Prepolarized Electroacoustic and Vibrational Sensors

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Introduction

New developments in the field of prepolarized capacitive sensors for sound and vibration are discussed. The sensors are either based on electrets or on piezoelectrets, the latter are also called ferroelectrets [1,2]. With such materials, novel microphones, ultrasonic transducers, accelerometers and vibration-based energy harvesters have been implemented. A few of these transducers will be described in this paper.

Electrets and Piezoelectrets

A comparison in Fig. 1 shows the important features of electrets and piezoelectrets [1,2]. While electrets consist of solid materials, such as the polymer polytetrafluoroethylene (PTFE) or the copolymer fluoroethylenepropylene (FEP), piezoelectrets are made of cellular polymers, for example cellular polypropylene (PP) or layers of polymers with air voids between them. The charging required for achieving electret or piezoelectret properties can be accomplished in both cases with a corona discharge. Thereafter, electrets exhibits surface charges, space charges or a dipole polarization while piezoelectrets show charges of opposite sign on the upper and lower surfaces of the voids, as depicted in the top and bottom parts of Fig. 1.

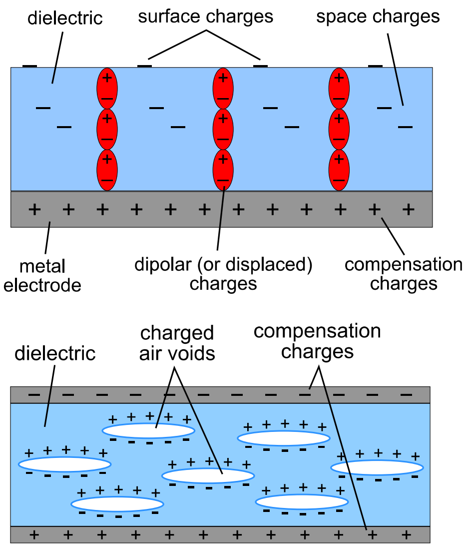

Figure 1: Schematic view of electret (top) and piezoelectret (bottom).

Electrets act through their external field in air gaps adjacent to them while piezoelectrets show a piezoelectric effect upon mechanical or electrical excitation. Typical properties of piezoelectrets are listed in Table 1. The Table indicates that the d_{33} or charge coefficient of piezoelectrets is comparable with that of PZT ceramics. This coefficient is important for sound transmitter applications. More prominent is the g_{33} or voltage coefficient which is important for sensor devices, where a high open-circuit voltage is desirable. Also, the small Young's modulus of these materials is evident; the corresponding softness is of importance in many applications where good acoustic matching with air is required.

	Cellular polypropylene	PZT (PI Ceramic)
Piezoelectric charge coefficient d_{33} (pC/N)	350	500
Piezoelectric voltage coefficient g_{33} (Vm/N)	30	0.02
$d_{33}\, g_{33}$ (GPa^{-1})	11	0.1
Density (g/cm^3)	0.5	7.8
Young's modulus (GPa)	0.0005	100

Table 1: Comparison of PP piezoelectret with PZT (lead ciconate titanate) ceramic.

Microphones

Schematic views of microphone designs based on electrets or piezoelectrets are shown in Fig. 2. The two microphone types differ chiefly by the absence of an air gap. This makes the design of piezoelectret microphones very simple.

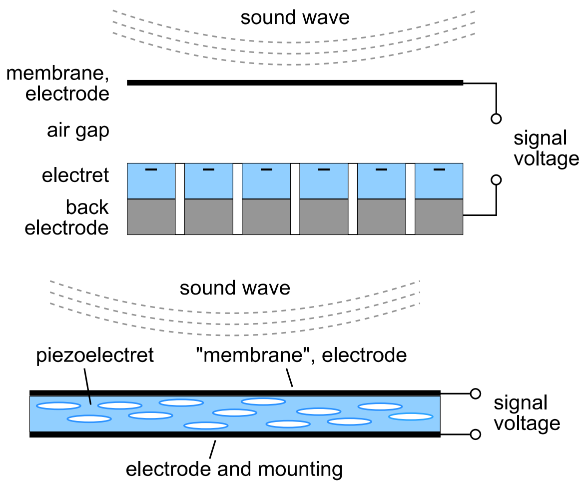

Figure 2: Schematic view of electret microphone (top) and piezoelectret microphone (bottom).

A novel electret microphone design is shown in Fig. 3 [3]. This microphone features a stiff diaphragm consisting of a 0.5 mm Aluminum plate carrying the FEP electret and a cellular polymer spacer ring used for obtaining both the air gap distance and the restoring force of the device. A tensioned PP or FEP membrane on top of the Al plate is used to mechanically adjust the pressure of the plate on the cellular ring and to stabilize the system. Advantages of this sensor are the robust and waterproof design, the reduction of distortion due to the piston-like motion of the diaphragm, and the avoidance of collapse by the stiff diaphragm design. Frequency responses of such a microphone with different tensions of the membrane are depicted in Fig. 4.

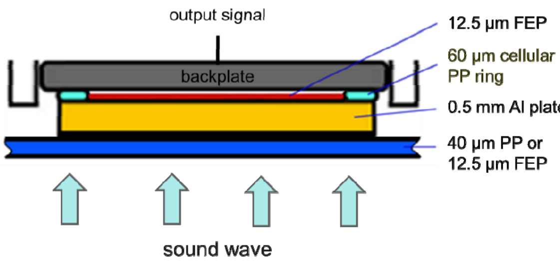

Figure 3: Schematic design of electret microphone with stiff diaphragm and cellular polymer spacer ring [3].

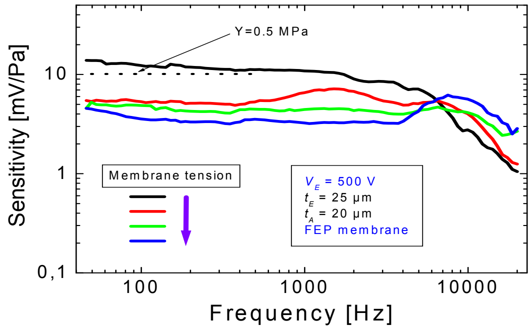

Figure 4: Frequency responses of electret microphones with a stiff diaphragm [3].

Electret microphones on printed circuit boards without an air cavity behind the backplate have also been designed [4]. This allows for a very flat construction which can be of importance in devices such as boundary layer microphones. The frequency responses of two such sensors are shown in Fig. 5. The measured results are in good agreement with simulations, which are also plotted in the figure.

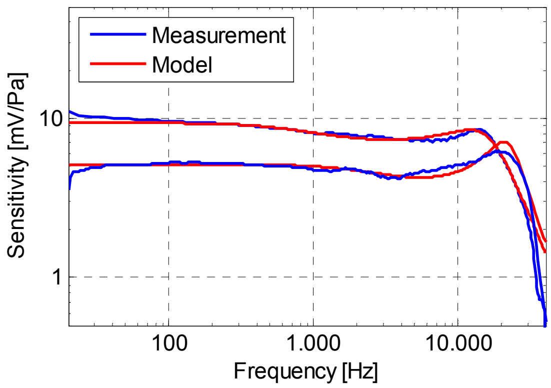

Figure 5: Measured and simulated frequency responses for two PCB integrated electret microphones [4].

Piezoelectret microphones are relatively new transducers [5,6] which consist merely of a piezoelectret with proper mounting and contacting, as shown in Fig. 2, bottom. They do not require an air gap; thus, several piezoelectret films can be stacked and therefore arranged in electrical series. In such an arrangement, the output voltages of the films add up and the obtained sensitivity is proportional to the number of layers. The frequency responses of microphones with stacks of one to six films, which confirm this dependency, are shown in Fig. 6. Sensitivities of about 15 mV/Pa at equivalent noise levels of 26 dB(A) can be obtained with such transducers.

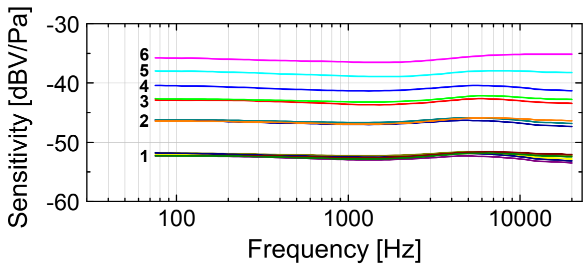

Figure 6: Frequency responses of stacked piezoelectret microphones.

Directional piezoelectret microphones can be designed by using two or more closely-spaced transducers of the design shown in Fig. 2 and feeding their output signals into sum and delay beamformers. Thus, bidirectional, cardioid and close-talking sensors have been designed and studied [7].

Ultrasonic Transducers

Piezoelectrets are very suitable for designing transmitters and receivers for the near ultrasonic frequency range, up to the thickness resonance at about 100 kHz [8]. Their sensitivity can also be improved by stacking and by additional DC-biasing [9,10].

The frequency response on axis of an ultrasonic transmitter consisting of three piezoelectret film layers is shown in Fig. 7. Parameter is the additional DC-bias applied. The maximum sensitivity at 60 to 90 kHz amounts to about 1 Pa/V. Considering size of the transducer, distance, and frequency, this is the highest sensitivity achieved with piezoelectret transmitters.

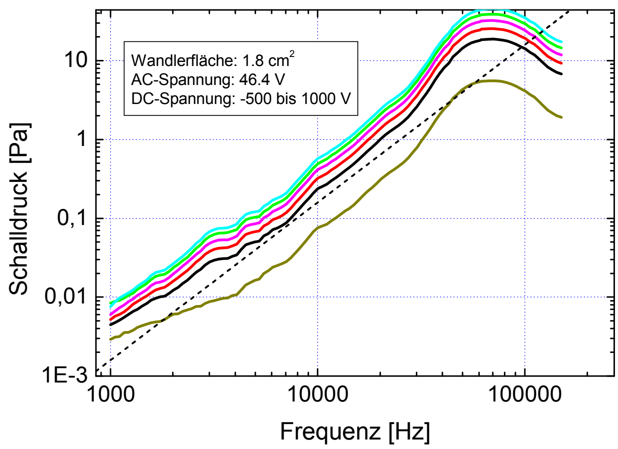

Figure 7: On-axis sound pressure generated at a distance of 60 mm by a three-layer piezoelectret transducer of 1.8 cm² area. The peak sensitivity at 60 to 90 kHz is 1 Pa/V. The dashed line is the calculated sound pressure for 0 V DC-bias, obtained for d_{33} = 1500 pC/N [8,10].

Accelerometers

The use of electrets and piezoelectrets in accelerometers is relatively new. These devices are lightweight, inexpensive, and sensitive. Furthermore, they can be used down to very low frequencies, since the signal charges are not dissipating due to the extremely low conductivity of the electret and piezoelectrets materials. Such accelerometers can be either operated in short or in open circuit, requiring either charge or voltage amplifiers, respectively.

The design of an *electret* accelerometer is depicted in Fig. 8 [11]. It consists of a back plate onto which an FEP electret is cemented. This electret is separated by an air gap from a seismic mass. The restoring force of the transducer is provided by a cellular PP spacer ring, just as in the plate microphone shown in Fig. 3.

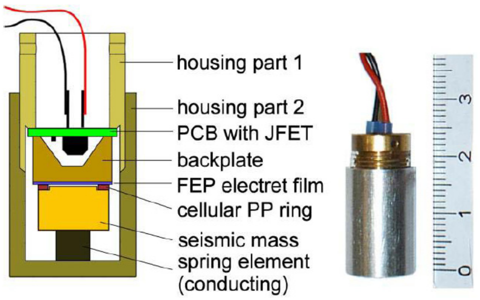

Figure 8: Cross section (left) and photograph (right) of an electret accelerometer [11].

The high sensitivities possible with such accelerometers are shown in Fig. 9. The three frequency responses were achieved by applying different static pressures on the cellular ring of one such device, with the smallest pressure yielding the largest sensitivity of 700 mV/*g*. This high sensitivity is due to the small air gap of nominally only 5 µm. For increasing static pressures, higher resonance frequencies and thus larger bandwidths are achieved with this accelerometer. A seismic mass of 2.13 g was used.

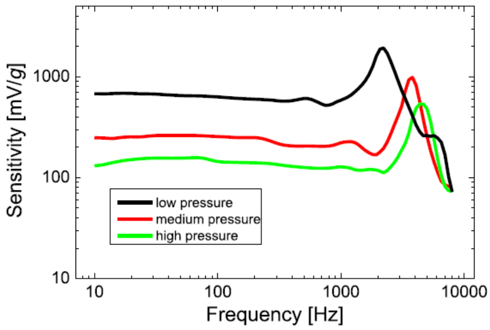

Figure 9: Frequency responses of the sensitivity of an electret accelerometer for different static pressures on the cellular PP ring [11].

Piezoelectret accelerometers are designed similarly to the electret types, with electret plus air gap replaced by one or several piezoelectret films or by a folded film. Just as with piezoelectret microphones, the use of several films in series increases the voltage sensitivity. Folding a film to obtain a zigzag-shaped multilayer, and applying a seismic mass to such a multilayer stack, the inertial forces due to the acceleration will act on each layer. If operated in short circuit with a charge amplifier, the charge sensitivity will then increase proportionally to the number of layers.

The sensitivity is also proportional to the seismic mass while the resonance frequency decreases inversely proportional to its square root. These relationships were confirmed experimentally for a three-layer piezoelectret accelerometer with different seismic masses, as shown in Fig. 10 [12].

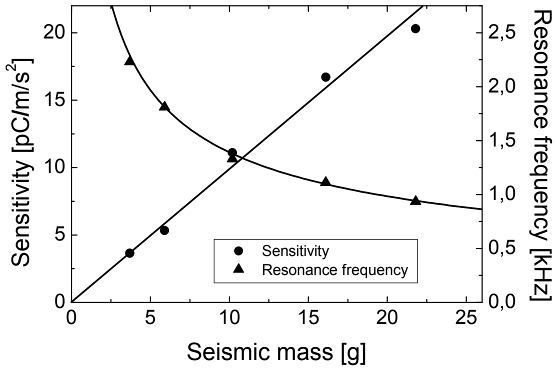

Figure 10: Charge sensitivity (at 100 Hz) and resonance frequency of a three-layer piezoelectret accelerometer as a function of its seismic mass [12].

Energy Harvesters

Energy harvesters transform thermal, optical or mechanical energy from the environment into electrical energy. The interest in this paper is in the conversion of vibrational mechanical energy by electret or piezoelectret transducers. Corresponding energy harvesters are similar to accelerometers, but are usually designed to have a lower resonance frequency. This frequency should be preferably in the range of the environmental vibration sources i.e. below a few 100 Hz.

The power output of a piezoelectret energy harvester with different seismic masses for an acceleration of 1 *g* as a function of frequency is shown in Fig. 11 [13,14]. The maximum power generated by this single-layer harvester is 18 µW at its resonance frequency of 400 Hz and an acceleration of 1 *g*. For harvesters with several film layers, lower resonance frequencies and higher harvested power is expected. New experiments with electret-based energy harvesters are under way [14].

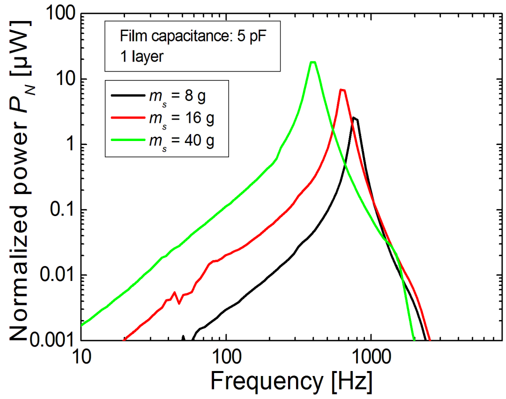

Figure 11: Power generated by a piezoelectret energy harvester at an acceleration of 1 *g* for different seismic masses [14].

Summary and Conclusions

The *electret* transducers discussed in this paper possess special constructional features, such as stiff diaphragms or novel restoring elements. Their design results in improved performance characteristics, for example greater robustness, reduced size and distortion, and the avoidance of system collapse. The *piezoelectret* transducers have the advantage that, because of the microscopic internal air voids of the cellular material, no external air gap is required. They have been designed as stacked systems, which improves the sensitivity of audio microphones, ultrasonic transducers and accelerometers and the power output of energy harvesters. The performance of the experimental transducers discussed are comparable to, or better than, those of conventional systems. Corresponding commercial applications are possible as soon as piezoelectret materials with improved thermal and mechanical properties are available.

Literature

[1] Sessler, G. M. and Gerhard-Multhaupt, R., Editors, Electrets, 3rd Ed., Laplacian Press, Morgan Hill Ca., 1998

[2] Bauer, S., Gerhard-Multhaupt R., and Sessler, G. M., Ferroelectrets: Soft electroactive foams for transducers, Physics Today 57 No. 2 (2004), 37 – 43

[3] Hillenbrand J., Haberzettl, S., and Sessler, G. M., Electret microphones with stiff diaphragms, J. Acoust. Soc. Am. 134 (2013), EL499 – EL505

[4] Pfeil, F., Hillenbrand, J., and Sessler, G. M., PCB integrated electret sensors for air- and structure-borne sound, Sensoren und Messsysteme 2014

[5] Kressmann, R., New piezoelectric polymer for air-borne and water-borne sound transducers, J. Acoust. Soc. Am. 109 (2001), 1412 – 1416

[6] Hillenbrand J. and Sessler, G. M., High-sensitivity piezoelectric microphones based on stacked cellular polymer films, J. Acoust. Soc. Am. 116 (2004), 3267 – 3270

[7] Hillenbrand, J., Haberzettl, S., and Sessler, G. M., Nahbesprechungseigenschaften von differentiellen Pidezoelektretmikrofon-Arrays, DAGA 2012, 101 – 102

[8] Hillenbrand, J. and Sessler, G. M., DC-biased piezoelectret film transducers for airborne ultrasound, Ferroelectrics 472 (2014), 77 – 89

[9] Hillenbrand, J. and Sessler, G. M., DC-biased ferroelectrets with large piezoelectric d_{33}-coefficients, J. Appl. Phys. 103 (2008), 074103

[10] Hillenbrand, J. and Sessler, G. M., Piezoelektret-Sender für Luftultraschall, DAGA 2015

[11] Hillenbrand, J., Motz, T., and Sessler, G. M., High sensitivity electret accelerometer with integrated FET, IEEE Sensors Journal 14 (2014), 1770 – 1777

[12] Hillenbrand, J., Kodejska, M., Garcin Y., von Seggern, H., and Sessler, G. M., High-sensitivity piezoelectret-film accelerometers, IEEE Trans. Dielectr. Electric. Insulat. 17 (2010), 1021 – 1027

[13] Pondrom, P., Hillenbrand, J., Sessler, G. M., Bös, J., and Melz, T., Vibration-based energy harvesting with stacked piezoelectrets, Appl. Phys. Lett. 104 (2014), 172901

[14] Pondrom, P., Hillenbrand, J., Sessler, G. M., Bös, J., and Melz, T., Schwingungsbasiertes Energy Harvesting auf Elektret- und Piezoelektretbasis, DAGA 2015