Chapter 36
Elastomer Transducers

Mikio Waki and Seiki Chiba

Abstract Dielectric elastomers, transducers that couple the deformation of a rubbery polymer film to an applied electric field, show particular promise with features such as simple fabrication in a variety of size scales, high strain and energy density, high efficiency and fast speed of response, and inherent flexibility, environmental tolerance, and ruggedness. A variety of actuator configurations has been demonstrated at various size scales including rolled "artificial muscle" actuators, framed and bending beam actuators for efficient opto-mechanical switches, and diaphragm and thickness-mode actuators for new types of motors, pumps, and valves. The performance benefits of dielectric elastomers can allow for new generations of devices in microrobotics, communications, biotechnology, aeronautics, and aerospace.

Dielectric elastomer has also been shown to operate in reverse as a generator. It has several characteristics, making it potentially well suited for power takeoff systems using wave, water current, wind, human motion, etc.

Keywords Artificial muscles · Generators · Sensors · Actuators · Electroactive polymers · EAP

36.1 Introduction

The human passes through the Iron Age from the Stone Age and has got into a plastic (polymer) century in the twenty-first century. Engineering stories developed in the SF world are approaching the day to realize it, using electroactive polymers that can obtain strain due to electric field or generate pressure. In the very near future, those

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who have obstacle due to accidents might be expected to be able to perform superior to that of ordinary people. Likewise, it seems that the day automobiles will run on EAP will be coming soon. It is also thought that EAP preventing the collapse of buildings due to earthquakes will also appear on the market.

We will discuss possible applications of DE actuators, DE sensors, and DE generators in this chapter.

36.2 Background on DE Transducers

DE transducers are a new transducer technology that began an investigation by SRI International (R. Perline, S. Chiba et al.) in 1991 [1].

DE transducers that couple the deformation of a rubbery polymer film to an applied electric field show particular promise with features such as simple fabrication in a variety of size scales (from micro to several meter scale), high strain (up 600%) and energy density of 1 W/g (for comparison, electric motor with gearbox is 0.05 W/g), high efficiency (80–90%) and fast speed of response (over 100 kHz), and inherent flexibility, environmental tolerance, and ruggedness [2–4] (see the detail of the principle in Chap. 14: "Dielectric Elastomers").

As shown in Fig. 36.1 [3–6], DE technology occupies a unique performance space for actuation, giving much higher actuation pressure/densities than electrostatic and electromagnetic actuation and much higher strains than piezoelectric and magnetostrictive actuation. It also is interesting to note that DE stress-strain performance is comparable to that of natural muscle. Hence the name "artificial muscle" is an appropriate description for DE technology.

DE transducers have moved from the research and development stage to the commercial domain with research and development on practical applications and furthermore to the mass production stage.

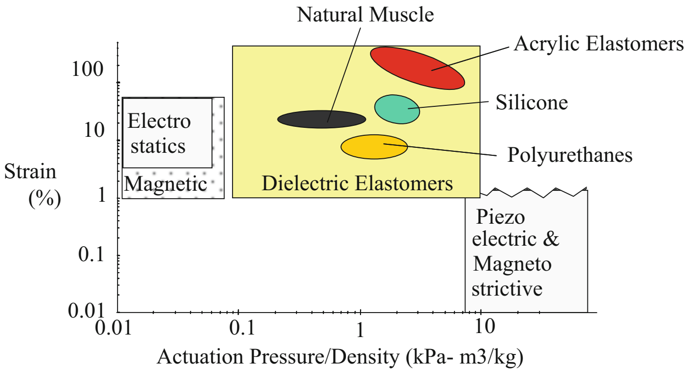


Fig. 36.1 Performance comparison of existing fast actuator technology, natural muscle, and DE [4]

36.3 DE Actuators and DE Sensors

As elastomers are light and deform like rubbers, they can show flexible movements like bionic actions. They can express “flexible and natural feeling” which systems with motors cannot imitate.

In addition to the above, DE actuators do not use any gears and cams, thus enabling high efficiency and safe and smooth driving even if the speed or direction of movement is suddenly changed.

36.3.1 Application of Robots (Includes Care and Rehabilitation Purposes) and Sensors

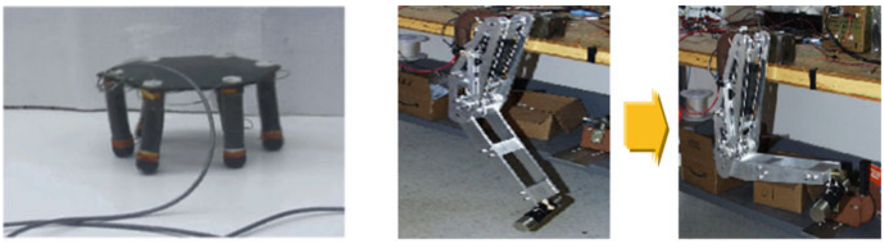
A wide array of proof-of-principle devices (see Photo 36.1) for use in leg robots, swimming robots, snakelike robots, compact inspection robots, gecko-like robots for climbing up perpendicular walls or across ceilings, and flying robots as well as in achieving compatibility with living organisms are currently developed [2, 7, 8].

The leg robot is particularly unique [7–10]. It has role actuators having 3-DOF, as shown in Fig. 36.2 [7, 8], so it enables sideways stepping like a crab without turning around, when it collides with the wall.

In the near future, the DE technology will be applied to robots for medical treatments, rescue, care, personal use, and industrial purposes..

We have already noted that DE actuators are also intrinsically position or strain sensors in Chap. 14, “Dielectric Elastomers,” since there is a direct proportionality between the change in the capacitance and elongation of DE actuators. As sensors, DEs can be used in all of the same configurations as actuators, as well as generators 3, [8–10]. In the near future, therefore, smart shape robots or care equipments shown in SF movies may appear.

The ribbon-form actuators having a sensor function can be used to measure force or pressure as well as motion at the same time [3]. This actuator can assist human motion. At the same time, it can work as motion feedback sensor [3, 4, 10]. We hope



Leg robot

Robot arm

Photo 36.1 Biologically inspired robots powered by DE rolls [2, 7]

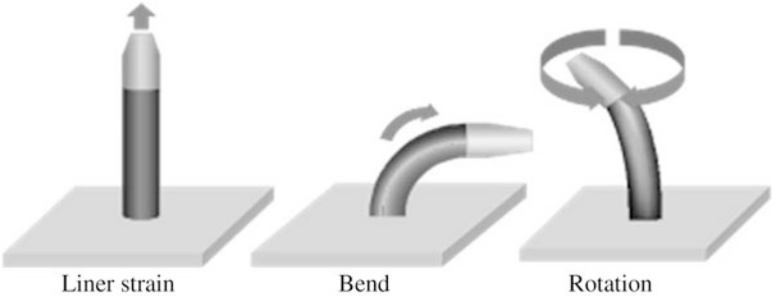


Fig. 36.2 Role actuator having 3-DOF

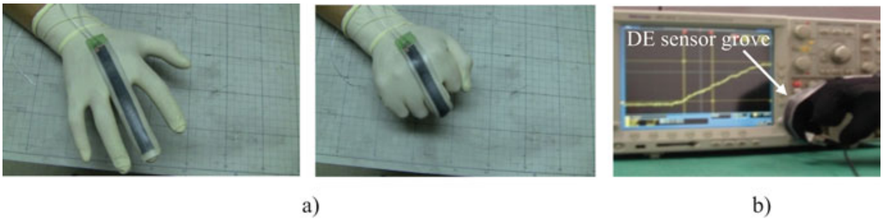


Photo 36.2 Ribbon-form actuators and DE sensor groves for rehabilitation purposes [3, 4, 10]. (**a**) Ribbon-form actuators. (**b**) DE sensor grove

that it may be useful for smart rehabilitation equipments for hands, legs, and fingers. Such equipments may be used to evaluate a recovery situation exactly. Photo 36.2 shows ribbon-form actuators and sensor groves for rehabilitation purposes [3, 4, 10].

36.3.2 Application to Audio Equipment

DE has a very wide frequency range, from DC to 100 kHz, far beyond the audible range. Applications using the wide frequency of the DE include musical instruments, acoustic equipment, and vibration devices. The operation principle of the DE as a loudspeaker is very simple. The sound signal is superimposed on a DC bias voltage, and the resulting voltage signal is applied across the electrodes of the DE. As the displacement of the DE can follow the temporal variation of the signals, sounds can be reproduced. There are several possible methods for the sound reproduction. Indeed, loudspeakers based on DE have already been demonstrated [3, 4, 11]. Here we describe a method using dipole speakers. This method has a very simple structure and effective performance.

Figure 36.3 shows a dipole speaker that has two opposed diaphragms located symmetrically about a central plane. The diaphragms can be operated in push-pull

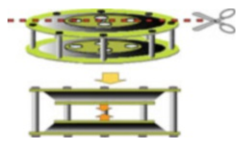


Fig. 36.3 Dipole speaker [3, 4]

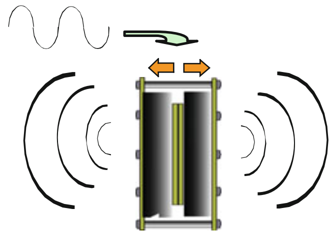


Fig. 36.4 Operations image of dipole speaker [3, 4]

mode. Figure 36.4 shows how the voltage signal (comprised of the audible signal superimposed on the DC bias) can be used to drive the DE to produce sound.

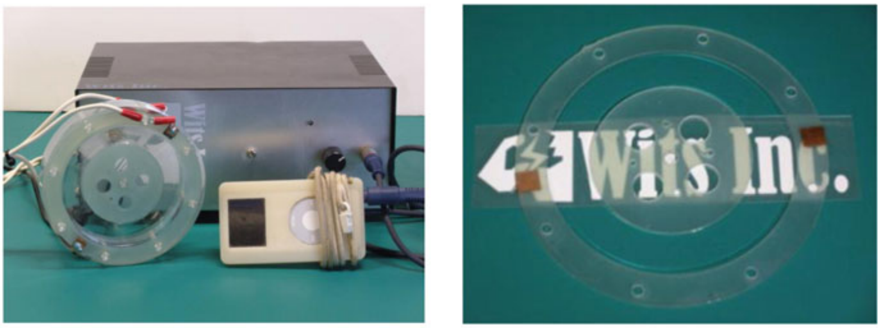
A prototype of the dipole speaker made by Wits Inc. (Tochigi, Japan) uses DE cartridges (diaphragm with frame shown in Fig. 36.3). The outer diameter of the diaphragm is 100 mm and the inner diameter is 50 mm. The bias voltage and the maximum of the input signals are set to be 2 kV and 1 kV_{p-p}, respectively.

The performance of this DE speaker was evaluated in the anechoic chamber of the Science and Technical Research Laboratories of Japan Broadcasting Corporation [11]. The loudspeaker was found to have moderately satisfactory frequency response from 0.5 kHz to more than 10 kHz (about 15 dB variation in SPL measured at 50 cm). The directionality of the speaker shows a significant difference between back-and-forth and right-and-left, confirming its expected desirable performance as a dipole speaker.

The harmonic distortion components are very small over the wide frequency range. This is another desirable feature of a DE dipole speaker. We believe that the performance of DE dipole speakers can be further improved by refining the design. We are currently evaluating the performance of the speaker mounted in enclosures and planning to evaluate next-generation speaker designs including spherical ones.

The DE cartridge used in the loudspeakers is thin and lightweight. When two pieces of the cartridge are used, the driving force that can be generated is up to 4 N. Thus, applications such as in sound insulation and vibration proofing, which use these cartridges as vibrators, also have been investigated [12]. Such application devices enable sound insulation and vibration proofing in the following manner. Actual vibrations and noise are detected by microphones or vibration pickups and converted into electric signals. Then, signals for canceling the electric signals are created and applied to the DE vibrators. The DE vibrators can act on the outer walls of buildings, the frames of equipment, and car bodies to counteract their vibrations or noise. In simple experiments with cars, it has been confirmed that sonic pressures larger than 50 dB can be reduced in a low-frequency region (100–300 Hz) by setting up a DE vibrator in the roof of the car.

Photo 36.3 DE cartridge (left); DE stereo speaker system (right) [4, 13]



a) b)

Photo 36.4 DE transparent dipole speaker using transparent electrodes [3, 10]. (**a**) Transparent diaphragm speakers. (**b**) Transparent DE cartridge

Since DE is a rubberlike film, it is lightweight and its shape can be easily changed. Thus, a DE loudspeaker could be made to conform to almost any shape or surface contour. DE loudspeakers might be incorporated in housing, cars, industrial machines, and electric home appliances. Photo 36.3 shows how a DE dipole speaker might be used as a home stereo system [4, 13].

Recently, we have developed DE transparent dipole speakers, as shown in Photo 36.4 [3, 10].

36.3.3 Other Applications

Many other applications have been identified and, in some cases, investigated including:

- Variable texture surfaces for fluid flow control, displays, and other novel applications such as smart skin [4, 9, 15].
- Control and propeller devices for Mars airplanes [16]

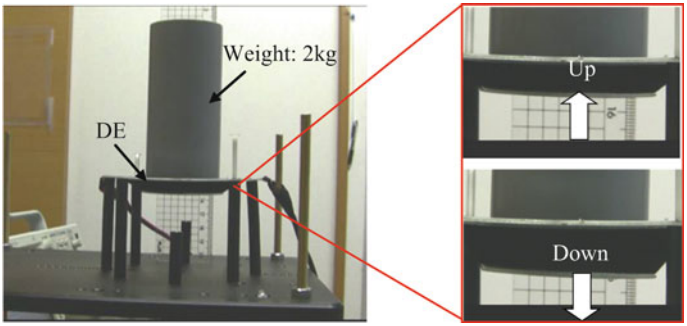


Photo 36.5 DE lifted the weight of 2.0 kg using carbon system electrodes [3].

- Micro-nano devices such as inkjets, microfluidics, valves, pumps, switches, sensors, and motor and micro generators [4, 9, 14, 15, 17].
- Micro-nano robots [14, 15, 17].

Airplanes are paid attention as a new platform for Mars exploration [18]. The Mars airplane must be lightweight to fly using aerodynamic forces in the rarefied Martian atmosphere. Therefore lightweight and high-power actuators are required for the Mars airplane. The advantages of the DE actuators are beneficial for the Mars airplane. The DE actuators have a possibility to be used as actuators for control surfaces (i.e., ailerons, rudder, and elevator), payloads, and a propeller of the Mars airplane. We investigated a feasibility of the DE actuators for the Mars airplane. A structural model of a wing and a control surface with a DE actuator was built. A chord length of the wing was 160 mm, including the control surface of 55 mm. A ϕ80 mm, diaphragm-shaped DE of 0.1 g was used with a bias voltage of 2.7 kV. The dynamic characteristics of the structural model were measured. The DE actuator generated a moment of 0.13 kgf·cm on the hinge of the control surface through a linkage. A roll-type, high-power, carbon-nanofiber DE actuator will be tested in the near future.

We also note our recent progress that a DE actuator having only 0.1 g of DE lifted the weight of 2.0 kg using carbon system electrodes [3] (see Photo 36.5).

36.4 Application of DE Generation Devices

Another working mode of the DE artificial muscle is the power generation mode [3, 6]. This is operatively the opposite of the actuator function. Application of mechanical energy to DE to stretch it causes compression in thickness and expansion of the surface area. At this moment, electrostatic energy is produced and stored on the polymer as electric charge. When the mechanical energy decreases, the recovery force of the dielectric elastomer acts to restore the original thickness and to decrease the in-plane area. At this time, the electric charge is pushed out to the electrode

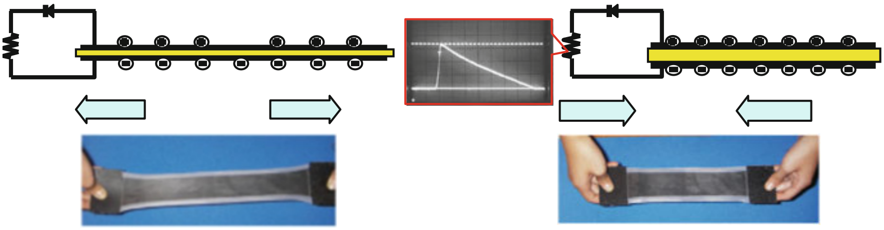


Fig. 36.5 Operating principle of DE power generation [4]

direction. This change in electric charge increases the voltage difference, resulting in an increase of electrostatic energy (see the detail in Chap. 14: "Dielectric Elastomers").

Figure 36.5 shows the operating principle of DE power generation [6].

DE can be used for traditional generator applications as a direct replacement for electromagnetic generators. One can, for example, connect a DE generator to an internal combustion engine to make a fuel-powered generator. For these traditional generator applications, DE may offer lower cost, lighter weight, smaller size, or other advantages [19]. However, it must be acknowledged that for these traditional high-frequency applications, DE is a new technology competing against a mature technology that is well suited for the task. Hence, while DE may eventually become competitive in traditional high-speed generator applications, other uses for both point and distributed generators may better exploit the advantages of DE in the nearer term (see the detail in Chap. 14: "Dielectric Elastomers").

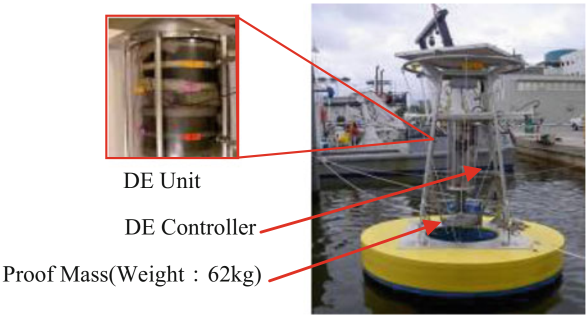
For point generator applications, DE is much more competitive if the mechanical input is intrinsically at low frequency or variable speed. For these applications, conventional generators must use transmissions with their added cost, complexity, and size, thus making DE more competitive in the low-frequency domain. Linear, as opposed to rotary motion, also favors DE.

Since this power generation phenomenon is not dependent on the speed of transformation, its power generation device can generate electric energy by utilizing natural energies such as up-and-down motions of waves, slowly flowing river water, human and animal movements, and vibration energies produced from vehicles and buildings [4, 6, 12, 20].

36.4.1 DE Wave Generation

In the spring of 2006, the first prototype for a wave power generator using DE was developed and tested in a tank having dimensions of 1.5 m width, 1.2 m depth, and 20 m length. Two DE sheets of 58 cm × 20 cm (total weight 40 g) were set at the center of the tank. A wave of 12 cm in height occurring every 3 s generated 1.8 W

Photo 36.6 DE generator system on the buoy used in December 2007



(one wave's energy is 5.4 J) of electricity. The conversion efficiency (the ratio of generated energy to applied force) is approximately 46% [21].

In August 2007 in Tampa Bay, Florida, USA, we carried out the world's first marine experiment into power generation by natural sea waves using a power generator having 150 g of DE [6]. The maximum measured electrical output capacity, verified in laboratory tests, was 12 J per stroke for the generator. However, wave activity was minimal during the test period. Wave heights were on the order of few centimeters, which made it very difficult to carry out tests for wave-powered generators. On occasion the weather generated waves 10 centimeters high. Even with the wave height of 10 centimeters, we were able to generate a peak power of 3.6 J at a bias voltage of 2000 V (see Photo 36.6).

The generator uses a proof mass to provide the mechanical forces that stretch and contract the DE, as shown in Photo 36.6 [6, 7].

Based on data from laboratory testing, we estimated that the energy conversion efficiency of DE generator is 70–75% (not including hydrodynamic losses).

We should note that these measurements were made with a small bias voltage of 2000 V applied to the DEs. By simply raising the applied voltage to 6000 V, we can estimate that a peak power of 11 W and an average power of 2.2 W could have been generated under these same small wave conditions [19].

In December 2008, oceanic tests were also carried out in California, USA, and it was confirmed that generated electric power was constantly stored in a battery [19].

Recently, Moretti et al. [22], Vertechy et al. [23], and Chiba et.al [24] also showed that one of the most promising applications for DE generators was in the field of wave energy harvesting.

An estimate based on data from our sea trial demonstration experiments has shown that even in seas where the wave height is only 1 m throughout the year (e.g., the sea close to Japan), if there are spaces of approximately 400 m in length and 60 m in width, the establishment of a sea-based facility generating 8.5 MW of power is possible [25]. Figure 36.6 shows the conceptual rendering of the DE wave power generator system [26].

The power generation efficiency estimated on the basis of the data obtained from our experiments is approximately 19 US cents/kWh [19]. In the near future, we expect that the electric power generation per unit mass or volume of DE material can

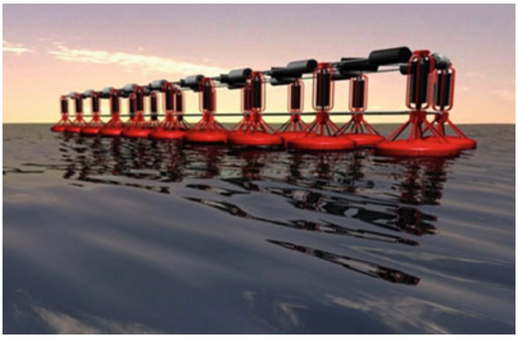


Fig. 36.6 Conceptual rendering of DE wave power generator system

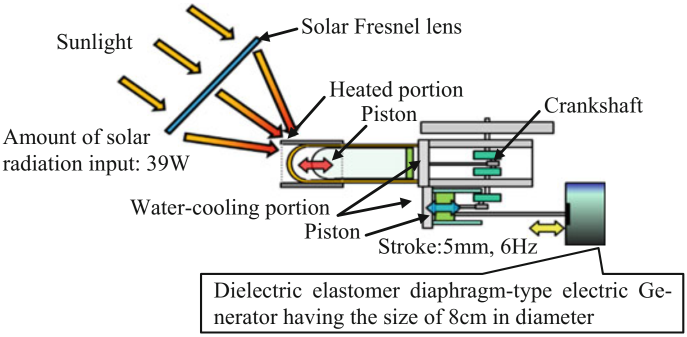


Fig. 36.7 DE solar heat generator: Fresnel lens having the effective size of 1000 mm × 1350 mm and thickness of 3 mm. The capacity of the tube was about 44 cm^3. The piston stroke was 24 mm, and the diameter of the piston was 25 mm [27]

double and that the expected power generation cost per kilowatt-hour is 5–7.5 US cents [19]. This value is comparable to that for fossil fuel thermal power plants. Of course, the wave power systems have the additional benefit of not releasing any pollution or greenhouse gasses.

36.4.2 Solar Heat Generator Using DE

We also consider a new type of solar heat generator based on DE which has a simple structure compared with existing solar power generators [20, 27]. Figure 36.7 shows a DE solar heat generator. When the air in front of the piston is heated by solar heat, its volume increases. The piston pushes a DE generator.

A DE cartridge has 2.8 g of acrylic elastomer and carbon black electrodes. It has a maximum power generation capability of 46.58 mJ per stroke. We used 30 cartridges. When a voltage of 3000 V is applied to a DE as a primary charge, its maximum energy generated is 1.4 J from 5 mm-stretched to relaxed states.

It turns out that a thermal loss becomes large when the temperature of a heating head becomes high. To improve power generation efficiency, it is necessary to generate at low temperatures. Moreover, the emitted heat should not be emitted into the air. It should be reflected and absorbed into the heating head. It could be better to use a liquid with the smaller boiling point to increase efficiency.

This system can be used anywhere solar heat may be obtained, so it has potential as a backup system for sensor network systems.

36.4.3 DE Water Mill Generators

Large-scale hydroelectric power generation is a clean and renewable energy resource, but it has a great environmental impact as a result of the dam, reservoir, and modification of the riverbed. Also, there are few new suitable locations for hydroelectric power. In contrast to "big hydro," with so-called micro hydro, generators are placed into flowing rivers or streams without the need for large dams (or in many cases, any dam at all) or modification to the riverbed.

A DE generator can be well suited for micro hydro [12]. As with wave power, the fact that DE can operate efficiently over a range of frequencies suggests that a DE generator can operate efficiently in the widely varying flow rates of many undammed streams and rivers. Since the DE material has a high energy density, DE generators do not require high-speed rotation from a converter. A simple structure that induces stretching and contracting of the DE is enough to generate electricity.

Photo 36.7 shows a water mill device that is 80 cm in diameter. This proof-of-principle device was tested in Wits Corp. A small water pump (1.12 L/s flow rate) was fixed to a test tank to move water that spun the waterwheel. The waterwheel was attached to a crankshaft with a push rod that was then attached to a diaphragm type of DE device. The up-and-down motion of the push rod stretched and contracted the DE in the diaphragm. In this simple test, each turn of the wheel produced 5 J of electricity.

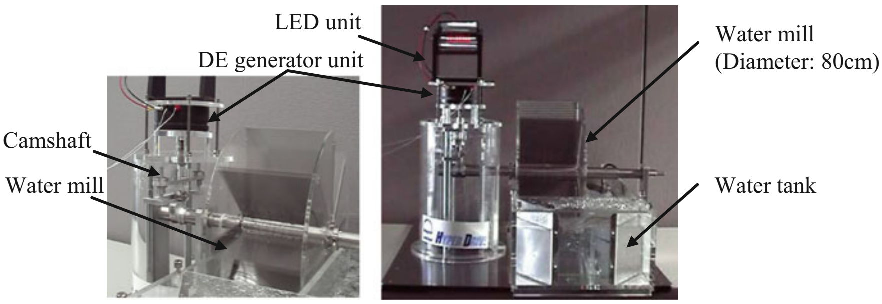


Photo 36.7 Water mill generator using DE [4]

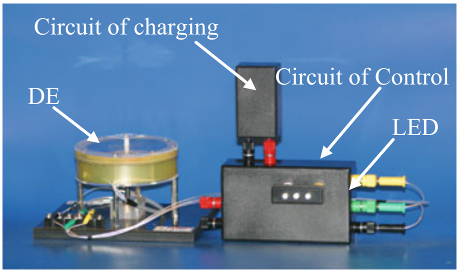


Photo 36.8 Small power generation device [4]

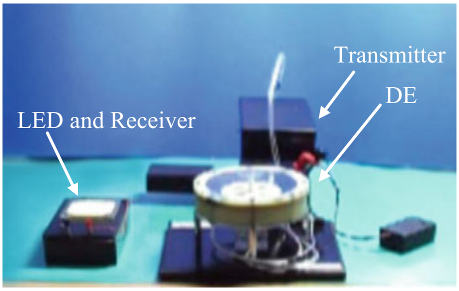


Photo 36.9 Small-scale power generation device and LED controlled by wireless signals [4]

36.4.4 Portable DE Generators

A small electric power generator developed by Wits Corp. uses the DE cartridge (see Photo 36.3) [12]. By pushing the central part of DE by 4–5 mm once a second, a power of approximately 0.12 W can be generated (see Photo 36.8). The energy generated by this device can light several LEDs, and it is also possible to control on/off operations of a remote device by coupling to a wireless system. In this case, the DE supplies electricity to the devices only when it receives mechanical energy. Thus it can be used as a switching system, and this simple structure can be easily incorporated into a wireless network (see Photo 36.9.) [7].

36.4.5 Wearable Generators

In a power generation experiment, a thin artificial muscle film (25 cm long × 5 cm wide, weight about 0.5 g) attached to a human arm was able to generate 80 mJ of electrical energy with one arm movement(see Fig. 36.8b) [7]. It is also possible to make them generate electricity putting up dielectric elastomers besides the arm to the side and the chest of the body (see Fig. 36.8a) [7].

Furthermore, in an experiment using different power generation equipment, artificial muscle film attached to the bottom of a shoe was verified to generate

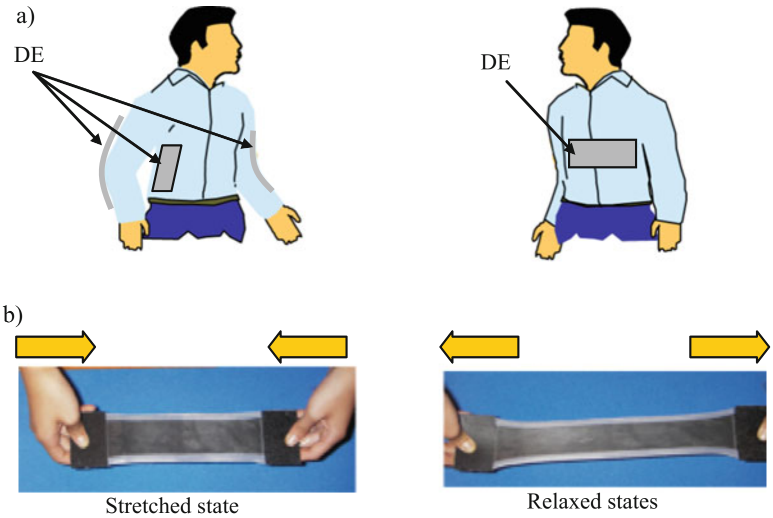


Fig. 36.8 Harvesting energy system from the human body [4]. (**a**) Conceptual rendering of DEs put up to the side and chest of the arm and body. (**b**) Stretched state of DE (left) and relaxed state of the elastomer (right)

electricity when the artificial muscle was distorted while walking. When an adult male took one step per second, one shoe was able to produce about 1 W of electrical power [4].

This confirmed that by utilizing human movement, enough electrical power could be obtained to recharge batteries for mobile telephones and similar devices [20]. In addition, electrical energy from the movements of animals could be used to construct livestock management systems. Other applications of animal-generated energy being investigated include scientific surveys of ecosystems of migratory birds and fish, among others.

36.4.6 Production of Hydrogen

We also carried out experiments on hydrogen production. In the experiments, the generated energy was first stored in a small battery (12 V/600 mAh) [19]. This battery was connected to a hydrogen generation system via a DC-DC converter. The hydrogen generation equipment used in the experiments was a simple electrolytic cell that used nickel electrodes of a mesh of 0.1 mm (150 mm × 100 mm) (Photo 36.10). A 3% aqueous solution of sodium hydroxide was used as a raw material. Applied voltages were reduced to 3 V by a DC-DC converter.

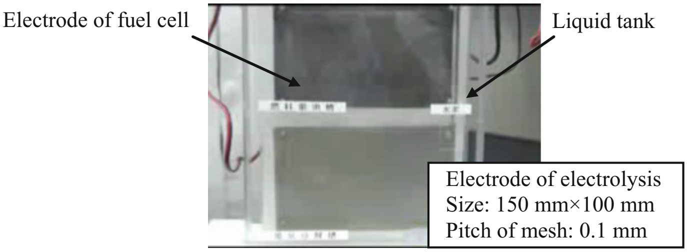


Photo 36.10 Hydrogen generation equipment by electrolysis [4]

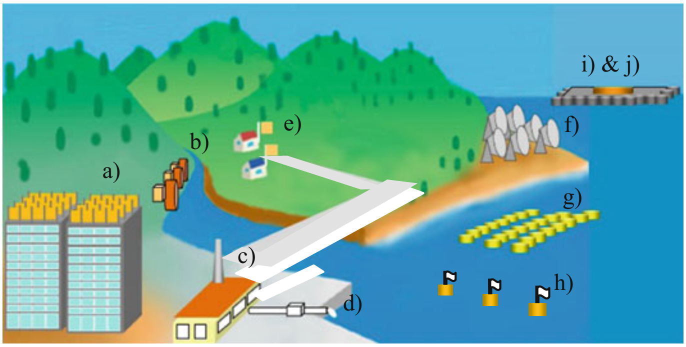


Fig. 36.9 Sites where power generation using DE is possible and conceptual rendering of the generation systems [28]. (**a**) Wind power generators on tops of buildings [21]. (**b**) Water mill generators [12]. (**c**) Waste energy generators [29]. (**d**) Drain generators [29]. (**e**) Wind power generators for personal houses [29]. (**f**) Solar heat generators [28]. (**g**) Wave generators [6, 19, 21, 25]. (**h**) Water flow generators [30]. (**i**) Wave generators in ocean [6, 19, 25, 31]. (**j**) Hydrogen production plant [4, 25]·

36.4.7 Sites Where Power Generation Using DEs Is Possible

Figure 36.9 shows sites where power generation using DEs is possible and conceptual rendering of the generation systems [28]. We hope that those systems may help to combat global warming and other environmental impacts, such as the growth in world population, to maintain a better standard of living throughout the world.

36.5 Future of DE

Helping to address critical issues such as global warming through the enabling of effective harvesting of highly distributed natural power sources is clearly a great potential benefit of DE. We are expecting the DE generators may become one of the promising technologies that not only produce power but also hydrogen in ocean and deserts in the future.

Next-generation DE actuators might enable the vibration reduction and control of the entire large structures. Other future applications might include new vehicles driven by innovative methods and construction machines or robots with more complex yet dexterous motions.

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