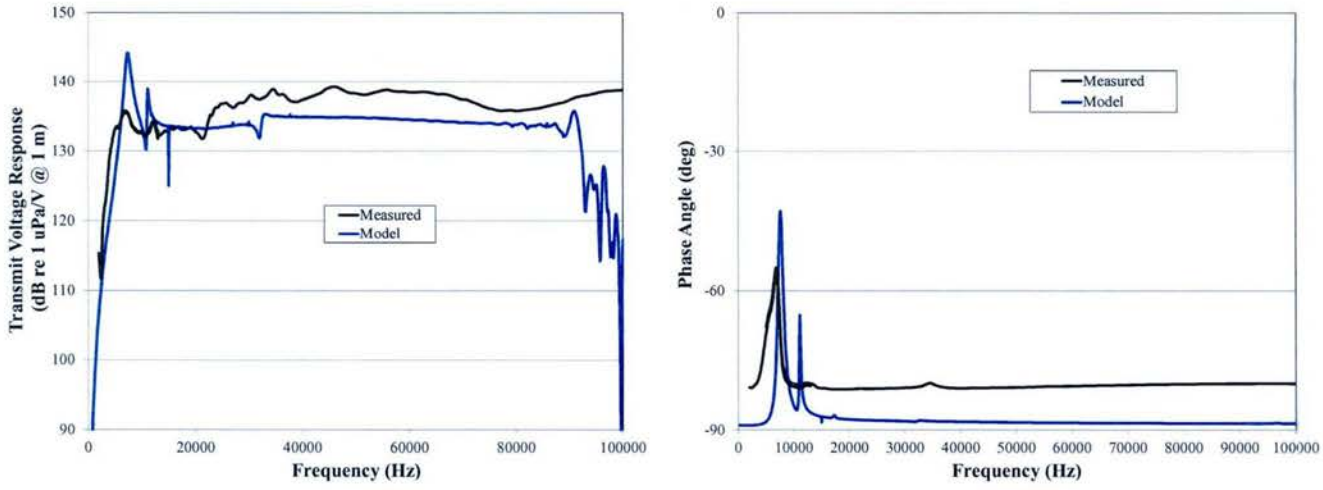


Figure 15 Transmit Voltage Response and Phase of the 4-Layer PZT5A MFC cylindrical geometry when tested with an air backing

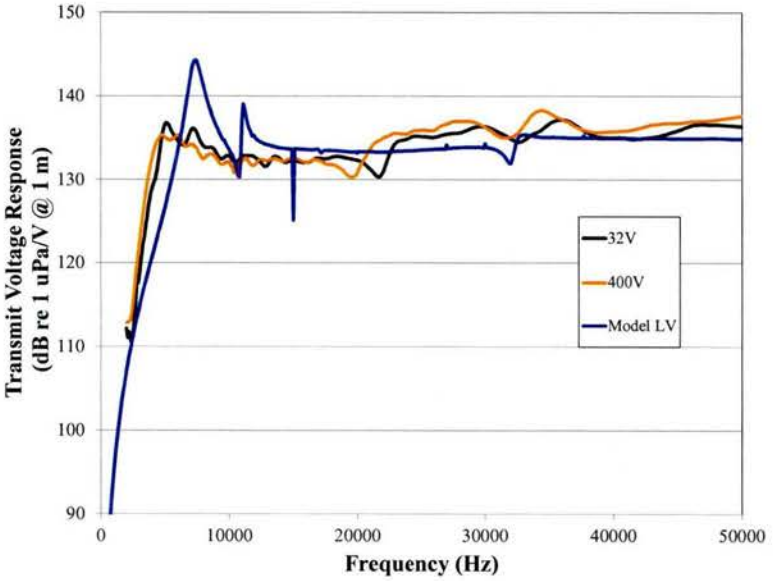


Figure 16 TVR of the 4-Layer PZT5A MFC ring showing voltage linearity

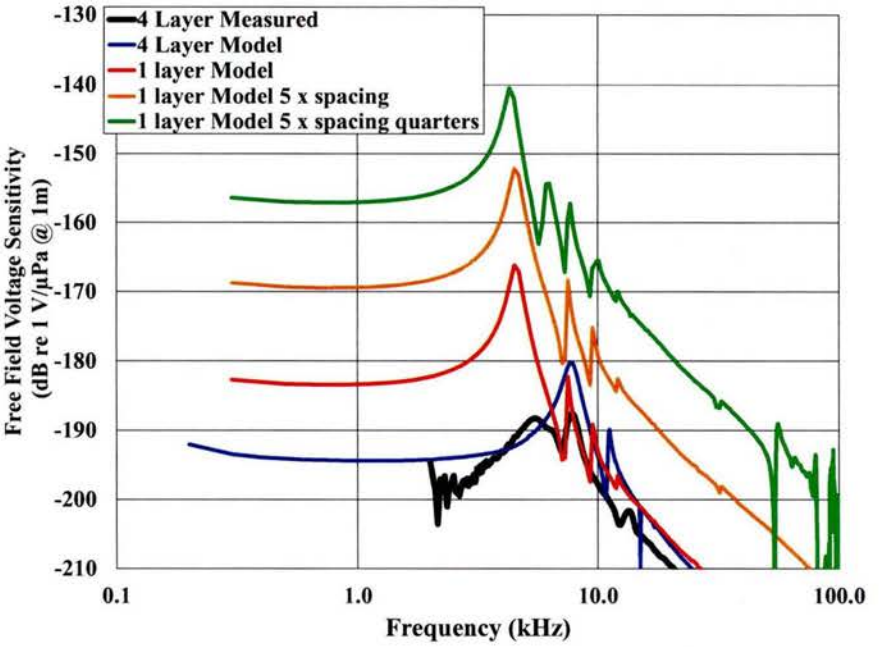


Figure 17 Free-Field Voltage Sensitivity of the MFC cylindrical geometry. Also showing the effects of reducing the number of layers or spreading the electrode gaps

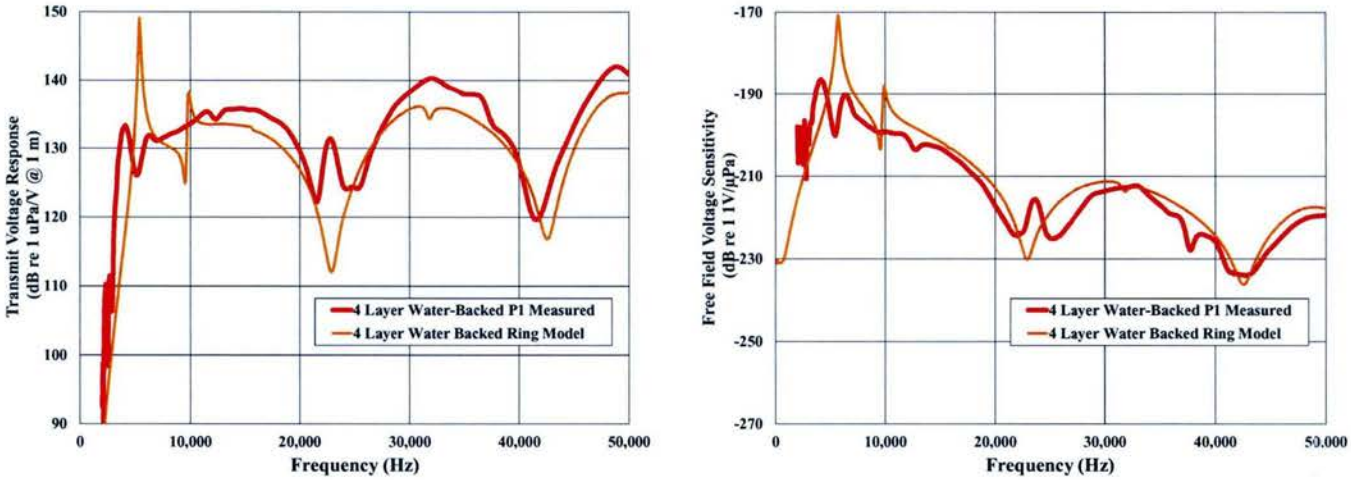


Figure 18 Transmit Voltage Response and Phase of the P1 type MFC cylindrical geometry when tested with water backing

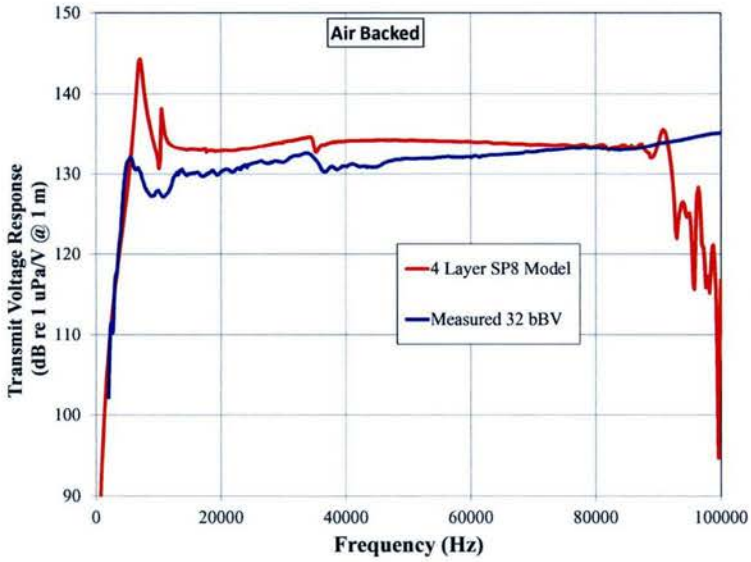


Figure 19 TVR of the PZT8 4-Layer MFC ring air-backed

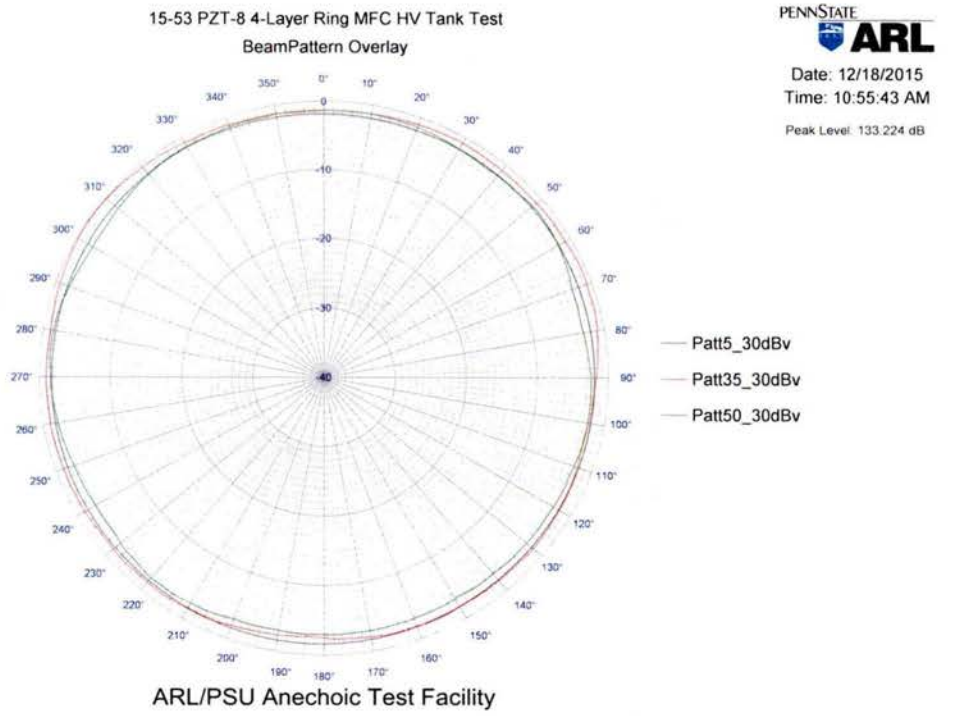


Figure 20SP8 (PZT8) 4-layer ring beam patterns at 5kHz, 35kHz, and 50kHz showing omnidirectional patterns

Adjustment of Flextensionals with MFC Patches

The ability of the MFC to affect the performance of flextensional transducers was investigated. First, M-25528-P1 strips were bonded to the OD of a slotted cylinder transducer equipped with PZT drivers on the ID. Figure 21 is a photograph of the assembled device. The MFC patches were bonded with Loctite-Hysol E-120HP epoxy. This device is made with an aluminum wall that is over 0.6 -inch thick, with an equal thickness of PZT ceramic lining the inside. The in-air impedance and phase of the device were monitored as the DC voltage on the MFC ranged from negative 500VDC to positive 1500VDC (i.e., the operational limits stated in SMC literature). Figure 22 shows that the resonance frequency of the device increased slightly as the voltage on the MFC increased. A second layer of MFC was applied, and the result was approximately double the observed change.

Figure 21 Photograph of an M-25585-P1 MFC bonded to a slotted cylinder transducer

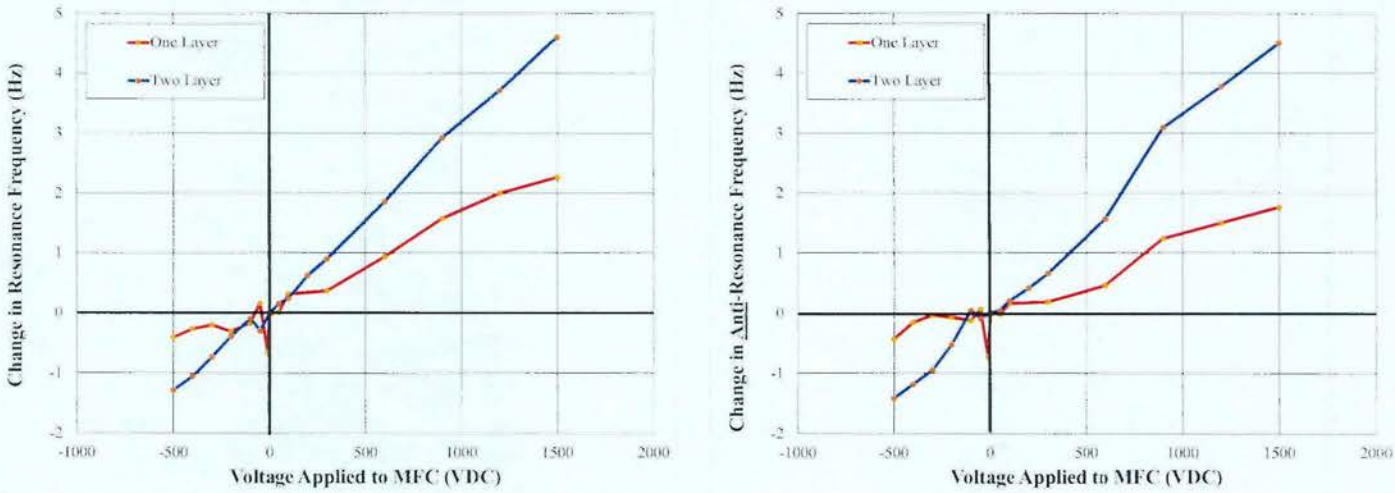


Figure 22 Slotted Cylinder - Change in resonance and anti-resonance frequencies caused by energizing the MFC

In a second test, an elliptical Class IV flextensional device was provided with P1 MFC strips across the span. An Atila++ model of this configuration appears in Figure 23. Currently there is no way in Atila++ to apply a DC voltage and an AC voltage simultaneously. Therefore, the model structure was constructed, and then the MFC was driven with 1VAC at 10 Hz while the PZT stack had no voltage applied. The maximum displacement at the shell of the ClassIV caused by deflection of the MFCs was determined, and then with the voltage on the MFCs at

0DC, an orthogonal force condition was applied to the contact surfaces between the MFC and the shell and increased until the same maximum displacement was achieved. This force condition was continuously applied while the ClassIV stack was itself driven with 1VAC through the frequency spectrum of interest.

The modeled and measured results are shown in Figure 24. The MFC patches were attached at one shell with cyanoacrylate glue, and then pulled under tension to attach the second end. This device has an aluminum shell that is about 1-inch thick. The changes in resonance that were predicted by the models were not fully realized in the measured device, but the MFCs had a measureable effect on the behavior of this very robust device. In particular, the negative voltage may not have produced sufficient shrinkage of the MFC to overcome any slight slack that may have resulted from the assembly technique.

These two experiments produced modest results, however, they illustrate that MFCs can affect the electromechanical performance of very robust devices, and point the way for more experimentation on transducers that are more sensitive. Investigation of commercially available flextensionals may lead to design of novel devices employing MFCs for active control.

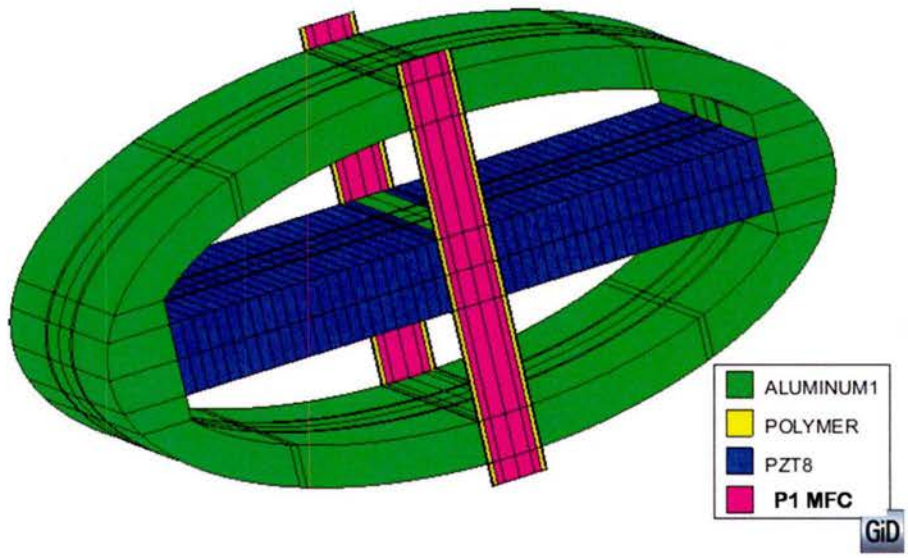


Figure 23 Class IV elliptical flextensional model with MFC patches across the span

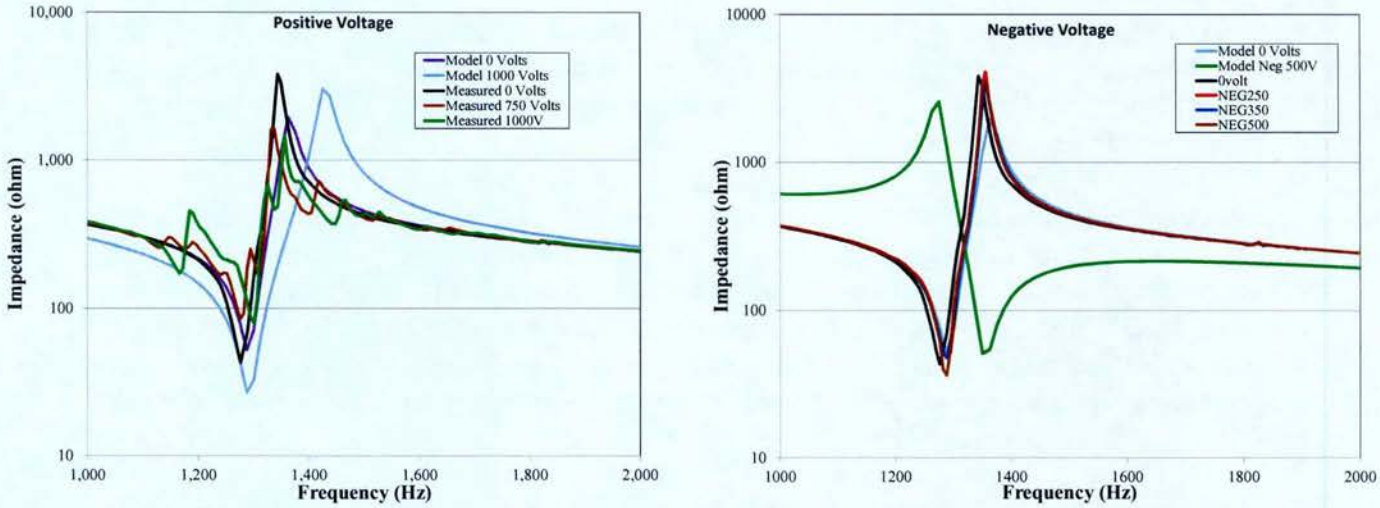


Figure 24 Class VI flextensional - changes in resonance with DC voltage applied to MFCs across the span

Alternative Transducer Designs

Some possible driving transducer designs were explored in the Atila ++ models.

One version is a cantilever/bender arrangement to use the bending motion of the MFCs bonded to steel plates as a driver for tonpilz type headmass. Figure 25 shows the conceptual idea.

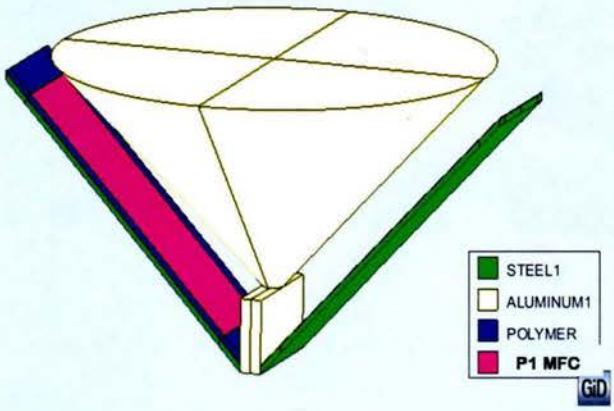


Figure 25 Modeled cantilever driven "tonpilz" type design

A second design involved using the MFC patches as drivers for a "1-3" composite style structure. Four or twelve MFC patches were embedded in an Araldite DBF matrix and fitted with a headmass and tailmass. The model is illustrated in Figure 26.

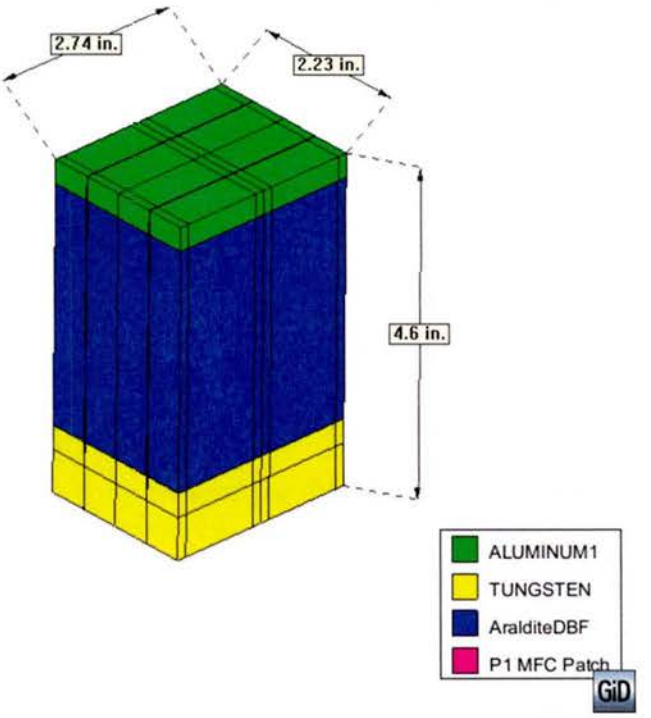


Figure 26 Modeled "1-3 Composite" type design

Another version is a traditional barrel-stave structure with MFC benders, (Figure 27).

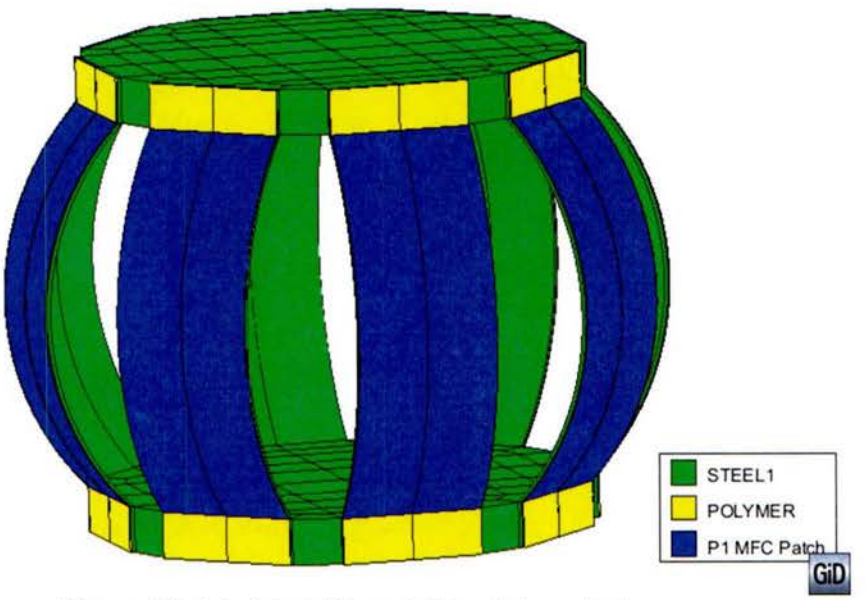


Figure 27 Modeled "Barrel-Stave" type design

Most of these alternate structures show low electromechanical coupling values. While they may not exhibit good projector qualities, they may find uses in hydrophone applications.

LITERATURE SURVEY RESULTS

Highlights

Optimal excitation of a double-curved shallow shell by a macro fiber composite actuator
Yahong, Zhang (State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, Xi'an, China); Yajun, Luo; Xinong, Zhang **Source:** *21st International Congress on Sound and Vibration 2014, ICSV 2014*, v 4, p 3354-3360, 2014
Double-curve vibration supression

Nonlinear actuation properties of Macro Fiber Composite actuators
Williams, R. Brett (Department of Mechanical Engineering, Ctr. Intelligent Mat. Syst./Struct., Virginia Tech, Blacksburg, VA 24061-0261, United States); Inman, Daniel J.; Wilkie, W. Keats **Source:** *American Society of Mechanical Engineers, Aerospace Division (Publication) AD*, v 68, p 11-18, 2003, *Proceedings of the ASME Aerospace*
High Field and Stress

Nonlinear response of the macro fiber composite actuator to monotonically increasing excitation voltage
Williams, R. Brett (Jet Propulsion Laboratory, Structures and Materials Technology Group, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, United States); Inman, Daniel J.; Wilkie, W. Keats **Source:** *Journal of Intelligent Material Systems and Structures*, v 17, n 7, p 601-608, July 2006
High Field and stress

Deformation of the upper and lower surfaces of an airfoil by macro fiber composite act
Debiasi, Marco (Temasek Laboratories, National University of Singapore, Singapore 117411, Singapore); Bouremel, Yann; Lu, Zhenbo; Ravichandran, Varsha **Source:** *31st AIAA Applied Aerodynamics Conference*, 2013, *31st AIAA Applied Aerodynamics Conference*

Design and validation of a fuzzy logic controller for a smart projectile fin with a piezoelectric macro-fiber composite bimorph actuator
Mudupu, V. (University of Nevada, Las Vegas, NV, United States); Trabia, M.B.; Yim, W.; Weinacht, P. **Source:** *Smart Materials and Structures*, v 17, n 3, June 1, 2008
Fiberglass Substrate

Quasi-Static Four-Point Bend Testing of Macro-Fiber Composite Unimorphs
LaCroix, B. (Department of Mechanical and Aerospace Engineering, University of Florida, MAE Receiving, 134 MAE-C, Gainesville, FL, 32611, United States); Ifju, P. **Source:** *Experimental Mechanics*, v 54, n 7, p 1139-1149, August 2014
Load bearing /study of substrate materials

Nonlinear response of the macro fiber composite actuator to monotonically increasing excitation voltages
Williams, R. Brett (Struct. and Mat. Technology Group, NASA Jet Propulsion Laboratory, MS 299-101, 4800 Oak Grove Dr., Pasadena, CA 91109, United States); Inman, Daniel J.; Wilkie, W. Keats **Source:** *American Society of Mechanical Engineers, Aerospace Division (Publication) AD*, v 69, p 49-54, 2004, *Proceedings of the ASME Aerospace Division - 2004: Adaptive Materials and Systems, Aerospace Materials and Structures*
Effects of DC Bias, d coefficients

Measurements of a symmetric airfoil morphed by macro fiber composite actuators
Bouremel, Yann (Temasek Laboratories, National University of Singapore, Singapore, 117411, Singapore); Chan, Woei Leong; Jones, Gareth; Debiasi, Marco **Source:** *32nd AIAA Applied Aerodynamics Conference*, 2014, *32nd AIAA Applied Aerodynamics Conference*

Control of a flexible beam actuated by macro-fiber composite patches: II. Hysteresis and creep compensation, experimental results
Schröck, Johannes (Automation and Control Institute, Gußhausstrasse 27-29, A-1040 Vienna, Austria); Meurer, Thomas; Kugi, Andreas **Source:** *Smart Materials and Structures*, v 20, n 1, January 2011
Modeling and experimental, creep and hysteresis

Shape change of the upper surface of an airfoil by macro fiber composite actuators
Debiasi, Marco (Temasek Laboratories, National University of Singapore, Singapore, 117411, Singapore); Bouremel, Yann; Hock Hee, Khoo; Siao Chung, Luo; Tan Zhiwei, Elvin **Source:** *29th AIAA Applied Aerodynamics Conference 2011*, 2011, *29th AIAA Applied Aerodynamics Conference 2011*

Structural sensing and actuation utilizing macro fiber composite
Nagata, Yoshinori (Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo 182-8585, Japan); Park, Seokyong; Ming, Aiguo **Source:** *2006 IEEE International Conference on Robotics and Biomimetics, ROBIO 2006*, p 1275-1280, 2006, *2006 IEEE International Conference on Robotics and Biomimetics, ROBIO 2006*
Sensing and Damping

Active control of thermally induced distortion in composite structures using Macro Fiber Composite actuators
Dano, M.-L. (Department of Mechanical Engineering, Université Laval, Québec, G1K 7P4, Canada); Jullière, B. **Source:** *Smart Materials and Structures*, v 16, n 6, p 2315-2322, December 1, 2007
Active Shape control – $[0/90_3]_T$ composite substrate

Material properties of single crystal macro fiber composite actuators for active twist rotor blades

Park, Jae-Sang (Seoul National University, Seoul, 151-742, Korea, Republic of); Kim, Ji-Hwan **Source:** *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, v 9, p 5802-5817, 2005, *Collec. of Technic. Pap. - 46th AIAA/ASME/ASCE/AHS/ASC Struc.,Struct. Dynam. and Mater. Conf., 13th AIAA/ASME/AHS Adap. Struc. Conf., 7th AIAA Non-Determin. Appr. Forum, 6th AIAA GSF 1st AIAA MDOSC*

Dynamic snap-through using piezoelectric fibers for morphing bi-stable structures
Senba, Atsuhiko (Composite Engineering Research Center, Nagoya University, Japan); Ikeda, Tadashige; Ueda, Tetsuhiko **Source:** *60th International Astronautical Congress 2009, IAC 2009*, v 7, p 5625-5633, 2009, *60th International Astronautical Congress 2009, IAC 2009*
Buckling

Other Papers of Interest

Control force enhancement of conical shells using piezoelectric macro-fiber composite
Li, H. (Department of Mechanical Engineering, State Key Lab of Fluid Power and Mechatronic Systems, Denmark); Li, H.Y.; Tzou, H.S. **Source:** *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, v 4 B, 2013, *ASME 2013 International Mechanical Engineering Congress and Exposition, IMECE 2013*
D31 cancelation effects for composite P1, P2, P3 types

Macro-fiber composite piezoelectric rosettes for acoustic source location in complex structures
Matt, Howard M. (Department of Structural Engineering, Structural Health Monitoring Laboratory, University of California, San Diego, 9500 Gilman Drive, San Diego, CA 92093-0085, United States); Di Scalea, Francesco Lanza **Source:** *Smart Materials and Structures*, v 16, n 4, p 1489-1499, August 1, 2007
Impact location using MFCs in "Rosette "pattern

Finite element analysis of the macro fiber composite actuator: Macroscopic elastic and piezoelectric properties and active control thereof by means of negative capacitance shunt circuit
Steiger, Kateina (Regional Centre for Special Optics and Optoelectronic Systems (TOPTEC), Institute of Plasma Physics, Academy of Sciences of the Czech Republic, Za Slovankou 1782/3, Prague 8, Czech Republic); Mokrý, Pavel **Source:** *Smart Materials and Structures*, v 24, n 2, February 1, 2015
Development of monolithic material property set for P2 type in FEA

Novel energy harvesting: A macro fiber composite piezoelectric energy harvester in the water vortex
Shan, Xiaobiao (School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, China); Song, Rujun; Liu, Bo; Xie, Tao **Source:** *Ceramics International*, v 41, n S1, p S763-S767, July 1, 2015
P2 type

Numerical simulation of mechanical behavior of a Macro Fiber Composite piezoelectric actuator shunted by a negative capacitor
Nováková, Katerina (Institute of Mechatronics and Computer Engineering, Technical University of Liberec, Czech Republic); Mokrý, Pavel **Source:** *2011 10th International Workshop on Electronics, Control, Measurement and Signals, ECMS 11*, 2011, *2011 10th International Workshop on Electronics, Control, Measurement and Signals, ECMS 11*

Investigating potential substrates to maximize out-of-plane deflection of piezoelectric macro-fiber composite actuators
LaCroix, Bradley W. (Mechanical and Aerospace Engineering, University of Florida, 134 MAE-C, Gainesville; FL, United States); Ifju, Peter G. **Source:** *Journal of Intelligent Material Systems and Structures*, v 26, n 7, p 781-795, May 4, 2015
Thin, stiff substrates give max deflection when curved.

Lamb wave transducers made of piezoelectric macro-fiber composite
Manka, Michał (Faculty of Mechanical Engineering and Robotics, Department of Robotics and Mechatronics, AGH University of Science and Technology, al. A. Mickiewicza 30, 30-059 Krakow, Poland); Rosiek, Mateusz; Martowicz, Adam; Stepinski, Tadeusz; Uhl, Tadeusz **Source:** *Structural Control and Health Monitoring*, v 20, n 8, p 1138-1158, August 2013

An Enhanced Piezoelectric Vibration Energy Harvesting System with Macro Fiber Composite
Zhang, Shuwen (State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'An Jiaotong University, Xianning West Road, Xi'an, China); Yan, Bo; Luo, Yajun; Miao, Weikai; Xu, Minglong **Source:** *Shock and Vibration*, v 2015, 2015

Application of piezoelectric macro-fiber-composite actuators to the suppression of noise transmission through curved glass plates
Nováková, Katerina (Institute of Mechatronics and Computer Engineering, Technical University of Liberec, Liberec, Czech Republic); Mokrý, Pavel; Václavík, Jan **Source:** *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, v 59, n 9, p 2004-2014, 2012

Finite element modeling of macro fiber composite piezoelectric actuators on micro air vehicles
LaCroix, Bradley W. (University of Florida, Mechanical and Aerospace Engineering, 134 MAE-C, Gainesville, FL, 32611, United States); Ifju, Peter G. **Source:** *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 2012*, 2012, *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 2012*

Wide frequency range noise shield using curved glass plates with piezoelectric macro fiber composite actuators
Steiger, Katerina (Regional Centre for Special Optics and Optoelectronic Systems (TOPTEC), Institute of Plasma Physics, AS CR, Turnov, Czech Republic); Mokry, Pavel; Vaclavik, Jan; Kodejska, Milos **Source:** *2014 Joint IEEE International Symposium on the Applications of*

Ferroelectric, International Workshop on Acoustic Transduction Materials and Devices and Workshop on Piezoresponse Force Microscopy, ISAF/IWATMD/PFM 2014, October 13, 2014

High-velocity impact location on aircraft panels using macro-fiber composite piezoelectric rosettes
Salamone, Salvatore (NDE and Structural Health Monitoring Laboratory, University of California, San Diego, 9500 Gilman Drive, San Diego, CA 92093-0085, United States); Bartoli, Ivan; Di Leo, Patrizia; Lanza Di Scalea, Francesco; Ajovalasit, Augusto; D'Acquisto, Leonardo; Rhymer, Jennifer; Kim, Hyonny **Source:** *Journal of Intelligent Material Systems and Structures*, v 21, n 9, p 887-896, June 2010

Stretch-tuning optical fiber Bragg gratings using Macro-Fiber Composite (MFC) piezoelectric actuators
Allison, Sidney G. (NASA Langley Research Center, Hampton, VA 23681, United States); Shams, Qamar A.; Geddis, Demetris L. **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 6004, 2005, *Fiber Optic Sensor Technology and Applications IV*
Optics

Health monitoring of cylindrical structures using torsional wave generated by piezoelectric macro-fiber composite
Cui, Lin (School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore); Liu, Yu; Soh, Chee Kiong **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 7984, 2011, *Health Monitoring of Structural and Biological Systems 2011*

Detection and monitoring of axial cracks in cylindrical structures using torsional wave generated by piezoelectric macro-fiber composite
Cui, Lin (School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore, Singapore); Lim, Say Ian; Shi, Miao; Liu, Yu; Soh, Chee Kiong **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 8348, 2012, *Health Monitoring of Structural and Biological Systems 2012*

Hydroelastic power and thrust generation using macro-fiber composite piezoelectrics
Erturk, Alper (George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States); Delporte, Ghislain **Source:** *ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2011*, v 2, p 377-385, 2011, *ASME 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2011*
Fish Robots

Macro-fiber composite piezoelectric rosettes for acoustic source location in complex structures
Matt, Howard (Dept. of Structural Engineering, NDE and Structural Health Monitoring Laboratory, Univ. of California, San Diego, 9500 Gilman Drive, San Diego, CA 92093-0085, United States); Di Scalea, Francesco Lanza **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 6529 PART 1, 2007, *Sensors and Smart Structures*

Technologies for Civil, Mechanical, and Aerospace Systems 2007

A review of macro fiber composite and its application
Di, Sisi (State Key Laboratory of Mechanics and Control for Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China); Li, Huafeng **Source:** *Zhendong Ceshi Yu Zhenduan/Journal of Vibration, Measurement and Diagnosis*, v 33, n SUPPL.2, p 157-160, October 2013

Manufacturing and mechanics-based characterization of macro fiber composite actuators
Williams, R. Brett (Department of Mechanical Engineering, Virginia Tech., 310 Durham Hall, Blacksburg, VA 24061-0261, United States); Grimsley, Brian W.; Inman, Daniel J.; Wilkie, W. Keats **Source:** *ASME International Mechanical Engineering Congress and Exposition, Proceedings*, p 79-89, 2002, *ASME 2002 International Mechanical Engineering Congress and Exposition, IMECE 2002*

Application of piezoelectric macro-fiber-composite actuators for the suppression of noise transmission through curved glass plates
Nováková, K. (Institute of Mechatronics and Computer Engineering, Technical University of Liberec, Studentská 2, Liberec I, CZ-46117, Czech Republic); Mokrý, P. **Source:** *2011 International Symposium on Applications of Ferroelectrics and 2011 International Symposium on Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials, ISAF/PFM 2011*, 2011, *2011 International Symposium on Applications of Ferroelectrics and 2011 International Symposium on Piezoresponse Force Microscopy and Nanoscale Phenomena in Polar Materials, ISAF/PFM 2011*

Passive damping augmentation using macro-fiber composite actuators
Adachi, Kazuhiko (Department of Mechanical Engineering, Kobe University, Kobe, Hyogo, 657-8501, Japan); Park, Gyuhae; Inman, Daniel J. **Source:** *ASME International Mechanical Engineering Congress and Exposition, Proceedings*, p 71-78, 2002, *ASME 2002 International Mechanical Engineering Congress and Exposition, IMECE 2002*

Experimental power harvesting from a pipe using a macro fiber composite (MFC)
Eziwarman (Department of Mechanical Engineering, Curtin University Perth, Bentley, WA, Australia); Forbes, G.L.; Howard, I.M. **Source:** *Advances in Intelligent and Soft Computing*, v 144 AISC, n VOL. 1, p 443-449, 2012, *Proceedings of the 2011 2nd International Congress on Computer Applications and Computational Science*

Manufacturing and cure kinetics modeling for macro fiber composite actuators
Williams, R. Brett (Department of Mechanical Engineering, Virginia Tech., 310 Durham Hall, Blacksburg, VA 24061-0261, United States); Grimsley, Brian W.; Inman, Daniel J.; Wilkie, W. Keats **Source:** *Journal of Reinforced Plastics and Composites*, v 23, n 16, p 1741-1754, 2004

Modeling and simulation of macro-fiber composite layered smart structures
Zhang, Shun-Qi (School of Mechanical Engineering, Northwestern Polytechnical University, West Youyi Street 127, Xi'an, China); Li, Ya-Xi; Schmidt, Rüdiger **Source:** *Composite*

Structures, v 126, p 89-100, August 01, 2015
FEA Theory

Underwater dynamic actuation of macro-fiber composite flaps with different aspect ratios: Electrohydroelastic modeling, testing, and characterization
Shahab, Shima (Smart Structures and Dynamical Systems Laboratory, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta; GA, United States); Erturk, Alper **Source:** *ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, SMASIS 2014*, v 2, 2014
Fish robots

Noise suppression in curved glass shells using macro-fiber-composite actuators studied by the means of digital holography and acoustic measurements
Mokrý, P. (Institute of Mechatronics and Computer Engineering, Technical University of Liberec, Studentská 2, Liberec, Czech Republic); Psota, P.; Steiger, K.; Václavík, J.; Doleek, R.; Lédl, V.; Šulc, M. **Source:** *AIP Advances*, v 5, n 2, February 1, 2015

Motion planning for a flexible link manipulator with macro-fiber composite actuators
Schröck, J. (Automation and Control Institute, Vienna University of Technology, Austria); Meurer, T.; Kugi, A. **Source:** *IFAC Proceedings Volumes (IFAC-PapersOnline)*, p 486-491, 2010, *5th IFAC Symposium on Mechatronic Systems, MECHATRONICS 2010 - Proceedings*

Active vibration control of ring-stiffened cylindrical shell structure using macro fiber composite actuators
Sohn, Jung Woo (Department of Mechanical Design Engineering, Kumoh National Institute of Technology, Gumi, Korea, Republic of); Jeon, Juncheol; Choi, Seung-Bok **Source:** *Journal of Nanoscience and Nanotechnology*, v 14, n 10, p 7526-7532, October 1, 2014

Application of macro-fiber composite to structural vibration suppression
Hou, Zhiwei (Aeronautical Science Key Lab. for Smart Materials and Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China); Chen, Renwen; Xu, Zhiwei; Liu, Qiang **Source:** *Zhendong Ceshi Yu Zhenduan/Journal of Vibration, Measurement and Diagnosis*, v 30, n 1, p 51-54, February 2010

Macro-Fiber Composite actuated thin clamped-free benders and thin simply-supported morphing airfoils
Bilgen, Onur (Department of Mechanical Engineering, Center for Intelligent Material Systems and Structures, Virginia Polytechnic Institute and State University, Blacksburg; VA, United States); Erturk, Alper; Inman, Daniel J.; Kochersberger, Kevin B. **Source:** *19th International Conference on Adaptive Structures and Technologies 2008, ICAST 2008*, p 542-553, 2008
Al, Brass, Steel substrates

Inverse model construction for control implementation of macro fiber composite actuators operating in hysteretic regimes
Stuebner, Michael (Dept. of Math., Center for Research in Scientific Comp., NCSU, Raleigh, NC 27695-8205, United States); Smith, Ralph C. **Source:** *Proceedings of SPIE - The*

International Society for Optical Engineering, v 7644, 2010, *Behavior and Mechanics of Multifunctional Materials and Composites 2010*
Modeling of hysteresis

Numerical evaluation of the equivalent properties of Macro Fiber Composite (MFC) transducers using periodic homogenization
Deraemaeker, Arnaud (Université Libre de Bruxelles - BATir, 50 av F.D. Roosevelt, B-1050, Brussels, Belgium); Nasser, Houssein **Source:** *International Journal of Solids and Structures*, v 47, n 24, p 3272-3285, December 1, 2010
FEA Bulk modeilng

Study on electric-mechanical hysteretic model of Macro-Fiber Composite actuator
Xiaomin, Xue (Department of Civil Engineering, Xi'An Jiaotong University, Xi'an, 710049, China); Luqi, Chen; Xiaohong, Wu; Qing, Sun **Source:** *Journal of Intelligent Material Systems and Structures*, v 25, n 12, p 1469-1483, August 2014
Modeling of hysteresis

Wrinkle localization in membrane structures patched with macro-fiber composite actuators: Inflatable space antenna applications
Fleurent-Wilson, Eric (Department of Mechanical and Mechatronics Engineering, University OfWaterloo, Waterloo; ON, Canada); Pollock, Tim E.; Su, Wei-Jiun; Warrier, Dileep; Salehian, Armaghan **Source:** *Journal of Intelligent Material Systems and Structures*, v 25, n 15, p 1978-2009, October 1, 2014
Mechanical Stiffening

Design, characterization, and testing of macro-fiber composite actuators for integration on a fixed-wing UAV
Prazenica, Richard J. (Aerospace Engineering Department, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd., Daytona Beach, FL 32114, United States); Kim, Daewon; Moncayo, Hever; Azizi, Boutros; Chan, May **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 9057, 2014, *Active and Passive Smart Structures and Integrated Systems 2014*
Fiberglass Substrate

Macro-Fiber Composite actuators for a swept wing unmanned aircraft
Bilgen, O. (Virginia Polytechnic Institute, State University, Blacksburg, United States); Kochersberger, K.B.; Inman, D.J. **Source:** *Aeronautical Journal*, v 113, n 1144, p 385-395, June 2009

Vibration control of a cylindrical shell structure using macro fiber composite actuators
Kim, Heung Soo (Department of Mechanical, Robotics and Energy Engineering, Dongguk University-Seoul, 26 Pil-dong 3-Ga, Jung-Gu, Seoul 100-715, Korea, Republic of); Sohn, Jung Woo; Choi, Seung-Bok **Source:** *Mechanics Based Design of Structures and Machines*, v 39, n 4, p 491-506, October 2011
Damping

ENergy Harvesting Devices Using Macro-Fiber Composite Materials
Song, Hyun Jeong (Smart Structures Laboratory, Department of Aerospace Engineering, University of Maryland College Park, MD 20742, United States); Choi, Young-Tai; Wereley, Norman M.; Purekar, Ashish S. **Source:** *Journal of Intelligent Material Systems and Structures*, v 21, n 6, p 647-658, April 2010
Self Explanatory

Design of a biomimetic fish caudal drive via macro fiber composite
Guan, Yuan-Lin (State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China); Xu, Zhi-Wei; Li, Hua-Feng **Source:** *Proceedings of the 2011 Symposium on Piezoelectricity, Acoustic Waves and Device Applications, SPAWDA 2011*, p 123-125, 2011, *Proceedings of the 2011 Symposium on Piezoelectricity, Acoustic Waves and Device Applications, SPAWDA 2011*
Fiberglass Substrate

Development of underwater robot using macro fiber composite
Nagata, Yoshinori (Department of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu-shi, Tokyo 182-8585, Japan); Park, Seokyong; Ming, Aiguo; Shimojo, Makoto **Source:** *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, p 955-960, 2008, *Proceedings of the 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM 2008*
Fish Robot

Performance evaluation of multi-tier energy harvesters using macro-fiber composite patches
Song, Hyun Jeong (Smart Structures Laboratory, Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, United States); Choi, Young-Tai; Purekar, Ashish S.; Wereley, Norman M. **Source:** *Journal of Intelligent Material Systems and Structures*, v 20, n 17, p 2077-2088, November 2009
Series and Parallel connection of multiple pieces not physically joined

Wind tunnel tests for a flapping wing model with a changeable camber using macro-fiber composite actuators
Kim, Dae-Kwan (COMS Systems Department, Korea Aerospace Research Institute, 115 Gwahangno, Yuseong-gu, Daejeon 305-333, Korea, Republic of); Han, Jae-Hung; Kwon, Ki-Jung **Source:** *Smart Materials and Structures*, v 18, n 2, 2009
PVC Skin substrate ornithopter

Electric field distribution in macro fiber composite using interdigitated electrodes
Nasser, H. (CRP Henri Tudor, 29 Avenue John F. Kennedy, Luxembourg); Deraemaeker, A.; Belouettar, S. **Source:** *Advanced Materials Research*, v 47-50, p 1173-1176, 2008
Model of electric field

Frequency wavenumber design of spiral macro fiber composite directional transducers
Carrara, Matteo (D. Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta; GA, United States); Ruzzene, Massimo **Source:** *Proceedings of SPIE - The*

International Society for Optical Engineering, v 9435, 2015
guided wave structural health monitoring

Analytical, numerical and experimental predictions of the effective electromechanical properties of macro-fiber composite (MFC)
Sreenivasa Prasath, S. (Department of Applied Mechanics, Indian Institute of Technology Madras, 600036 Chennai, India); Arockiarajan, A. **Source:** *Sensors and Actuators, A: Physical*, v 214, p 31-44, August 1, 2014

Control of a space rigidizable inflatable boom using macro-fiber composite actuators
Tarazaga, Pablo A. (Center for Intelligent Material Systems and Structures, 310 Durham Hall, State University, Blacksburg, VA 24061, United States); Inman, Daniel J.; Wilkie, W. Keats **Source:** *JVC/Journal of Vibration and Control*, v 13, n 7, p 935-950, July 2007
Flexible lightweight actuator

Control of a flexible beam actuated by macro-fiber composite patches: I. Modeling and feedforward trajectory control
Schröck, Johannes (Automation and Control Institute, Gußhausstrasse 27-29, A-1040 Vienna, Austria); Meurer, Thomas; Kugi, Andreas **Source:** *Smart Materials and Structures*, v 20, n 1, January 2011
Hysteresis modeling and measured

On the directional decoupling effect of macro fiber composite actuators for high precision shape control of optical plate structures
Philen, Michael (Structural Dynamics and Controls Lab., Pennsylvania State University, 157E Hammond Building, University Park, PA 16802, United States); Wang, K.W. **Source:** *16th International Conference on Adaptive Structures and Technologies*, p 77-85, 2006, *16th International Conference on Adaptive Structures and Technologies*

Vibration suppression of hull structure using macro fiber composite actuators and sensors
Sohn, Jung Woo (Smart Structures and Systems Laboratory, Department of Mechanical Engineering, Inha University, 253 Yonghyun-Dong, Nam-Ku Incheon 402-751, Korea, Republic of); Kim, Heung Soo; Kim, Chan-Jung; Ha, Sung Hoon; Choi, Seung-Bok **Source:** *Proceedings of SPIE - The International Society for Optical Engineering*, v 6525, 2007, *Active and Passive Smart Structures and Integrated Systems 2007*

Material properties of single crystal macro fiber composite actuators for active twist rotor blades
Park, Jae-Sang (Seoul National University, Seoul, 151-742, Korea, Republic of); Kim, Ji-Hwan **Source:** *Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, v 9, p 5802-5817, 2005, *Collec. of Technic. Pap. - 46th AIAA/ASME/ASCE/AHS/ASC Struc.,Struct. Dynam. and Mater. Conf., 13th AIAA/ASME/AHS Adap. Struc. Conf., 7th AIAA Non-Determin. Appr. Forum, 6th AIAA GSF 1st AIAA MDOSC*

An additional 240 papers not listed here have been sourced and are being explored.

Conclusions

MFC-based transduction schemes have the potential to supply the fleet with low cost, low frequency sources or hydrophones. They may also provide unique transducer structures that provide improved performance capability and/or packaging.