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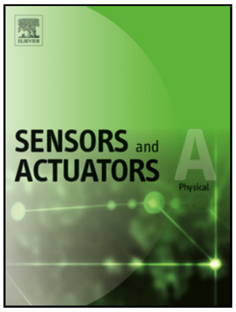

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Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

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Highlights

- *Novel bandwidth widening concept validated using sloshing liquid metal mass*
- *Increased bandwidth achieved using a liquid metal filled mass*
- *Bandwidth widening dependent on acceleration due to oxide skin on liquid metal*
- Liquid metal damping effects show enhanced performance

Abstract:

Linear vibrational energy harvesting devices typically have narrow bandwidths, which limits their practical use, because the resonant frequency needs to match the frequency of the vibration source in order to maximize power generated. This paper presents a method of widening the bandwidth by using a highly dense liquid metal filled mass, which creates a sloshing effect that changes the center of gravity of the cantilever device during motion. The shift in center of gravity causes the resonant frequency of the cantilever to change. Since the resonant frequency of the device is constantly change during oscillation of the cantilever, this results in a widening of the bandwidth. The displacement of the dense liquid metal has more influence on the center of gravity compared to other less dense liquids thus increasing the bandwidth. The paper demonstrates a 6.5x increase in bandwidth for the liquid metal filled mass compared to a typical air-filled mass with only a 9.6% reduction in power at 1 g acceleration. Acceleration effects and mechanical damping were also investigated and presented within the paper.

Keywords: Bandwidth, Energy Harvester, Piezoelectric, Cantilever, liquid metal

Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

1. Introduction:

Vibrational energy harvesting systems have been extensively investigated over the past decade and their demand continues to increase due to the Internet of Things. Their main goal is to replace batteries to create a completely self-sustaining system that harvests energy from the ambient environment. There are various methods of harvesting energy from vibrations, the two most common methods include: piezoelectric and electromagnetic which operate based on matching the resonant frequency of the device to the frequency of the vibration source. Cantilever-based structures typically include: a beam, an energy harvesting material (piezoelectric or coils), and a mass. Typically, these devices have a high Q-factor or narrow bandwidth (1-4), which allow them to generate high power but also makes the device not practical, because if the vibration source does not match the resonant frequency the power generated is significantly reduced. Linear energy harvesters with < 250 Hz resonant frequency typically have bandwidths of < 2 Hz (1, 3, 5), and the resonant frequency of micro-scale devices can deviate by 1-5% due to manufacturing or design issues (6, 7), so at the very least the bandwidth needs to cover potential frequency errors due to manufacturing, but ideally it will cover a larger frequency ranges to compensate for any frequency shift from the vibration source.

Previous attempts to increase the bandwidth include: non-linear cantilever design (duffing resonators) (8-10), mechanical stoppers (11), repulsive forces (12), array of devices (3), and sliding masses (13). All of these methods increased the bandwidth but did so by lowering the Q-factor which resulted in a decrease in power density. Recent attempts of increasing bandwidth without significantly reducing power have involved methods of altering the center of gravity of the mass during cantilever oscillation, such as a water filled mass to create sloshing effect (14, 15) and a rolling mass (16). Another method of compensating for frequency mismatch is tuneable devices, which involve altering the stiffness of the beam material (17-19), but these usually involve complex materials/structures that require power in order to generate power.

This paper builds upon the previous attempt at widening the bandwidth using water filled mass (14) by using a highly dense liquid (liquid-metal, Galinstan^{TM}). The aim of this paper is to experimentally demonstrate that the sloshing effect of a denser liquid filled mass will lead to an increase in bandwidth without significant reduction in power. A liquid filled mass is the preferred option over rolling masses because it is easier to integrate into both macro and micro-scale devices. Rolling masses are difficult to implement in micro-scale devices, due to complex microfabrication technique requirements. Previous attempts have demonstrated the capability of embedding liquids and powders into silicon masses (20). Liquid metal is about 6x denser than water thus the liquid material will have a more significant effect on the change of the center of gravity as the liquid is sloshed inside the mass. This paper investigates the bandwidth affects as well as acceleration, frequency sweep, and mechanical damping affects.

2. Materials and Methods

The concept of using a liquid filled mass to widen the bandwidth has been demonstrated previously with water based liquids (14, 15). The mechanism is based on altering the center of gravity of the mass by creating a sloshing affect. Typical rectangular cantilever structures have a resonant frequency that is based on a single point mass and is presented using the following equation:

$$f = \left(\frac{1}{2\pi}\sqrt{\frac{E}{4m}}\right)\sqrt{\frac{wt^3}{L^3}} \quad (1)$$

Where E is the elastic modulus of the beam, m is the mass, w, t, and L are the width, thickness, and length of the beam. Adding liquid to the mass creates another load component to the mass, and if it were a solid mass the equation would remain the same. However, if the liquid is sloshing then the center of gravity changes as a function of time and the equation is no longer valid as the mass cannot be modelled as a simple point mass. Fig. 1a and Fig. 1b demonstrate the concept of a center of gravity shift due to sloshing liquid mass. Using the Rayleigh principle, the equation for a non-center point mass becomes:

$$f^{'} = \frac{1}{2\pi}\sqrt{\frac{Ewt^{3}}{12mL^{3}} * \frac{r^{2}+6r+2}{8r^{4}+14r^{3}+10.5r^{2}+4r+\frac{2}{3}}} \quad (2)$$

Where r= $\Delta x/(L+l_m)$ where l_m is the length of the mass and L is the overall length of the cantilever and Δx is lateral displacement change in the center of gravity from the initial position as demonstrated in Fig. 1c. The formula and derivation were previously described in more detail (12, 14), however the formula describes how the resonant frequency changes due to a change in the center of gravity. Previously it was demonstrated that density of the liquid significantly influenced the amount of bandwidth, and the viscosity of the fluid was important for creating the sloshing effect at a specific acceleration. The mass of the cantilever in this case is comprised of the cantilever beam (which is negligible), the mass of the chamber (plexiglass), and the mass of the liquid. Therefore, a denser liquid will have a more significant affect on the overall mass, and any displacement of the liquids center of gravity due to sloshing will significantly alter the resonant frequency. The sloshing of the liquid causes the resonant frequency to change as the cantilever is in motion. The summation of all of these resonant frequencies accounts for the increase in bandwidth. The increase in bandwidth is dependent on the density of the liquid, the viscosity (as this affects the sloshing properties), the displacement of the cantilever beam due to applied acceleration, and the frequency.

In order to significantly increase the bandwidth, a liquid metal (Galinstan$^{\text{TM}}$) was embedded within the mass and filled to 50% volume, as a 100% fill would prevent a sloshing affect. Galinstan is a metal consisting of Ga, In, and Sn and is a liquid at temperatures > -19°C, has a density of 6.44 g cm^{-3} (~6.4x of water), and a viscosity of 0.002 Pa s (~2x of water). The material has been highly researched over the past few years in the area of stretchable electronics (21). Galinstan was chosen as the liquid because of its high density and low viscosity, which makes it an ideal candidate for this application. The low viscosity should allow sloshing to occur at low acceleration, while the high density will allow increased bandwidth. However, Galinstan forms an oxide layer when exposed to air, which will limit the sloshing effects. The oxide formation can be reduced chemically or physically by applying surface stress to the film. If sloshing does not occur, then the liquid metal will behave like a stationary mass with a linear energy harvester. A commercial piezoelectric energy harvester (Volture V25W, Mide) was used as the cantilever substrate in this paper in order to validate the concept at the macro-scale. The mass and beam were a scaled up version of a typical MEMS device (1, 5, 22) A custom mass was manufactured from plexiglass with cavity dimensions of 2 x 2 x 2 cm^3 and a wall thickness of 5mm and a top lid thickness of 5mm that was screwed in to prevent liquid from leaking along with a rubber O-ring. The cavity held 8 ml of liquid of which only 4 ml of liquid metal was inserted into the mass. The mass was attached to the cantilever beam using double sided adhesive. A picture of the manufactured device is shown in Fig. 1d. The device was then mounted on a vibration shaker (ET-126, Labworks), with an accelerometer to give acceleration feedback. The cantilever was connected to an oscilloscope along with a variable resistor for impedance matching. The experimental concept investigated a comparison between a liquid-metal filled mass, an empty cavity mass (air-filled mass), and a water filled mass.

--Figure 1--

3. Results and Discussion

Experimental results comparing the power as a function of normalized frequency of a typical mass with empty cavity (air-filled) and a liquid metal filled mass are shown in Fig. 2. A normalized frequency was used as the liquid metal filled mass had reduced resonant frequency due to the added mass from the liquid metal. The additional mass from the liquid metal decreased the resonant frequency from ~30 Hz to approximately 20 Hz., which is in agreement with equation (1). The air-filled cavity demonstrated a typical linear cantilever response with a narrow bandwidth and a full-width-half-maximum (FWHM) of 1.34 Hz and a peak power of 16.03 mW for a 1 g sinusoidal acceleration. The liquid metal filled mass demonstrated a significant increase in bandwidth of 8.67 Hz, which represents an increase of 6.5x. The power was reduced by 9.6% to a peak power of 14.48 mW. The reduction of power was due to non-linear effects from the sloshing liquid metal. Previous reports with water filled mass demonstrated an increase in bandwidth of 2.6x and a reduction of approximately 3-4% (14). This validates that using a denser liquid will significantly increase the bandwidth with only a small reduction in power. The liquid-metal filled mass results shown in Fig. 2 demonstrates the non-linear dynamic behaviour due to sloshing. The air-filled mass shows a smooth curve, whereas the liquid-metal filled mass demonstrates areas of peaks and troughs due to sloshing. These deviations can cause small variations in power at specific frequencies, but the overall power values are not significantly affected.

--Figure 2--

The amount of acceleration was believed to have a significant effect on the widening properties as it will affect the sloshing properties of the liquid. To verify this, we investigated three different accelerations (0.1 g, 0.5 g, and 1 g). The results are demonstrated in Fig. 3. The bandwidth values were measured at 1.9, 3.3, and 8.67 Hz for 0.1, 0.5, and 1 g accelerations respectively. At low accelerations < 0.5 g no sloshing of the liquid metal was observed, so the cantilever behaved as a linear energy harvester. This is due to the oxide skin formation on the Galinstan. Galinstan when exposed to air forms a native surface oxide that is about 1-3 nm thick, this oxide layer prevents the material from acting as a liquid (21). A surface stress of ~ 0.5 N/m is required to break through the skin and allow the material to flow as a liquid (23), so an acceleration that produces >0.5 N/m of surface stress was required to break the oxide formation. This occurred at a value of around 0.4 g for this application but depends on size and mass of the liquid metal. Therefore, this technique is valid for high accelerations, but if the accelerations are lower than the threshold to break the oxide skin then sloshing will not occur and the bandwidth will not be significantly increased. Preventing the oxide layer from forming could allow for increase in bandwidth with low acceleration. The oxxide layer of Galinstan can be prevented through the addition chemicals such asHCL or NaOH, as well as electrochemically (24)), or by preventing oxygen into the cavity by using vacuum sealing.

--Figure 3--

Duffing oscillators and commonly used non-linear resonators often have frequency sweep dependencies, which means that frequency sweeps up and down give different results. This impacts the practicality of the device as typical vibration sources do not sweep but instead have random vibrations. The liquid metal filled device was measured for both up and down sweeping and the results are shown in Fig. 4. This demonstrates that similar values were obtained for sweeping up and down, therefore the device is not dependent on frequency sweeping.

--Figure 4--

Damping effects are critical for vibrational cantilevers, and the mechanical damping properties were experimentally determined by applying an impulse square wave of 50 ms and 1 g acceleration. Then the voltage as a function of time was monitored and the damping was calculated based on the decay over a certain number of cycles. Fig. 5a compares damping of an air-filled mass and a water filled mass, because of the low density of water the damping of the two systems were similar with values of 0.067 and 0.066 for air and water respectively. The water and air devices had similar mass (within 10%) in order to keep the resonant frequency similar. Fig. 5b compares a metal (Aluminum) mass with exact same dimensions as the plexiglass mass to the liquid metal filled device. A metal mass was used in comparison to match the mass values to that of the liquid metal filled mass, so the resonant frequencies would be similar. The liquid metal mass with plexiglass was 55g as the metal mass with air filled cavity was 56 g. The results demonstrate that the metal mass had a mechanical damping ratio of 0.045 whereas the liquid metal mass had a damping ratio of 0.03. Fig. 5c compares the water filled mass with the liquid metal filled mass, which shows that the liquid metal mass has a lower damping ratio thus the decay in voltage is not as quick. This is important as some vibration sources are based on plucking or impulse, and if the duty cycle is low then a slower decaying energy harvester will have a higher average power (6, 25, 26).

--Figure 5--

Table 1 compares results from previous liquid filled mass papers and compares the results from this paper. The use of a denser liquid has resulted in an increased bandwidth without significant reduction of power. In addition, the damping ratio was lower, which is desired for impulse based vibration source.

--Table 1--

4. Conclusions

In summary, the paper presented a method of widening the bandwidth of a cantilever vibrational energy harvesting device using a liquid metal filled mass. The liquid metal mass demonstrated a significant increase in bandwidth compared to previous water-based liquid masses. The highly dense liquid metal represents a greater portion of the overall mass of the system compared to water-based devices, so any change in the center of gravity of the liquid metal mass causes a more significant change in resonant frequency resulting in a wider bandwidth. However, at low accelerations the liquid metal filled mass behaves like a traditional linear system as an oxide skin was formed on the liquid metal, but once enough force was applied to break the skin the liquid began to slosh, and the system increased its bandwidth. However, the oxide skin effects could be resolved by creating a vacuum in the chamber, which would prevent the formation of the oxide and allow sloshing at low accelerations. Unlike other non-linear systems (stoppers or duffing resonators) this system does not suffer from differences in up or down frequencies sweeps. In addition, the mechanical damping ratio is affected by the liquid metal which will be beneficial to impulse based vibrational sources with low duty cycles. The liquid filled mass is beneficial compared to other sphere or rolling pin designs as it can be implemented in macro or micro-scale vibrational energy harvesters.

Acknowledgements

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Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

Figure Captions:

Figure 1- Schematic of the vibration energy harvester device with custom mass filled with Galinstan (a) demonstrates the system when the device was at rest and the black circle represents the center of gravity of the cantilever, (b) demonstrates the system in motion where liquid metal creates a sloshing effect thus changing the center of gravity (black circle is the center of gravity during motion and the red circle was the initial center of gravity, (c) schematic demonstrating the center of gravity shift (d) is the experimental device setup with Galinstan filled mass, which demonstrates the sloshing effect.

Figure 2- Experimental results demonstrating the power generated as a function of normalized frequency for an air-filled mass with no change in center of gravity and a liquid metal (50% filled) mass with sloshing effects.

Figure 3- Demonstrates the logarithmic power scale as a function of normalized frequency for a liquid metal filled mass with varying acceleration.

Figure 4- Experimental results demonstrating an up and down sweep in frequency of a liquid metal mass as a function of power. Acceleration was 1 g in both cases and sweep rate was held constant. The results are an average over 5 different devices.

Figure 5- Experimental results of voltage as a function of time for various cantilever devices with an applied impulse (1g, 50 ms) masses. Masses were similar in all comparison cases. The results demonstrate the damping effects for (a) air filled vs water filled mass, (b) metal air filled mass and liquid metal filled mass, and (c) water filled mass and liquid metal filled mass.

Table 1- Summary of the results in this paper compared to previous reports of various liquid filled masses.

Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

Figures:

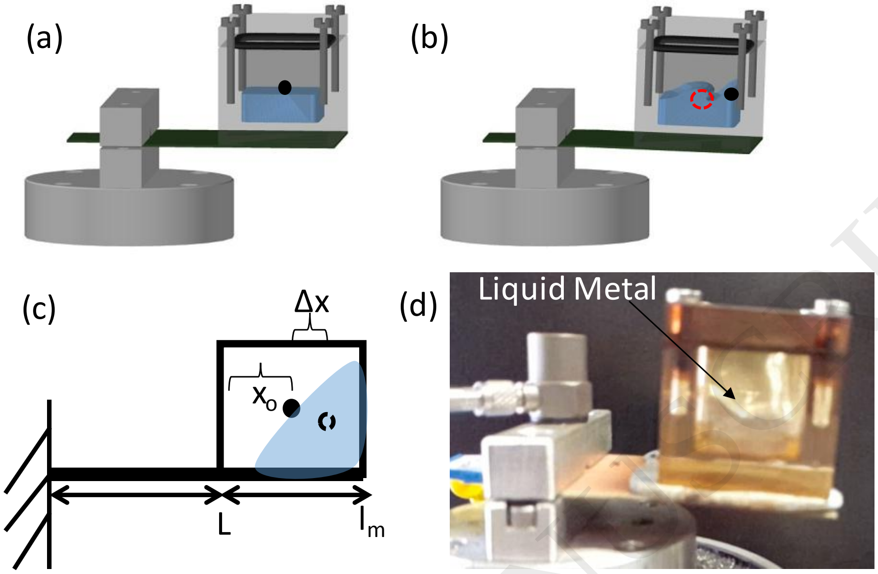
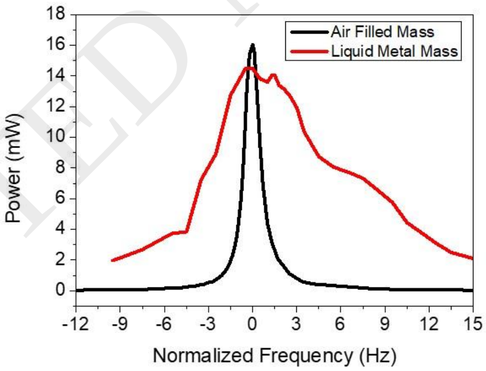


Figure 1



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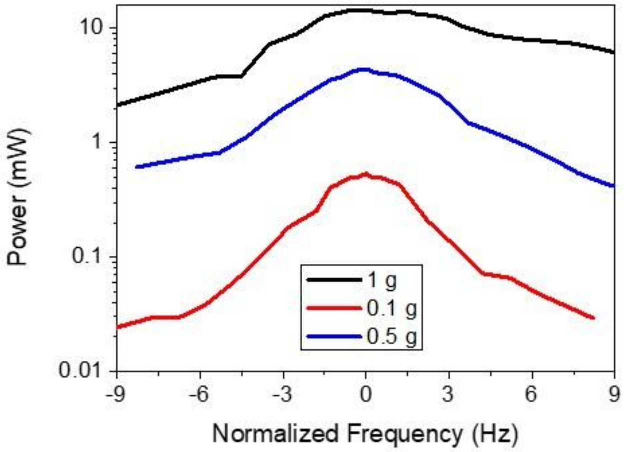

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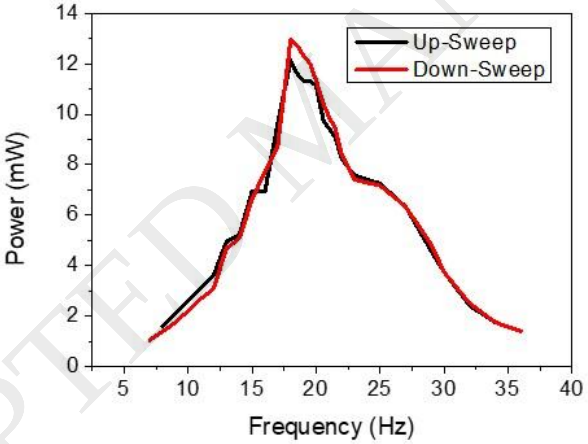

Figure 4

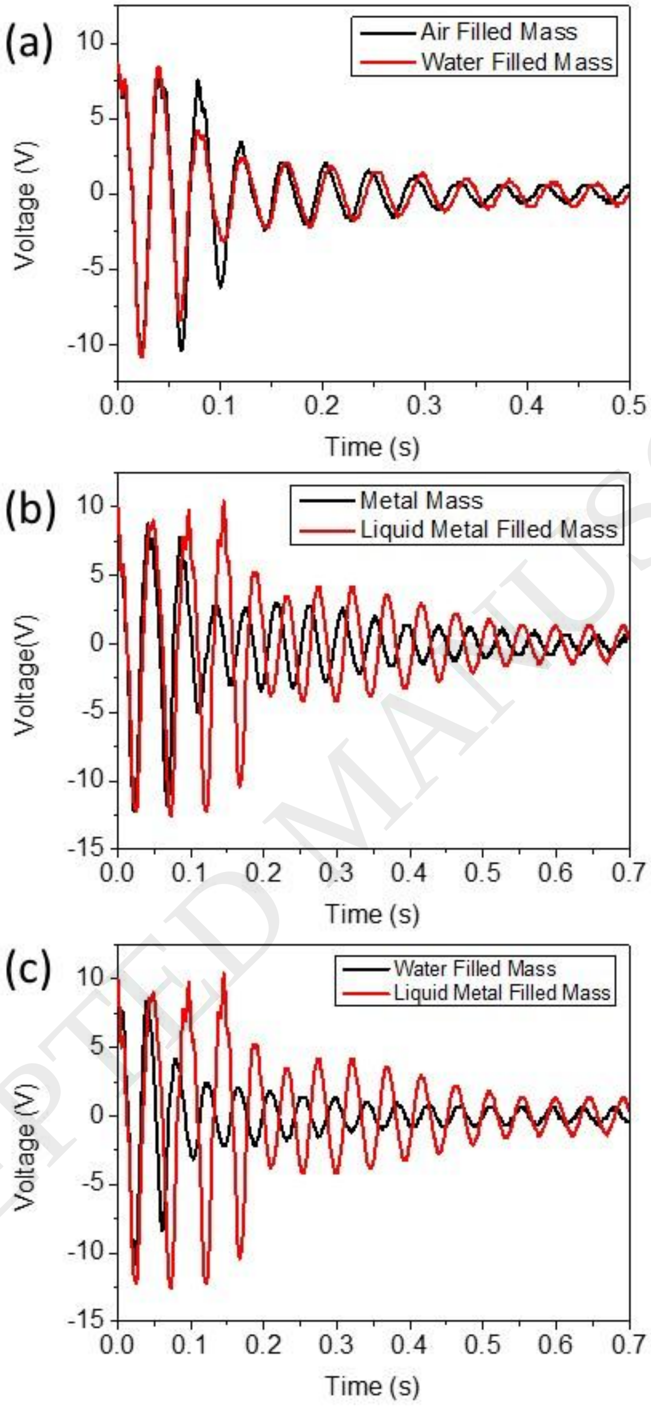
(a)
Air Filled Mass
Water Filled Mass
Voltage (V)
10
5
0
-5
-10
0.0
0.1
0.2
0.3
0.4
0.5
Time (s)
(b)
Metal Mass
Liquid Metal Filled Mass
Voltage(V)
10
5
0
-5
-10
-15
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time (s)
(c)
Water Filled Mass
Liquid Metal Filled Mass
Voltage (V)
10
5
0
-5
-10
-15
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time (s)

Figure 5

Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

Table 1

Work	Liquid	Acceleration (g)	Bandwidth (Hz)	Increase in BW (%)
Previous work (15)	Water	1	4.6	256
Previous work (14)	Dense Water	1	5.13	285
Previous work (14)	Glycerol	1	4.75	264
This Work	EGaIn	1	8.67	647

Sloshing liquid-metal mass for widening the bandwidth of a vibration energy harvester

Biographies:

Nathan Jackson received the B.S.E degree (*summa cum laude*) in bioengineering in 2003, the M.S degree in bioengineering in 2008 and Ph.D degree in bioengineering in 2009 all from Arizona State University, Arizona, USA. He then worked as a Senior Research Scientist in the Micro Nano System Centre at Tyndall National Institute, Cork, Ireland. He is now an Assistant Professor at the University of New Mexico in the Mechanical Engineering Department and head of the SMART Laboratory. His research interests include: Piezoelectrics, Smart Materials, MEMS, energy harvesters, acoustic resonators, BioMEMS, and flexible/stretchable circuits.

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Frank Stam received his MEngSc (Mechanical Engineering, 1989) from University of Twente, The Netherlands. He was a project engineer with Digital Equipment Corporation (DEC), Galway, Ireland (1989–1992), to develop microelectronics interconnection processes for mainframe computer systems. He joined the Tyndall National Institute, in Cork, Ireland (1992) where he became involved in metal and polymer-based interconnect material and joint characterization. Since 2001 he has applied his expertise to the development of biomedical microsystems.