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.

14. ABSTRACT

15. SUBJECT TERMS
Macro-Fiber Composite Based Transduction

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Principal Investigator: Richard J. Meyer Jr.

Final Report

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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.
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 flexextensional transducers by imparting tensile or compressive strains to the elastic members of the flexextensionals. 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 flexextensional transducers was tested. An MFC patch was bonded to the outside of a slotted-cylinder transducer and across the span of a ClassIV flexextensional 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.](image)

**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

- $1/S_{33} = 4 \times \text{dens} \times (f_r^2 \times L^2)$
- $1/E3 = S_{33}D / (1 - k_{33}^2)$
- $K' = (\text{Cap.} \times \text{electrode gap}) / (\text{Area} \times \varepsilon_0 \times n)$

Table 2 Calculation Methodology for Piezoelectric Coefficients

<table>
<thead>
<tr>
<th>Strain</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{33}$</td>
<td>$\Delta X / \Delta Y$</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>$\Delta Y / (\Delta X + \Delta Y)$</td>
</tr>
</tbody>
</table>

Table 2 Calculation Methodology for Piezoelectric Coefficients

- $d_{33} \text{ effective } = \frac{\Delta X_{\text{total}}}{V + n_{\text{gap}}}$

$V = d_{33} \times V \times n_{\text{gap}} = \Delta X_{\text{total}}$

ATILA ++ has an input for electrode spacing. That combined with the modeled piece length and polarization direction gives $n_{\text{gap}}$

- $d_{31} \text{ effective } = \frac{\Delta Y \times X}{Y + V}$

Total $\Delta Y = \Delta Y_{\text{rod}} \times n_{\text{rod}}$

$X = \text{electrode gap}$

However, Atila++ has no place to enter rod count – Therefore it uses the full width monolithically
The refined Atila input material properties (1-volt properties) are listed in Table 3.

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

<table>
<thead>
<tr>
<th>General</th>
<th>PZT5A (P1)</th>
<th>PZT8 (SP8)</th>
<th>Average Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>5077</td>
<td>5612</td>
<td></td>
</tr>
<tr>
<td>Spacing</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

| 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 |

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![Thin Piezo Patch](image)
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](image1.png)  
**Figure 2** M-8528-P1 sized PZT5 patch modeled and measured impedance and phase (average of 12 samples)

![Figure 3](image2.png)  
**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)
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 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-P1 patches 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](image-url)
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
Adjustment of Flexextensionals with MFC Patches

The ability of the MFC to affect the performance of flexextensional 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.
In a second test, an elliptical Class IV flexextensional 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 Class IV caused by deflection of the MFCs was determined, and then with the voltage on the MFCs at
ODC, 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
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.

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


**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


**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


**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


**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**
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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

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]T composite substrate

Material properties of single crystal macro fiber composite actuators for active twist rotor blades
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); Mokry, 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

Investigating potential substrates to maximize out-of-plane deflection of piezoelectric macro-fiber composite actuators
Thin, stiff substrates give max deflection when curved.

Lamb wave transducers made of piezoelectric macro-fiber composite
Manka, Michal (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

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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
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Finite element modeling of macro fiber composite piezoelectric actuators on micro air vehicles

Wide frequency range noise shield using curved glass plates with piezoelectric macro fiber composite actuators
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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

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Hydroelastic power and thrust generation using macro-fiber composite piezoelectrics
Fish Robots

Macro-fiber composite piezoelectric rosettes for acoustic source location in complex structures
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Fish robots

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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.