Extreme Mechanics Letters 4 (2015) 38–44

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

# Electrostatic converter with an electret-like elastomer membrane for large scale energy harvesting of low density energy sources

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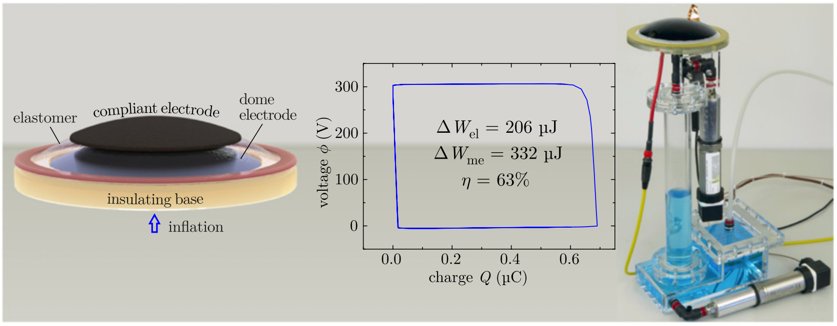
## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 1 June 2015
Received in revised form 27 July 2015
Accepted 27 July 2015
Available online 29 July 2015

*Keywords:*
Energy harvesting
Dielectric elastomer
Electret

## ABSTRACT

Low density energy sources, like wind and solar energy, are widely available and they are increasingly used for electricity conversion worldwide. Ambient energy sources with even lower energy densities are universally available and could equally be converted into electricity with large scale special purpose converter systems. This work discusses a simple concept for an electret-based electrostatic converter suitable for large scale conversion of ambient low density energy sources. The converter is a capacitive charge pump capable of working at low frequencies ($\leq$1 Hz) with a very low mechanical input energy and a high conversion efficiency. With a charged electret-like elastomer membrane the converter can operate without an initial bias voltage supply. First tests with a simple proof-of-concept demonstrator resulted in a mechanical input energy of 332 µJ (9.1 µJ/cm$^2$) and a converted electrical output energy of 206 µJ (5.7 µJ/cm$^2$) per conversion cycle. This gives a total conversion efficiency of 63%.



## 1. Introduction

Ecological as well as economical reasons have led worldwide to a strong increase in the use of low density energy sources for the generation of electricity [1–3]. Notably

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http://dx.doi.org/10.1016/j.eml.2015.07.008
2352-4316/

the use of wind and solar energy is currently expanding exponentially [4,5], because these energy sources are virtually omnipresent and efficiently accessible with modern state-of-the-art technology. Besides wind and solar energy, many other ambient energy sources are readily available in various forms, e.g. with small temperature or pressure gradients, gentle movements of air or water, or small mechanical deformations, etc.; but these energy sources are at present largely unused.

With this work we propose and demonstrate an electrostatic energy converter (EEC) suitable for an efficient large scale mechanical-to-electrical energy conversion of ambient low density energy sources. Our simple not optimized EEC system (Fig. 1) measures ca. 10 cm in diameter; it works with 60% efficiency and converts in a single conversion cycle ca. 9 μJ/cm$^2$ mechanical input energy into 5.5 μJ/cm$^2$ electrical output energy.

The EEC is an electret based variable capacitor converter with an inflatable, very thin and strongly pre-stretched electret elastomer membrane. The illustrations in Fig. 1(a) and (b) show the disk-like system with the relaxed and with the actuated elastomer membrane respectively. The transition from the relaxed into an actuated state is achieved by membrane inflation with a gentle flow of compressed gas. The cross-sectional schematic in Fig. 1(c) shows the inflated elastomer membrane with a surface charge layer on the inner side and with a compliant electrode [6] on top. The membrane covers a rigid counter electrode which has the convex shape of a shallow spherical dome. One or more holes through this dome electrode allow the membrane inflation by an increase in pressure, $\Delta p$, of the enclosed gas below. The pressure related driving force is always directed normal to the pre-stretch direction of the membrane. Already a very low pressure increase is sufficient to lift the membrane from the dome electrode. Actuation is thus possible with very little mechanical input energy. The electrical output energy is related to the change of the variable capacitance build by the dome electrode and the grounded compliant electrode. The capacitive change is large since the pre-stretched membrane measures only a few tens of μm in thickness. This gives a large capacitance in the relaxed state and small capacitances in actuated states when the electrode distance is expanded by several orders of magnitude.

The EEC typically operates with cycle frequencies in the order of approx. 1 Hz. Such a slow operation speed allows an efficient energy coupling to many gradually changing low density energy sources. The low frequency operation is an important difference to many energy harvesting systems discussed in literature. The majority of energy harvesting systems work best in resonance conditions and require vibrational sources of much higher frequencies (>100 Hz). Also, most harvesting systems are small scale as they are designed to power small, autonomous and service free sensors and transducers in inaccessible locations [7,8]. These small systems have generally a small energy output and they are difficult to upscale because of costly fabrication techniques and/or materials. In the ongoing search for more efficient and more competitive harvesting systems, simple polymer materials are being increasingly used for electromechanical conversion elements: A vibration-based harvesting system with a stacked multilayer piezoelectret, made from cellular polypropylene, was reported recently [9], and a number of publications over the last years proposed nano-structured polymer layers as a key-element for efficient and powerful triboelectric nanogenerators [10–12]. Polymer materials allow a low-cost approach to energy harvesting with a particular focus on large scale applications. A promising energy harvesting system for large scale applications are dielectric elastomer generators. A dielectric elastomer generator is an electrostatic converter which converts a large mechanical deformation of one or more elastomer capacitors into electrical energy [13–16]. The energy conversion is accomplished with the help of a connected high-voltage bias source or with a low-voltage biased self-priming circuit [17]. Dielectric elastomer generators are considered to be particularly interesting for ocean wave energy harvesting [18,19]. The high energy density of ocean waves provides enough mechanical power to operate these systems efficiently. The efficient conversion of ambient sources with a lower energy density however, may benefit from a slightly modified design. The key concept of a dielectric elastomer generator – a charge transfer via a variable elastomer capacitance – can be adopted: Here, we propose the EEC for large-scale conversion of low density energy sources and we demonstrate the efficient performance with comprehensive investigations.

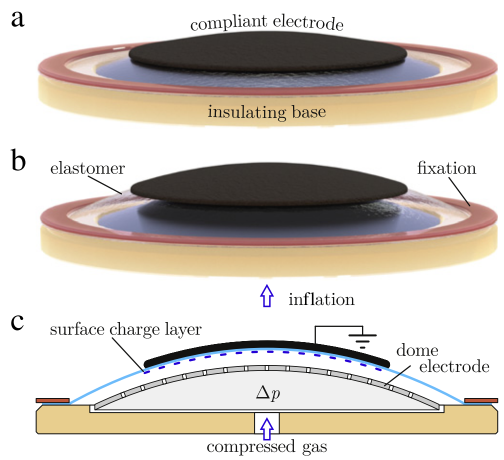


**Fig. 1.** Electrostatic elastomer converter in the relaxed (a) and in an actuated (b) state of operation. Cross-sectional view of the EEC showing a surface charge layer on the inner side of the elastomer (c).

## 2. Theory of operation

The electrical structure of the EEC is described with an equivalent circuit as shown within the dashed outline in Fig. 2(a). The variable capacitance, $C_v$, associated with the air gap between the dome electrode and the elastomer membrane, is connected in series with the static electret capacitance of the elastomer membrane, $C_e$. A permanent surface charge layer with a surface charge density $\sigma$ is located on the inner side of the membrane across the electro-active area, $A$, and causes a built-in voltage, $\phi_{bi} = A\sigma/C_e$ parallel to $C_e$. The electro-active area is defined by the area