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Self-Powered Dynamic Systems

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Abstract

This article concerns the concept of energy harvesting associated with dynamic systems. The particular area of work is the concept of fully or partially self-powered dynamic systems requiring zero or reduced external energy inputs. A self-powered dynamic system, in this paper, is defined as a dynamic system powered by its own excessive kinetic energy, renewable energy or a combination of both. The technologies explored in the paper are associated with self-powered devices (e.g. sensors), regenerative actuators, and energy harvesting. The power produced by human motion is reported as a potential energy input to mechanical devices. A solar powered airship system is used as an example of a self-sustained system. A bio-inspired design is investigated to demonstrate the advantage of employing biomimetics in improving the power density of an energy harvesting system.

1. Introduction

Energy harvesting enables the design of fully or partially self-powered devices requiring zero or reduced external energy inputs. An energy harvester can extract the excessive/unwanted kinetic energy in the system and convert the kinetic energy to electrical power. The generated electricity can be stored or employed to activate any component in a system which requires power for its operation. The most common applications of self-powered systems can be associated with sensors and actuators. Sensors and actuators can benefit from such energy harvesting as self-powered schemes [1]-[2]. For instance, in a case of a sensor, the harvested energy can be utilized to provide the power required for sensing and other operations of the sensor such as storing and transferring data. In an actuator, the generated power is used for self-powered actuation. The source of power for such systems, particularly those studied in this article, can be categorized as the unwanted vibration is a system, renewable energies, or biological sources of energy. The power conversion for mechanical kinetic energy to electrical energy is normally implemented through piezoelectric, electromagnetic or electrostatic conversion mechanisms [3]. A review of such self-powered systems is presented below along with the advantage of biologically inspired design in improving power density of energy harvesting systems.

The energy harvesting techniques has been incorporated in various technologies such as a self-powered sensors and actuators. Examples for recent advances in these areas are addressed below. As mentioned above, self-powered sensors can use electrostatic, piezoelectric and electromagnetic energy conversion schemes to provide the required power for the sensor operations [4]-[8]. Developing a self-powered sensor eliminates the use of batteries in sensors and therefore a self-powered sensor is considered as a self-sustained system which does not required maintenance (e.g. replacing the battery of the sensor at the end of the battery life). This is particularly beneficial in condition monitoring and remote sensing in hostile or inaccessible environments. The piezoelectric energy convertors do not require voltage source. However, integrating piezoelectric material at micro/nano scale can be challenging. The electrostatic based energy harvesters are more desirable for microsystems where they are more adoptable for systems at micro scale. Nevertheless separate voltage source is required for electrostatic based devices. The electro-magnetic convertors do not need voltage source. However the output voltage of the electro-magnetic system can be limited. A vibration energy harvester can extract the maximum power from ambient vibration or machinery/structural induced

vibration when the excitation frequency matches the natural frequency of the energy harvester. On the other hand when the excitation frequency is not equal to the natural frequency of the system, the harvested power is reduced. Various mechanisms are designed to tune the natural frequency of the harvester with the excitation frequency, in order to maximize the generated power [9]. For instance, a nonlinear oscillator is capable of operating over a broader range of frequencies relative to linear oscillators and therefore a desirable choice for broadband energy harvesting. This technology is particularly suitable for ambient energy harvesting which is a random, multi-frequency, and time varying source [10]-[11]. For random and broadband excitation frequencies, a higher damping characteristic is preferred in the absence of tuneable frequency technology [12]-[13]. Energy harvesters can be designed based on the operational frequency range of systems. For instance, low frequency energy harvesters can generate sufficient power for small electronic components using electromagnetic mechanism [14] and piezoelectric mechanism [15]. Developing technologies for self-powered micro/nano sensors is crucial in health care, environmental monitoring, infrastructure monitoring, national security, etc. applications [16]. A nanogenerator that converts vibration energy into electricity can act as a sensor for detecting the vibration spectrum without the use of an external power source. In comparison to the laser vibrometer, which is excessively complex and expensive, this nanogenerator is small and low cost with many potential applications such as sound wave detection, environmental/infrastructure monitoring, medical, etc. [17]. An elastic-spring-substrated nanogenerator gives an electric output signal without applying an external power which is used as a self-powered weighing device. This is a piezoelectric based active sensor which monolithically integrated onto an elastic spring by growing nanowire arrays on the surface of the spring [18].
Many self-powered sensor applications can be found specifically in machinery and structural condition and health monitoring. As an example of some of recent advances in this area, a sensor embedded in a road vehicle tire monitors the behaviour of the tire and therefore used as a safety measure in the vehicle dynamics. A self-powered mechanism in such system generates electricity from tire mechanical energy produced by tire deformation during driving. The system uses the generated electrical energy to power the sensor operational power demand [41].

Regenerative actuators can harvest energy from vibration and use that energy as a power source to its own operation or powering other electrical instruments. A regenerative actuator can be built on the basis of a linear DC motor/generator [19]-[20]. A regenerative actuator can control the source of the vibration energy itself as a self-powered system and also generate electrical energy to be stored in the system [21]-[25]. The potential power that can be generated by a regenerative shock absorber is in the range of 10's W to 1000's W in a regenerative vehicle shock absorber [26]-[33]. Suspension control is normally carried out in passive, semi-active and active schemes and typical control techniques includes skyhook, ground-hook and hybrid controls [34]-[36] particularly in vehicle suspension systems applications. Active-damping techniques using active controllers provide better damping performance than passive. However they require complex algorithms for active controlling and the technology is more cost effective than passive-damping strategy. The trade-offs in the cost and complexity would be switch shunting or semi-passive techniques which can also be designed as a self-powered element [37]. A self-powered digital vibration control technique benefits from both the sophisticated control logic and a self-powered semiactive system [38]. A self-powered vibration control system converts unwanted vibration energy in the system to electrical energy and use the same electrical output to control the excessive vibration. A semi-active vibration control system based on a magnetorheological based damper device harvests vibration energy using an electromagnetic transduction mechanism. The extracted energy is supplied to the motor/actuator in order to control the mechanical damping by controlling the electrical properties of the regenerative motor [39]. A recent application of magnetorheological damper includes the damper with stiction effect that is exploited as a seismic protection system of structures [40]. This semi-active seismic protection device in conjunction with a controller system reduces the vibration of the structure in an earthquake event. A self-powered control and monitoring system can supply the power for both detection and actuation power demand of the system [42]. Such self-powered control and monitoring device can be realized using a pendulum-type tuned mass damper, a rotary electromagnetic/regenerative device, an energy harvesting circuit and a wireless smart sensor. The regenerative electromagnetic mechanism is able to convert vibration energy to electrical energy. Energy harvesting in water distribution systems can employ the hydraulic energy in bypass water pipes, thermal energy in the water-air temperature gradient, and kinetic energy in the water pressure fluctuation to power wireless sensors. The harvester can be built based on a various schemes such as a micro-turbine system, thermoelectric system, or piezoelectric mechanism [43]. In a hydraulic hose and piping system, the flow that induces high energy intensity can power wireless sensors of a hydraulic system and pumps for structural health monitoring [44]. It should be noted that vibration is one of the most high power and efficient ambient energy sources such as solar energy and temperature difference [45]. Various applications for energy harvesting devices are found. In addition to the examples mentioned above, energy harvesting devices embedded in animal bodies use the kinetic energy of the system as a power source. For instance, a piezoelectric based shoe sole or cloths fabric can generate electricity from human motion [46].

"Biological systems and animals are products of nature which have evolved to better respond to life activities". Biomimetics allows improvement in design of engineering systems. For instance, studies of the mechanics of fish by zoologists and biologists have shown that "even a dead trout can swim upstream by extracting energy and generating thrust-producing body deflections, and that whale flukes are capable of absorbing energy from surface waves and creating thrust whether the whale is alive or dead" [47]-[50]. A fish is capable of utilizing energy in upstream vortices to enhance its swimming performance and use less muscle energy. It was demonstrated that "through passive body deformations and vorticity control, a fish could even propel itself forward inside a Kármán vortex street without energy expense" [51]. This is a motivation on learning how animals can extract environmental energy and how this strategy can be applied to improve an engineering system. For instance, a piezoelectric energy harvester in a bio-inspired array of harvesters (when placing piezoelectric cantilevers next to each other in configuration analogues to a group of fish swimming next to each other) can generate more power compared to a piezoelectric energy harvester in isolation [52]-[55]. Vertical wind turbines designed on the basis of fish schooling shows an order of magnitude improvement in improving the power density of the wind farms [56]. Piezoelectric energy harvesters can therefore be used as the power source for self-powered systems. [57].
This paper addressed the concept of self-powered dynamic systems in Section 2. The theoretical background of such systems is presented in section 3. Section 4 discusses an example of a bioinspired design which improves power density of an energy harvesting system. Section 5 reports a renewable energy based dynamic system and Section 6 gives the results of an experimental investigation into of human power as the basis of power source for mechanical devices.

2. The concept of Self-powered Dynamic Systems

In this article, a Self-powered Dynamic System is defined as a dynamic system powered by its own excessive kinetic energy, renewable energy or a combination of both. The particular area of work is the concept of fully or partially self-powered dynamic systems requiring zero or reduced external energy inputs. The technologies exploited in this paper are particularly associated with self-powered sensors, regenerative actuators, human powered devices, and a solar powered dynamic system as self-sustained systems. Various strategies can be employed to improve the design of a self-powered system and among them adopting a bio-inspired design is investigated to demonstrate the advantage of biomimetics in improving power density. The concept of Self-powered Dynamic Systems is illustrated in Figure 1.

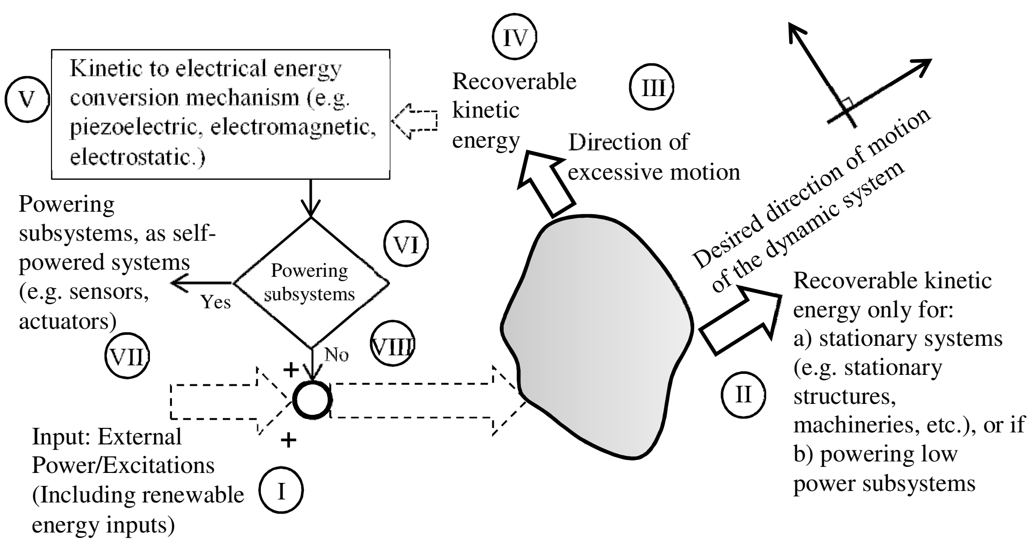


Figure 1: The concept of self-powered dynamic systems

The concept of Self-powered Dynamic Systems in Figure 1 is explained below.

I. Input power (e.g. fuel energy powering a vehicle engine or propulsion system), or input excitation (e.g. vibration excitation to a structure) to the system. The source of this input energy can be of renewable energy source (e.g. solar powered for a dynamic system).

II. The kinetic energy in the direction of motion of a dynamic system is only recovered if the system is stationery (e.g. a bridge structure), or the recoverable energy is negligible in comparison with the power required for motion (e.g. a low powered sensor).
III. The movement of the dynamic system perpendicular to the desired direction of the motion is usually the wasted kinetic energy in the system (e.g. the vertical motion of an automobile suspension is wasted to heat energy in the shock absorbers, or vibration of an aircraft wing is converted into heat energy trough structural damping).
IV. The vertical movement of the dynamic system is a source of recoverable kinetic energy.
V. The recoverable kinetic energy can be converted to electrical energy through an energy conversion mechanism such as an electromagnetic scheme (e.g. replacing the viscous damper of a car shock absorber with regenerative actuator), piezoelectric (e.g. embedding piezoelectric material in aircraft wings), or electrostatic (e.g. vibration of a micro cantilever in a MEMS sensor).
VI. The recovered electrical power can be stored or used as a power source.
VII. The recovered electrical energy can power subsystems of the dynamic system such as sensors and actuators.
VIII. The recovered electrical power can be realized as an input to the dynamic system itself.

The succeeding section provides the theoretical background associated with the concept of Self-powered Dynamic systems.

3. The theory of self-powered systems

A self-powered system consist of a regenerative scheme is represented in Figure 2. The experimental rig in the figure consists of mass, spring and an electromagnetic regenerative linear motor. The input excitation is generated using an actuator as in the figure. A controller system is designed to provide the input signal to the input actuator, and adjust the regenerative system for various modes of operation. The operation modes of a regenerative system can include drive, regeneration and brake modes. The drive mode controls the motion which can use the recovered powered from the system for its actuation. The brake mode provides equivalent damping for the system. In the regeneration mode the kinetic energy is converted to electrical energy. A practical example for application of this rig can be referred to a self-powered regenerative shock absorber in vehicle (e.g. [2] and [23]).

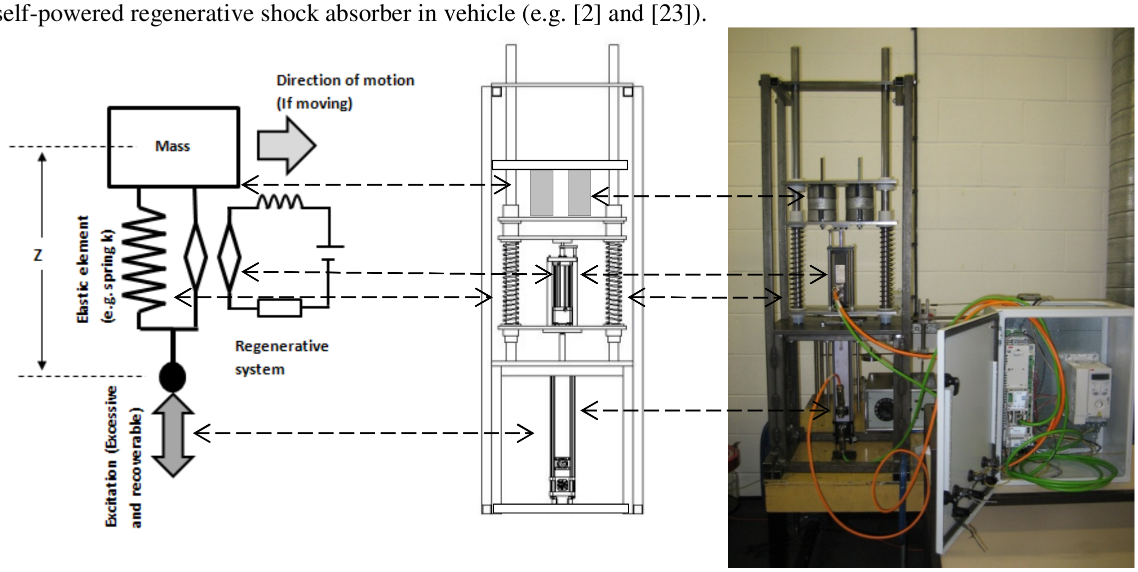


Figure 2: Representation of a Self-powered Dynamic System experimental rig

The equation of motion of the system in Figure 2 is given by

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \tag{1}$$

where m denotes the mass, c is the damping constant, k is the stiffness, y denotes the input excitation and x is the mass displacement. If $z = x - y$ is the relative displacement of at the excitation point relative to the mass, the above equation becomes

$$m\ddot{z} + c\dot{z} + kz = m\ddot{y} \tag{2}$$

For a harmonic excitation of $y = Y sin\omega t$ and steady state solution of $z = Zsin(\omega t - \phi)$, where ω is the frequency of the excitation, t is the time, the amplitude of the motion obtained as

$$Z = \frac{m\omega^2 Y}{\sqrt{(k - \omega^2 m)^2 + c^2\omega^2}} \tag{3}$$

If the recoverable kinetic energy is harvested through a regenerative mechanism (Figure 1 and Figure 2) then the generated power is determined as

$$P = c\dot{z} \times \dot{z} \tag{4}$$

where $\dot{z}$ is the relative velocity. Therefore the power can be calculated as [2] and [12]

$$P = c\omega^2 Z^2 cos^2(\omega t - \phi) \tag{5}$$

In one cycle with period of $\tau = 2\pi/\omega$ the energy is determined by

$$E = c\omega^2 Z^2 \int_0^{2\pi/\omega} cos^2(\omega t - \phi)\mathrm{d}t = \pi c\omega Z^2 \tag{6}$$

The average power can be calculated as

$$P = E/\tau = c\omega^2 Z^2/2 \tag{7}$$

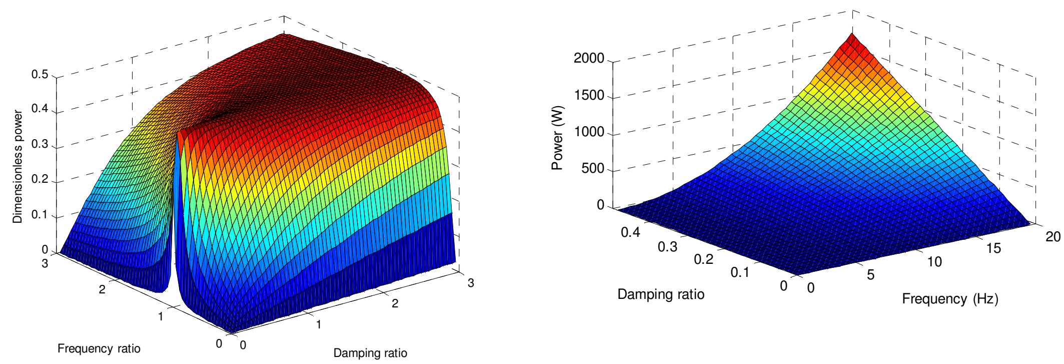
and hence the power can be obtained as

$$P = \frac{cm\omega^4 Y Z_{max}}{2\sqrt{(k - \omega^2 m)^2 + c^2\omega^2}} \tag{8}$$

where Z_{max} is the maximum relative displacement.
The dimensionless power can be considered as [1], [2] and [58]

$$P_d = \frac{P}{m\omega^3 Y Z_{max}} = \frac{\zeta.\eta}{\sqrt{(1-\eta^2)^2 + (2\zeta\eta)^2}} \tag{9}$$

where ζ denotes the damping ratio and η is the frequency ratio, and $\frac{c}{m} = 2\zeta\omega_n$ and $\eta = \frac{\omega}{\omega_n}$.
The dimensionless power P_d is plotted versus the damping ratio ζ and the frequency ratio η in Figure 3(a).



(a) (b)

Figure 3: a) Dimensionless power versus frequency ratio and damping ratio; b) Harvested power versus frequency and damping ratio

The dimensionless power P_d in Figure 3(a) represents the behaviour of a general vibratory system with the maximum response at frequency ratio $\eta = 1$. It also represents the effect of damping in the harvested power. The actual power value is investigated further using Equation (9) as below

$$P = m\omega^3 Y Z_{max}\zeta.\eta/((1-\eta^2)^2 + (2\zeta\eta)^2)^{1/2} \tag{10}$$

The power P in Equation (10) is plotted versus the damping ratio ζ and the frequency f (Hz) in Figure 3(b). The parameters used for the above figures are: stiffness, k = 16 kN/m and the mass, m = 280 kg. It is observed, from Figure 3(b), that the power is proportional to the cube of the excitation frequency.
In a DC linear motor the relationship between force and velocity in terms of the motor parameters can be expressed as [3] and [23]:

$$V = -k_a\dot{z} \tag{11}$$

$$F = k_a i \tag{12}$$

From the above we can obtain

$$F = -\frac{{k_a}^2}{r}\dot{z} \tag{13}$$

where V denotes the induced voltage, F is motor force, i is the electric current in armature, k_a is the motor constant and r is the resistance of the armature. If the power source voltage is V_p then the force in the actuator is obtained as

$$F = k_a \frac{V_p - k_a \dot{z}}{r} \tag{14}$$

In order to generate the force, F, the consumed power by the voltage source is

$$P_c = V_p i = \left(\frac{rF + k_a \dot{z}}{k_a}\right)\frac{F}{k_a} \tag{15}$$

By comparing Equation (15) with the force in a viscous damper, the equivalent damping for the motor is stated as

$$c_{eq} = -\frac{{k_a}^2}{r}$$

and therefore the consumed power is determined as

$$P_c = V_p i = \frac{1}{c_{eq}} F^2 + F\dot{z} \tag{16}$$

If λ is defined as (for $\dot{z} \neq 0$)

$$\lambda = \frac{F}{-c_{eq}\dot{z}}$$

then, the power consumption in Equation (16) can be rewritten as

$$P_c = c_{eq}\dot{z}^2 \lambda(\lambda - 1) \tag{17}$$

Figure 4 illustrates the behaviour of this equation with regards to power generation. In Figure 4(a), the normalized power consumption, $P_c/c_{eq}\dot{z}^2$, is plotted versus λ. The regeneration of energy corresponds to the region of the plot when the power consumption is negative (Figure 4(a)). The plot in Figure 4(b) shows P_c versus λ and $\dot{z}$ when $c_{eq} = 2\zeta\omega_n m$, for $\zeta = 0.3$ and $\omega_n = (k/m)^{1/2}$. The values for these parameters are selected to represent dynamic characteristics of a regenerative system for a quarter of a vehicle model, as an example. Figure 4(c) and (d) are the graphs of P_c versus $\dot{z}$ and F which gives a general overview of the behaviour of Equation (17).

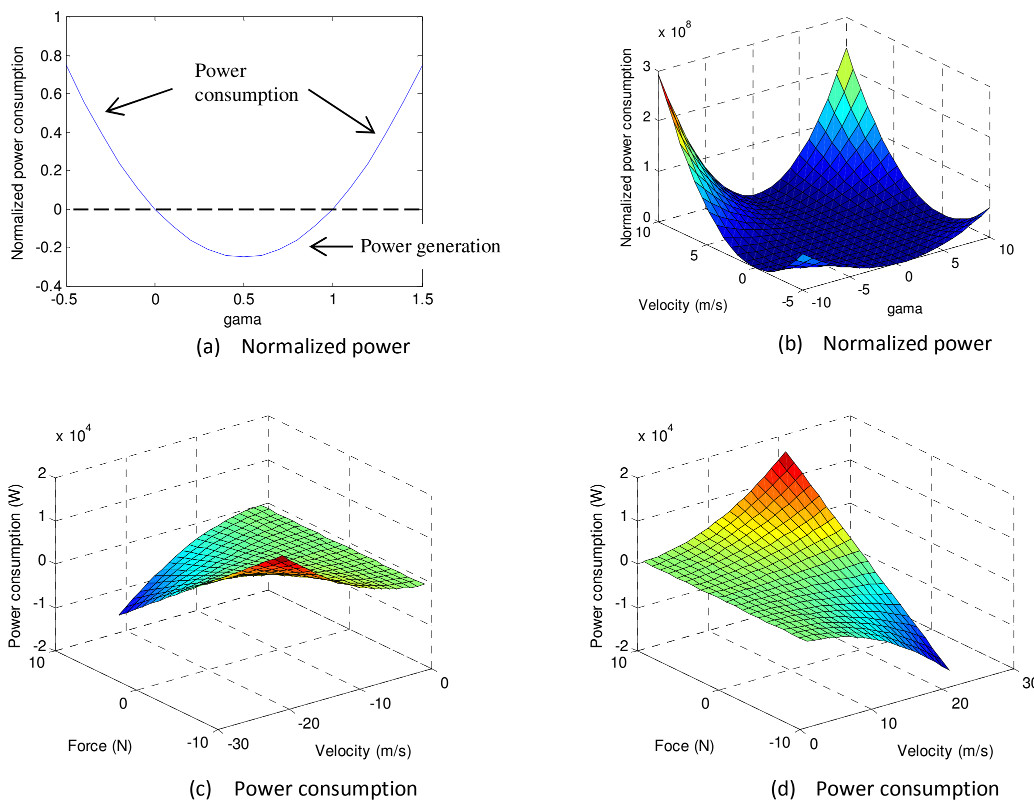
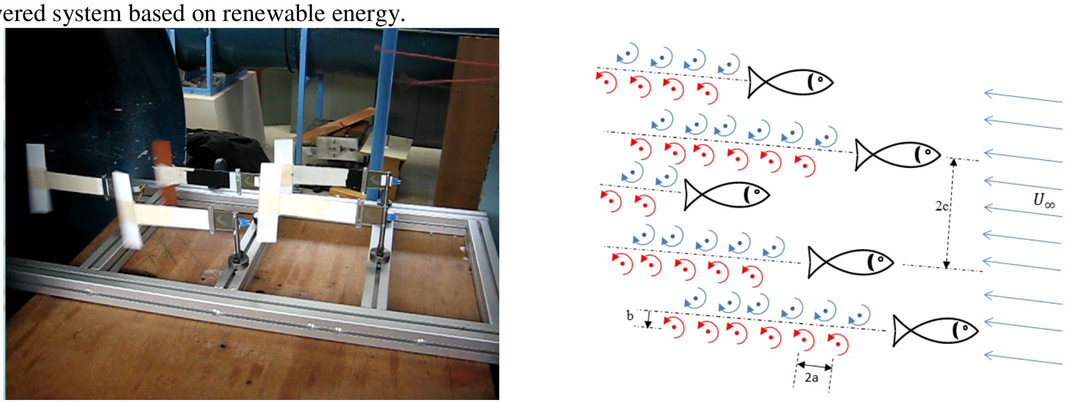


Figure 4: Power consumption and power generation by a regenerative system

The theory addressed below is applicable to self-powered systems including sensors, actuators, etc.. The energy conversion mechanism can be chosen as electromagnetic, piezoelectric, electrostatic, etc. based on what is most suitable to the specific application (e.g. [1], [2], [6], [23]), and therefore the electromechanical properties are defined accordingly to be used for Equations (11) and (12).

4. Bio-inspired design of energy harvesters

Biomimetics helps in improving engineering designs. For instance, a bio-inspired design of vertical wind turbines can improve the efficiency of wind farms inspired by fish schooling [56]. Accordingly, improving energy efficiency of a piezoelectric energy harvesting system is discussed below. Figure 5 illustrates the analogy between fish schooling and piezoelectric energy harvesters. This piezoelectric energy harvesting scheme is designed based on aquatic animal locomotion. The piezoelectric material imbedded in the cantilevers, in the figure, converts the kinetic energy due to the vibration of the cantilevers to electrical energy. The power density of this array of piezoelectric energy harvesters can be improved by arranging them in a certain distance relative to each other inspired by how fish swim in groups to use less muscle energy. The harvested energy from these energy harvesters can be utilized to power electronic components such as sensors. The energy supply is a renewable energy source (i.e. wind energy) and therefore the sensor will not require any battery or external power source. Hence the device operates as a self-powered system based on renewable energy.



(a) Bioinspired Piezoelectric Energy Harvesters – Experimental setup in the wind tunnel

(b) Fish schooling and the vortices generated by fish locomotion as the basis of energy harvesters design

Figure 5: Bioinspired piezoelectric energy harvesters

A sample experimental result of such bioinspired energy harvesters is given in Figure 6 [54]. The stream wise distance of Y= 14 cm and 25.5cm, and cross stream distance of X= 5.5 cm, 8.5 cm and 13.5cm are chosen in this experiment. It is obtained that there is an optimum separation between the cantilevers where an energy harvester can generate the maximum power (Figure 6). This is due to the interaction of harvesters with each other thorough the flutter induced vortices in the fluid flow. Therefore a cantilever device harvests the dynamic energy in the fluid flow generated by other energy harvesters, analogues to how fish swim in groups or birds formation flight for using less muscle energy.

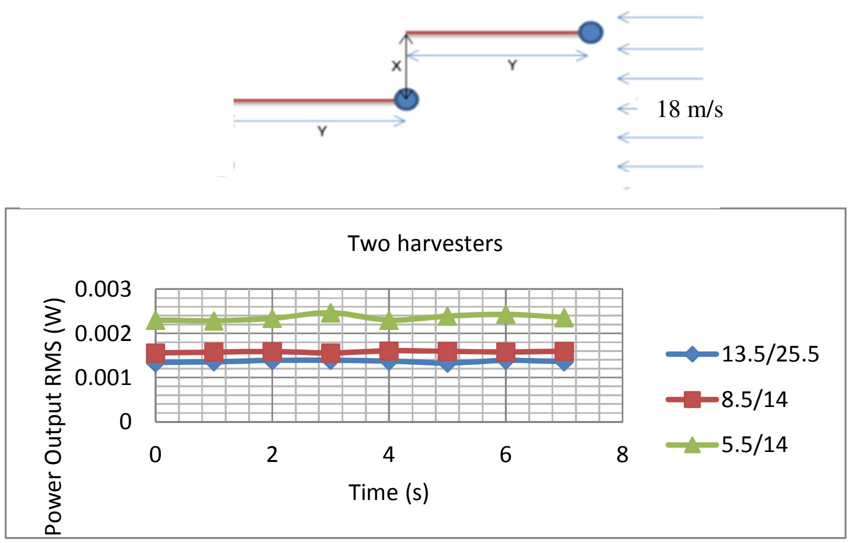


Figure 6: Experimental power output for the bioinspired piezoelectric energy harvesters [54]

5. Renewable energy for dynamic systems

A solar powered airship is introduced in this section as an example of a self-sustained dynamic system, fully powered by renewable energy. Multibody Advance Airship for Transport (MAAT) [59]-[63] (Figure 7) is a self-sustained system powered by solar energy during the day and storing the solar power in fuel cells as a power supply during the night, for long distance journeys. In particular MAAT is based on the concept of feeder-cruiser airships which allows more flexibility for transport relative to existing airships. The feeders can travel individually from the main cruiser airship which allows multiple operations and missions with an airship complex (Figure 7).

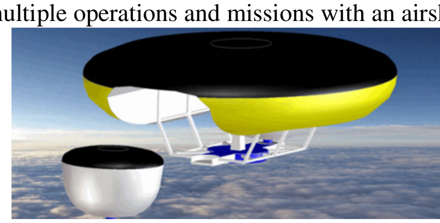


Figure 7: Multibody Advance Airship for Transport (MAAT).

6. Human-powered systems

Experimental investigation is carried out to obtain the power that can be generated by human motion. The facility used for this investigation is an instrumented bike in Figure 8. In this experiment the power output is fixed to a certain value (e.g. 50 W, 100 W, 200 W, etc.) by the system. Therefore the generated power produced by the bike is fixed to a certain value no matter how fast or powerful is the pedalling.

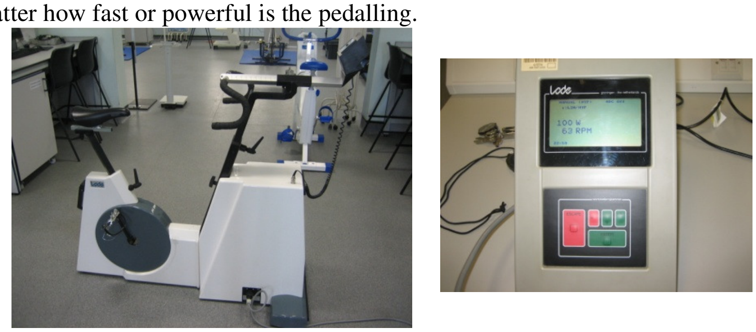


Figure 8: The facility dedicated to measuring the amount of power generated by human motion

The result of this experiment is shown in Table 1.

Table 1: Human power experiment

	Power(w)	**Average cycling speed (RPM)**	**Heart rate**
Age 25	50 w	130	172
Age 40	50 w	110	149
Age 25	100 w	60	133
Age 40	100 w	60	138
Age 25	200 w	90	185

The duration of the generated power depends on the heart rate. The formula to obtain this duration time is

The theoretical maximum heart rate of a person = 220 - Age of the cyclist

If the heart rate of a person is equal to the 75% to 85% of the theoretical maximum heart rate, then the person can continue the activity for about 10 to 15 minutes. For a heart rate of 60% to 75% of the maximum calculated heart rate, an activity of about 30 minutes to 1 hour is predicted. For the heart rate of less than 60% of the theoretical maximum, the person can keep up the activity with this heart rate unless the individual is fatigued.

7. Conclusions

In this article the concept of self-powered dynamic systems was introduced as fully or partially self-powered systems requiring zero or reduced external energy inputs. In such systems, the dynamic system is powered by its own excessive kinetic energy, renewable energy or a combination of both. The illustrative concept was presented along with the background theory. Various applications and scenarios were addressed in regards with self-powered dynamic systems as self-powered sensors, regenerative actuators, human powered devices, and solar powered airships, as examples of self-sustained systems. A bio-inspired piezoelectric energy harvester design was investigated to demonstrate the advantage of employing biomimetics to improve power density of an energy harvesting system.

Acknowledgement

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