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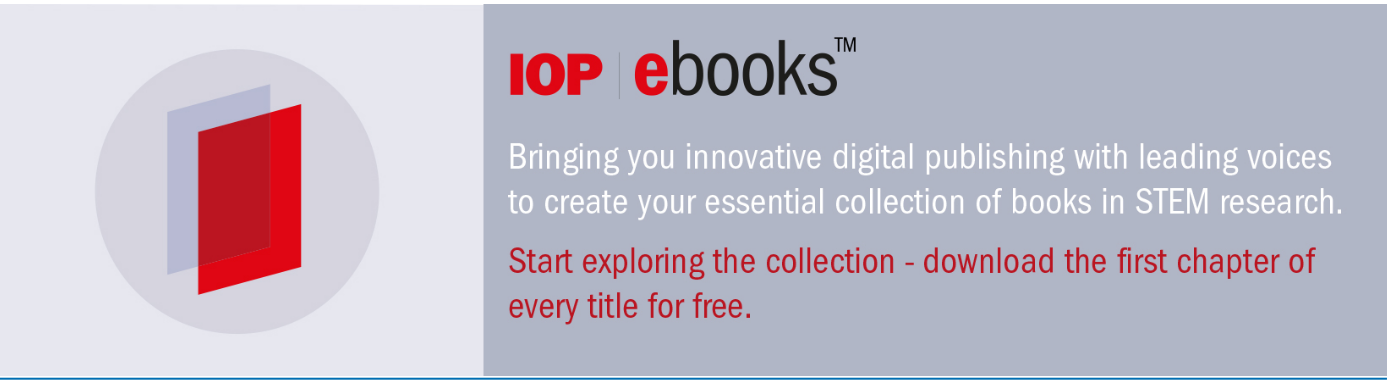

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Electrostatic energy harvesters and fundamental limits to power

Einar Halvorsen

Department of Microsystems, University College of Southeast Norway, Campus Vestfold, Raveien 215, 3184 Borre, Norway

E-mail: `Einar.Halvorsen@usn.no`

Abstract. Analysis of fundamental performance limits to vibration energy harvesting reveal how damping and electromechanical coupling affect performance both for narrow and wide-band excitations. This talk summarizes the performance limits and presents examples of how electrostatic energy harvesters should be made to perform close to the fundamental limits. It is demonstrated how the overwhelmingly dominant contribution to loss, gas damping, can be understood and limited in an electrostatic harvester. It is seen that for wide-band noise excitations, minimizing loss and maximizing coupling largely suffice to approach the fundamental limits closely. For narrow band harvesting, a successful reduction of damping in a design can make optimization complicated because proof mass displacement increases and displacement limitations become important. Performance optimization then also involves adjusting the electrical load and the mechanical stiffness when the acceleration amplitude changes. Approaches to optimize performance are presented and discussed.

Ever since microscale vibration energy harvesting was proposed as a solution to power wireless microsystems [1, 2], there has been much focus on how much power can be obtained and how to do it. This is of course always a pertinent question for a power system, but it is particularly pressing in this case since the devices are driven by inertia so that minimizing size reduces proof mass and therefore the excitation force.

Much insight into the limits of energy harvester performance has been obtained by optimizing linear models with one mechanical degree of freedom [2, 3]. The mathematical structure of such a model is the same regardless of whether the harvester is electrostatic, piezoelectric or electromagnetic even though the physics represented is significantly different between electromagnetic harvesters and the two other types of devices. The model is an electromechanical two-port transducer driven by the forced motion of a damped proof mass and loaded electrically by a resistor. A major insight is that for linear devices driven by harmonic vibrations, a product of electromechanical coupling factor k^2 and mechanical quality factor Q is decisive for the performance. Below a certain value (≈ 2) of k^2Q, this parameter acts like a figure of merit and above this value, the output power of the linear, unconstrained device levels out at its maximum value. It should be mentioned that different authors differ in whether they prefer to use k^2 or the expedient coupling factor $k_e^2 = k^2/(1-k^2)$ as a measure of coupling, and open-circuit Q, short-circuit Q or short-circuit damping ratio as measure of loss.

For large enough k^2Q there is a choice of optimal load resistance that makes it possible to represent the conversion of energy by a linear mechanical damper, hence the damping force is proportional to velocity and we talk of a velocity damped generator (VDRG) [4]. This results in a simpler, more transparent model with analytical expressions for all important quantities. Hence, the model can be conveniently used to estimate power when it is applicable. When it is not, it is still a useful standard to compare to as when defining energy harvester effectiveness [5]. Two other such canonical architectures are also useful, i.e. the Coulomb-damped resonant generator and Coulomb force parametric generator. These have all been analyzed thoroughly, also when there are displacement limits [4].

With random-noise input it is possible to show that the output power of a linear device is governed by the input power and k^2Q [6, 7]. Quite generally, the input power depends only on the proof mass and spectral density of acceleration for this excitation regardless of whether the device is linear or not. For specific nonlinear architectures, i.e. a device with linear transducer and nonlinear springs, it is possible to make rather explicit and sometimes tight bounds on the output power [8]. However, since the input power is more or less given and must either be delivered out or be lost, it is clear that low loss and high coupling is what is needed for this type of excitation. Experimentally, one can exploit the versatility of MEMS electrostatic energy harvesters to demonstrate that by increasing the coupling by increasing the bias of an externally biased electrostatic device, the output power levels out towards the the input power limit [9].

Loss in vibration energy harvesting devices tend to be dominated by gas-damping, see e.g. [10]. It is therefore important to understand and counteract this mechanism. To this end we have revisited a previous electret-based harvester [11] for which damping as a function of cavity pressure has been measured [12, 13]. At atmospheric pressure we measure $Q = 5.1$. A simple estimate based on incompressible flow and simple formulas for hydraulic resistance R to the flow around the mass gives a damping constant $b = A^2R$ corresponding to $Q = 6.9$. A is the cross-sectional area of the mass. The Q has the same of order of magnitude as the experiment, but is constant with pressure while the experiments give $Q > 200$ at 2.5 mbar. Taking into account compressibility of the gas in the cavities at the ends of the proof mass, gives a squeezed-film-like form of damping with the same damping constant and a cut-off $\omega_c = 2P_0/V_0R$ where P_0 is the nominal cavity pressure and V_0 is the nominal cavity volume. This confirms the qualitative pressure dependency of the quality factor and suggests that squeezing of the gas and flow around the mass is the correct mechanism. Finite element calculations in the hydrodynamic limit improves greatly on the accuracy and confirms that the damping can be explained by gas compressibility and constrained flow. Hence damping can be reduced and performance improved by ensuring low cavity pressure and wide channels for gas flow. As a small gap may be desired for the electrostatic transducer, wider channels could be made outside the transducer area. Packaging would beneficially be hermetic and at low pressure.

With successful reduction of damping, the effect of a finite available displacement range becomes important for harmonic excitation of a resonant harvester. A possible method to improve output power under displacement constrained operation, is to use transducing end-stops [14]. However, it can be difficult to benefit from this approach at intermediate accelerations. For the VDRG and the linear two-port harvester, this limitation can be handled by increasing the damping to contain the motion within the limit [4, 15, 16]. For the linear two-port device, one can optimize both stiffness and load resistance[17]. For sufficiently large values of a figure of merit $M \approx k^2Q$, the result follows the VDRG exactly up to a maximum power determined by M. Furthermore, the VDRG performance coincide first exactly then approximately to fundamental upper bounds on power [18] as acceleration is increased.

Motivated by the above considerations, we have investigated load optimization for an electrostatic harvester [19]. Surprisingly, we find that even under displacement-limited operation, the VDRG behaviour is followed up to a maximum power level which is then sustained. This happens even tough we do not perform stiffness optimization, but rather let the proof mass collide with rigid end-stops. This is contrary to the theory on the linear two-port harvester where stiffness optimization is essential to reach this performance. Analysis shows that the reason is that the first harmonic of the force due to end-stop impacts has a value that coincides with a spring force of optimal stiffness. Hence, it is possible to obtain performance close to the theoretical maximum over a range of accelerations that includes displacement limited operation just by adapting the electrical load.

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