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Dielectric Elastomers: Generator Mode Fundamentals and Applications

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ABSTRACT

Dielectric elastomers have shown great promise as actuator materials. Their advantages in converting mechanical to electrical energy in a generator mode are less well known. If a low voltage charge is placed on a stretched elastomer prior to contraction, the contraction works against the electrostatic field pressure and raises the voltage of the charge, thus generating electrical energy. The generator mode of operation has much in common with the actuator mode, but also has important differences. This paper discusses the fundamentals of dielectric elastomer generators, experimental verification of the phenomenon, practical issues, and potential applications. Acrylic elastomers have demonstrated an estimated 0.4 J/g specific energy density, greater than that of piezoelectric materials. Much higher energy densities, over 1 J/g, are predicted. Conversion efficiency can also be high, theoretically up to 80–90%; the paper discusses the operating conditions and materials required for high efficiency. Practical considerations may limit the specific outputs and efficiencies of dielectric elastomeric generators; tradeoffs between electronics and generator material performance are discussed. Lastly, the paper describes work on potential applications such as an ongoing effort to develop a boot generator based on dielectric elastomers, as well as other applications such as conventional power generators, backpack generators, and wave power applications.

1. INTRODUCTION

The high actuator performance recently demonstrated by various dielectric elastomers[1] has attracted much recent interest. Less well known is the fact that such materials can achieve good performance in a generator mode. Generator materials have many potential applications in energy production (e.g., coupled to engines or in wind or wave power), human-power (e.g., shoe and other human-power generators), and in harvesting available mechanical energy for low-power devices such as remote sensors. Dielectric elastomer (DE) materials offer distinct advantages for many of these applications, such as high energy densities, low cost, good impedance matching to many energy sources, and the ability to tailor properties and/or shapes to given applications.

Dielectric elastomer transducers consist of a relatively soft polymer, such as a silicone rubber, sandwiched between two compliant electrodes. Dielectric elastomers in the actuator mode convert electrical to mechanical energy because the electric field pressure acts to exert work on the material and load.[2] Electrically, the actuator mode brings opposite charges closer together and like charges further apart as the film contracts in thickness and expands in area. These changes reduce the stored electrical energy, and the difference is converted to mechanical work. The generator mode is basically the reverse of this process. Electrical charge is placed on the film in the stretched state. When the film is allowed to contract, the elastic stresses in the film work against the electric field pressure, thus increasing electrical energy. On a microscopic level, opposite charges are pushed farther apart at the film thickness increases, while like charges are compressed together as the film area contracts. Electrically, these changes raise the voltage of the charge. Figure 1 illustrates the basic mechanism.

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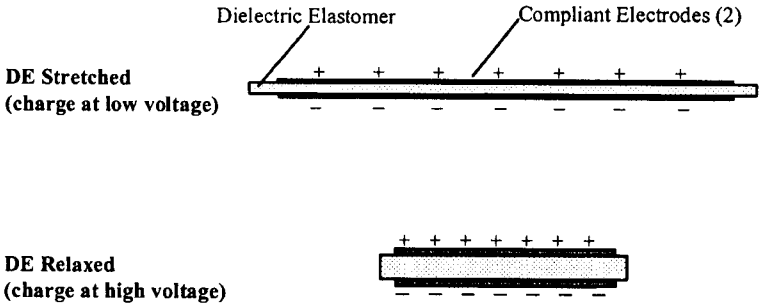


Figure 1. Basic mechanism of dielectric elastomer generator mode.

The focus of this paper is on dielectric elastomers, but many of the results reported here are valid for electrostrictive polymers.[3] The major difference is that with dielectric elastomers the dielectric constant is truly constant, whereas with electrostrictive polymers it may change depending on the polymer state, and the change needs to be taken into account.

2. THEORY AND EXPERIMENTS USING DIELECTRIC ELASTOMER GENERATORS

Dielectric elastomers act electrically like variable capacitors. The capacitance, C, can be expressed by the usual capacitance equation

$$C = \varepsilon \varepsilon_o A/z \tag{1}$$

where ε is the relative dielectric constant, ε_o is the permittivity of free space (8.85×10^{-12} F/m), A is the total area of the polymer film, and z is the thickness. Both A and z depend on the strain. Because they are elastomers, the volume of the polymer stays the same during stretching,* that is,

$$Az = \text{constant} = P$$

$$z = P/A \tag{2}$$

where P is the polymer volume.

The electric energy, e, on the film at any given moment can be calculated by the usual capacitor formulas, i.e.,

$$e = 0.5\, C\, V^2 = 0.5\, Q^2/C = 0.5\, Q\, V = 0.5\, Q^2\, P / (\varepsilon \varepsilon_o A^2) \tag{3}$$

$$V = Q/C = Q\, P / (\varepsilon \varepsilon_o A^2) \tag{4}$$

where V is the voltage, Q is the charge, and the last equalities in Equations 3 and 4 use Equations 1 and 2 to replace the capacitance in terms of the area.

The charge and energy on the film depend on electrical loading. One special case occurs if no charge is removed from the film during a contraction. In this case, we note from Equations 3 and 4 with constant Q that both the energy and the voltage vary as the inverse of the area, A, squared.

This constant charge condition on a contracting polymer can be relatively easily implemented and therefore can easily be used to compare theories and experiments. We can implement this condition by initially biasing the film with a bias voltage supplied through a diode, as shown in Figure 2. A drain resistor in parallel is chosen with a resistance high enough that negligible charge is drained during contraction. The drain resistor could be eliminated in the measurement, but some dielectric elastomers are such good insulators that the decay back to the bias voltage can take tens of seconds or more, an inconvenient amount of time to wait until the next experiment.

* The bulk modulus is much higher than the elastic modulus.

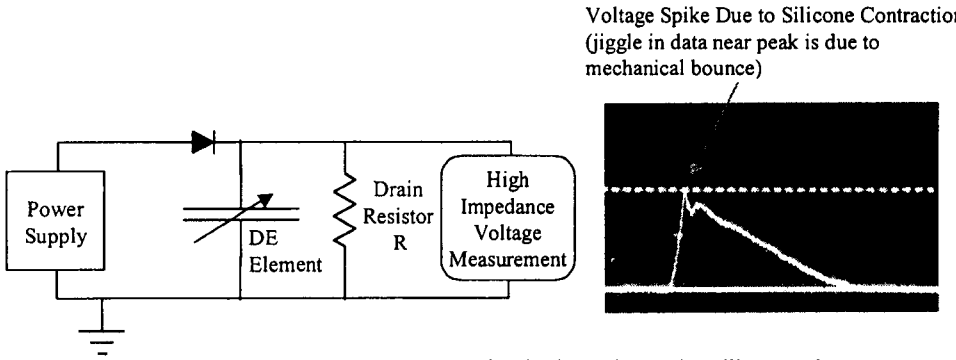


Figure 2. Measurement circuit and example of voltage data, using silicone polymers.

Equation 4 gives a clear experimental signature that can be compared with the data. Complications arise primarily from the difficulty of precisely determining A during stretching, since the change in A from stretching in one direction depends on the boundary conditions on the perpendicular planar direction. Other possible difficulties can arise from nonuniform electrode coverage at high strains, and from using too small a film capacitance for the instrument impedance. In spite of these experimental complications, Equation 4 has been verified to high accuracy in a number of cases. Figure 3 shows an example of the excellent agreement between theory and data, using a silicone film.

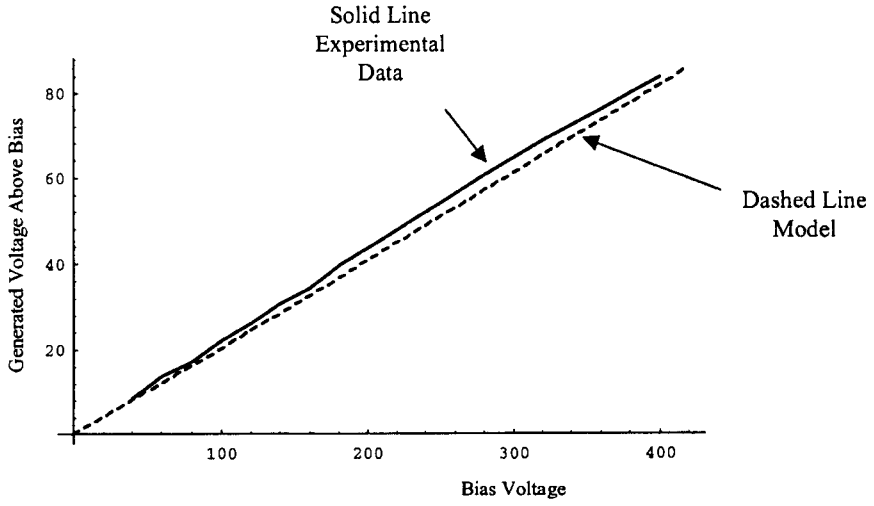
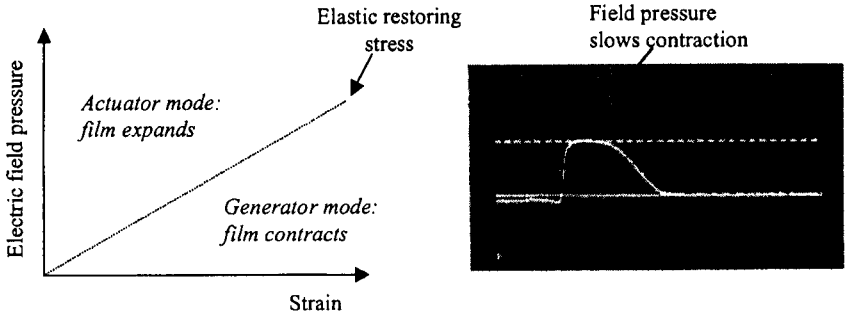


Figure 3. Example data showing good agreement between theory and experiment in a silicone film.

Equations 3 and 4 can also be used to estimate the electrical energy production from a contracting polymer film. The electrical energy initially placed on the film can be compared to the final electrical energy after contraction. This direct technique works for simple situations, but subtle factors can arise. The reader may have noted that both the actuator (film area expanding) and generator (film area contracting) modes involve charge being placed on the compliant electrodes. What determines which mode will actually take place for a given film and a given applied voltage or charge? The answer is that the film will contract if the field pressure is below the elastic restoring stresses (taking into account any applied mechanical load), and will expand when the field pressure is greater, as illustrated in Figure 4a. If we graph the field pressure versus strain, and plot the line of elastic restoring stress (shown for simplicity as a straight line in Figure 4a), then above the line the film will expand and act as an actuator, and below the stress line the film will contract and act as a generator. The film will maintain its existing strain state when the field pressure exactly balances the elastic stress along the line. Thus, when a film contracts and its voltage increases, a point can be reached where the field pressure increases, or the elastic stresses decrease, to a value where the two are equal. In this case the contraction ceases, and the film will not contract further until charge is removed.

We refer to the case where the field pressure equals the elastic restoring stress as the field-supported regime. The existence of this regime has been verified experimentally as illustrated in Figure 4b. Note that, in contrast to the sharp voltage peak in Figure 3 where full contraction occurs immediately, the voltage rise in Figure 4 has a very smooth peak, indicating that the field-supported regime has been reached and contraction only continues as charge is drained from the film.



(a) Field pressure vs. strain **(b) Data in field-supported regime**

Figure 4. The different transducer modes and the field-supported regime.

Let e_s and e_c be the stored electrical energy in the dielectric elastomer capacitor in the stretched and contracted states, respectively. A bias voltage V_b is applied in the stretched state, and the same voltage V_b is on the polymer capacitor in the contracted state after some amount of charge has drained through the drain resistor R. Let e_o be the energy dissipated through the drain resistor. The electrical energy generated by the polymer, e_g, is then $e_g = e_o + e_c - e_s$. If q is the charge that goes through the drain resistor, and Q_s and Q_c are the stretched and contracted charges on the film, then we have the following relationships:

$$q = Q_s - Q_c = \int [V(t)/R]dt \qquad (5)$$

$$e_c = 0.5\, V_b\, Q_c$$

$$e_s = 0.5\, V_b\, Q_s$$

$$e_o = \int [V(t)^2/R]dt$$

$$e_g = e_o + e_c - e_s = \int [V(t)^2/R]dt - 0.5 V_b q \qquad (6)$$

Thus, the generated energy e_g can be calculated numerically by means of Equations 5 and 6 with the measured voltage-time curve $V(t)$. This estimate assumes negligible leakage through the polymer, a condition that is generally satisfied as long as the time to return to the bias voltage is fast compared to the leakage time scales of the film.

Estimated energy densities of dielectric elastomers can be quite large compared with those of conventional generator materials such as piezoelectric and magnetic materials. With acrylic elastomer[1] we have demonstrated up to 0.4 J/g energy production,* compared to around 0.13 J/g for advanced single crystal ceramics,[4] using a material that is orders of magnitude lower in cost. (See Pelrine et al.[1] for descriptions of specific acrylic and silicone materials.) The comparison to electromagnetics is even more striking, where peak electromagnetic energy densities are around 0.04 J/g and densities are usually much lower.

Data on other dielectric elastomers is limited. We have measured up to 0.013 J/g, using silicone, but this was preliminary. The expected energy density is expected to be much higher, based on the breakdown strength and demonstrated actuator energy density of silicones up to about 0.75 J/g.[1]

* Note: the densities of DE materials are usually close to 1 g/cm3. Thus, the numbers given for specific energy and power densities are also valid for per-cubic-centimeter volume.

Generator power density is also a parameter of interest. An attractive feature of DE generator materials is that their higher energy densities allow good power densities at low frequencies of operation. The low frequencies can be attractive for better load coupling, eliminating transmissions, or quieter operation. At the high-frequency end of the spectrum, DE materials may be capable of very high power densities. Acrylic elastomers appear to be limited to perhaps 10–50 Hz operation by viscoelastic losses. Corresponding power densities should be in the range of 2–20 W/g, depending on the assumptions. Silicone materials typically have 5–20% viscoelastic losses and virtually no significant leakage losses above 0.1 Hz, so efficiencies of 80–90% may be feasible. Tests indicate that silicones have very flat response to well beyond 1 kHz in actuator tests.[4,5] Even the few energy density tests to date suggest that 13 W/g at 1 kHz is feasible, and theoretical numbers described below suggest that the ultimate performance of silicone could be over 1000 W/g at 1 kHz. These extraordinarily high theoretical power densities at 1 kHz have not been demonstrated or attempted. Nonetheless, they serve to illustrate the potential of the technology.

The maximum theoretical energy densities of various polymers can be estimated on the basis of various assumptions about the limiting factors. The simplest estimates can be made by using Equations 1 – 4 to express the energy difference between contracted and stored states as (constant charge)

$$e = 0.5\ C\ V^2 = 0.5\ \{(\varepsilon\ \varepsilon_o\ A^2)/P\}\ V^2 = 0.5\ P\ (\varepsilon\ \varepsilon_o)\ (V/z)^2 \qquad (7)$$

$$e_c - e_s = 0.5\ P\ (\varepsilon\ \varepsilon_o)\ \{E_c^2 - E_s^2\} \qquad (8)$$

$$= 0.5\ P\ (\varepsilon\ \varepsilon_o)\ E_c^2 \qquad \text{(large strain approximation)} \qquad (9)$$

where $E = V/z$ is just the electric field and the subscripts s and c denote the stretched and contracted states, respectively. The simplification for large strains in Equation 9 can be easily satisfied for most dielectric elastomers, since the field squared in the constant charge case varies as the inverse of the area squared. Most polymers of interest can easily achieve changes in area by a factor of 2, and many, such as certain acrylic and silicone elastomers, can achieve changes in area by factors of up to 50.

We see from Equation 9 that a simple estimate of the generated energy density can be made from the maximum dielectric breakdown strength. Breakdown strengths as high as 350 MV/m have been recorded for some silicones.[1] From this number, one could predict generator energy densities of up to around 1.5 MJ/m^3, or 1.5 J/g should be feasible with these materials.

The above analysis is simplified in two respects. First, it assumes that the polymer actually contracts to produce the desired maximum field strength. As noted above, this will not happen if the material enters the field-supported regime before reaching the maximum field strength. For theoretical estimates this is not a significant restriction, since it means that the polymer will contract only to a state with some finite strain rather than all the way back to a zero strain state. A more significant simplification, using Equation 9, is that the constant charge case has a low field pressure at the beginning of the contraction and a high one at the end, i.e., the field pressure does not match the elastic stress for maximum material performance. A slightly more sophisticated analysis can address these two assumptions.

Figure 5 shows a graph of a charging cycle for a dielectric elastomer that will give maximum theoretical performance under the assumption of constant modulus and constant dielectric breakdown strength. The charging cycle is as follows. On path 1-2, the film is stretched with zero charge. On path 2-3, charge is placed on the film up to the breakdown strength. On path 3-4, the film is allowed to contract but charge is removed from it to hold the electric field at the breakdown strength. At point 4, the film has reached the field-supported regime, and charge is gradually removed on path 4-1 to return it to its zero charge, zero strain starting state at point 1.

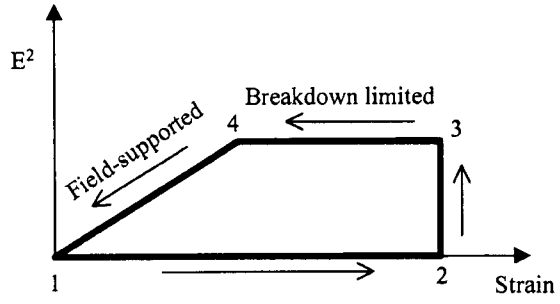


Figure 5. Theoretical optimal charging cycle.

The theoretical cycle in Figure 5 can, in principle, give even higher energy densities than those indicated by Equation 9. One can analyze the optimal cycle to derive higher predicted energy densities, but the analysis is fairly complex and in practice the assumptions of constant breakdown strength and constant modulus are unlikely to hold for many polymers over their large range of strains. This cycle does, however, indicate the important features of more practical charging cycles such as the field-supported regime and the breakdown-limited regime. In this sense the optimal cycle is analogous to the Carnot cycle in thermodynamics, in that it is useful for analyzing systems but it is not generally considered a practical cycle.

3. PRACTICAL CONSIDERATIONS FOR DIELECTRIC ELASTOMER GENERATORS

The optimal cycle in Figure 5 is unattractive for reasons that go beyond the fundamental dielectric elastomer properties. Ultimately, any charging cycle for dielectric elastomers involves putting charge on the film and taking it off at different times for a net electrical energy gain. The cycle in Figure 5 assumes that all the charge is taken off the film at point 1, at which point the voltage difference across the film is zero. The voltage reaches its maximum value at point 4, where the field times the film thickness is highest. Thus, the electronics must be able to efficiently handle the maximum voltage swing of the material. Electronics in general, and transistors in particular, are generally most efficient with small voltage swings. Thus, most, though not all, electronics for dielectric elastomers are intended to limit the voltage swing to some fraction of the maximum possible swing, and leave some charge on the film during stretching. Note, however, that charge on the film during stretching is lowered in voltage because the material is acting in an actuator mode to convert electrical to mechanical energy. It is therefore desirable to remove as much charge as possible prior to or during stretching, to maintain a high level of net mechanical-to-electrical conversion. The competing aims of efficient electronics and maximum generator output for the given amount of material must be balanced in the overall generator design.

Dielectric elastomers, in common with piezoelectrics and electrostatic transducers, generally need relatively high voltage. Good actuator performance has been demonstrated down to 100–300 V, but films that operate at those voltage levels are typically very thin and yields are an issue for all but the smallest devices. More typically, dielectric elastomers use 1–6 kV. At these voltages, the film thickness is high enough for easy handling and good yields. Prestrained acrylic film is typically 50 μm thick and is quite easy to handle.

The relatively high voltages of dielectric elastomers requires careful consideration of the electronic design. Generally speaking, the electronic designs are similar to well-known circuits employing buck or boost configurations with inductors, and/or transformer circuits for high efficiency manipulation of the charge or step-down to lower voltages for power use. The high voltages do, however, mean that components must be selected to handle the voltage. Inductors and transformers can handle very high voltages with suitable winding insulation and layout.

High-voltage transistors are more limited. Transistors with ratings of 2.5 kV are now commercially available. These transistors are typically rated at much higher currents and power than are needed for the current state of dielectric elastomer technology. While oversize transistors can be used, they have an undesirably high capacitance that forces the electronic design to operate at low frequencies with larger magnetic components, or at high frequencies with large switching losses. Fortunately, discussions with the semiconductor industry indicate that the absence of low-power, high-voltage transistors above about 600 V appears to be more a market than a technology limitation. That is, if a sufficiently large market for low-power, high-voltage transistors is demonstrated, current semiconductor technology can, with some engineering development, produce the needed transistors.

Specific dielectric elastomer generator applications are discussed in more detail in the next section. Here we note that practical applications require a specific range of temperature and lifetime performance. Data on these properties of dielectric elastomers is currently limited, even more so for the generator mode compared to the actuator mode. Silicone actuators have been operated for 10,000,000 cycles in older, low strain tests. Acrylic materials are newer but have been demonstrated at the 100,000 cycle level with > 20% actuation strains. Generator lifetime tests are planned but data is not yet available. In general, we would expect generator lifetime and environmental performance to be similar to performance in the actuator mode.

4. APPLICATIONS

There are many potential generator applications for dielectric elastomers. Some might be regarded as niche applications, while others are major applications. Table 1 lists some potential applications along with the potential advantages and disadvantages of the competing technologies. This table assumes that dielectric elastomer generator technology matures to demonstrate good lifetimes and reasonable environmental tolerances.

Table 1. Potential applications of dielectric elastomer generator technology.

Generator Application	Competing Technology	DE Potential Advantage	DE Potential Disadvantage	Comments
Engine-driven generators	Electromagnetics	Higher energy density, lower cost, good low speed performance, higher temperature performance	Electronic cost and weight (very small engines)	Electronics are probably not an issue for large engine applications
Shoe generators	Electromagnetics, Piezoelectrics	Low cost, good load matching eliminates much mechanical complexity; lightweight; high energy density	Electronics more complex than electromagnetics	Demonstrated 0.28 J energy/stroke generation in heel-size device (not including electronics)
Parasitic energy harvesting for remote sensors	Electromagnetics, piezoelectrics	Good load matching to some available energy sources enables simpler designs; lower cost	Electronic cost an issue for some applications	Remote sensing can eliminate wires and potentially reduce cost for a number of applications, but power sources are currently limited
Wave energy	Electromagnetics	Good matching to load; low cost materials	Water compatibility unresolved	Water compatibility can probably be achieved with protective layers

Considering Table 1, we see a number of recurring advantages and disadvantages for DE generator technology that indicate both fundamental capabilities to exploit and needed development to address current shortcomings. Dielectric elastomers have fundamental advantages for almost all applications listed, in terms of better load matching. The competitive technology is typically electromagnetics, but electromagnetic generators perform poorly at slow speeds. This means one must add gearing to increase the generator speed, thus increasing generator cost, weight, and noise. Dielectric elastomers also have a large potential advantage in terms of using lower-cost materials. The extent to which this advantage can be exploited depends to a large extent on the application. For larger-scale applications, electronic cost is less likely to be an issue, particularly since many larger-scale applications need voltages above 100 V, and some need 500 V or higher. In this case, the electronics will be switching moderate to high voltage, no matter how the generator material operates. For smaller-scale applications, the added electronic cost may be a significant disadvantage. How serious a disadvantage it will be depends to large extent on circuit and component developments, and how the electronic issue is perceived by device manufacturers. We note, however, that successful low–medium power, high-voltage devices are already being used in widespread applications. Examples include fluorescent lights, conventional cathode ray tube monitors, room ionizers for particle filtering, and electrostatic speakers.

Practical designs of DE generator applications are illustrated by shoe generators, where much of our work has been focused. A shoe generator uses the mechanical energy from walking to generate portable electricity. Most of the energy from walking is dissipated during the heel strike, so shoe generators generally are located in the heel. Heel-strike generators using electromagnetics and piezoelectrics have been investigated in the past.[6] Typical reported energies generated with these materials are around 10 mJ/stroke, but it is straightforward to calculate that much higher energies of 1–5 J/stroke should be feasible if more of the energy of the heel strike is converted to electrical energy. One can easily derive this number by noting that displacements of 2–4 mm are seen in heels; slightly higher values might be acceptable. An average person's weight produces 500–1000 N, leading to available energy estimates of around 1–4 J, obtained by multiplying the weight by the displacement. A more detailed analysis would take into account factors such as the need to return some mechanical energy elastically for shoe comfort (which reduces the available energy) as well as the dynamic forces that are higher than the person's weight (which increase the available energy).

This application is a good illustration of the advantages of dielectric elastomer generators. Walking frequencies are typically around 1 step/s, which is too low a frequency to efficiently convert by using electromagnetics with a direct coupling to the load. Hence, an electromagnetic approach is forced to use transmissions to convert the 1 Hz input to a higher frequency, adding cost and complexity to the device. Similarly, piezoelectrics typically couple well at strains below 1%, so piezoelectric approaches typically must use devices to convert the large-displacement, low-force load into a smaller-displacement, higher-force load on the piezoelectric element. Alternatively, the piezoelectric approach can use transmissions analogous to those used for electromagnetics, with a smaller piezoelectric element operating at high frequencies. In any case, the competing approaches involve additional mechanical complexity and cost, quite apart from energy density, material cost, and weight performance.

In contrast to these approaches, dielectric elastomer can directly couple to the heel-strike load. A displacement of 2–6 mm can easily drive a polymer to 50–100% area strain, depending on the configuration. With an energy density of roughly 0.2 J/g in a practical device, one needs only 5 g of polymer, a negligible fraction of the weight of a heel.

Figure 6 shows the output from a multilayer acrylic elastomer in a heel-size generator device. The device uses a diaphragm arrangement to stretch DE diaphragms upon heel strike. Note that the output has reached the field-supported regime, indicating good mechanical-to-electrical conversion. Output from the device is up to 0.28 J. We expect to test higher energy output devices above 1 J in the near future by increasing the number of polymer layers.

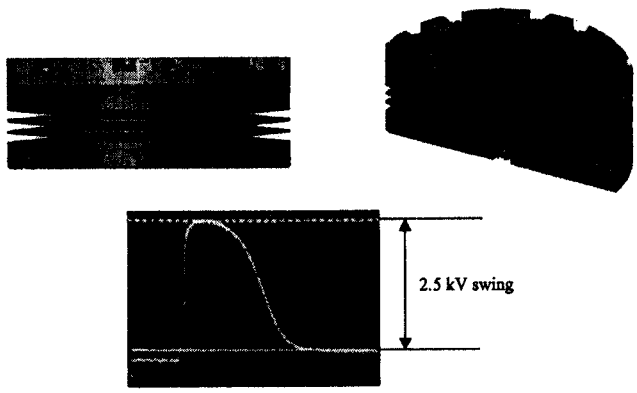


Figure 6. Heel generator drawing and data.

Shoe generator testing is reaching useful levels of power for a number of portable applications. Other human-powered applications are also well addressed by dielectric elastomers, for technical reasons and because the applications cannot support the cost of a complex, expensive device.

5. SUMMARY

Dielectric elastomers are a promising new generator material, in addition to their better-known potential as actuators. Investigations into the use of DE materials as generators are less mature than corresponding investigations into their use as actuators. Nonetheless, very good generator performance up to 0.4 J/g electrical output has been demonstrated, and theoretical calculations indicate that up to 1.5 J/g or greater should be feasible. Many applications for high-performance generator materials exist, including engine-generators, shoe generators, and wave and wind generators. The low cost of DE materials is promising for their applications, but more development of DE electronics is needed before we know how they will compare to competitive approaches in smaller, cost-sensitive applications. Further work is also needed to show good lifetime and environmental tolerances with these materials.

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