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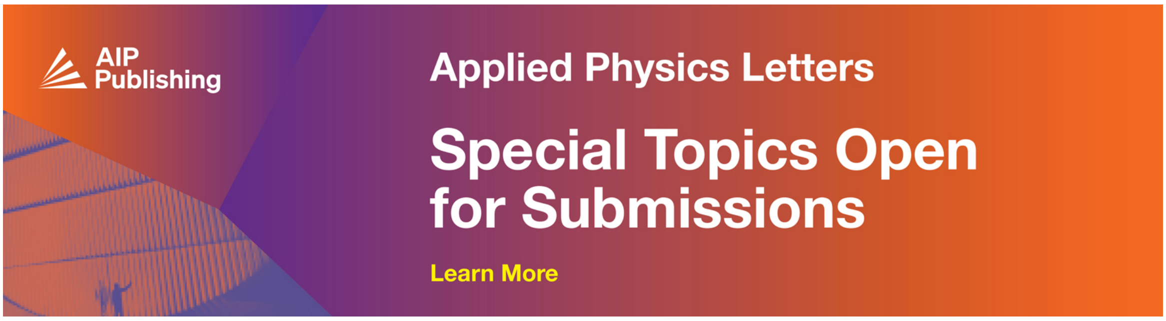

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Electret transducer for vibration-based energy harvesting

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Vibration-based electret energy harvesters with soft cellular spacer rings are presented. These harvesters are closely related to recently introduced electret accelerometers; however, their development targets are partially differing. Various harvesters with seismic masses from 8 to 23 g and surface potentials in the 500 V regime were built and characterized and powers of up to 8 μW at about 2 kHz and an acceleration of 1 g were measured. An analytical model is presented which, for instance, allows the calculation of the frequency response of the power output into a given load resistance. Finally, experimental and calculated results are compared. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4919875]

A number of environmental sources for harvesting energy are available. Among these are light, electromagnetic radiation, thermal gradients, and motion.[1,2] The motional sources are frequently vibrations whose energy may be converted to electrical energy by electromagnetic, electrostatic, or piezoelectric transduction. From these, the electrostatic method has the advantage of being relatively simple to realize with only inexpensive components required for its implementation. This method delivers comparatively high output voltages into high-impedance circuits and can be easily miniaturized. Particularly, electret-based or piezoelectret-based transducers, which do not require an external biasing source, are frequently used for electrostatic energy harvesting.[3–8]

Electret harvesters have been implemented according to a variety of designs. All such devices employ an electret in an air gap between two electrodes. The electret generates the electric field required for the operation of the device. Electret harvesters may be classified, just as the other electrostatic transducers, as in-plane or out-of-plane devices.[3,9,10] The former operate with constant air gap thickness by performing a sideways displacement of the electrodes[4,11–17] while the out-of-plane devices function by means of a modulation of the air gap thickness,[18–20] just as an electret microphone,[21] or electret accelerometer.[22] While some of the electret devices are of conventional design, others are micromachined MEMS systems.

In the present study, an electret harvester of the gap-modulation type, based on electret accelerometers,[22–24] is described. The device differs from existing harvesters by the use of a soft cellular polypropylene spacer ring which provides two essential functions of electret devices. First, it establishes an air gap of defined thickness; and second it supplies the main restoring force of the transducer. Such a ring allows for the construction of compact, simple, and inexpensive harvesters that can be implemented in a wide range of sizes and working frequencies.

In the following, after a description of the electret harvester design and the experimental setup, an analytical model for the harvester is presented and theoretical data for the harvested power are given. Next, experimental results for the power as function of frequency, seismic mass, static pressure on the cellular ring, and air gap thickness are described and compared with the theoretical predictions and with data from piezoelectret energy harvesters. At last, a summary and some conclusions are presented.

Vibration-based energy harvesters basically consist of one or more seismic masses and one or more springs or spring elements. The vibration-based electret harvester used for the present investigations is shown schematically in Figure 1. Two spring/screw combinations, allowing the adjustment of the static forces in the harvester, are acting via a metal arbor on the seismic mass and the attached electret film which in turn compresses the soft cellular polymer spacer ring, placed between the electret film and a metallic backplate. The static forces of the two springs and the cellular ring, the other involved spring element, anchors the stack, consisting of arbor, seismic mass, electret film, cellular ring, and backplate, in horizontal direction but allow free movement in vertical direction. An additional spring element may be involved if the air volume enclosed by the cellular ring is sealed. This, however, was not the case for the presented harvesters. Besides its role as a spring element, the cellular ring with a typical thickness of 40 μm, in conjunction with a recess in the back plate, also acts as a spacer and adjusts the height of the air gap (distance between electret film and

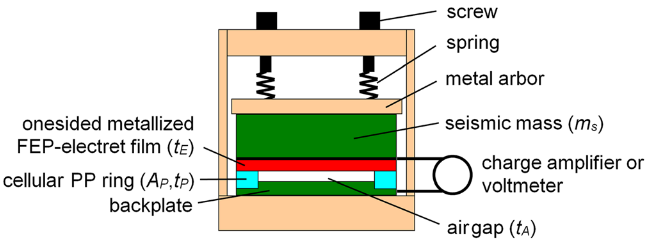

FIG. 1. Design of the electret energy harvester. A static force is generated by two spring/screw-combinations allowing free movement and vibration of the seismic mass in vertical direction. The output signal is taken from the metallized layer of the FEP film and the metallic backplate.

[a)]Electronic mail: j.hillenbrand@nt.tu-darmstadt.de backplate). For a typical harvester, an air gap thickness of nominally 10 μm was achieved by using a recess of 30 μm depth. The fluoroethylene propylene (FEP) electret films were metalized on the upper side, cemented onto the seismic mass, thereafter corona charged to a typical voltage of 500 V, and finally mounted into the harvester. The two output electrodes of the harvester are the metallic back plate and the metal layer of the FEP film.

For the frequency response measurements, the electret harvester is mounted on an electrodynamic vibration exciter (B&K 4809) which is driven by a power amplifier (B&K 2713). The harvester is either connected to a charge amplifier (B&K2635) or to a voltmeter (Keithley 600B) and their output signal is filtered and recorded by an audio analyzer (R&S UPD) which also generates the sinusoidal input signal for the power amplifier. From the short-circuit charge or the open-circuit voltage measurements, both the frequency response of the power generated in a load resistance R_l and the optimal power at resonance are calculated as discussed below.

An analytical model for the power generated by an *electret* energy harvester in response to an input acceleration with the RMS value a can be easily derived from the model for a single-layer *piezoelectret* energy harvester,[7,8] if the piezoelectric constant d_{33} in the *piezoelectret* harvester model is replaced by an equivalent piezoelectric constant $d_{33,\mathrm{eq}}$ in the *electret* harvester model. Assuming that the deflection of the seismic mass relative to the housing, which is identical to the dynamic thickness change of the air gap, is small compared to the thickness of the air gap, the generated power P of an *electret* harvester can then be written as[7]

$$P = \frac{m_s^2\, R_l\, d_{33,eq}^2\, \omega^2\, a^2}{\left[\left(\frac{\omega^2}{\omega_0^2}-1\right)^2 + 4\,\varsigma^2\,\frac{\omega^2}{\omega_0^2}\right]\left[1+(R_l\, C_s\, \omega)^2\right]}, \tag{1}$$

where R_l is the load resistance, ω_0 is the resonance frequency of the harvester, ω is the circular frequency, and ζ is the damping ratio. The equivalent piezoelectric constant $d_{33,eq}$ in the *electret* harvester model has to be defined in analogy to the piezoelectric charge constant of the *piezoelectret* film in the *piezoelectret* harvester and thus corresponds to the charge density σ (or charge Q) generated in short circuit by an *electret* transducer[22–24] in response to a given applied stress T (or force F). The restoring forces are due to the cellular ring, the mechanical springs, and the air gap. Assuming that the springs are much softer than the cellular ring, only this ring and the air gap have to be taken into consideration. Then $d_{33,eq}$ can be calculated as[24]

$$d_{33,eq} = \frac{\sigma}{T} = \left(\frac{Y\,A_P}{t_P} + \frac{\gamma\, p_0\, A_A}{t_A}\right)^{-1} \frac{C_s\, \varepsilon_r\, V_E}{(\varepsilon_r\, t_A + t_E)}, \tag{2}$$

where the terms with Y and p_0 correspond to the stiffness of the ring and of the air gap, respectively, and C_s is the sensor capacitance, ε_r is the relative dielectric constant of the electret, V_E is the polarization voltage, t_A is the thickness of the air gap between the electret layer and the backplate, t_E is the thickness of the electret film, ε_r is the relative dielectric constant of the electret, V_E is the polarization voltage, t_P is the thickness of the polypropylene spacer, A_P its area, Y its Young's modulus, γ is the adiabatic index of air, p_0 is the atmospheric pressure, A_A is the area of the air gap, and t_A its thickness.

To enhance the sensitivity of the harvester, it is desirable to open the air gap such that air can freely stream in and out in order to reduce the stiffness. This is achieved by the irregular and leaky interface between the electret film and the rough surface of the spacer ring.[23] The stiffness of the electret transducer is then only given by the cellular polypropylene spacer.

The resonance frequency ω_0 may be expressed as a function of the seismic mass and the mechanical compliance c_m of the energy harvester as

$$\omega_0 = \sqrt{\frac{1}{m_s\, c_m}} = \sqrt{\frac{1}{m_s}\left(\frac{Y\,A_P}{t_P} + \frac{\gamma\, p_0\, A_A}{t_A}\right)}, \tag{3}$$

where m_s is the seismic mass.

The power generated by the energy harvester reaches a maximum at the resonance frequency ω_0 when ω_0 and the electrical cutoff frequency are matched.[7] This is achieved with the optimal resistance $R_{opt} = \frac{1}{\omega_0\, C_s}$. The optimal (maximum) power P_{opt} can then be calculated from Eqs. (1)–(3) and, if the stiffness of the air volume is neglected, amounts to

$$P_{opt} = \frac{a^2\, C_s\, \varepsilon_r^2\, V_E^2}{\omega_0^3\, (\varepsilon_r\, t_A + t_E)^2\, 8\, \varsigma^2} = \sqrt{\frac{m_s^3\, t_P^3}{A_P^3\, Y^3}}\, \frac{a^2\, C_s\, \varepsilon_r^2\, V_E^2}{(\varepsilon_r\, t_A + t_E)^2\, 8\, \varsigma^2}. \tag{4}$$

As stated above, the model holds when the deflection of the seismic mass is much smaller than the air gap. For the present harvesters, this condition is fulfilled for accelerations up to about 1 g. For accelerations of approximately 10 g, the deflection of the seismic mass reaches the air gap thickness and the electret film on the seismic mass touches the backplate. This limits the generated power and may lead to a discharge of the electret.

P_{opt} can be determined experimentally either from the measurement of the charge flowing through R_{opt} or from the measurement of the voltage across R_{opt}.[7] Alternatively in the present work, P_{opt} is computed from measurements of the short-circuit charge q_0 or the open-circuit voltage V_0 at the resonance frequency (equal to the electrical cutoff frequency). For the optimal resistance R_{opt}, q_0 and V_0 must be divided by a factor of $\sqrt{2}$.[25] Thus, the power is given by

$$P_{opt} = R_{opt}\left(\frac{1}{\sqrt{2}}\, q_0\, \omega_0\right)^2 = \frac{\omega_0\, q_0^2}{2\, C_s} \tag{5a}$$

and

$$P_{opt} = \frac{1}{R_{opt}}\left(\frac{1}{\sqrt{2}}\, V_0\right)^2 = \frac{1}{2}\,\omega_0\, C_s\, V_0^2. \tag{5b}$$

The results of the experimental investigation of several electret energy harvesters are shown in Figs. 2–5. The effects of various parameters, having a significant influence on the harvested power, were investigated. These parameters are the seismic mass (Figs. 2 and 3), the static pressure applied by

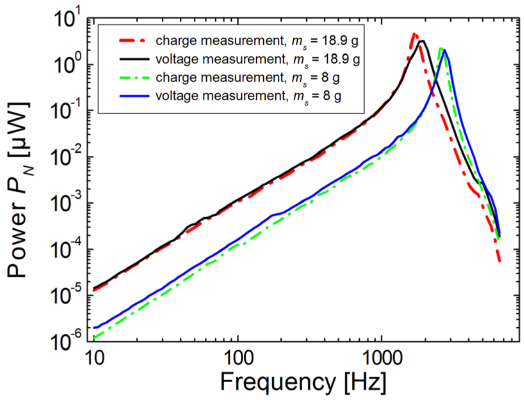

FIG. 2. Normalized power calculated from charge (dashed lines) and voltage (full lines) measurements for two different seismic masses.

the two springs (Fig. 4) and the air gap thickness (Fig. 5). In all investigated energy harvesters, electret films with a thickness $t_E = 25\,\mu$m were used. The area of the air gap was $A_A = 0.8\,\text{cm}^2$. In these figures, the normalized power P_N, corresponding to an input acceleration of $1\,g = 9.81\,\text{m/s}^2$ (RMS), is plotted.[7,26]

The frequency responses of the normalized power of energy harvesters with seismic masses of 8 g and 22.6 g are shown in Fig. 2. The power is calculated from charge and voltage measurements according, respectively, to Eqs. (5a) and (5b). The results obtained from charge and voltage measurements agree very well below the resonance frequency, whereas some discrepancy can be observed in the location of the resonance frequencies and the quality factor. This may be explained by the fact that the voltage measurements were performed several days after the charge measurements. In this period of time, the response at resonance is likely to be altered by creeping of the cellular polypropylene spacer. The ratio of the resonance frequencies with seismic masses of 8 g and 18.9 g is in good agreement with the square root of the ratio of the seismic masses, as expected.

A more detailed investigation of the dependence of resonance frequency and the normalized power generated at resonance on the seismic mass is shown in Fig. 3. The theoretical calculations (solid curves) were performed according to Eqs. (3) and (4), respectively, by using the parameter values of the energy harvesters $t_A = 22\,\mu$m, $t_E = 25\,\mu$m, $A_p = 25\,\text{mm}^2$, and $t_p = 40\,\mu$m. The quantities Y and ζ were determined from the response at the resonance frequency and the value $V_E = 450\,$V was obtained from the charge and voltage sensitivities of the harvesters used as accelerometers below their resonance frequency. A capacitance of $C_s = 21.5\,$pF was measured with an LCR Databridge 451 from Telemeter Electronic GmbH. The agreement between the measured resonance frequencies and the theoretical values from Eq. (3) (full red line online) is good. Despite a slight scatter due to variations of the damping ratio, the measured normalized power shows also good agreement with the curve calculated from Eq. (4), which confirms experimentally the expected proportionality of the maximum power generated by electret energy harvesters with $\sqrt{m_s^3}$.

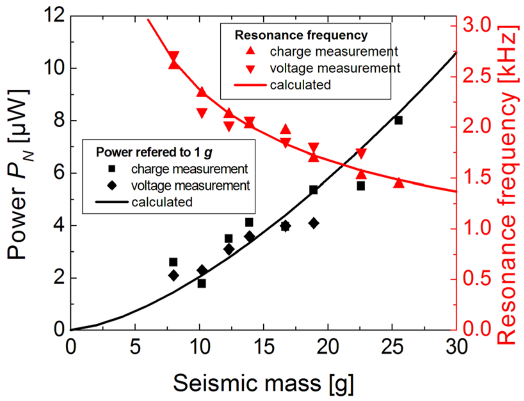

FIG. 3. Dependence of the resonance frequency and the normalized power generated at this frequency on the seismic mass, calculated from charge and voltage measurements.

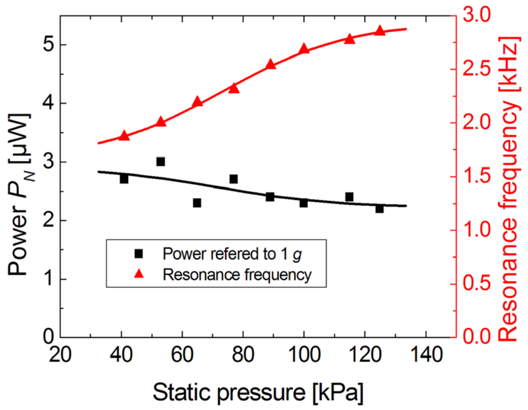

FIG. 4. Dependence of the resonance frequency and the normalized power generated at this frequency on the static pressure applied to the seismic mass of 8 g. Experimental values calculated from charge measurements, the curves are best fits.

Measurements of resonance frequency and maximum normalized power of an energy harvester as a function of the static pressure applied to the seismic mass are shown in Fig. 4. The springs used to hold together the seismic mass, the cellular spacer ring, and the back plate apply a stress to the cellular polypropylene. This is expected to increase its Young's modulus, leading to a larger resonance frequency of the harvester and a decrease of the generated power. As shown in Fig. 4, this rise of the resonance frequency is observed in the entire measuring range of the static pressure

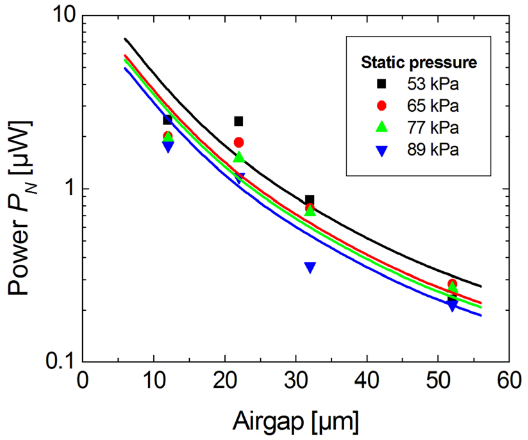

FIG. 5. Dependence of the normalized power at resonance generated by an electret energy harvester on the air gap thickness (see Section V.A. in Ref. 23) for various applied static pressures with a seismic mass of 8 g.

from 40 to 125 kPa. The power generated at the resonance frequency has a decreasing trend, which confirms the expected behavior of the harvester. The slight scatter of the power data, especially in the range below 80 kPa, is due to variations of the damping ratios that cannot be controlled accurately.

Besides the seismic mass, the elastic properties of the polypropylene spacer ring and the electret voltage, the thickness of the air gap between the electret layer and the upper electrode is another parameter that significantly influences the power generated by an electret harvester. Fig. 5 shows the normalized power at the resonance frequency of about 2.3 kHz generated by harvesters with a seismic mass of 8 g and various air gap thicknesses obtained with recesses in the back plate from 0 μm to 40 μm (see above). For all measurements, the deflection of the seismic mass was small compared to the air gap thickness. The static pressure exerted by the two springs is a parameter for the measurements. The value of Young's modulus was calculated for each static pressure from the resonance frequency of the harvesters (see Eq. (3)). This allows one to calculate the generated power with Eq. (4). The measured dependence of the generated power on the air gap thickness t_A agrees relatively well with the calculated curves.

In this paper, compact electret energy harvesters of simple design are presented in which the air gap between the seismic mass and the electret is controlled by a soft cellular polypropylene spacer ring. This design is similar to that of piezoelectret energy harvesters when the piezoelectret stack is replaced by the combination of the electret film, the air gap, and the spacer ring. With seismic masses of 8–22.6 g the generation of power up to 8 μW at frequencies between 1.5 and 2.5 kHz is possible with an input acceleration of 1 g (RMS). It was experimentally verified that the power generated at the resonance frequency in the optimal load resistance is proportional to $m_s^{3/2}$. The calculated dependence of the harvested power on the air gap thickness was quantitatively confirmed by the experimental data, and the influence of the static pressure applied on the cellular spacer ring was explained qualitatively.

Energy harvesters based on the presented design with a soft cellular spacer have several advantages: First, compact harvesters merely larger than the seismic mass can be built, since cellular ring, air gap and backplate are relatively flat and have no larger diameter than the seismic mass. Second, harvesters with seismic masses from the g-up to the kg-regime can be realized when spacer geometry, air gap thickness, and electret voltage are adapted. Third, the temperature stability of the electret harvesters is comparable to that of electret microphones, thus much better than that of piezoelectret harvesters, and good enough for many applications. Fourth, in contrast to piezoelectret harvesters, mechanical and electrical properties of the electret harvesters can be designed quite independently since the mechanical properties are depending mainly on the spacer ring, while the electrical properties are determined by the electret voltage and the air gap thickness.

This allows, in particular, the construction of electret harvesters with very low resonance frequencies ($<$100 Hz) and, according to Eq. (4), large output power. For such low resonance frequencies, however, large deflections of the seismic mass are obtained. Thus, if lower operating frequencies are desired, the air gap thickness has to be increased correspondingly to avoid contact between electret and backplate.[20]

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