

POWER FROM THE PEOPLE



Human-powered small-scale generation system for a sustainable dance club

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MOST HUMAN-POWERED ENERGY-HARVESTING SYSTEMS are used to power ubiquitously deployed sensor networks and mobile electronics. These systems scavenge power from human activity or derive limited energy from ambient heat, light, or vibrations. In this article, systems that use human power by walking or running are analyzed, where an alternative system has been designed and implemented that generates energy from people dancing in a club environment.

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Power Generation

Humans are a rich source of energy. An average-sized person stores as much energy in fat as a 1,000 kg battery [1]. People use muscle to convert this stored chemical energy into a positive mechanical work with a peak efficiency of about 25%. This work can be performed at a high rate, with 100 W easily sustainable [2]. Many devices take advantage of human power capacity to produce electricity, including hand-crank generators as well as windup flashlights, radios, and mobile phone chargers [3]. In most of these conventional methods, users must focus their attention on power generation at the expense of other activities, typically resulting in a short burst of generation. For electrical power generation over longer durations, it would be desirable to harvest energy from everyday activities such as walking, running, cycling, or even dancing. However, producing substantial energy from these activities is not trivial.

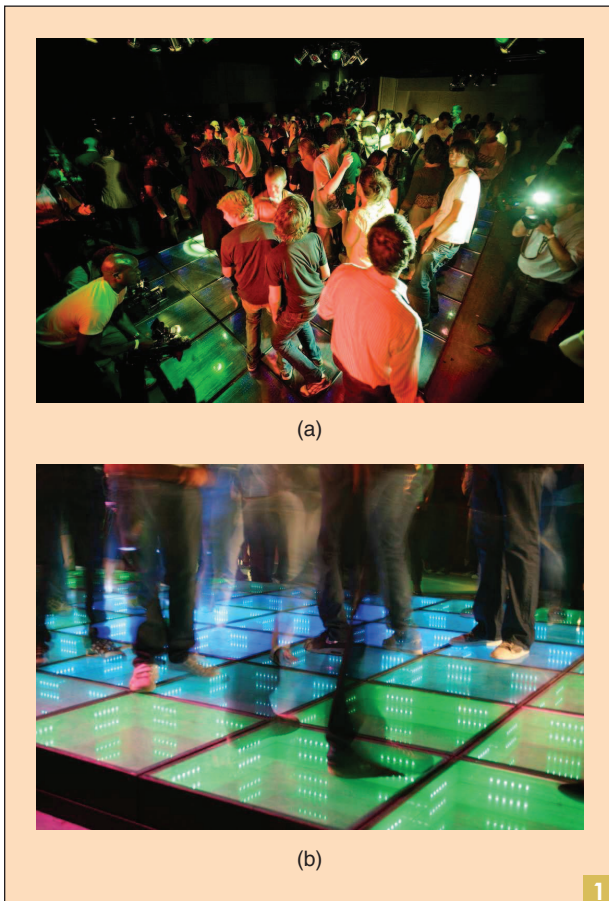
Recently, research on energy harvesting has focused on generating electrical power from the shoe sole, with the best devices being generated around 0.8 W [3]. Alternatively, a spring-loaded backpack [5] has harnessed approximately 7.4 W of maximum electrical power obtained on the flat during fast walking, using the vertical oscillations of a 38 kg load. While the backpack does generate significant power levels to other existing devices, the additional degree of freedom provided to the load could impair the user's dexterity and lead to increased fatigue. Harvesting

human energy in a club environment would significantly impair comfort since, in this case, the person is situated at the same position, and a nonmobile system has been created to convert the human dancing motion into electrical energy. As such, a system has been researched that generates energy from human dancing in a club environment and directly powers a light-emitting diode (LED) light show situated on the top of the floor tile or around the dancing floor (Figure 1).

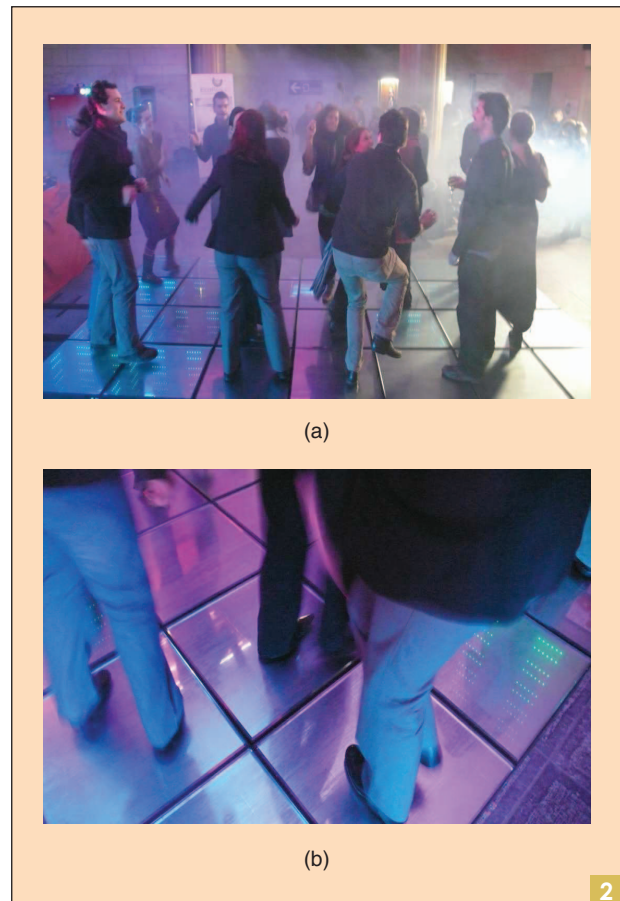
Motivation for a Sustainable Dance Club

Greener clubbing obviously will not solve the problem of rising greenhouse gas emissions, where clubs, with their woofers and strobes, are large electricity consumers and unlikely to ever be carbon neutral. The European Union and United Nations have said that the greenhouse gases should at least be reduced by 20% by 2020, with a share of 20% of renewable energy generation to prevent dangerous global warming [6]. Most of that reduction has to come from large changes, e.g., closing coal-fired plants and improved protection of rain forests. However, it is also necessary to investigate gains that can come from doing the things everyone does now but in ways that are a bit more efficient and environmentally friendly.

As such, the environmental issues have even reached the clubbing scene, where in Rotterdam, The Netherlands, a sustainable dance club, as shown in Figure 2, has



Sustainable dance floor at the sustainable club Watt in Rotterdam, The Netherlands [4]. (Photo courtesy of Sustainable Dance Club BV.)



Power from dancing people at Watt-a-party in the Congress station, Brussels on 4 December 2008 [4]. (Photo courtesy of Sustainable Dance Club BV.)

been established [4]. An average size club with around 200,000 visitors on a yearly basis uses around 430 kWh (50% for lighting, 20% for heating, 15% for sound systems, and 10% for cooling). Subsequently, 10 million liters of water are flushed and 136,000 kg of waste is created. The club has taken many measures to become sustainable (i.e., reducing the energy consumption by: electricity 30%, water 50%, and waste 50%), where the largest energy reduction has been achieved using LEDs, rainwater, and smart cooling systems. In addition to energy savings, a general public awareness needs to be introduced, which could be achieved by visualizing power from the people to the clubbing public. This need for visualization was one of the drives to create a sustainable dance floor. In addition to awareness, the energy consumption for lighting has been reduced since the energy harvested during dancing is directly used in the top part of the tile to power the light show in and around the floor. As such, when young people start to comprehend about energy and the scarcity of energy, they will try to treat it with much more care. The dance floor consists of individual modules (or tiles) separated in two parts: energy harvesting and lighting. In future larger systems, besides lighting the top of the modules, the human-powered electrical energy will also be used for additional lighting, sound, and disc-jockey apparatus.

Harvesting Energy from People

As sustainable living gets an increasing foothold in people's lives, unobtrusively tapping some fraction of energy available from human activity has recently gained popularity. In the last few decades, energy harvesting has grown from long-established concepts into devices, in general, used for powering ubiquitously deployed sensor networks and/or mobile electronics [7]. Recent developments in the field have led to the design of a number of mechanisms that can be used to generate electrical energy from a variety of sources including thermal, solar, strain, and inertia. The clubbing experience application considered in this article requires a power level of a couple of watts to power an LED-lighting show. In general, solar cells (sometimes combined with wind power) are the most commonly used devices to provide energy generation; however, this is an unfeasible solution in a club environment. Hence, when the only available energy sources are dancing (or jumping) people, only a few sources of power remain, respectively, human heat or vibrations. In indoor applications, thermoelectric converters on the human skin can provide more power per square centimeter than solar cells, particularly in adverse illumination conditions such as clubs [8]. Alternatively (or complementary), vibrations could be harvested, provided that parasitic effects, which disrupt the clubbers dancing experience, are minimized.

Thermoelectric

Objects (or environments) at different temperatures offer the opportunity for energy harvesting via heat transfer. To

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enable this, a basic thermoelectric conversion unit can be used, which consists of two different semiconducting materials that are connected together as a thermocouple. In general, thermoelectric devices are modules constructed from a number of thermocouples, hence in effect, heat drives an electrical current used to generate power ($20 \mu\text{Wcm}^2$ for a human environment [8]). Considering the high reliability, small size, and no noise, thermoelectric technology is highly competitive. However, the relatively low efficiency means that the large-scale use of thermoelectrics will remain limited to applications served poorly or not at all by existing technology [9]. Therefore, harvesting this energy from warm-blooded animals (including humans) using thermoelectric conversion can only be a feasible

solution to provide power autonomy for miniaturized and/or wearable electronic products operating at very low power, e.g., watches [10]. Further, also in medical, automotive, and industrial environments, compact and reliable self-powered sensor devices could be feasible solutions to replace wired counterparts featuring huge amounts of corroding wires [11]. Accordingly, thermoelectric generators can deliver significant energy levels with high-temperature sources (i.e., a hot exhaust pipe) but are much more limited for temperate environments or wearable applications. Therefore, we have mainly focused on harvesting the energy from vibrations, as will be discussed in the next section.

Vibration

During dancing, the environment does no work on the body, and, vice versa, humans do no work on the environment. Rather, almost all of the mechanical work is generated and dissipated inside the body [13]. This makes it exceedingly difficult to capture mechanical energy to drive an electrical energy-conversion apparatus because the device would need to be either surgically placed within the body or attached to the outside of the body (such as an exoskeleton on the knee [14]). However, these exoskeletons would certainly impede the maneuverability and comfort of the dancing persons.

An alternative solution to harvest electrical energy available from human power, used for centuries, is the self-winding wristwatch. This system uses the natural wave of the arms of walking people to power wrist-mounted platforms. As such, a modern self-winding wristwatch contains a rotary-proof mass mounted off-center on a spindle, which reacts inertially. This is consequently used to directly spin an electrical generator or alternatively stores the energy in a spring, where it is transferred to the generator at its optimal rate [15]. Alternatively, these systems can also be used in, e.g., a flashlight, where they produce around 200 mW under normal motion when the hand is shaken at approximately 200 cycles/min [3], [16]. However, these systems impede the comfort of the dancing people, especially, if larger amounts of energy need to be harvested.

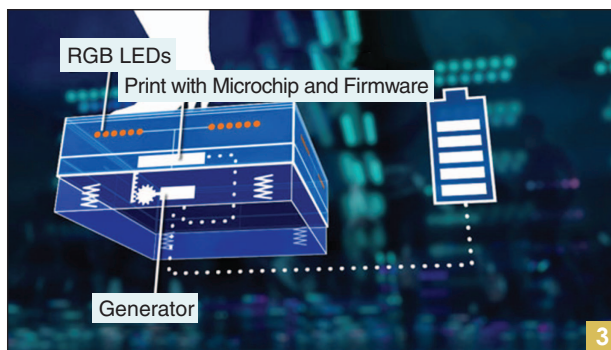
Recently, research on energy harvesting has focused on generating electrical power parasitically while walking from the shoe sole, with the best devices generating around 0.8 W [17]. In general, these systems use the pressure of the heel to, for example, spin a flywheel attached to the generator and extract the power from the pressure of the heel during walking. However, these systems are difficult to reliably integrate into standard footwear [3]. Therefore, systems that use the bending strain of the shoe sole are investigated, which generates electrical charge by laminating piezofilms, where [18] calculated that approximately 67 W of power is lost during walking and that a piezoelectric device mounted inside a shoe with a conversion efficiency of 12.5% could achieve 8.4 W of power. It needs to be noted that most current-implemented systems generate power levels in the order of milliwatts to watts [19]. This clearly gives relatively low efficiencies, and, therefore, alternatives to piezosolutions were investigated.

The most attractive alternative available to harvest substantial energy levels from dancing people is a spring-loaded backpack, which converts mechanical energy from the vertical movement of carried loads to electricity. This system harnessed approximately 7.4 W of peak power during fast walking while using the vertical oscillations of a 38 kg load [5]. While the backpack does generate the necessary power levels for a light show, an additional degree of freedom provided to the load would impair the user and lead to increased fatigue. Harvesting human energy in a club environment would significantly impair the experience of the clubber. As such, in a clubbing environment, the human is based at the same position, and nonmobile systems could be a suitable alternative to transfer the human dancing motion into electrical energy. This energy should then be directly used to power the LED lighting show situated on the top of the tile or around the floor to further enhance the systems utilization, as shown in Figure 3.

Model of the Harvesting Part of the Tile

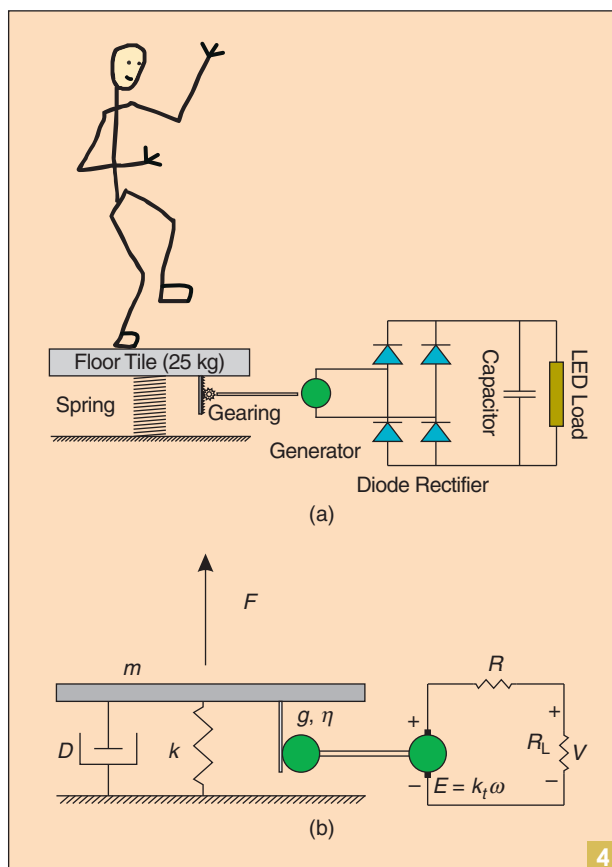
To study the physical behavior of energy-generation system of the dance floor, as shown in Figure 4(a), rather than using finite-element methods coupling together with Maxwell's equations and dynamics of the structure, a simplified circuitual approach was selected. This allows for time- and frequency domain analyses of the entire system and is preferred due to its simplicity and ease of parameter changes without significant computational overhead. Consequently, using this model to understand the basic characteristics of the components, many of the performance limitations of the system will be remedied, and a system optimization can be explored. The load of the harvesting part of the dance floor is the LED light show in the top part of the tile. This electrical load consists of arrays of LED devices, which can be either voltage- or current-source supplied. To obtain linear control of the light intensity, a voltage-regulated dimming scheme for the LEDs is adopted. As such, a simple downconverter has been implemented since the brightness and power consumption of the LEDs are directly related to their forward current. This converter has been simplified in the equivalent schematic to a load resistor connected in parallel to the storage capacitor.

The simplified harvesting model of the dance-floor tile [20], as shown in Figure 4(b), consists of a tile suspended



Artist impression of a single dance-floor module [12]. (Photo courtesy of Sustainable Dance Club BV.)

by springs and modeled by a simplified mass, m , mechanical springs combined to a single spring coefficient k , and a damper D . In this system, the linear vertical motion of the moving part of the tile is converted to a rotary motion by a gear with gear ratio g and efficiency η , where the energy is harvested with a commercial high-efficient brushed dc generator. This dc machine is modeled by its motor constant, K_t , and armature resistance, R , with a load resistance, R_L . As such, the armature winding inductance ($L = 1.67$ mH) has been neglected because of the low excitation frequency of the system (below



Equivalent dance-floor model of the energy harvesting, illustrating (a) the simple mechanical and electrical model and (b) the schematic of the energy-harvesting part.

TABLE 1. PARAMETERS OF THE STATE-SPACE MODEL OF A DANCE-FLOOR TILE.

Parameter	Value	Unit
Suspended mass (without dancer), m	35	kg
Spring coefficient, k	150,000	N/m
Mechanical damping, D	10	Ns/m
Efficiency gears, η	50	%
Motor constant, K_t	0.0728	N/A
Internal resistance motor, R	19.2	Ω

2.5 Hz). The state-space equivalent model of the system is given by

$$\begin{aligned} \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ \frac{k}{m} & -\frac{D}{m} - \frac{(K_t g)^2}{m\eta(R+R_L)} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \Rightarrow \\ \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ \frac{k}{m} & -\frac{D}{m} - \frac{(K_t g)^2}{m\eta(R+R_L)} \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \end{aligned} \quad (1)$$

and

$$V = \begin{bmatrix} 0 & \frac{K_t g R_L}{(R+R_L)} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} \Rightarrow V = \begin{bmatrix} 0 & \frac{K_t g R_L}{(R+R_L)} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} \quad (2)$$

where x is the position and V the voltage across the load resistance.

The values of the parameters of the state-space model are given in Table 1. Although the dancer is aware that energy is generated from the dance floor, the dancing experience should only be disturbed a little. Therefore, only little movement (several millimeters) of the suspended floor is allowed, and a high spring stiffness has been selected to achieve this. When energy is generated for lighting, the damping of the system is determined by the dc generator

and its electrical load. In that case, the mechanical damping may be neglected. The efficiency of the system has been determined from several measurements, as discussed in the “Measurements” section. Because of the nature of dance music, only a limited frequency range of 1–2.5 Hz is considered in the analysis.

The proper matching of loads to the generating system is required for optimum system sizing and higher utilization of energy. In this respect, measures have been introduced for the quality of matching based on the energy consumed by the load to the amount of maximum harvested energy. This implies that the optimum load parameters have been determined with the objective to maximize the amount of harvested energy. To generalize the analysis, a mass of 70–100 kg is assumed, which combines both the mass of the person and lighting part of the dance floor. An analysis of the matching factor around the optimum has been studied, where Figure 5 demonstrates that the output power strongly depends on the load resistance and gear ratio. For the system, a gear ratio of $g = 22,000$ rad/m and a load resistance of $R_L = 150 \Omega$ are selected.

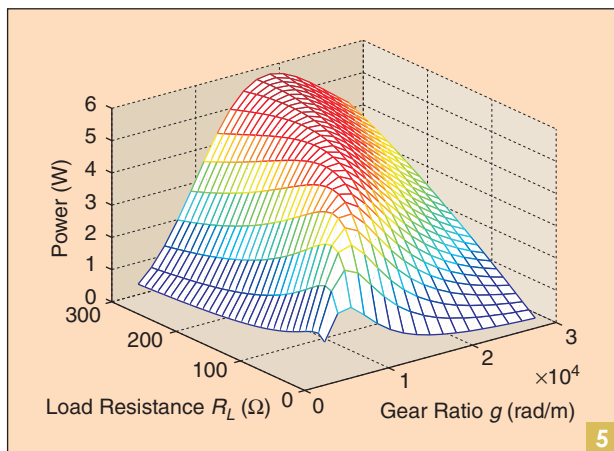
Prototype

To validate the design and analysis techniques that have been developed, prototypes have been created to perform measurements. The electromechanics and embedded electronics are integrated into a single module to minimize the height of the harvesting part of the tile. The dancing feeling can be manually adjusted by varying the preloading of the spring. A further important parameter is the integration of torque compensation into the design, which occurs when the people dancing are exciting the tile off-center. The stainless steel tile modules (RVS316L) of $65 \times 65 \times 5$ cm with a maximum movement of 1 cm, as shown in Figure 6(a), has been used to measure the amount of harvested energy, as will be discussed in the next section.

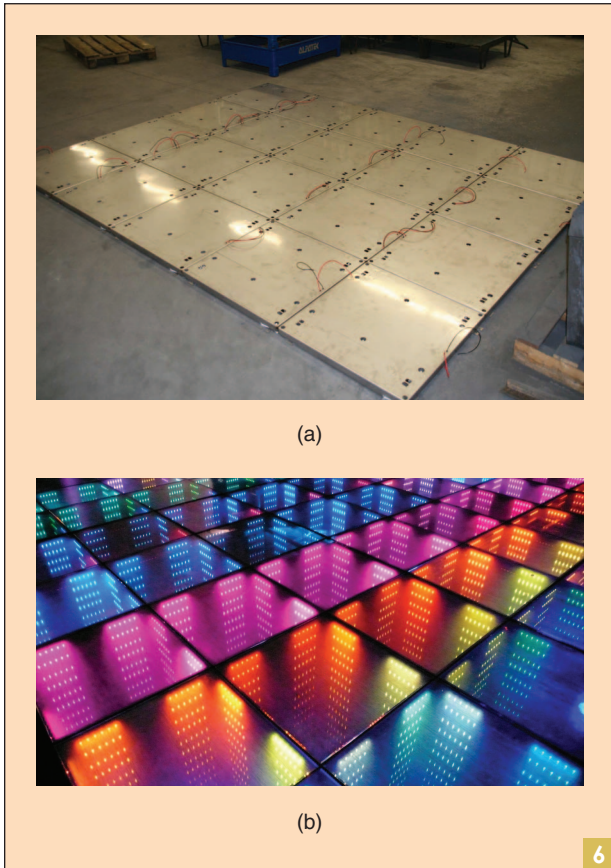
To create a clubbing experience, the top part of the tile ($65 \times 65 \times 14.5$ cm) has an integrated light show that visualizes energy generation. To create a very sustainable solution with minimized energy use, the lighting tile [combination of reused polyvinyl chloride (PVC), mirrors and hardened glass] has been equipped with a smart mirror construction combined with LED arrays on the sides to maximize the use of light. A variable virtual depth can be created by varying the light intensity, to visualize a single LED array of up to 20 slowly fading arrays, as shown in Figure 6(b) [21]. In this respect, both the harvesting and the lighting part of the tile have many features to account for future developments of the floor, e.g., for implementation of control alternatives to alter the behavior of the dance floor.

Measurements

The measured voltage, current, and power waveforms of the dance-floor system are shown in Figure 7, respectively. This shows that energy is both generated when the tile moves downward due to the force applied by the dancer and when the tile moves upward due to the spring even when there is no contact with the dancer. The measured maximum average output power indicated about 24.1 W, i.e., without rectifier and averaged above 10 s. It needs to



Output power as a function of the load and gear ratio.



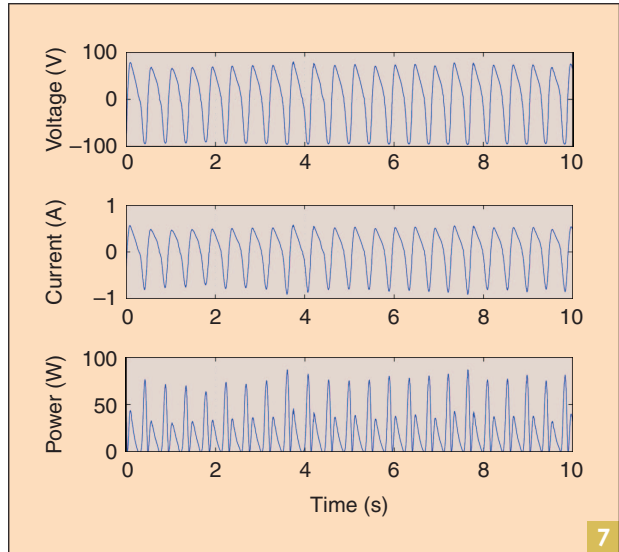
Dance-floor modules: (a) interconnected harvesting tiles and (b) the light show [21]. (Photo courtesy of Sustainable Dance Club BV.)

be noted that, by using different dancers, the maximum average power levels varied around 20–30 W, which were easily sustainable for extended periods of some minutes. In these measurements, during short intervals, the harvested output power peaks at approximately 60–100 W (some additional measurements even showed peak power levels of more than 100 W). When using a very standard low-cost diode rectifier and a large capacitor, this maximum average output power reduces to 22.4 W.

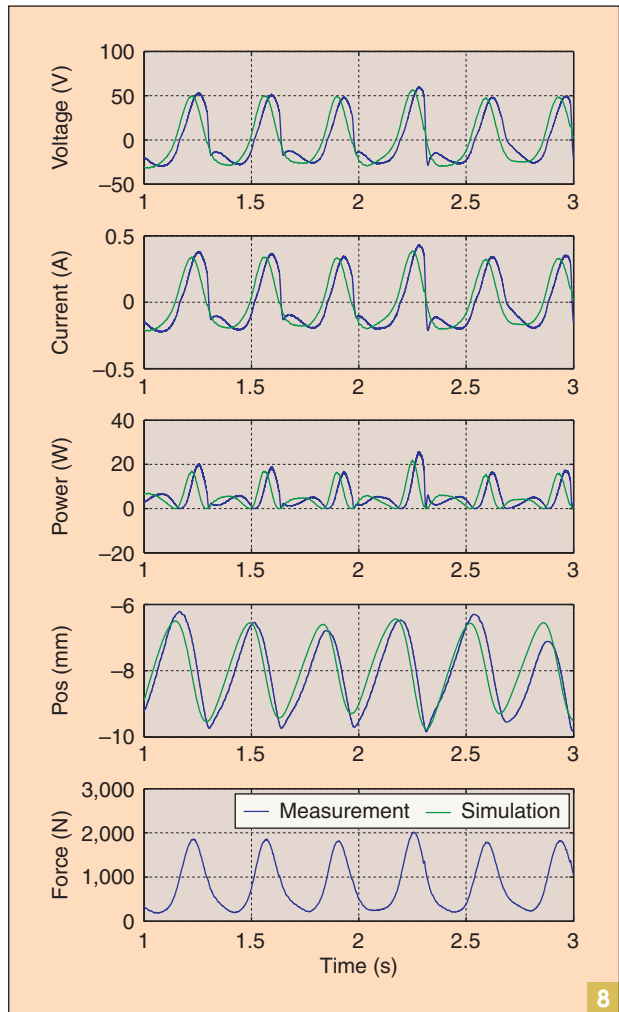
Figure 8 compares the predicted and measured output waveforms of an almost continuously sustainable input for a single dancing person, respectively, with a harvested energy of 5.3 W average power and a peak power of 26 W. This figure clearly shows the agreement of the measured and simulated waveforms. The force exerted on the dancer is measured with a Kistler 6286AA multicomponent force plate, which was placed on top of the suspended tile. The measurement shows that during dancing the dancer (mass: 83 kg) was always in contact with the tile. Force peaks up to 2 kN have been measured. Figure 8 also shows the relative position profile of a dancing person, which has been measured with respect to the top of the harvesting tile. The system efficiency determined from these measurements is 48%.

Conclusions

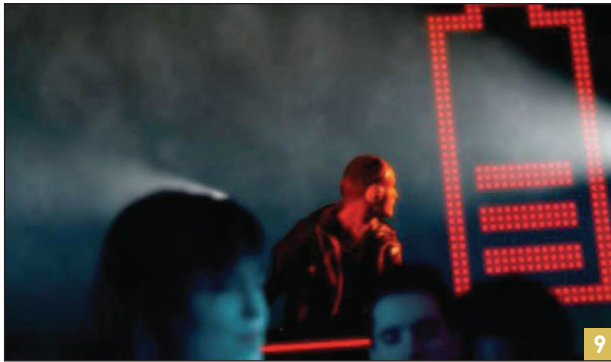
An energy-harvesting tile has been created, which converts the energy of dancers into electrical energy that powers a



Measured waveforms from the harvesting part of the dance floor without rectifier (mean power is 24.1 W).



Average sustainable dancing measurement waveforms from the harvesting part without rectifier (mean power is 4.8 W), which shows output voltage (V), current (A), power (W), relative position (mm), and measured force input (N).



The energy of the dancers has turned into electrical energy that powers a light show within the floor modules or in close proximity to an energy meter. (Photo courtesy of Sustainable Dance Club BV.)

light show in the top part of the module or in close proximity to the floor, as shown in Figure 9. A model of the power-generation system that achieves maximum output power from people dancing has been presented. Further, measurements have shown that approximately 20–30 W can be generated for a period of 10 s, where the peak power of some 80–100 W is harvested during very short intervals. A single person dancing for longer periods of time would generate average power levels of approximately 2–8 W.

Considering the measured harvested power levels, it should be taken into account that a further energy saving is apparent, when comparing this dance floor to grid-connected devices, due to the lack of electric transmission losses. Only small energy savings are apparent from this system due to the relatively low power levels. However, arguably more important, this dance floor has increased the public awareness by visualizing power from the people to the clubbing public. This visualization, combined with a generating experience, is a very important factor to let young people understand what energy generation comprehends, and the finite energy resources ultimately make people to use energy with much more care.

Social and environmental issues are worldwide and will always demand attention. As such, sustainability is more the beginning of a new corporate attitude or lifestyle than a dying trend. Numerous examples exist, and companies working on their sustainability are very profitable, e.g., due to loyalty and motivation of employees, loyalty of customers, imagination, and innovation. Therefore, in addition to club environments, improved systems are being developed that unnoticeably harvest or steal power from the people for application within train stations, busy traffic intersections, and airports.

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